Basics on electric motors

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Background

Electric motors are essentially inverse generators: a current through coils of wire causes some mechanical device to rotate. The core principle underlying motors is electromagnetic induction. By Ampere's law, the current induces a magnetic field, which can interact with another magnetic field to produce a force, and that force can cause mechanical motion. A motor is basically a generator run backwards (using current to produce motion rather than motion to produce current), and in fact the modern era of practical motors was initiated by accident when one DC generator was accidentally connected to another in 1873, producing motion and leading Zenobe Gramme to realize that his generators could also be used as motors. The first AC motors (synchronous and then induction) were invented by Tesla in the 1880s.

Electric motors are estimated to now consume over 25% U.S. electricity use (though some estimates are even higher, to up to 50%, and over 20% of U.S. total primary energy). While large electric motors can be extremely efficient at converting electrical energy to kinetic energy ($\epsilon > 90\%$), those efficiencies are only achieved when motors are well-matched to their loads. Actual efficiencies in normal usage practice in the U.S. are substantially sub-optimal (motors are oversized for the loads they drive). Small electric motors are also inherently less efficient (more like 50%). Motor design and, even more importantly, motor choice and use practices are an important area of potential energy conservation.

This reading is a (very brief) introduction to four most basic types of electric motors:

- Brushed DC
- Brushless DC
- Synchronous AC
- Induction

(Remember, anything you plug directly into the wall is AC; anything you run directly off a battery must be DC).

Like generators, electric motors consist of a stator and a rotor and the three ingredients: electric current, magnetic fields, and something rotating. A basic rule of thumb is that in an AC motor, as in an AC generator used for industrial power production, the magnet is on the rotor and the current flows in the stator. In most DC motors, the magnet is in the stator and the current is flowing in the rotor; hence the need for brushes.

Motor specifications usually involve several quantities: the voltage (or range of voltages, for DC motors) that the motor can be run at, the rotor speed (or range of speeds), the electrical power drawn by the motor (often given in horsepower rather than Watts), and finally, the "torque" or effective turning force of the motor (discussed further below). Modern motors span a wide range of all these quantities. In particular motors can span 8 orders of magnitude in power consumed. Tiny DC motors of the kind used in toys are a few Watts in power; big AC hydro generators that are also run backward as motors to pump water can be over 100 Megawatts. (For more comparison of motors in daily life: the motor in a household power tool is often 1/4 hp (< 200 W) (though they take much more power when starting up); a ceiling or floor fan is < 100 W; the compressor in an air conditioner is > 1000 W).

Torque is a useful concept when describing forces that produce rotation rather than linear motion - it's a measure of the ability of a device to turn something. Everyone has an instinctive idea of the power of a lever: if you try to move something by prying with lever (think of turning a stubborn bolt with a long wrench), you can exert more "turning force" with a longer lever than with a short one. Torque (we'll call it $\mathbf{T}$) is that "turning force". In this definition and the math that follows, the bold-face means that quantities have a direction as well as a magnitude.

Physics (optional)

The definition of torque is

$$\mathbf{T} = \mathbf{r} \times \mathbf{F}$$

where $\mathbf{r}$ is the lever arm and $\mathbf{F}$ is the force, and the cross product means that you consider only the component of force that is perpendicular to your lever arm, i.e.

$$T = r \cdot F_{\perp}$$

Newton's law $\mathbf{F} = m\mathbf{a}$ then has an analogous form for this "tuining force" as:

$$\mathbf{T} = I\alpha$$

where I is the "moment of inertia" (a measure of how difficult a body is to rotate) and α is the rate of change of angular velocity ($\frac{d\omega}{dt}$, where ω is the angular velocity). Note that although torque desribes an ability to push something around, its units are force times distance, or energy.

In plain(er) English, torque is a measure of how much ability a device has to rotate a load. Because the function of a motor is to rotate things, that's the ability you care about. In particular, in motors one often wants to know the torque-speed curve. How does the rate at which a motor rotates relate to its ability to turn a load? Some motor have better turning ability at high speeds, other at low speeds. Which you choose depends on what job you want the motor to do. If the motor torque is too low, it won't be able to do the job. Alternately, as discussed above, if your motor is more powerful (higher torque) than you need for a particular job, it will do the job but will have unnecessary energy inefficiency. (It will waste energy as heating rather than converting it to work).

DC motors

Brushed DC motors

The simplest (and cheapest) DC motor is the brushed DC motor. A brushed DC motor is like the simple loop generators we've seen in cartoons (or the Jensen generator used with the steam engine), only run backwards: the magnet is stationary and the DC-current-carrying coil (or coils), connected to a shaft, rotates through the fixed magnetic field. Loop generators we've seen use "slip rings" to make electrical contact between fixed current-carrying wires and the rotor. But remember, in the simple loop generators, steady rotation in one direction with a slip ring produced alternating current. And a motor is the converse of a generator. So if you drove the slip-ringed generator as a motor with *alternating* current, you could get steady rotation. If drive it with *direct current*, though, the loop would just move to a place where force was zero and would stay there. To keep the loop moving and produce rotation in one direction requires not slip rings but some kind of "commutator" that essentially switches the diretion of the current, putting it first on one side of the loop and then on the other, mimicking alternating current. Only if you manage to continue to kick the loop around will it keep turning.

The simplest commutator is a "split ring" that makes contact with two separate brushes. In the simple AC loop generator, the rotating and fixed conductors are connected with two slip rings, each of which maintains a

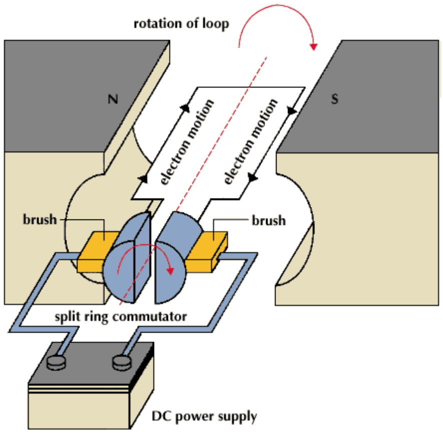

Figure 1: DC motor with rotating loop, brushes and split-ring commutator (*Encyclopedia Brittanica*)

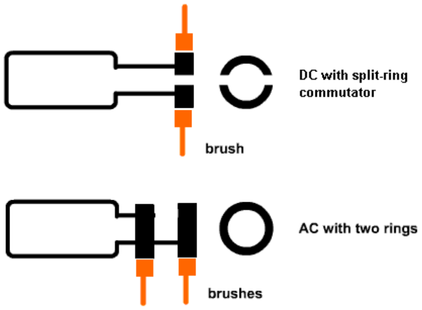

Figure 2: Slip rings for AC generators/motor (bottom) and split rings for DC generation/motors (top). From *http://www.school-for-champions.com/science/ electrical_generation.htm.*

continuous connection between one end of the rotating loop and a fixed wire. The split ring commutators joins both ends of the loop to fixed wires, and every half-rotation, the contacts are switched.

In a generator, the simple split ring commutator on a single loop generator would produce a voltage (and current) around the loop that is a single rectified sine wave, varying between zero and maximum every quarter revolution. In a DC motor with a simple split ring commutator, the torque provide by the motor is similarly irregular, varying from zero to maximum every quarter revolution. The motor doesn't provide steady even rotational force but a jerky force, wich is obviously not ideal for industrial applications. This is termed “torque ripple.” To minimize torque ripple, DC motors use the same strategies that DC generators use to minimize voltage ripple: increasing the number of windings on the rotor or magnetic poles on the stator. (The windings on the rotor are also called the “armature”). By producing many out-of-sync rectified sine waves superimposed on each other, adding windings or poles begins to approximate a constant torque.

Brushed DC motors seem like a relatively practical solution, but there are drawbacks. The brushes themselves wear out fairly fast, and it is not wise to put big amounts of current through brushes that make sliding contacts, as they will spark as contacts are made and then broken. If the rotor turns too quickly, the sparking can damage or destroy the commutator. Designing

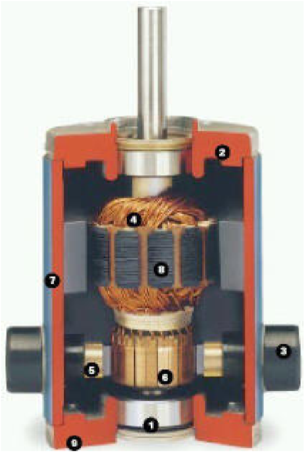

Figure 3: Small commercial DC motor w/ permanent magnet, cut away to show insides

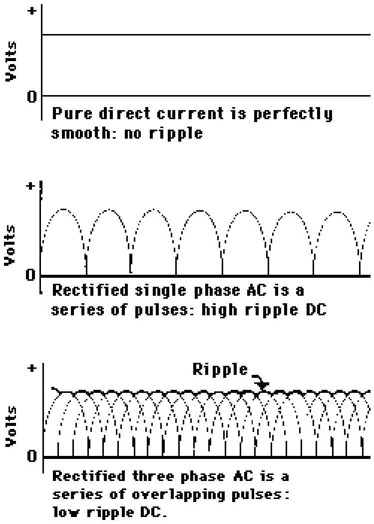

Figure 4: Reduction of torque ripple in DC motors by adding multiple rectified sine waves.

a brushed DC motor involves tradeoffs between power, speed, and repair frequency/cost.

One obvious application for brushed DC motors is in the cheapest of all motors, small lightweight low-power essentially disposable motors that power cheap battery powered devices (e.g. toys). These cost a few dollars at most and wear out relatively quickly but are then just thrown away. These simple motors use permanent magnets in the stator instead of electromagnets. Permanent magnets are heavier but simpler and cheaper. They also have relatively simple armatures and so significant torque ripple.

DC motors are now just cheap options for unimportant uses, though. Their behavior has some very appealing characteristics that make DC motors versatile and desirable for many uses, more so than AC motors. First, the rotation speed of a DC motor is directly tied to its supply voltage, which can itself be varied within some range to produce variable motor speed. DC motors can also be designed to rotate at any desired speed for a fixed supply voltage, unlike AC motors, which (as discussed in the problem set and below) are constrained to only certain rotation speeds. Secondly, DC motors have strong torque at low speeds (again unlike AC motors, where torque goes to zero as the motor stops). The bigger the load on a DC motor, the slower it will go, but the bigger its torque will also be. If you suddenly increase the load on DC motor (e.g. attach something difficult to push to its rotor), the motor will slow down but will eventually reach some equilibrium where its torque has increased sufficiently to continue pushing the load around. In contrast, an AC motor, if overloaded, will just stop. DC motors are therefore useful at low rotation speeds and versatile when confronted by varying loads.

Brushless DC motors

Before the age of electronics, all DC motors had to have brushes or some other type of mechanical commutator. The electronic age offers other options. It is now possible to electronically switch current directions, in effect making AC power from a DC power source. A brushless DC motor is essentially a synchronous AC motor (discussed below) with electronic commutation. Like an AC motor, the magnet is on the rotor and the drive current on the stator rather than the other way arund of brushed DC motors. The electronic commutation switches the current back and forth to mimic AC current and keep the motor turning. [1]

In brushless DC motors the user can actually do better than just mimic an AC motor from a DC power source. Electronic commutation gives you total control over the effective frequency of the "faux AC" you're producing, and therefore lets you build an AC-like motor that can rotate at different speeds - you now have total electronic control over motor speed. (The advantage of this will be more clear when you read about AC limitations below). This controllability means that servo motors for complicated mechanical systems involving controls and electronic feedbacks (e.g. robotics) are now exclusively brushless DC.

There are also many uses for brushless DC that don't involve the need for total user control. Brushless DC motors are more reliable than brushed motors, since it has no commutators that can break and wear out. You get the other good features of AC motors, e.g. reliable operation at high power. It does have higher cost (for all those electronics). Brushless DC in your daily

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[1] What really happens in electronic commutation is that a set of magnetic position sensors tells the electronics the location of the rotor. The electronics then decide which coils to send power to in order to apply torque to the rotor. When the rotor is turning, this means that current to each coil is ramped up and down just like ac power.

life include cooling fans for PCs, which must be reliable, and the motors in hybrid or electric vehicles. Car electric motors must be DC, as they run on batteries; reliable, since they're keeping your car running; and high-power, since it takes a lot of current to turn the wheels of a whole car.

AC motors

In modern AC motors, as in modern AC generators, the current is applied to the stationary part of the motor and the magnet is on the rotor. The varying current in the stator generates a rotating magnetic field (via Ampere's law) which interacts with the rotor magnetic field, pushing the rotor around. AC motors in use now come have several options for generating the rotor magnetic field. In some the rotor has permanent magnets; in others the rotor carries an electromagnets driven by an external DC power source; in still others (induction motors) the rotor merely picks up induced magnetic fields from the magnetic field of the stator.

Synchronous AC motors

A synchronous AC motor really is essentially the same as the AC generators described in a previous reading. As before, the rotor speed and the frequency of the alternating current are irrevocably tied together. The motor must turn at the exact frequency of the alternating current that drives it (modulated only by the number of magnetic poles).

What are the benefits of a synchronous AC motor? One very large benefit is that you can avoid brushes, with their short lifetimes. You will need either a permanent magnet in the motor or slip rings to pass current to an electromagnet, but those currents are smaller than the drive current, and slip rings don't spark like brushes and so are longer-lived in general. [2] In practice, most small AC synchronous motors just use permanent magnets. That produces a sturdy, reliable, if not readily controllable motor. But if you just want to turn something, and you're OK with letting our 60 Hz grid system constrain that turning rate (think: household fans), an AC motor is just fine.

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[2] Only the very largest synchronous motors - basically power generators run backwards, in the tens to hundreds of MW range - are big enough to have the clever generator trick of putting a small DC generator for rotor electromagnets in the rotor itself.

Synchronous AC motors do have to be designed to counteract torque ripple, as did the DC motors discussed earlier. The simplest AC motor, a single coil driven by a single rotating magnet, actually has the worst possible torque ripple, since torque in one position actually goes to zero. Just as with DC motors, the answer to torque ripple is more complexity in the windings and the motor poles. Synchronous AC motors are also sometimes driven by three-phase power (passed to three separate systems of coils) for this reason, because the three out-of-phase systems provide a steadier turning force on the rotor. Note: it's easy to identify a three-phase motor by its plug: anything driven by 3-phase power has a larger plug with a different pattern of prongs than the plugs you're used to in everyday experience. If a motor can plug into an ordinary wall socket, it's just single-phase.

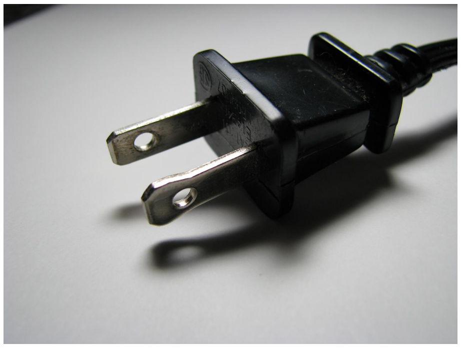

Figure 5: Ordinary single-phase U.S. electrical plug.

Figure 6: Three-phase U.S. electrical plug.

Synchronous AC motors do have some drawbacks that are particularly troublesome. First, the torque-speed curve for a synchronous motor is very different from that of a DC motor. As discussed below, the torque actually goes to zero as speed goes to zero. A synchronous AC motor likes to rotate at one and only one speed. If you gradually increase its load, it will simply draw more and more current while turning at precisely the same speed, until it hits the threshold where it can't handle the load anymore, at which point the motor will come crashing to a stop.

You might at this point ask the obvious question: if there is no torque at zero speed, how does a synchronous AC motor ever start? The answer is, you do need to include some system to give the motor a kick at first turn-on, or else it would in fact never start (without a manual push), since there is no torque at zero speed. In practice, some relatively simple electrical design involving only passive components can provide that kick. (Capacitors "blunt" the AC at first and make it act for a very brief time like a DC motor, just long enough for the motor to get started turning).

Beyond that need for some clever kick-starting, though, synchronous AC motors are reliable, steady, simple, and durable, if a little boring and predictable. As long as they're operated within their appropriate operating range, they do exactly what they are supposed to regardless of load size.

Induction motors

The induction motor was the last great invention in electric motors before the age of silicon and semiconductors that gave us the brushless DC motor. Like so many other inventions of the 1880s, it was a product of Tesla's amazing brain. An induction motor is in some sense the simplest motor of all. The drive current is passed through coils on the stator, just as in the synchronous AC motor. But in an induction motor, the rotor holds nothing except for some windings of wire. No magnet, no current sent through an electromagnet. How does it work then? The drive current in the stator induces a magnetic field in the stator, and the stator field in turn induces one in the rotor wires, and the two fields interact to allow the rotor to be pushed around and effectively convert electrical energy to mechanical energy.

Of all the motor types, the induction motor can seem the most mysterious or even impossible because it seems like it creates motion out of nothing, as though it were driving itself. Really, however, it is not very different from the other types. All work by the interaction of magnetic fields in stator and rotor. In the induction motor case, the production of one of those magnetic fields is just very indirect. But if designed right, this induction works very well, and the resulting motor is about as simple as possible. Its ruggedness and simplicity means that it is the dominant electric motor type for industrial use.

Induction motors do differ in behavior from synchronous motors in two important ways. First, they do not rotate at *exactly* the same frequency as that of the alternating drive current. Instead there is some "slip" - the rotor turns slightly slower than the AC current frequency. Second, the torque of the induction motor is actually proportional to that slip. This means that torque is not zero at no zero speed, but is actually maximum, because the slip is maximum: 60 Hz minus zero. While a synchronous AC motor requires

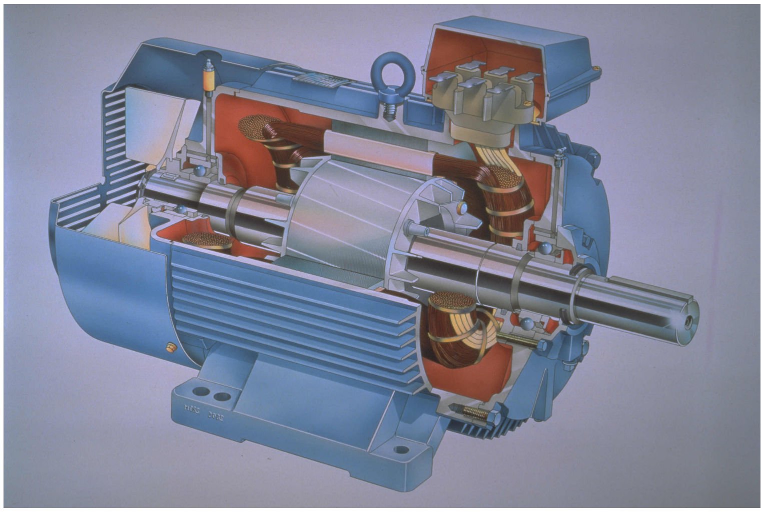

Figure 7: Commercial AC "squirrel-cage" induction motor, so-called because the wires on the rotor are arranged in a cage shape, permitting current to flow along multiple alternate pathways as it (and the rotor magnetic field) are induced by the stator. It was invented in 1889, a year after Tesla's induction motor patent.

some engineering to get to start at all, an induction motor requires some engineering to keep from starting too fast.

Finally, in case you are wondering how the large variety of electric motors now have been designed.... the design of windings on an electric motor is as much art as it is science. Once you've designed a motor winding, you can model the effects. But you can't write a computer program that itself designs the optimal motor. Motors and their interacting electric and magnetic fields are complex enough that the human brain is still needed to explore new designs, and there is some room for performance improvement and hence energy savings still.

More sources of information

One great source of some introductory explanations and beautiful animations is a website from the University of New South Wales in Australia. And a website at Georgia Tech also has some nice interactive figures.