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ELECTRIC MACHINES

FOURTH EDITION

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*Dedicated
to*

Shobha

—D P Kothari

and

Pushpa

—I J Nagrath

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PREFACE

The aim of this book is to give deep exposition of the theory of electromechanical devices, with specific emphasis on the theory of rotating electric machines. The basic concepts have remained more or less the same over the years since the first edition of this text appeared in 1985.

Since the appearance of the third edition in 2004, most of the advances in the application and control of electric machines have taken place owing to the further breakthroughs in power electronics and microprocessor/computer-based control systems. As a result, a much broader spectrum of electric machine types are now available. Particularly, permanent-magnet and variable-reluctance machines are now used in many applications and this is bound to increase further in future. AC drives are becoming more and more attractive in many applications, such as those requiring variable speed and flexible control, while earlier dc machines were the only choice. Realising this fact, these machine types find increased coverage in the fourth edition.

This book presents simple, explicit, and yet rigorous and comprehensive treatment of transformers and electric machines in a single volume. Considerable emphasis is laid on the fundamentals, physical concepts, principles and on rigorous development of circuit model equivalents of both transformers and machines. Each circuit model is closely related to the physical reality, the underlying assumptions are sharply focussed and consequent limitations on the range of operation over which the model is valid are fully explained. The clarity of the physical basis of models developed would be most satisfying to the reader and it would enable him to make intelligent use of the models in the solution of machine problems and in the design of systems using these devices. The prediction of device performance follows as an immediate sequel to its model. Furthermore, as a next step (not covered in this book), the circuit parameters could be conveniently related to the physical dimensions and properties of the materials used in the device. While the circuit theory approach to electro-mechanical devices is introduced early in Chapter 2, the machine analysis in the bulk of the book follows the field-theory approach which, as is well-known, is better understood and appreciated by undergraduates and provides a deep insight into and a clear understanding of the electric machine.

This is the only book which clearly brings home to the reader the distinction in the sign convention between the synchronous machine model and the transformer-type model, also employed for the induction machine. Another distinguishing feature of the book is the clarity with which it brings out the difference between a sinusoidally spaced distributed quantity (field) represented as a vector and sinusoidally time-varying quantities represented as phasors and how a rotating vector creates a time phasor. In order that the teacher and student can both make convenient use of symbols on the blackboard or on paper, the phasors are symbolically represented by capital letters with superbars and the vectors are represented by capital letters with superarrows.

The book covers all the essential ingredients of machine knowledge expected of a modern-day undergraduate in electrical engineering. With new and vital topics crowding the curriculum in electrical engineering, machine courses have rightly been squeezed into two time slots of one-semester duration each.

The book is designed to meet this need. The book is primarily designed to cater to a one-semester core course common for all engineering disciplines and a one-semester topping off course for those majoring in electrical engineering. The core course may comprise Chapters 1, 2, Secs 3.1 to 3.9 (except Sumpner's test), 3.11, 3.12 (partly), Chapters 4,5 and Secs 7.1 to 7.4 for dc machine coverage along with a quick resume of armature reaction, commutation, methods of excitation and characteristics of generators and motors. These topics are covered in initial portions of the relevant sections of Chapter 7. The dc machine winding can be explained to the class by merely projecting the two developed winding diagrams of Chapter 6. The remaining portions of the book would then comprise the second course. The book is written in a flexible style and a high degree of selectivity is inbuilt so that the teacher may leave out advanced articles of various topics in coping with the time factor without any loss of continuity. It is even possible to select a single one-semester course out of the book where time exigencies so demand.

The theory and applications of various machines as control-system actuators is treated at appropriate places in the book. The methods of control-system analysis have not been included as these form a full course in a modern curriculum. Linear approximations are employed for tackling non-linearities associated with most machines. Wherever warranted, the effect of magnetic nonlinearity is accounted for in steady-state analysis.

Although the models advanced are strictly applicable for steady-state analysis of device performance, these are extended to the dynamic case at a few places by making strong assumptions. The transient analysis of the synchronous machine is treated qualitatively and a graphical picture of the phenomenon is presented.

The reader is expected to have a prior grounding in electricity and magnetism, introductory circuit theory, basic mechanics and elementary differential equations. However, appendices on ac steady-state circuit analysis and three-phase systems have been included for ready reference.

New to this Edition

The chapters on dc machines and synchronous machines are re-written completely. The highlights of this edition are large number of **solved problems** and practice problems that have been added in all the chapters.

The key features of this edition are

- New chapter on 'Generalized Theory of Electric Machines'
- Detailed description of Transformers, dc Machines, dc Machines Excitation, Predetermination of external characteristics of dc Generator, Parallel operation of dc Generators, Efficiency and Testing of dc Machines, Speed control of Induction Motor, Linear Induction Motor
- Enhanced coverage of Permanent Magnet dc Motors, Permanent Magnet Materials and their applications
- Discussion on Silicon Controlled Rectifier (SCR), Insulated Gate Bipolar Transistor (IGBT), MOS Turn off Thyristor (MTO) and Emitter Turn off Thyristor (ETO) to cover new trends
- Synchronous generator (alternator), MMF Method, ASA Method, V curves and inverted V curves, Rating of alternator, phasor diagrams, Reactive power flow from generator
- MATLAB examples to facilitate problem-solving skills
- Excellent pedagogy including
 - Over 200 Solved examples
 - Over 300 Practice questions, most provided with answers
 - Over 140 Review questions

- Over 50 Objective type questions
- 10 MATLAB Examples

Though no sophisticated knowledge of mathematics is required for the reader of this book, the mathematics involved in this subject at times can get messy and tedious. This is particularly true in the analysis of ac machines in which there is a significant amount of algebra involving complex numbers. One of the significant positive developments in the recent years is the widespread availability of software such as MATLAB which greatly facilitates the solution of such problems. MATLAB is freely used in many institutions and colleges and is also available in a student version (<http://www.mathworks.com>). This edition, therefore, incorporates MATLAB in some sample solved examples. It should be emphasized here that the use of MATLAB is not a prerequisite for using this book. It is just an enhancement, an important one though! Further, it may be noted that even in the cases where it is not specifically suggested, some of the problems in the book can be attempted using MATLAB or an equivalent program. Some additional programs for solving problems using MATLAB are included in this book.

The **introductory chapter** discusses electrical–electrical and electromechanical energy conversion processes and devices from a general point of view with the explicit purpose of motivating the reader for studying transformers and electric machines. This chapter, however, is not a prerequisite for the rest of the book. **Chapter 2** brushes up magnetic circuits and the principle of induction.

In **Chapter 3**, the transformer is treated exhaustively. The circuit-model approach is emphasized and for obvious reasons the role of the phasor diagram is underplayed. This chapter lays the ground work for the understanding of electromechanical energy conversion processes in machines and the circuit model of the induction machine in particular.

Then follows **Chapter 4** on the underlying principles of electromechanical energy conversion in the end of which is answered the question, “Why is electric field not used as a coupling medium instead of the magnetic field?” Cases of both linear and nonlinear magnetization (saturation) are treated.

Exposition of the basic concepts of rotating machines from a generalized point of view as well as engineering aspects, such as cooling, rating and load mechanics is advanced in **Chapter 5**. General expressions for emf and torque are derived. The torque production is explained here via interaction of two magnetic fields assumed to be sinusoidally distributed. An alternative current-sheet approach is also given for the interested reader. Elementary treatment of specific machine types—synchronous and induction—then follows and their important characteristics are visualized on a field-interaction basis. Since interacting fields are assumed to be sinusoidal, which is justified in these two classes of machines only, a most rudimentary treatment of the dc machine is given here because the fields in this class of machines are essentially nonsinusoidally distributed.

While Chapter 5 gives the essential treatment of ac windings, the details including important practical features are dealt with in **Chapter 6** devoted entirely to ac windings. Also given is a reasonably detailed account of dc armature windings in **Chapter 7**. Where time is a limiting factor, ac winding details can be skipped and dc winding directly introduced via the two developed diagrams with a brief explanation of parallel paths, commutation and brush location.

Chapters 7–9 cover in depth the three basic machine types—the dc machine, synchronous machine and induction machine. The approach adopted in all the three is one of rigorous modelling with due stress on explanation of the underlying assumptions. The dc machine is the first to be dealt with as its steady-state model is the simplest. The modelling in each machine results in a circuit model of the linear kind by virtue of the assumptions made, which for all practical purposes are quite valid for steady-state performance analysis as well as under certain transient situations. In **Chapter 8**, on the synchronous machine, a heuristic methods are advanced to account for the effect of strong magnetic nonlinearity on the machine performance.

Tests to determine circuit-model parameters are advanced at appropriate places. Assumptions involved in machine modelling are once again stressed at this stage. Once the circuit model of the machine has been arrived at, the discussion is then focussed on power flow and operating characteristics. The constructional features and important practical details are included at suitable places and the circumstances under which a particular machine would be employed as a motor are discussed.

With the availability of electronic calculators, circle-diagram methods have lost their significance. However, the circle diagram for the induction machine is included as it gives the complete machine performance at a glance and is quite useful in qualitative reasoning.

A simple approach to machine dynamics is given in all the three machine types. In the case of the synchronous machine, dynamics is restricted to the phenomenon of “hunting”, while transient stability receives elementary treatment.

Chapter 10 deals with the important topic of fractional-kW motors. A qualitative-cum-heuristic analysis of a single-phase induction motor and its circuit model are followed by a rigorously developed circuit model for a two-winding motor. This rigorous coverage may be skipped when time does not permit it. A variety of single-phase induction, synchronous and series commutator types of motors are treated. Comprehensiveness is imparted to this chapter by the inclusion of stepper motors, ac servomotor and ac tachometer; the latter two follow simply as a corollary from the two-winding motor analysis.

Chapter 11 is an entirely new chapter and deals with the generalised theory of electrical machines.

Probably the most significant development in recent years in the allied area of motor control is the use of power semiconductors—diodes, power transistors and thyristors. The growth in this area has already qualified for a separate undergraduate level course. However, for the sake of completeness, a comprehensive chapter is included in this book. This in our view is a better approach than to burden the previous chapters by spreading out the relevant details. **Chapter 12** on this topic has a wide coverage and includes all the three varieties of SCR (silicon controlled rectifier) circuitry, namely converters, choppers and inverters. The contents and effects of non-smooth dc and nonsinusoidal ac outputs of these control equipment on the circuit behaviour and on machine performance are beyond the scope of this book.

With the phenomenal developments in SCR circuitry for power control, cross-field machines and ac commutator machines have become almost obsolete. However, to fulfil the need of such universities which still include these topics in their curriculum, fairly detailed appendices (IV and V) on these topics are added.

A number of cross-sectional views of built-up machines and their parts are included and the student is exhorted to carefully study these to help him visualize the physical picture of the machine being modelled. Laboratory exercises always associated with a machines course will further aid this process.

A large number and variety of illustrative examples are spread throughout the book. These would greatly help in imprinting a clear physical picture of the devices and associated physical reasoning on the student’s mind. An equally large number of unsolved problems are given as exercises at the end of each chapter. Answers to all the unsolved problems are given. Some of these problems are devised to illustrate some points beyond what is directly covered in the text.

International Standard (SI) units are used throughout the book. The list of symbols is necessarily large. Apart from being illustrated at the point of occurrence, the symbols used are listed in the beginning of the book.

Web Supplements

The web supplements can be accessed at <http://www.mhne.com/electmach4e> and contain the following material:

For Instructors: Solution Manual and Power Point Lecture Slides

For Students: Interactive Quiz and Web links for Study Material.

Acknowledgements

While revising the text, we have had the benefit of valuable advice and suggestions from many teachers, students and other readers who used the earlier editions of this book. All these individuals have influenced this edition. We express our thanks and appreciation to them. We hope this support / response would continue in future also.

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Feedback

We welcome any constructive criticism of the book and will be grateful for any appraisal by the readers. The suggestions can be sent on my email: dpk0710@yahoo.com

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INTRODUCTION

1

1.1 INTRODUCTION

Electricity does not occur naturally in usable form and it also cannot be stored* in usefully large quantities. Therefore, it must be generated continuously to meet the demand (of power) at all times. An efficient and convenient way to generate electric power is by conversion of mechanical power into electrical form in a *rotating device*** called a *generator*. In the process a small part of power is lost in the generator (efficiencies in large generators are above 90%). The mechanical power is itself obtained from heat power by thermodynamical means in a steam turbine (efficiency in the range of 40–50% as the present upper limit) or by conversion of potential energy of water in a hydraulic turbine with very little loss. The basic source of mechanical power—steam/hydraulic turbine is called the *prime mover*. Electricity can also be generated directly from hot gases in *plasma* form, obviating the need of converging heat power to intermediate mechanical power. This process† is still in an experimental stage. The electromechanical process of electric power generation is shown schematically in Fig. 1.1. Under steady conversion conditions,

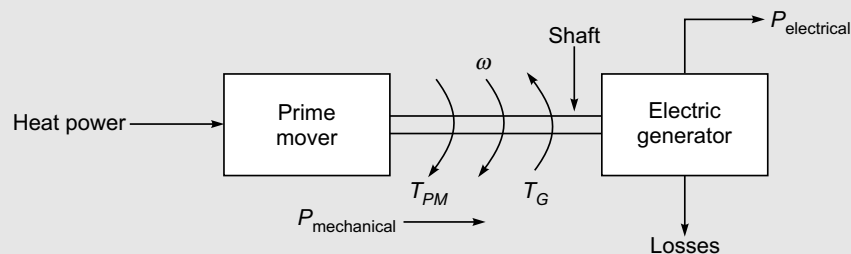


Fig. 1.1 Electric generator

T_{PM} (prime mover) = T_G (generator) and the turbine and generator run at steady speed.

Other than lighting and heating††, the major use of electric energy is made by converting it back to the mechanical form to run the wheels of industry as well as tiny household appliances. The intermediary, the

* Attempts are on to store a sizeable amount of electric energy in large superconducting coils. While these attempts are not likely to succeed in the near future, this stored energy would only be sufficient to meet sharp load peaks.

** The device always has an outer stationary member (refer to Sec. 1.2).

† The process is known as *magnetohydrodynamics* (MHD) which uses the Hall effect to generate electric power. The process is inefficient because the outlet gases are at high temperature. By utilizing the hot gases in a convenient gas turbine, the composite process could be made more efficient than the conventional steam turbine.

†† It is expensive to use electricity for heating except in special processes (e.g. electric arc furnaces) and where highly accurate controlled heating is required (e.g. induction heating).

electric power, permits the use of large efficient central generating stations, while it is easily transported to the myriads of use points. The electromechanical energy conversion process is a *reversible* one and simple adjustment of mechanical shaft and electrical conditions reverses the flow of power as illustrated in Fig. 1.2. In this mode of operation, the electromechanical device, in general called the *electric machine*, is known as the *motor* and the machine is said to be in the motoring mode. Under steady speed operation, again T_M (motor) = T_L (load). Both in generating and motoring modes, losses occur in the electric machine but the overall conversion efficiencies are very high (close to or above 90%).

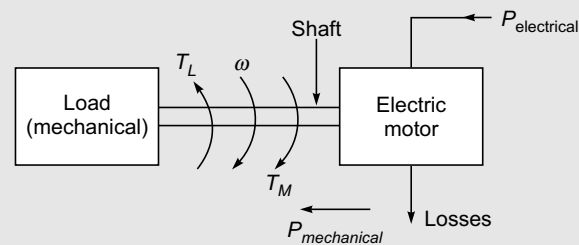


Fig. 1.2 Motoring mode of operation of an electric machine

Electric machines are employed in almost every industrial and manufacturing process. Pages can be filled in listing the applications of electric machines right from giant-size generators (500 MW and above), industrial motors ranging up to a few megawatts to fractional-kW domestic appliances and to sophisticated aerospace applications requiring stringent reliability in operation.

This book deals with the important topic of electric machines, the indepth understanding of which is necessary to tackle the problems of energy, pollution and poverty that presently confront the whole of mankind.

Since Thomas Alva Edison developed an electric generator, more than hundred years ago, engineers have continually strived and successfully reduced the size and revised upwards the efficiencies of electric machines by the use of improved materials and optimal design strategies. We appear to have reached close to the upper limit imposed by nature.

A *transformer* is a static device that transforms electric energy from one ac voltage level to another. It is this device that has made the electric system almost universally ac. The electric power is generated at relatively low voltages (up to a maximum of 33 kV) which then is raised to very high voltages (e.g. 756 kV) by means of a transformer and then transmitted. High voltages are associated with low currents and reduced transmission losses. Geographically close to the use points, the electric power is transformed back to safe low utility voltages (400/231 V). A transformer consists basically of two coils (three sets of coil pairs for a 3-phase system) tightly coupled by means of magnetic (steel) core. Figure 1.3(a) gives the symbolic

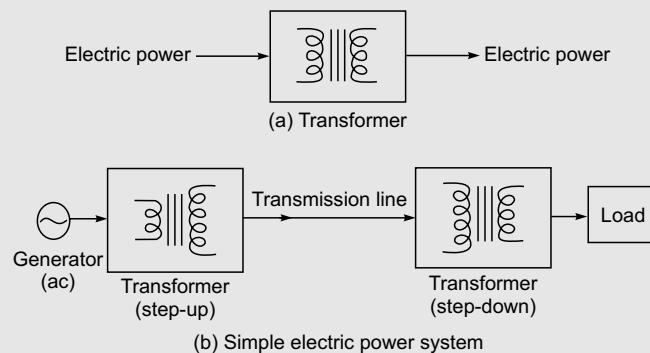


Fig. 1.3

representation of a transformer and Fig. 1.3(b) shows a simple electric power generation transmission and reception system. A practical electric power system is an integrated one, far more complex than the simple diagrammatic representation of Fig. 1.3(b), and is in the form of an interconnected network for reasons of economy, operational efficiency and reliability.

Because the principle of rotating ac machines is akin to that of a transformer, these two are always studied together in a book. Further, since the transformer analogy can be extended to both the ac machine types, the transformer study usually precedes the machine study.

1.2 BASIC PRINCIPLE, TYPES AND CONSTRUCTIONAL FEATURES OF ELECTRIC MACHINES

There are three basic rotating electric machine types, namely

1. the dc machine,
2. the polyphase synchronous machine (ac), and
3. the polyphase induction machine (ac).

Three materials are mainly used in machine manufacture; *steel* to conduct magnetic flux, *copper* (or *aluminium*) to conduct electric current and *insulation* to insulate the voltage induced in conductors confining currents to them.

All electric machines comprise of two parts: the cylindrical rotating member called the *rotor* and the annular stationary member called the *stator* with the intervening air-gap as illustrated in Fig. 1.4. The rotor has an axial *shaft* which is carried on bearings at each end located in *end covers* bolted to the stator. The shaft extends out of the end cover usually at one end and is coupled to either the prime mover or the load.

The stator and rotor are both made of magnetic material (steel) which conducts the magnetic flux upon which depends the process of energy conversion. In both dc and synchronous machines, the main field is created by field poles excited with direct current.

The winding on the field poles is called the *field winding*. The relative motion of the field past a second winding located in the other member induces emf in it. The winding interchanges current with the external electric system depending upon the circuit conditions. It is this winding, called the *armature winding*, which handles the load power of the machine, while the field winding consumes a small percentage (0.5% to 2%) of the rated load power. The load dependent armature current is known as *load current*.

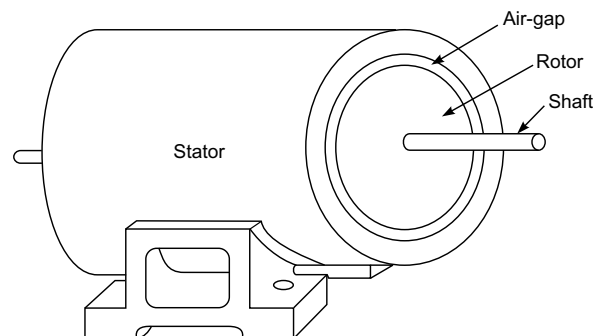


Fig. 1.4 An electric machine

In a *dc machine* the field poles are on the stator while the rotor is the armature as shown in the cross-sectional view of Fig. 1.5. The field poles are symmetrical and are even in number, alternately north and south. As the armature rotates, alternating emf and current induced in the armature winding are rectified to dc form by a rotating mechanical switch called the *commutator*, which is tapped by means of stationary carbon *brushes*. The commutator is cylindrical in shape and comprises several wedge-shaped copper segments

bound together while they are insulated from each other. The armature is made of laminated steel with slots cut out on the periphery to accommodate the insulated armature winding. The ends of each armature coil are connected to the commutator segments to form a closed winding. The armature when carrying current produces stationary poles (same as number of field poles) which interact with the field poles to produce the electromagnetic torque.

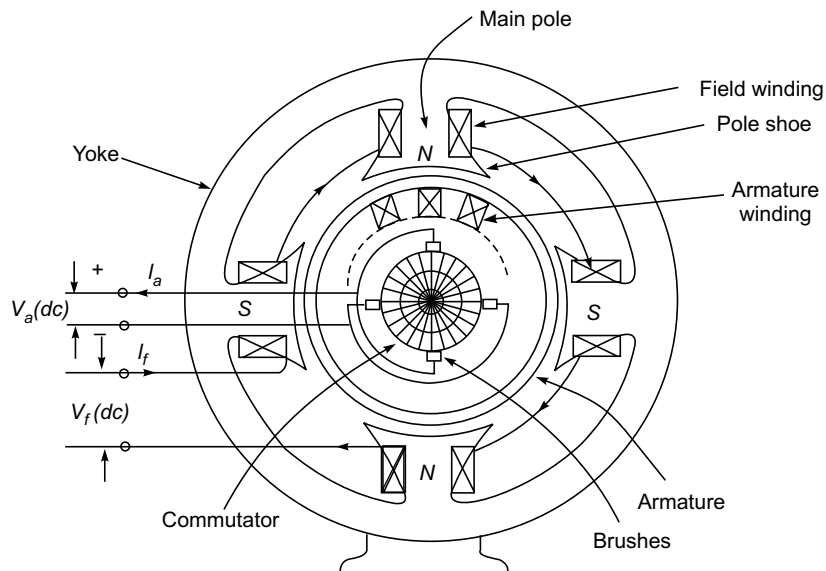


Fig. 1.5 Cross-sectional view of dc machine

In a *synchronous machine* the field poles could be either on the stator or rotor, but in all practical machines the rotor carries the field poles as shown in the cross-sectional view of Fig. 1.6. The field poles are excited

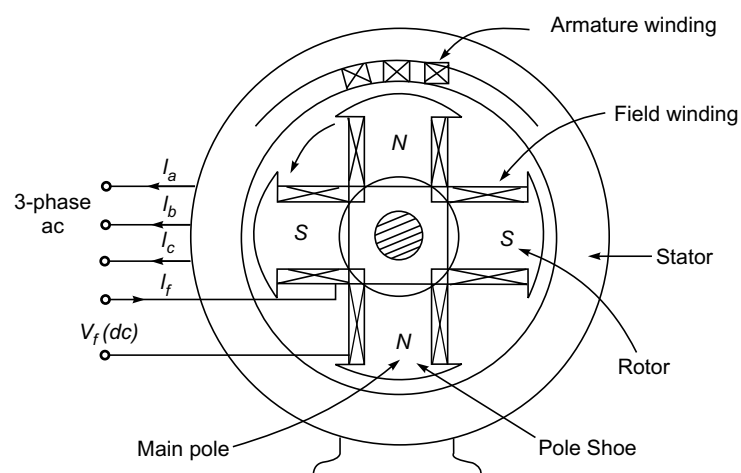


Fig. 1.6 Cross-sectional view of synchronous machine

by direct current. The stator forms the armature carrying a 3-phase winding wound for the same number of poles as the rotor. All the three phases have identical windings with the same angular displacement between any pair of phases. When the rotor rotates, it produces alternating emf in each phase forming a balanced set with frequency given by

$$f = \frac{nP}{120} \quad (1.1)$$

where f = frequency in Hz
 n = rotor speed in rpm
 P = number of field poles

For a given number of poles, there is a fixed correspondence between the rotor speed and the stator frequency; the rotor speed is therefore called the *synchronous speed*. When balanced 3-phase currents are allowed to flow in the armature winding, these produce a synchronously rotating field, stationary with respect to the rotor field as a result of which the machine produces torque of electromagnetic origin. The synchronous motor is, however, *nonselfstarting*.

In both dc and synchronous machines the power handling capacity is determined by the voltage and current of the armature winding, while the field is excited from low power dc. Thus these machine types are doubly excited. Quite different from these, an *induction machine* is singly excited from 3-phase mains on the stator side. The stator winding must therefore carry both load current and field-producing excitation current. The stator winding is 3-phase, similar to the armature winding of a synchronous machine. When excited it produces a synchronously rotating field. Two types of rotor constructions are employed which distinguish the type of induction motor.

1. Squirrel-cage rotor Here the rotor has copper (or aluminium) bars embedded in slots which are short-circuited at each end as shown in Fig. 1.7(a). It is a rugged economical construction but develops low starting torque.

2. Slip-ring (or wound-rotor) rotor The rotor has a proper 3-phase winding with three leads brought out through slip-rings and brushes as shown in Fig. 1.7(b). These leads are normally short-circuited when the motor is running. Resistances are introduced in the rotor circuit via the slip-rings at the time of starting to improve the starting torque.

The rotating field created by the stator winding moves past the shorted rotor conductors inducing currents in the latter. These induced currents produce their own field which rotates at the same speed (synchronous) with respect to the stator as the stator-produced field. Torque is developed by the interaction of these two relatively stationary fields. The rotor runs at a *speed close* to synchronous but always slightly lower than it. At the synchronous speed no torque can be developed as zero relative speed between the stator field and the rotor implies no induced rotor currents and therefore no torque.

Single-phase ac motors are employed for low-voltage, low-power applications—fractional-kW motors. They operate on the same basic principles as the 3-phase motor, but the pulsating single-phase field produces additional losses, reducing motor torque and the pulsating torque component increases the noise level of the motor.

An induction machine connected to the mains when driven at *supersynchronous* speed behaves as a generator feeding power into the electric system. It is used in small hydroelectric stations and wind and aerospace applications.

The insulation of a machine (or transformer) is its most vulnerable part because it cannot be stressed beyond a certain temperature. For a given frame size, the steady temperature rise is determined by the machine loading,