IT 318 – SUPPLEMENTARY MATERIAL
CHAPTER 4

Electric Motors

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# Table of Contents

Chapter 4: Electric Motors

- **Overview** .................................................................................................................................................. 2
- **4-1 Commutation** .................................................................................................................................. 2
- **4-2 Stepper Motors** ............................................................................................................................... 3
- **4-3 DC Brushless Motors** ..................................................................................................................... 4
- **4-4 DC Permanent-Magnet Motors** ...................................................................................................... 4
- **4-5 Universal Motors** ........................................................................................................................... 5
- **4-6 AC Induction Motors** ..................................................................................................................... 5
- **4-7 AC Synchronous Motors** ................................................................................................................ 6
- **Summary** ............................................................................................................................................... 6
Chapter 4: Electric Motors

Overview

Electric motors have become one of the most useful devices in the world. They are manufactured by the millions, and there are many in every home and automobile, as well as most machines, and they are generally ubiquitous in most manufacturing environments. In general, they are highly efficient, are readily controlled by computers or other electronic circuitry, and last a long time.

While there are some very unique motors in specialty applications, the six motor types we will cover in this chapter are, by far, the most common in the world. Each is unique in its characteristics, which is why each type exists. Knowing their characteristics will help when you need to replace one, or specify a motor for a given application.

The six motor types we will discuss are Stepper and DC Brushless, which are similar in many ways; DC Permanent Magnet and Universal, which are also similar in many ways, and AC Induction and AC Synchronous, which are also similar in many ways. Examples of these motors are shown in Figure 4-1.

All motors consist of some common elements, as shown in Figure 4-2. However, this figure does not show one common element: commutation. This is because commutation in some motors is not physically part of the motor but is supplied another way – but more about this later.

4-1 Commutation

The root of this word is the same as *commute*, which means to travel back and forth regularly. To keep the rotor (the rotating part of a motor) spinning, there must be something in the stator (the stationary part of the motor), or the rotor, which makes the rotor want to move. But when the rotor turns to where the stator or rotor wanted it to turn, the rotation would end if something in the stator or rotor did not
change. This is the commutation of an electric motor: the constant rotation of an electromagnetic field in the stator or rotor, which in turn causes the rotor to want to also rotate. Because we can create this rotating electromagnetic field in the stator or rotor electrically, we can thus convert electrical energy to rotating mechanical energy, which is what electric motors do.

In the first two motor types (stepper and DC brushless), the commutation is supplied by external electronics (often within the housing of the motor, but not in the stator/rotor part of the motor). In the next two motor types (DC permanent magnet and universal), the commutation is supplied by way of a segmented armature and brushes, which are an integral part of the stator/rotor part of the motor. In the final two motor types (AC induction and AC synchronous), the commutation is supplied by the constantly-changing AC voltage which drives the motor.

We should acknowledge here that there are also linear electric motors, but because they are more specialized, and because they work on the same principles as rotating electric motors, we will cover only rotating electric motors in this text.

4-2 Stepper Motors

Stepper motors are among the newest of the six types of motors, having gained their current popularity with the advent of electronic control circuits and inexpensive computers. They use toothed permanent magnets for the armature and wound stator coils with teeth. They are ideal for applications which require precise positioning. Their characteristics include the following (the +, -, or ~ after each characteristic indicates whether that characteristic is good (+), bad (-), or neutral (~):

1. Extremely flat speed-torque curve (see Stepper in Figure 4-3). This means that as the load varies, the speed remains constant. (+)
2. Low-speed operation, with a maximum RPM of about 1000. (-)
3. Very low efficiency; not meant for continuous operation. (-)
4. Holding torque (stalled) is equal to its operational torque. (+)
5. Steps in discrete increments. (~)
6. Provides highly accurate and repeatable speeds and positions. (+)
7. Long lifetime and low EMI (no brushes). (+)
8. Great for digital applications. (~)
9. Requires external commutation. (-)
10. Smooth rotation is difficult. (-)
11. Changing speeds requires excellent commutation control. (-)
12. Relatively high cost. (-)

Common applications for stepper motors are in positioning of heads in optical-disc drives, hard-disk
drives and printers; X-Y tables; servo motors; and some machining.

A word about stalling (characteristic #4) is important. To stall a motor means to prevent it from turning
while power is applied (the motor is trying to turn). Only one motor type is meant to be used in the stalled
condition, and that is stepper motors. All other motors types should never be stalled.

4-3 DC Brushless Motors

DC brushless motors are very similar to stepper motors, except that they do not have teeth, and they are
not commutated with steps, but rather with sine waves. Like stepper motors, they are relatively new, also owing
their current popularity to the advent of electronic control circuits and inexpensive computers. They are ideal for
applications which require precise speeds. Their characteristics include the following:

1. Extremely flat speed-torque curve (see DC Brushless in Figure 4-3). This means that as the load varies,
the speed remains constant. (+)
2. Wide range of operational speeds, from 0 – 15,000 RPM. (+)
3. Very high efficiency, typically from 70 – 90+. (+)
4. Provides highly accurate and repeatable speeds. (+)
5. Provides high starting torque. (+)
7. Great for digital applications. (~)
8. Requires external commutation. (-)
9. High power levels for size. (+)
10. Relatively high cost. (-)
11. Exhibits cogging at low speeds. (-)

Common applications for DC brushless motors include rotating the disc in optical-disc drives, hard-disk
drives, and laser scanners; electric cars; servo motors; and some machining.

4-4 DC Permanent-Magnet Motors

DC permanent-magnet motors have been around for a very long time. They use a permanent magnet for
the stator, and a wound armature. They are best for applications which require DC voltage. Their characteristics
include the following:

1. Straight and relatively flat speed-torque curve (see PM DC in Figure 4-3). (+)
2. Wide range of operational speeds, from 0 – 15,000 RPM. (+)
3. Very high efficiency, typically from 60 – 90+. (+)
4. Provides high starting torque. (+)
5. Operates on DC voltage only. (~)
6. Relatively short lifetime and high EMI (has brushes). (-)
7. Does not require external commutation. (+)
8. High power levels for size. (+)
9. Relatively low cost. (+)
10. Some cogging at low speeds. (-)
Common applications for DC PM motors include battery-operated tools, automotive electric motors, remote-control cars and airplanes, and electric cars. They are generally not used for high-power applications because the brushes create significant problems with high currents.

4-5 Universal Motors

Universal motors are similar to DC-PM motors in that they have brushes and internal commutation. They are different in that they do not use a permanent magnet for the stator but instead use a wound field, which makes them less efficient. They are called “universal” because they can be used with AC or DC voltage. Their characteristics include the following:

1. Steep and curving speed-torque curve (see Universal in Figure 4-3). This means that precise speed control is difficult. (-)
2. Wide range of operational speeds, from 0 – 15,000 RPM. (+)
3. Medium efficiency, typically from 35 – 60+. (-)
4. Provides high starting torque. (+)
5. Operates on either AC or DC voltage. (+)
6. Relatively short lifetime and high EMI (has brushes). (-)
7. Does not require external commutation. (+)
8. Very high power levels for size. (+)
9. Relatively low cost. (+)
10. Some cogging at low speeds. (-)
11. Burns out quickly if stalled or overloaded. (-)

The most common application for universal motors is in corded portable power tools (drills, skill saws, routers, jig saws, etc.), because they provide such an excellent power density; for example, a typical skill saw can deliver 3 horsepower while weighing only 10 to 15 pounds.

4-6 AC Induction Motors

AC induction motors are the first of the last family of motors, and as the name implies, they work only with AC voltage. This is because they are built to depend on the constantly-changing nature of AC to provide the necessary commutation. Neither the rotor nor the stator uses a permanent magnet. The rotor gets its current via induction, just as the secondary of a transformer does, so no brushes are necessary. Their characteristics include the following:

1. Straight and relatively flat speed-torque curve (see AC Induction in Figure 4-3). (+)
2. Without variable-frequency drives (VFDs), they are limited to integer factors of just under 3600 RPM. With VFDs, they can have a very wide speed range, but still limited to less than 3600 RPM. (~)
3. VFDs are relatively expensive. (-)
4. High efficiency, typically from 60 – 90+. (~)
5. Single-phase AC induction motors suffer from low starting torque. (-)
6. Three-phase AC induction motors have excellent starting torque and outstanding efficiency. (+)
7. Operates only on AC voltage. (-)
8. Long lifetime and low EMI (no brushes). (+)
9. Does not require external commutation. (+)
10. Large and heavy for given power levels (poor power density). (-)
11. Relatively low cost. (+)
12. Smooth operation at all speeds. (+)
13. Single-phase AC induction motors are relatively tolerant of being stalled or overloaded. (+) Three-phase AC induction motors are not. (-)
Common applications for AC induction motors include fans, pumps, garage door openers, garbage disposals, air conditioning compressors, conveyors, and nearly all high-power (>10 horsepower) uses.

4-7 AC Synchronous Motors

AC synchronous motors take extreme advantage of the constantly-changing AC voltage that drives them. The astute reader in the previous section will have noted that the speeds of AC induction motors are a function of the frequency of the AC voltage, since 60 Hz (cycles/second) = 3600 cycles/minute (RPM). But AC induction motors depend on a difference between the frequency of the applied AC voltage and the RPM of the rotor – when they are the same, it has no torque. AC synchronous motors are exactly the opposite – they have almost no torque until the synchronous speed (3600 RPM), at which speed they have maximum torque (see AC Synchronous in Figure 4-3). Because they have almost no start-up torque, most AC synchronous motors also have a built-in small AC induction motor to get them up to synchronous speed.

The characteristics of AC synchronous motors include the following:

1. Straight and relatively flat speed-torque curve (see AC Synchronous in Figure 4-3), but only at synchronous speed. (~)
2. Without variable-frequency drives (VFDs), they are limited to integer factors of 3600 RPM. With VFDs, they can have a very wide speed range, but still limited to 3600 RPM. (~)
3. VFDs are relatively expensive. (-)
4. High efficiency, typically from 80 – 90+. (~)
5. Relatively low torque. (-)
6. Low starting torque. (-)
7. Operates only on AC voltage. (-)
8. Long lifetime and low EMI (no brushes). (+)
9. Does not require external commutation. (+)
10. Large and heavy for given power levels (poor power density). (-)
11. Relatively low cost. (+)
12. Smooth operation at all speeds. (+)

The main application of AC synchronous motors is in timers, clocks, automation drums, and anything else that is tightly controlled with respect to time. With VFDs, they have also found some application in electric race cars.

Summary

Electric motors have branched out into three families, with two types in each family. Each motor type is extremely well suited to its respective applications, as evidenced by the fact that there are millions of them in operation, and millions more are made every year.

The efficiency of a motor can be readily found if we know its mechanical output (usually in horsepower) and the electrical power input (usually in Watts), by using the simple conversion of 1 hp = 745.7 Watts. For example, if a given motor produces 3 hp while using 2500 W, its efficiency would be:

Efficiency = Mechanical Power (in Watts) / Electrical Power = (745.7 * 3) / 2500 W
= 2237.1 W / 2500 W = 89.48%

When choosing a motor for a given application, the following factors should be taken into consideration:

1. What kind of voltage will be used (AC or DC)?
2. How much power is the motor required to provide?
3. What is the duty cycle required of the motor? (continuous or intermittent)
4. How will the motor be controlled? (simple on/off, or is an exact speed or position important?)
5. What will be the operating conditions? (submerged; high-altitude; explosive atmosphere; ingress protection; ambient temperature)
6. What physical size and weight is acceptable?
7. What efficiency is required?

Regardless of the exact requirements for your given application, it is highly likely that some manufacturer somewhere makes a motor which will be almost perfect for you.

**Problems**

1. Discuss why stepper motors are commonly used in computer-controlled applications. (5 points)

2. A stepper motor is rated at 3°/step. Each complete rotation of the motor moves the X-axis of a milling machine head by 1mm. Find the number of complete and partial rotations (in degrees), and the number of steps necessary to move the milling machine head from 35.350 mm to 43.59167 mm. Also, find the resolution of the milling machine head in mm. Assume the stepper motor is moved in full steps. (15 points)

3. Give two of the main advantages of DC PM motors in a common application in automobiles, such as electric windows. Also give one disadvantage. (15 points)

4. Give two of the advantages of AC induction motors over AC synchronous motors in common industrial applications. (10 points)

5. For a given AC induction motor, the efficiency rating is 92%, and the rated output is 4 hp. What is the total power used by the motor? (5 points)

6. An AC synchronous motor designed purely for synchronous operation develops no starting torque. Describe how AC synchronous motors are actually designed to circumvent this problem. (5 points)

**Answers to numerical problems:**

2. Rotations = 8 full rotations plus 87.0°, (or 29 steps.)
   Steps = 989 steps
   Resolution = 1/120 mm

5. Power in = 3243.48 Watts