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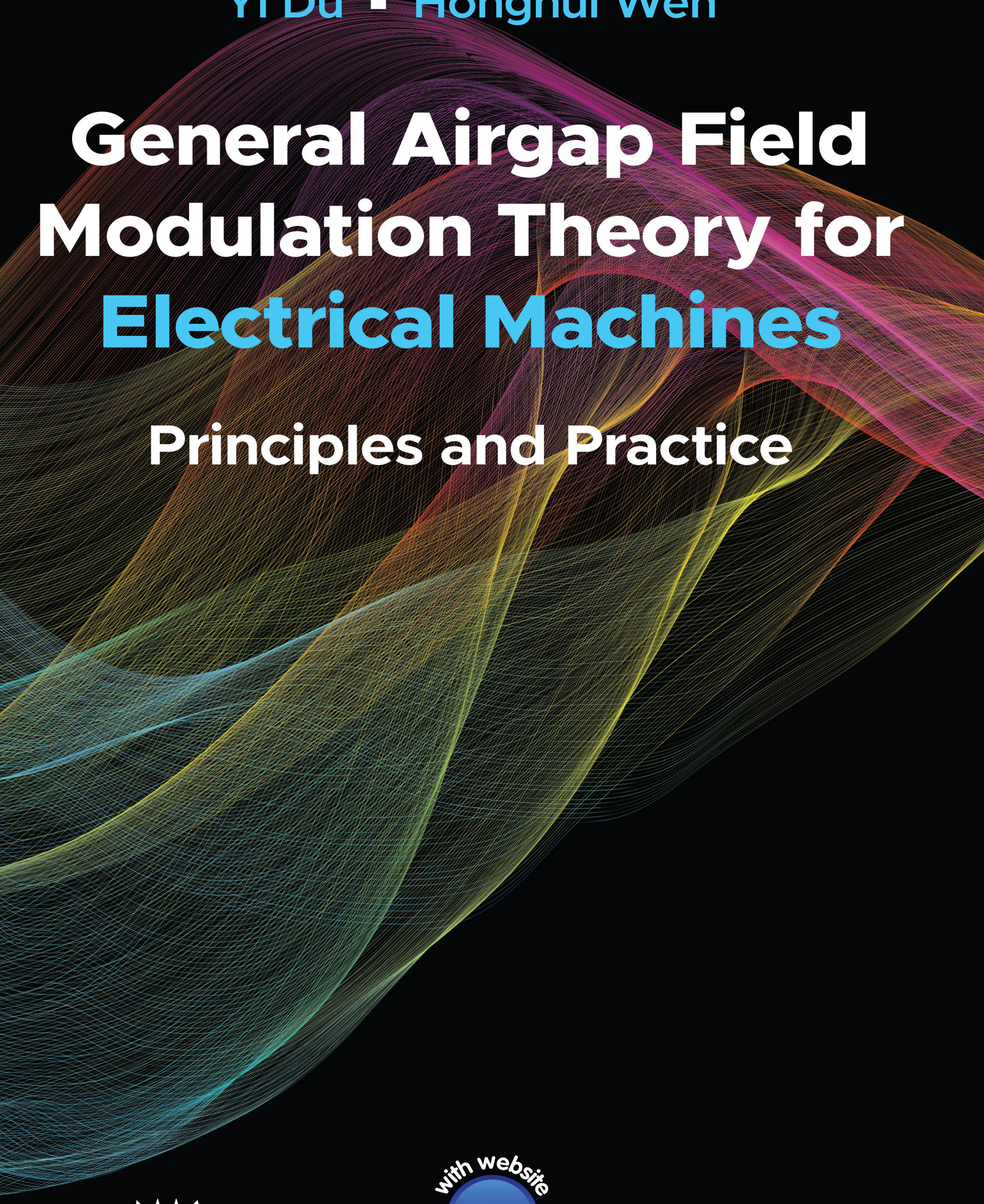

General Airgap Field Modulation Theory for Electrical Machines

Principles and Practice

with website

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IEEE Press
445 Hoes Lane
Piscataway, NJ 08854

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Principles and Practice

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Library of Congress Cataloging-in-Publication Data applied for
Hardback ISBN: 9781119900344

Cover Design: Wiley
Cover Image: © Vectorig/Getty Images

Set in 9.5/12.5pt STIXTwoText by Straive, Chennai, India

Contents

Preface

Electrical machines are devices that convert mechanical energy into electrical energy or vice versa. They were invented in the 1800s and have a history of nearly 200 years. Other inventions of similar ages, such as the Watt steam engine, telegraph, incandescent light bulb, etc., have been outdated by emerging technologies. By contrast, the electrical machine shows great tenacity and vitality, becoming a living fossil of the Industrial Revolution.

Demand for high-performance electrical machines is increasing day by day with the rapid development of our social economy. Application areas of electrical machines have extended from conventional industrial drive to aerospace, transportation, numerical control machine tools, robots, and other high-tech fields, ranging from deep below the surface of the earth to deep space, from the furthest depths of the ocean to the surfaces of land and sea.

The diversity in performance requirements for different applications leads to the invention of novel electrical machine topologies with different performance advantages, especially those having multiple working spatial harmonics, such as the magnetically geared machine (MGM), permanent magnet vernier (PMV) machine, brushless doubly fed machines, just to name a few.

These new machine topologies show significant magnetic field modulation effects, posing great challenges to existing theories for the analysis of electrical machines. The operation of some emerging electrical machines, such as the PMV machine with dissimilar numbers of stator winding pole pairs and magnet polarities, can hardly be explained directly by the well-established theory for induction machines and synchronous machines. In addition, most theories and methods for the analysis of electrical machines were developed and therefore valid for only certain machine types.

Based on the extensive scientific and industrial research for high-performance electrical machines and drive technologies conducted by the Jiangsu Electrical Machines & Power Electronics League (JEMPEL), Southeast University, Nanjing, China, over the past decades, the authors noticed the generality of airgap magnetic field modulation phenomena in electrical machines and its instrumental role in improving performance of electrical machines. The discoveries were further examined against almost all the known electrical machine topologies, and then theorized to develop the general airgap field modulation theory.

The book is organized into seven chapters and three appendices, as outlined below:

- Chapter 1 reviews the historical development of electrical machines and their theories.
- Chapter 2 analyzes the airgap magnetic field modulation phenomena in common machine topologies, aiming to reveal the ubiquity of magnetic field modulation phenomena in electrical machines.
- Chapter 3 abstracts a unit machine with one stator, one rotor and one layer of airgap as a cascade of three key elements, based on which generalized mathematical models for the three elements are proposed, forming the general airgap field modulation theory framework for electrical machines.
- Chapter 4 analyzes the relationship between different modulation behaviors and their torque compositions.
- Chapter 5 applies the general airgap magnetic field modulation theory to multiple representative machine topologies to show its application in qualitative analysis and quantitative calculation of machine performance.
- Chapter 6 covers the innovation of machine topology with the guidance of the general airgap field modulation theory.
- Chapter 7 presents more application examples of the developed theory.
- Appendix A shows the mathematical derivation of the three typical modulation operators.
- Appendix B clarifies the relationship between electromagnetic forces/torques on conductors placed in the airgap and in-slot conductors.
- Appendix C presents the Maxwell Stress Tensor method and principle of virtual work, which are the basis of force/torque analysis using the general airgap field modulation theory.

The contents presented in this book are a selected collection of scientific and industrial research work conducted by the JEMPEL and its extended research groups during the past decades. The authors are very grateful to all the JEMPEL members, especially Prof. Xiaoyong Zhu, Prof. Yubin Wang, Dr. Le Sun, Dr. Xinkai Zhu, Dr. Jingxia Wang, Dr. Yu Zeng for their dedicated assistance in preparing the manuscript, and Dr. Gan Zhang, Mr. Zhengzhou Ma, Ms. Chenchen Zhao for their tremendous help in the preparation of main figures.

The authors would also like to express their sincere gratitude to Prof. Wei Hua, Prof. Jianzhong Zhang, Prof. Wenxiang Zhao, Prof. Xianglin Li, Dr. Qiang Sun, Dr. Hongyun Jia, Dr. Feng Yu, Dr. Feng Li, Dr. Lingyun Shao, Dr. Peng Su, Dr. Minghao Tong, Dr. Xiaofeng Zhu and Dr. Peixin Wang for their excellent research outcomes, which are essential ingredients of this book.

We are deeply indebted to our colleagues and friends worldwide for their continuous support, encouragement, and discussion on the subject matter over the years, especially Prof. Ayman EL-Refaie, Prof. C.C. Chan, Prof. Dan M. Ionel, Prof. Hossein Torkaman, Prof. Ion Boldea, Prof. Iqbal Husain, Prof. James Kirtley, Prof. Jianguo Zhu, Prof. K.T. Chau, Prof. Longya Xu, Prof. W.N. Fu, Prof. Ying Fan, Prof. Z.Q. Zhu, Prof. Zhe Chen, Prof. Zheng Wang, Dr. Arijit Banerjee, Dr. Baoyun Ge, Dr. Hao Huang, Dr. Jianning Dong, Dr. Kaiyuan Lu, Dr. Ming Xu, Dr. Sa Zhu, Dr. Shengyi Liu, Dr. Ying Pang, Ms. Xiaoping Li, for their valuable feedback on this theory.

We also much appreciate the reviewers of this book for their thoughtful and constructive comments, and Editors of John Wiley & Sons for their professional and timely support in the review and production process.

Last but not least, we thank our families for nurturing and unconditionally supporting the writing of this book.

About the Authors

Ming Cheng received his B.Sc. and M.Sc. degrees from Southeast University, Nanjing, China, in 1982 and 1987, respectively, and his Ph.D. degree from the University of Hong Kong, Hong Kong, in 2001, all in electrical engineering. Since 1987, he has been with Southeast University, where he is currently an Endowed Chair Professor at the School of Electrical Engineering and the Director of the Research Center for Wind Power Generation.

He is a Fellow of the Institute of Electrical and Electronics Engineers (IEEE) and the Institution of Engineering and Technology (IET) and was a Distinguished Lecturer of the IEEE Industry Applications Society for 2015/2016. He has served as editor-in-chief, editor and editorial board member of various international journals, as well as chair and organizing committee member of many international conferences, especially in the area of Electrical Machines and Power Electronics.

His teaching and research interests include electrical machines, motor drives for EV, renewable energy generation, and servo motor & control. In these areas, he has published over 500 refereed technical papers and 7 books and holds over 150 invention patents.

He has received many awards, including Second Prize in the State Technological Invention Awards (given by the State Council of the People's Republic of China); First Prize in China's Ministry of Education's Natural Science Awards; First Prize in Jiangsu Provincial Government's Science and Technology Award; the IET Achievement Award; and the Environmental Excellence in Transportation Award for Education, Training, and Public Awareness by SAE International.

Peng Han received B.Sc. and Ph.D. degrees in electrical engineering from the School of Electrical Engineering, Southeast University, Nanjing, China, in 2012 and 2017, respectively.

From November 2014 to November 2015, he was a Guest Ph.D. student at the Department of Energy Technology, Aalborg University, Aalborg, Denmark, where he focused on brushless doubly fed machines' application in wind energy conversion and high-power drives. He is currently with Ansys, Inc., USA, as a Senior Application Engineer. Before joining Ansys, he was a Postdoctoral Researcher with the Center for High Performance Power Electronics (CHPPE) Department of Electrical and Computer Engineering, The Ohio State University, and later the SPARK Laboratory, Department of Electrical and Computer Engineering, University of Kentucky. His current research interests include electrical machines, machine drives, power electronics, and renewable energy.

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Honghui Wen received B.Sc. and Ph.D. degrees in electrical engineering from the School of Electrical Engineering, Southeast University, Nanjing, China, in 2016 and 2021, respectively.

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About the Companion Website

This book is accompanied by a companion website:

www.wiley.com/go/genairgapfieldmodulationtheory

The website includes models and scripts.

1

Introduction

1.1 Review of Historical Development of Electrical Machines

Electrical machines are electromagnetic devices to achieve electromechanical energy conversion. Since Jacobi invented the DC machine (DCM) in 1834 and Tesla invented the induction machine (IM) in 1880s, electrical machine technology has developed rapidly, and its application has become more and more extensive. Electrical machines have become one of the most important energy and power technologies to support the national economy. Various types of machines with power levels ranging from several milliwatts to hundreds of megawatts, especially the three traditional machine topologies, namely the DCM, AC induction (asynchronous) machine, and AC synchronous machine (SM), have made great contributions to the development of human society [1, 2].

It is worth mentioning that the steam engine, telegraph, incandescent lamp, etc., which appeared at virtually the same time as electrical machines, have been replaced by emerging technologies and have gradually faded into disuse. By contrast, the electrical machine presents a tenacious vitality, and can be considered a surviving fossil of the modern industrial revolution, one which constantly renews its life. Correspondingly, the development and innovation of electrical machine theories and technologies have never stopped.

With the proliferation of electrification and automation technologies, the application of electrical machines has expanded from conventional industrial drive to aerospace, transportation, CNC equipment, robotics and other high-tech fields, and from ground to deep space, deep sea, and deep earth. The performance requirements of machines for different applications are constantly refined, and the traditional brushed DCMs, IMs, and SMs are difficult to meet the demanding requirements of new fields and applications. Meanwhile, the rapid development of material technology, processing and manufacturing technology, and control technology, combined with new application requirements, has given

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First Edition. Ming Cheng, Peng Han, Yi Du, and Honghui Wen.

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rise to various new electrical machines with different constructions, different working principles, and different performance advantages, such as: synchronous reluctance machines (SynRMs) [3–5], permanent magnet (PM) brushless machines [6, 7], vernier machines [8], brushless doubly-fed induction machines (BDFIMs) [9–11], brushless doubly-fed reluctance machines (BDFRMs) [12, 13], transverse flux machines [14], switched reluctance machines (SRMs) [15, 16], stator-PM brushless machines [17–20], PM vernier (PMV) machines [21, 22], magnetically-geared machines (MGMs) [23–26], dual-mechanical-port (DMP) machines [27, 28], etc.

In order to provide an overview of the relevant research on electrical machines, a bibliometric analysis was performed in IEEE Xplore digital library database at the end of 2021. The results summarized in Figure 1.1 show the diversity of machine topologies and soaring numbers of publications on these "unconventional" machines.

- As representative traditional electrical machines, IMs and wound-field salient-pole SMs have experienced the longest history of research. Considerable research work had been done before the field-oriented control (FOC) method was invented by F. Blaschke in 1971. Research on IMs grows steadily and peaked at 2014–2015. In contrast, research on wound-field salient-pole SMs was interrupted in the 1970s and 1980s and resumed later, but it is much less popular than that of IMs.

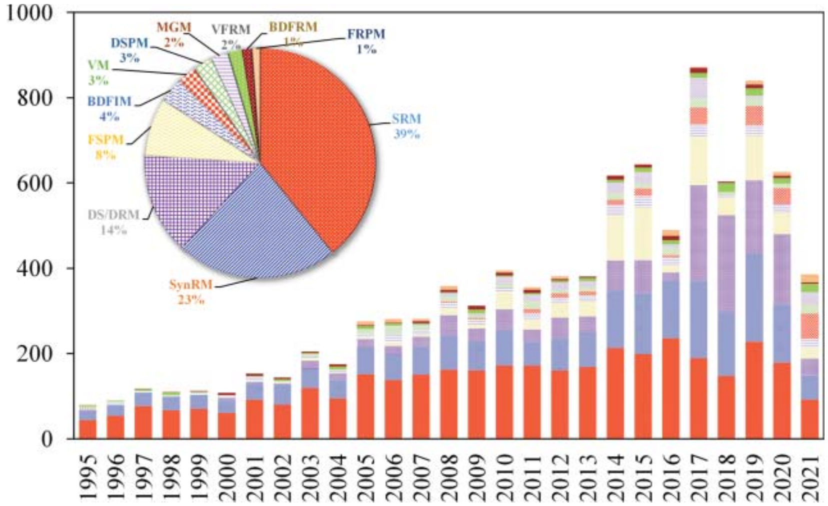


Figure 1.1 Number of publications on "unconventional machines" indexed by IEEE Xplore digital library database. DS/DRM – Dual-stator/dual-rotor machine, FSPM – Flux-switching PM, VM – Vernier machine, DSPM – Doubly-salient-pole PM, VFRM – Variable flux reluctance machine, FRPM – Flux-reversal PM.

- High-energy-product PM materials were introduced into the manufacturing and performance improvement of electrical machines in the late 1970s, after which the research on PM brushless machines began to grow steadily, with a dramatic increase in 2010. Afterwards, the research on PM machines decreased due to the large price fluctuation of PM materials, but still stayed at a high level.
- In addition to IMs and PMSMs, research on SRMs has continued to grow steadily since its revival in 1980. By contrast, research on SynRMs has been more stable, with a dramatic growth in 2014 and 2015. It was probably caused by the large price fluctuation of PM materials, which led to the concepts of "PM-free" and "less-PM" electrical machines.
- The so-called "stator-PM machines" invented in the 1990s which mainly include doubly-salient-pole PM machines, flux-switching PM machines (FSPMs) and flux-reversal PM machines started to gain their popularity after 2005. Compared to doubly-salient-pole PM machines and flux-reversal PM machines, FSPMs were more attractive to researchers in both academia and industry. Research on FSPMs witnessed a dramatic increase in 2014 and peaked in 2014–2015.
- Research on BDFIMs and BDFRMs dates back to early 1970s. It has been increasing since the 1990s and peaked in 2014–2015.
- Research on MGMs and vernier machines started in the early 1990s but did not receive much attention until 2010. It was hardly affected by the price fluctuation of PM materials.
- Dual-stator/dual-rotor machine topologies started to gain popularity after 2004 and keep increasing steadily afterwards, peaking in 2014–2015.

At the same time, theories for electrical machines have also been enriched and improved. In addition to the basic physical laws (such as the law of electromagnetic induction and the law of electromagnetic force) followed by electrical machines, a variety of theories and analysis methods have emerged accordingly to conduct the performance analysis and calculation of different machines.

For example, to address the difficulties caused by the unequal direct-axis (d-axis) and quadrature-axis (q-axis) reluctance of the salient-pole SM in armature reaction calculation, A. Blondel proposed the two-reaction theory [29, 30]. When the axis of the armature magnetomotive force (MMF) F_a coincides neither with the d-axis nor with the q-axis, F_a can be decomposed into the d-axis component F_{ad} and the q-axis component F_{aq}, as shown in Figure 1.2. Then the d-axis and q-axis armature reaction magnetic fields can be calculated separately, and finally they are superimposed. It has been proved that satisfactory results can be obtained by using the two-reaction theory when the magnetic circuit saturation is not taken into account. After that, R.H. Park further generalized and extended the two-reaction theory and proposed the famous Park transformation, thereby establishing general calculation formula for the current, voltage, power and torque of SMs under

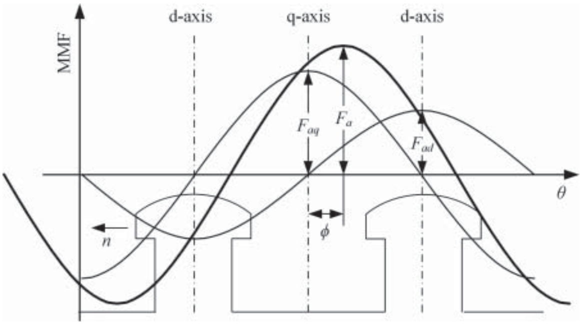


Figure 1.2 Decomposition of armature MMF of would-field salient-pole SM into *d*-axis and *q*-axis components.

steady and transient states [31], which brings great convenience to the analysis and calculation of SMs.

Another example is that G. Kron proposed a unified theory for analyzing electrical machines [32], which raised the theory of electrical machines to a new level. He analyzed machine characteristics from the perspective of energy for the first time. According to the law of energy conservation [33], there are four forms of energy in electrical machines: electrical energy, mechanical energy, electromagnetic field storage energy and thermal energy. According to the motor convention, the energy equation can be written as

$$\begin{pmatrix}\text{Input energy}\\ \text{from source}\end{pmatrix} = \begin{pmatrix}\text{Coupled field energy}\\ \text{storage increment}\end{pmatrix} + \begin{pmatrix}\text{Output mechanical}\\ \text{energy}\end{pmatrix} + \begin{pmatrix}\text{Energy loss}\\ \text{converted to heat}\end{pmatrix} \tag{1.1}$$

In addition, the concept of magnetic co-energy was proposed, and the relationship between magnetic co-energy and magnetic energy is:

$$W_m = \int_0^{\psi_1} i d\psi = i_1\psi_1 - \int_0^{i_1} \psi di = i_1\psi_1 - W'_m \tag{1.2}$$

where W_m is the magnetic energy, W'_m the magnetic co-energy, i_1 the winding current, and ψ_1 the magnetic flux linkage. When represented graphically, the magnetic co-energy is the area of the vertically shaded part in Figure 1.3. The rate of change of the magnetic co-energy to the mechanical displacement is the electromagnetic torque:

$$T_{em} = \frac{dW'_m}{d\theta} \tag{1.3}$$

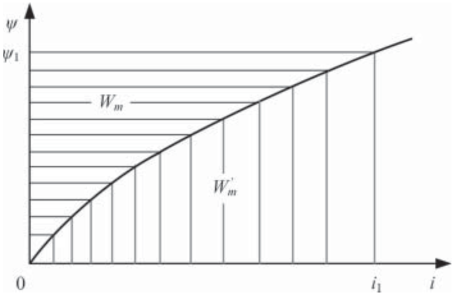


Figure 1.3 Magnetic energy W_m and magnetic co-energy W_m'.

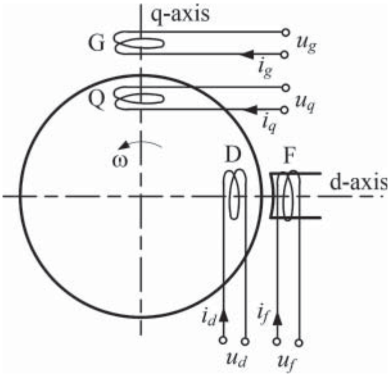


Figure 1.4 Two-axis primitive machine.

where T_{em} is the electromagnetic torque and θ the mechanical displacement angle of electrical machines.

Again, B. Adkins et al. proposed the general theory of AC machines. Any electrical machines can be equivalent to a primitive machine model by coordinate transformation, as shown in Figure 1.4. Based on this primitive machine model, a set of voltage equations representing the relationship between voltage and current of the primitive machine and torque equations representing the relationship between torque and current can be derived and then solved using a unified approach [34].

Cells with solid-line borders in Table 1.1 list typical electrical machine theories in the history of machine development as well as their applications, authors and other information, which together constitute the classical electrical machine theory and lay a solid theoretical foundation for the development of machine technology represented by DCMs, IMs, and SMs.

Table 1.1 Typical theories for electrical machines.

Year	Name of theory	Typical applications	Authors
1913	Two-reaction theory [29, 30]	Wound-field salient-pole SMs and SynRMs	A. Blondel (France)
1925	Rotating magnetic field theory [35]	AC electrical machines with sinusoidal back-electromotive force (back-EMF)	K.L. Hansen (United States)
1926	Cross-field theory [36]	AC electrical machines with sinusoidal back-EMF	H.R. West (United States)
1929	Park transformation [31]	AC electrical machines with sinusoidal back-EMF	R.H. Park (United States)
1930	Generalized theory of electrical machinery [32]	Electromechanical energy conversion devices	G. Kron (United States)
1954	Symmetrical components [37]	AC electrical machines with sinusoidal back-EMF	W.V. Lyon (United States)
1959	Space vector theory for transient analysis [38]	IMs and SMs	Pák K. Kovács (Hungary)
1973	General theory using equivalent magnetic circuit [39]	SMs and DCMs	J. Fienne (United Kingdom)
1975	The general theory of AC machines [34]	AC electrical machines	B. Adkins (United Kingdom)
1965	Winding function theory [40, 41]	IMs and SMs	N.L. Schmitz and D.W. Novotny (further improved by T.A. Lipo) (United States)
1992	Spiral vector theory [42]	AC circuits and machines	S. Yamamura (Japan)
1994	Unified theory of torque production [43]	All electrical machines	D.A. Staton, T.J.E. Miller, et al. (United Kingdom)
2017	General airgap field modulation theory [44]	All electrical machines	M. Cheng, P. Han, W. Hua (China)

1.2 Limitations of Classical Electrical Machine Theories

Although the classical electrical machine theory has brought great convenience to the analysis of traditional DC, induction and synchronous machines, it still seems to be inadequate in analyzing large numbers of new machine topologies. In summary, limitations of the classical electrical machine theory mainly lie in the following three aspects.

1.2.1 Fragmentation of Electrical Machine Theories

Among existing electrical machine theories, the two-reaction theory was primarily used to analyze SMs [29–31]. The rotating magnetic field theory [35] and cross-field theory [36] were suitable for AC machines with sinusoidal back-electromotive forces (EMFs). The unified theory of torque production based on magnetic flux linkage-current trajectories was employed to analyze all electrical machines by numerical methods [43]. The winding function theory was mainly for IMs and SMs [41]. The general theory of AC machines based on the two-axis primitive machine [34] and general theory using equivalent magnetic circuits [39] were mainly applied to IMs and SMs, though they can also be further extended for DCMs. It can be concluded that the existing theories are only valid for certain machine topologies and none of them are applicable to all machine types.

In addition, some theories can only be used as tools for quantitative analysis of machine performance, but fail to interpret the physics behind the machine operation, or vice versa. For instance, the general theory of AC electrical machines developed by B. Adkins et al. based on the two-axis idealized machine or primitive machine model [34] is only valid for conventional AC machines with explicit direct and quadrature axes and DCMs. The general theory using equivalent magnetic circuits developed by J. Fienne et al. [39] can be used for both AC machines and DCMs, but it can only be used for performance calculations and cannot reveal the internal mechanism and physical nature of electromechanical energy conversion.

On the other hand, machines with the same or similar structures can be treated as different machine types from different perspectives. For example, both machines shown in Figures 1.5 and 1.6 have three layers from the inside to the outside in the mechanical structure, namely, the innermost PM layer, the salient-pole rotor layer in the middle, and the outermost winding layer. However, the machine shown in Figure 1.5 was well known as a MGM [45], while the one shown in Figure 1.6 was considered as a partitioned-stator FSPM machine [46].

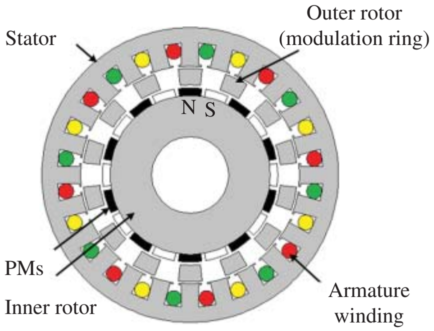


Figure 1.5 Dual-rotor MGM Adapted from [45].

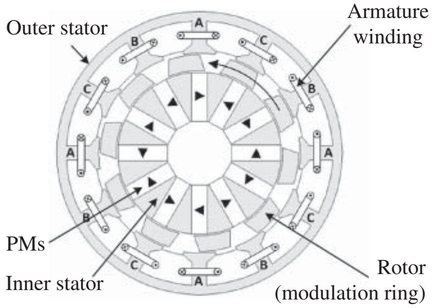
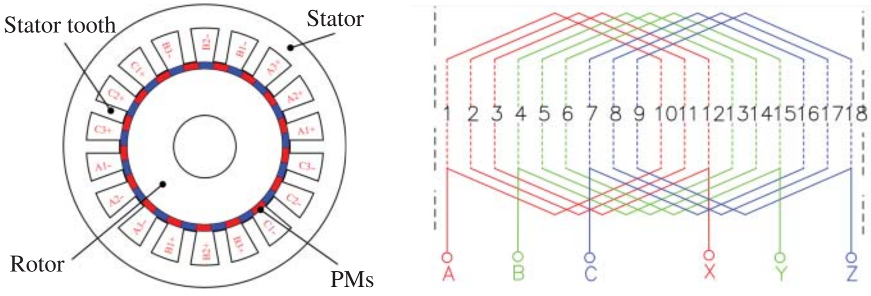


Figure 1.6 Partitioned-stator FSPM machine [46].

1.2.2 Limitations in Analysis of Operating Principles

For some new/special machines, the classical electrical machine theory is no longer fully applicable. In other words, it is difficult to directly use the classical theory to interpret the working principle and analyze the performance of these machines. For example, according to the classical electrical machine theory and the basic principles of electromechanical energy conversion [1, 2], the numbers of pole pairs of the stator winding and rotor field are required to be identical so as to achieve continuous electromechanical energy conversion. However, for the PMV machine [21] shown in Figure 1.7, the armature field created by the armature winding has one pole pair, but the rotor has 34 PM poles. Obviously, the numbers of stator and rotor pole pairs are unequal, so intuitively, the machine will not be able to operate. Even if the winding MMF harmonics are considered, the 17-pole-pair MMF harmonic is of a very low amplitude and the corresponding torque component is almost negligible. Therefore, this type of machine seems to be of no practical value according to the classical theory. However, research results show that this machine type can not only realize electromechanical energy



(a) (b)

Figure 1.7 PMV machine, (a) cross-sectional view, (b) linear winding pattern.

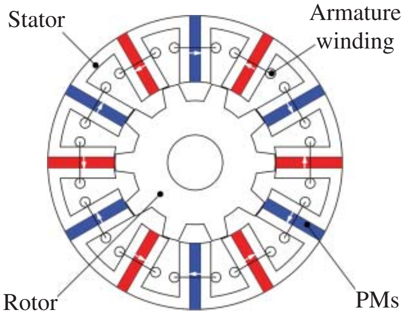


Figure 1.8 12/10 FSPM machine.

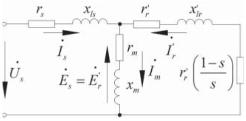
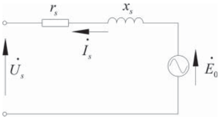
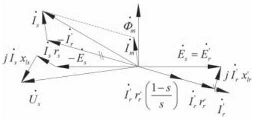
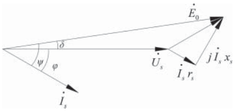
conversion, but also offers higher torque density than conventional PM machines [47], the reason of which will be explained later in this book.

FSPM machines are another example. Figure 1.8 shows a 12-slot stator and 10-pole rotor (12/10) FSPM machine [48, 49] with both the armature windings and PMs located in the stator and a simple salient-pole rotor. This machine has 12 PMs on the stator and adjacent magnets are magnetized in opposite directions, forming a stationary magnetic field with 6 pairs of poles, and 10 salient poles on the rotor. The equivalent number of main pole pairs obtained according to its speed and current frequency is 4, which neither equals to the number of pole pairs of the stator PM field nor the number of salient poles of the rotor. It is difficult to explain this mismatch by definitions of pole pairs in the classical machine theory.

1.2.3 Lack of Uniformity in Performance Analysis

The analysis of different types of machines is isolated from each other and lacks internal uniformity due to the fragmentation of electrical machine theories. Even for IMs and SMs, though both of them are AC machines, the analyses

Table 1.2 Comparison of analysis models for IMs and SMs.

	IM	**SM (taking the non-salient-pole type as an example)**
Electrical equivalent circuit (per-phase)		
Phasor diagram (per-phase)		
Torque equation	$T = \frac{p}{\omega} U_s^2 \frac{s r_r'}{\left(s r_s + c_1 r_r'\right)^2 + s^2\left(x_{ls} + c_1 x_{lr}'\right)^2}$	$T = \frac{p}{\omega}\frac{E_0 U_s}{x_s}\sin\delta$
Torque characteristic