

# ENERGY-EFFICIENT ELECTRIC MOTORS

*Third Edition, Revised and Expanded*

ALI EMADI

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*Illinois Institute of Technology  
Chicago, Illinois*



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To John C. Andreas

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## Preface

The main purpose of this new edition continues to be to provide guidelines for selecting and utilizing electric motors on the basis of energy efficiency and life-cycle cost. In previous editions of this book, particular emphasis was given to three-phase and single-phase induction motors in the 1–200 hp range since this was the range offering maximum opportunities for energy savings. However, since the second edition, there has been a growing demand in the direction of solid-state intensive electric motor drives as adjustable or variable speed drives. New electric motors such as brushless DC and switched reluctance have also been mass-produced and made commercially available. The impetus toward this expansion of power electronics has been provided by recent advancements in the areas of solid-state switching devices, control electronics, and advanced microcontrollers, microprocessors, and digital signal processors (DSP). These advancements facilitate high-tech applications and enable the introduction of power electronic converters with highest performance, maximum efficiency, and minimum

volume and weight. In fact, electric motors with advanced power electronic drivers have real and significant potential for improving not only efficiency and life-cycle cost, but also reliability, performance, and safety.

In this edition, Chapters 1, 2, 4, 5, and 7 from the previous editions have been updated, rearranged, and revised. These chapters present energy-efficient single-phase and three-phase induction motors comprehensively. Chapters 3, 6, 8, 9, and 10 are new. Chapter 3 presents the fundamentals of power electronics applicable to electric motor drives. Adjustable speed drives and their applications are explained in Chapter 6. Advanced permanent magnet (PM) and brushless DC (BLDC) motor drives as well as switched reluctance motor (SRM) drives are presented in Chapters 8 and 9, respectively. Finally, utility interface issues including power factor correction (PFC) and active filters (AF) are discussed in Chapter 10.

I would like to acknowledge gratefully the contributions of many graduate students at Illinois Institute of Technology in different sections/chapters of this book. They are Mr. Brian Kaczor contributing in Chapter 3, Mr. Timothy R. Cooke, Mr. Anthony Villagomez, and Mr. Semih Aslan contributing in Chapter 6, Mr. Manas C. Phadke and Mr. Aly A. Aboul-Naga contributing in Chapter 8, Mr. Himanshu Ray, Ms. Alpa Bhesania, Mr. Madan M. Jalla, Mr. Sheldon S. Williamson, Mr. Piyush C. Desai, and Mr. Ranjit Jayabalan contributing in Chapter 9, and Mr. Ritesh Oza and Mr. Abdolhosein Nasiri contributing in Chapter 10.

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*Ali Emadi*

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# 1

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## Induction Motor Characteristics

### 1.1 THREE-PHASE INDUCTION MOTORS

In the integral horsepower sizes, i.e., above 1 hp, three-phase induction motors of various types drive more industrial equipment than any other means. The most common three-phase (polyphase) induction motors fall within the following major types:

**NEMA** (*National Electrical Manufacturers Association*)

design B: Normal torques, normal slip, normal locked amperes

NEMA design A: High torques, low slip, high locked amperes

NEMA design C: High torques, normal slip, normal locked amperes

NEMA design D: High locked-rotor torque, high slip

Wound-rotor: Characteristics depend on external resistance

**Multispeed:** Characteristics depend on design—variable torque, constant torque, constant horsepower

There are many specially designed electric motors with unique characteristics to meet specific needs. However, the majority of needs can be met with the preceding motors.

### 1.1.1 NEMA Design B Motors

The NEMA design B motor is the basic integral horsepower motor. It is a three-phase motor designed with normal torque and normal starting current and generally has a slip at the rated load of less than 4%. Thus, the motor speed in revolutions per minute is 96% or more of the synchronous speed for the motor. For example, a four-pole motor operating on a 60-Hz line frequency has a synchronous speed of 1800 rpm or a full-load speed of

$$\begin{aligned}1800 - (1800 \times \text{slip}) &= 1800 - (1800 \times 0.04) \\&= 1800 - 72 \\&= 1728 \text{ rpm}\end{aligned}$$

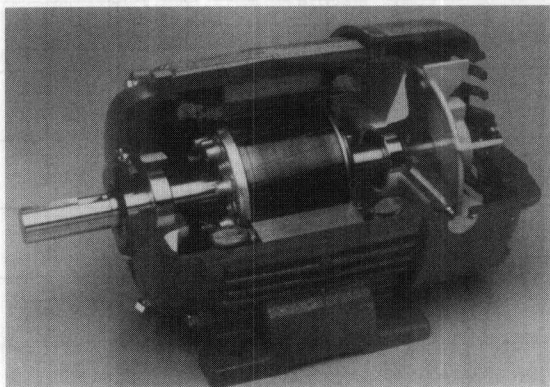
or

$$1800 \times 0.96 = 1728 \text{ rpm}$$

In general, most three-phase motors in the 1- to 200-hp range have a slip at the rated load of approximately 3% or, in the case of four-pole motors, a full-load speed of 1745 rpm. Figure 1.1 shows the typical construction for a totally enclosed, fan-cooled NEMA design B motor with a die-cast aluminum single-cage rotor.

Figure 1.2 shows the typical speed-torque curve for the NEMA design B motor. This type of motor has moderate starting torque, a pull-up torque exceeding the full-load torque, and a breakdown torque (or maximum torque) several times the full-load torque. Thus, it can provide starting and smooth acceleration for most loads and, in addition, can sustain temporary peak loads without stalling. The NEMA performance standards for design B motors are shown in Tables 1.1–1.3.





**FIGURE 1.1** NEMA design B totally enclosed, fan-cooled polyphase induction motor. (Courtesy Magnetek, St. Louis, MO.)

In the past, there were no established standards for efficiency or power factor for NEMA design B induction motors. However, NEMA had established standards for testing and labeling induction motors. Recently, NEMA has established efficiency standards for energy-efficient polyphase induction motors. These standards are discussed in detail in Chapter 2.

### 1.1.2 NEMA Design A Motors

The NEMA design A motor is a polyphase, squirrel-cage induction motor designed with torques and locked-rotor current that exceed the corresponding values for NEMA design B motors. The criterion for classification as a design A motor is that the value of the locked-rotor current be in excess of the value for NEMA design B motors. The NEMA design A motor is usually applied to special applications that cannot be served by NEMA design B motors, and most often these applications require motors with higher than normal breakdown torques to meet the requirements of high transient or short-duration loads. The NEMA design A motor is also applied to loads requiring extremely low slip, on the order of 1% or less.