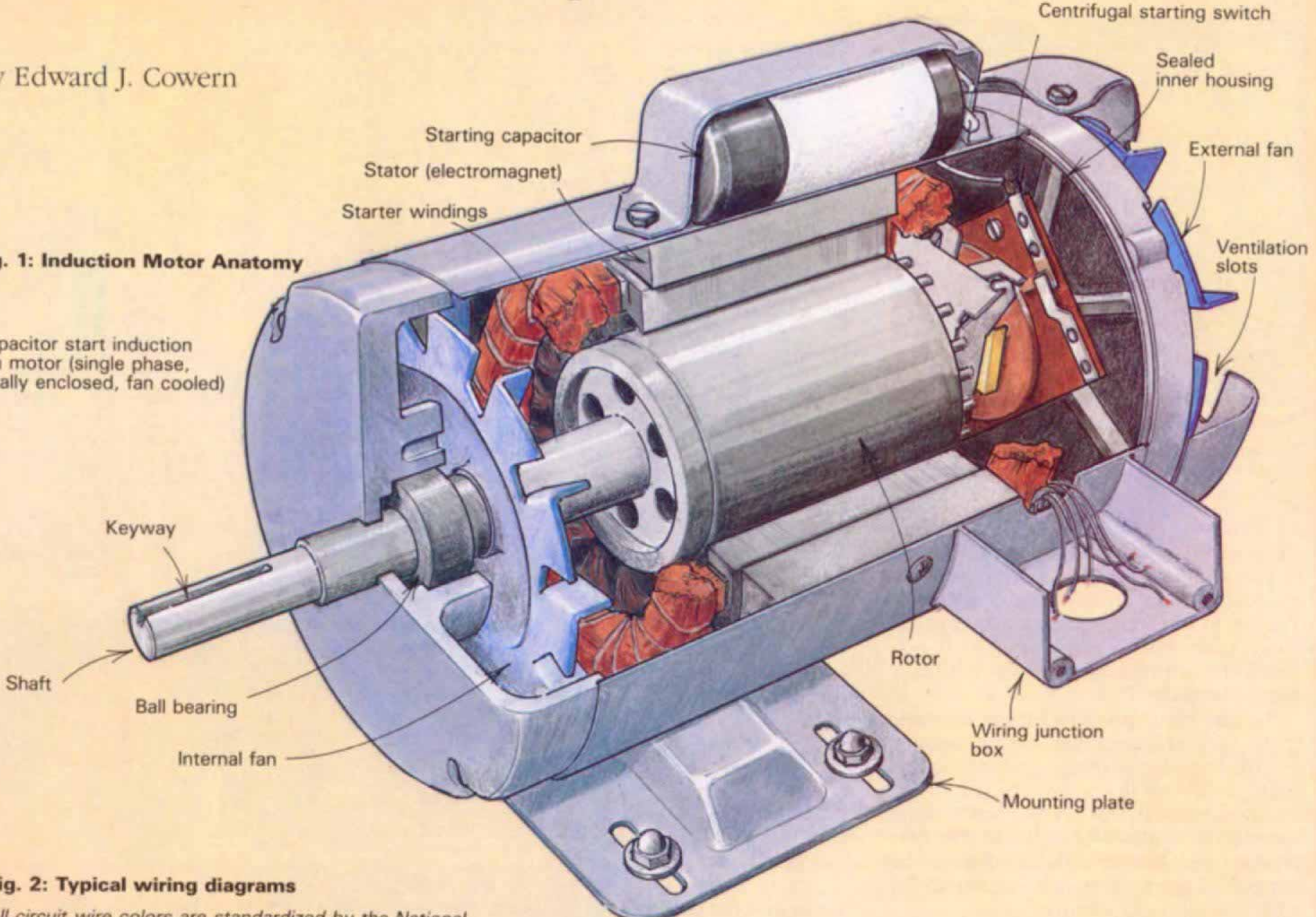
Power Primer

Electric motors in the woodshop

by Edward J. Cowern

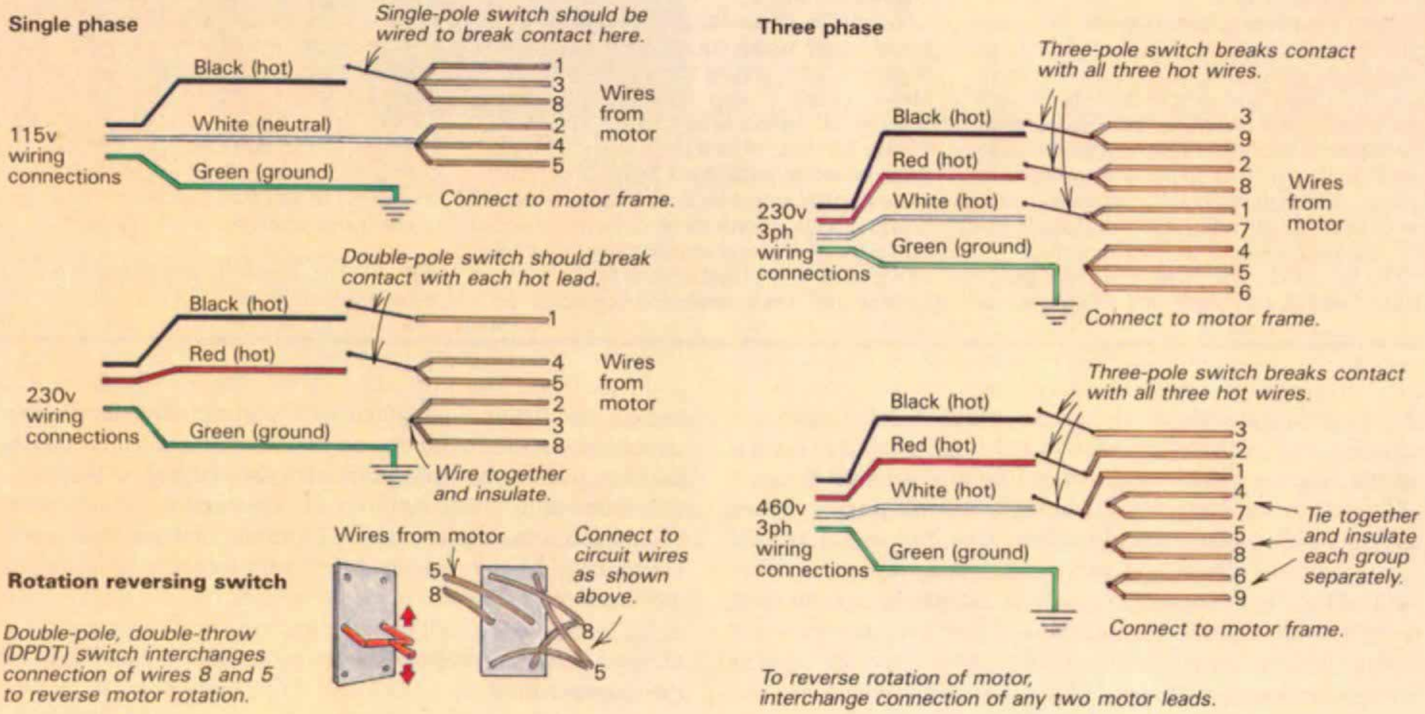
Fig. 1: Induction Motor Anatomy



Capacitor start induction run motor (single phase, totally enclosed, fan cooled)

Fig. 2: Typical wiring diagrams

All circuit wire colors are standardized by the National Electrical Code. Induction motor lead numbering is standardized by the National Electrical Manufacturers Association (NEMA).



Rotation reversing switch

Double-pole, double-throw (DPDT) switch interchanges connection of wires 8 and 5 to reverse motor rotation.

To reverse rotation of motor, interchange connection of any two motor leads.

There was a time not too long ago when a woodworker had to open a sluice gate to a waterwheel or stoke the fire beneath a steam engine's boiler before any powered machinery in the shop could be operated. Nowadays, the relative luxury of just flipping a switch makes electric motors an essential part of the woodshop.

In this article, I'll explain a bit about how electric motors work, why they might stop working and how you can intelligently choose new motors to use as replacements or incorporate in the machines you build. I won't attempt to entirely demystify motor theory, but I can convey enough knowledge to help you make sensible, safe decisions when choosing, connecting and operating electric motors in your workshop.

Motor types—Broadly speaking, two major types of motors are commonly used by woodworkers: induction motors for stationary power tools, and universal motors for portable tools. A third type, the direct-current permanent-magnet motor, is becoming popular for battery-operated cordless tools and in applications where controlled speed is important. However, I'll deal only with induction motors (see figure 1), the basic workhorse found on most stationary equipment—tablesaws, lathes, shapers, jointers, drill presses, etc.

This type of motor converts electricity into rotary motion by taking advantage of the fact that alternating current (AC) reverses its direction of flow 60 times per second. Inside the motor, these alternating electric impulses reverse the polarity of a fixed electromagnet, the stator, around a cylindrical drum called a rotor. These current reversals actually produce a rotating magnetic field inside the stator which, in turn, induces currents inside the rotor, producing a strong magnetic field in the rotor. The interaction of these two magnetic fields causes the rotor to spin as it attempts to match the speed of the stator's rotating field.

Since electrical power is available in either single or three phase, induction motors are designed specifically to operate on one or the other. "Phase" refers to the number of pulses of power delivered during one cycle (1⁄60 of a second for 60-cycle power). Therefore, three-phase electricity delivers six pulses of power in the same time that single-phase electricity produces only two.

Whether you choose single- or 3-phase induction motors may depend on what kind of power is available to your shop. When 3-phase power is available, usually in industrial areas, use 3-phase motors if you can. They are simpler and have longer service lives than their single-phase equivalents, and they are more efficient to operate. It's possible to use 3-phase motors on single-phase power, but you'll need to provide your own third phase. There are several ways of doing this. One is the type of phase converter described by Mac Campbell in *FWW on Woodworking Machines* (The Taunton Press, 1985).

The best all-around quick-starting single-phase induction motors are either capacitor start/induction run (⅙ HP through 1½ HP) or capacitor start/capacitor run (2 HP through 10 HP). Both types depend on an electrolytic capacitor to energize a starter winding to get the motor spinning (see figure 1). Capacitor-start types use a centrifugal switch to disconnect the starter winding once the motor comes up to speed, while two-value capacitor motors have a separate, oil-filled capacitor that remains connected to the starter winding to provide useful power output after the motor has started. Split-phase motors—a third type—lack starting capacitors entirely and are found on machines that don't require much start-up torque, such as bench grinders.

Most capacitor-start induction motors can be wired to operate on either 115v or 230v and can be made to rotate in either direction. Normally, 115v operation is adequate for motors through % HP, but when possible, 230v should be used for motors 1 HP and larger. This is because amperage halves as voltage doubles, so a 2-HP motor requiring 13 amps at 220v would need 26 amps at 115v. Most household wiring is not capable of delivering that much current without a significant voltage drop at the motor terminals, a condition which substantially reduces motor performance.

Establishing the correct direction of rotation is simply a matter of wiring. Figure 2 shows standard wiring diagrams for both single- and 3-phase motors. If you wish to reverse a motor's rotation, say on a shaper or disc sander, you can wire in a reversing switch that reconnects the starter winding wires while leaving other connections intact. *Avoid using reversing switches on tools with threaded arbors, since the reversed direction could unscrew a blade's locknut or release the faceplate on a lathe.*

The major shortcoming of the induction motor—either single- or 3-phase—is its operating speed, which is fixed by the frequency of the power source and the number of magnetic poles designed into the motor. For example, on 60-cycle power, a two-pole motor will run at a maximum no-load speed of 3,600 RPM. As the load increases during operation, the motor will slow down to a full-load speed of approximately 3,450 RPM. Similarly, a motor with four poles will have a no-load speed of 1,800 RPM and a full-load speed of about 1,725 RPM.

Since most induction motors used in the shop are either 3,450 RPM or 1,725 RPM, speed adjustments must be made mechanically. By varying the diameters of the drive and driven pulleys, the speed of a blade or cutter can be made faster or slower than the speed of the motor. On certain machines where variable speeds are desirable, such as lathes, drill presses and shapers, multi-step pulleys offer a choice of a few preset speeds. Alternately, a mechanical adjustable-speed drive can provide a continuously adjustable range of speeds.

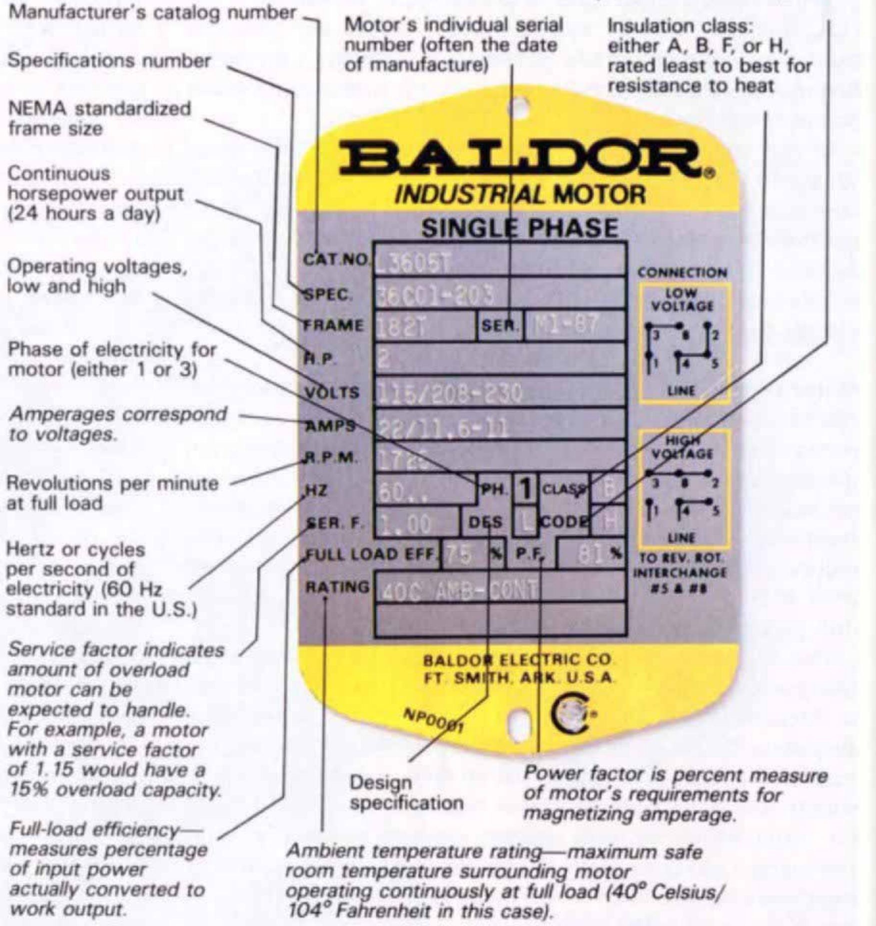
Enclosure types—Modern industrial-duty induction motors are available in three enclosure types. The open drip-proof motor (top left photo, next page) is the least expensive. Its louvered end brackets allow cooling air to freely circulate inside, while preventing water from dripping in directly. It's a fine motor for many applications where relatively clean and dry operating conditions exist, such as an air compressor located in an area of the shop unaffected by sawdust, or a drill press with its motor mounted high and away from the chips generated by the machine.

The second type, the totally enclosed fan-cooled (TEFC) motor, was originally developed for the metalworking industry where oil mist and metal chips are present. Its internal housing is completely closed (bottom left photo, next page) so that dirty air can't circulate through the inside of the motor. Since heat can be a problem for any motor, this type is cooled by both internal and external fans driven by the motor itself. The totally enclosed motor carries a slight price premium, but is an excellent choice for virtually all woodworking machines exposed to sawdust. Some debris will collect on the back of the fan cover, but routine housekeeping will keep this from causing trouble.

The third type of motor enclosure is the so-called hazardous location or explosion-proof. It looks like the TEFC type, but has tightly fitting seams and a rupture-proof casing to prevent internal explosions from igniting vapors or gases from combustible solvents or dusts outside the motor. Explosion-proof motors—UL-rated for Class 1, Group D applications—are the definitive choice for

You can see the wire windings in the open drip-proof motor frame on top, while the totally enclosed, fan-cooled (TEFC) motor above is sealed tight to prevent the invasion of dust and grime. The TEFC motor uses both an internal and an external fan to circulate cooling air and dissipate harmful heat buildup.

Fig. 3: Motor identification plate



Code letter indicates the amount of current required to start the motor.

Manufacturer's catalog number

Motor's individual serial number (often the date of manufacture)

Insulation class: either A, B, F, or H, rated least to best for resistance to heat

Specifications number

NEMA standardized frame size

Continuous horsepower output (24 hours a day)

Operating voltages, low and high

Phase of electricity for motor (either 1 or 3)

Amperages correspond to voltages.

Revolutions per minute at full load

Hertz or cycles per second of electricity (60 Hz standard in the U.S.)

Service factor indicates amount of overload motor can be expected to handle. For example, a motor with a service factor of 1.15 would have a 15% overload capacity.

Full-load efficiency—measures percentage of input power actually converted to work output.

Design specification

Power factor is percent measure of motor's requirements for magnetizing amperage.

Ambient temperature rating—maximum safe room temperature surrounding motor operating continuously at full load (40° Celsius/104° Fahrenheit in this case).

spray-booth exhaust fans, where volatile fumes from woodworking finishes are encountered.

Frame size and mounting When choosing a motor for a particular application, it's important that the physical characteristics of the motor fit the mounting situation. Fortunately, the frame sizes of modern electric motors have been standardized by the National Electrical Manufacturers Association (NEMA), so motors with the same size and power specifications made by different manufacturers are interchangeable. The frame number stamped on the information plate (see figure 3) is indexed to an extensive NEMA-compiled chart listing all motor dimensions and statistics, such as shaft diameter and housing size. Although the chart lists dozens of different frame sizes, most motors in the ⅓- to 5-HP range are either size number 56, 143, 145, 182 or 184.

The motor should be solidly attached to the stationary power tool's mounting plate to reduce any vibration a running motor and belt drive may produce. Better-quality machines have a cast iron, rather than pressed-steel, motor mount. A flimsy mounting plate can be reinforced with flat iron bars if necessary.

In addition to firm mounting, a motor needs well-aligned pulleys and the correct belts to deliver power effectively. Pulleys are made from either cast iron or zinc alloy, the former being more durable, the latter less expensive. These are almost always keyed to the motor shaft or arbor with a Woodruff or square key, then fixed with a setscrew. V-belts come in standard cross-sectional sizes. The most common are A-size and fractional horsepower (FHP) belts, which are narrow, and wider B-size belts. Belts must be selected to match pulley width. The general rule is this: for low-torque, high-speed applications (such as jointers), smaller-section belts can be used; in high-torque applications—tablesaws, for instance—larger-section or multiple belts are required. If you're not sure about the length of the belt you need, an approximate length can be determined by adding twice the distance between the center of the motor and arbor shafts to half the sum of the circumference of the drive and driven pulleys (measured around the rims). Belt tensioning should strike a balance between too much, which places strain on the bearings, and too little, which allows belt slippage. Ideally, a belt should flex about ¹⁄₃₂ in. for every inch of span between pulleys when slight pressure is applied.

Motor controls—In addition to installing the motor correctly, single- and 3-phase motors 2 HP and larger should be protected with magnetic motor starters. Beside providing a regular on/off switch, this starter has a small heating element selected to match the amperage rating of the motor with which it's used. When heat generated from the current draw of the motor exceeds a certain threshold (lower than a temperature which would damage the motor), the element trips a thermal switch and shuts off the power. A magnetic starter has one additional safety advantage: if power in the shop suddenly quits, an electromagnet disconnects the starter in the switch; the motor stays off, even after the power is restored. To start the motor again, you have to deliberately switch it on.

Many single-phase motors are equipped with a built-in manual overload device that can be used with a separate on/off switch. The device adds a small amount to the cost of the motor, but provides substantial burnout protection. The device is normally mounted on the side or end of the motor housing and is designed to sense the motor's current load and internal temperature, as well as ambient air temperature. After excess heat or an overload trips the device, the operator must wait for the motor to cool off before resetting the button and putting the motor back to work.

I *strongly* urge woodworkers to avoid, at all costs, motors with built-in thermal protectors that automatically reset after an overload shutdown. These motors, often found on pumps and air conditioners, can be bought used at tempting prices. They look and work just like any induction motor, but the automatic resetting feature can have potentially disastrous consequences.

For motors under one HP, a fractional-horsepower manual motor starter (simply an on/off switch with a heating element) can provide thermal protection for a fraction of the cost of the magnetic type. These must, however, be manually turned off in the event of a power failure. Other small, low-amperage motors may be started with regular toggle switches as long as the voltage and amperage rating on the switch match the voltage and maximum current draw of the motor. Regardless of which type of motor or control you use, always make sure that the switch is connected to break continuity with the *hot* lead(s), not the neutral (see figure 2). Also, make sure the motor and switchbox are properly grounded.

Once you have your motor ready to plug in, consider what you're going to plug it into. An inadequate power supply will cause the voltage to drop and the wiring to heat up during heavy use. Sagging voltage dims the lights; more important, it causes motors to draw excessive current. Since voltage (the measure of electrical force or pressure) and amperage (the measure of electrical flow) are inversely related, a 10% voltage drop results in a 10% amperage increase. This diminishes motor performance, leading to overheating and a subsequent shortening of motor life. Even worse, overheated wires could ignite workshop sawdust and start a fire. It's fairly normal to see a slight flickering or momentary dimming of the lights when one of your larger machines is switched on. But if you notice this effect during routine operations, you probably need to consider upgrading

Understanding horsepower

Few shops these days employ the power of the hoof, but for the sake of evaluating electric motors, we've inherited the measure of horsepower established during the 1800s to compare the output of the steam engine to that of the horse. "Power" is defined as work per unit of time, and since the average workhorse can lift 33,000 pounds one foot in one minute, 33,000 foot-pounds per minute is the force equivalent to one horsepower.

Since induction motors run on electricity, it seems logical to determine their power output by figuring the amount of electricity they consume. If we calculate a motor's power consumption in terms of wattage—a measure of electrical power equal to voltage times amperage—the following formula should give us its horsepower:

$$\frac{\text{Amperage} \times \text{Voltage}}{746 \text{ (No. of watts in 1 HP)}} = \text{HP}$$

But, in practice, it doesn't work this way: a motor can't convert all of the electrical energy it uses into mechanical power. Some energy goes toward magnetizing the rotor and the windings. Power factor is a measure of this. Generally, the more powerful a motor, the higher its power factor. Also, a motor's full-load efficiency is the percentage of electrical input that's successfully converted into mechanical power. The rest is lost to friction, windage and electrical resistance. On new motors, efficiency and power factor are printed on the motor's nameplate (see figure 3).

As with motor design and construction, the National Electrical Manufacturers Association (NEMA) has standards for measuring and labeling motor output. These standards consider a motor's work capacity (stated as horsepower) and the allowable amount of temperature rise while performing at that capacity. A motor's output must be tested by connecting it to a dynamometer, a mechanical device that measures torque. The horsepower is then determined with the formula:

$$\text{Horsepower} = \frac{\text{Torque (in ft. lb.)} \times \text{RPM}}{5{,}252 \text{ (constant)}}$$

As the motor is forced to run under full load at its rated horsepower capacity, the rise in its internal temperature is carefully measured. The amount of allowable temperature rise depends on the type of insulation used in the motor's windings. A motor with Class B insulation, for instance, is allowed to heat to 80°C or less above the specified 40°C standard ambient temperature of the air surrounding the running motor. If it gets any hotter, its full-load nameplate horsepower rating must be lowered, or the motor must be redesigned for better cooling.

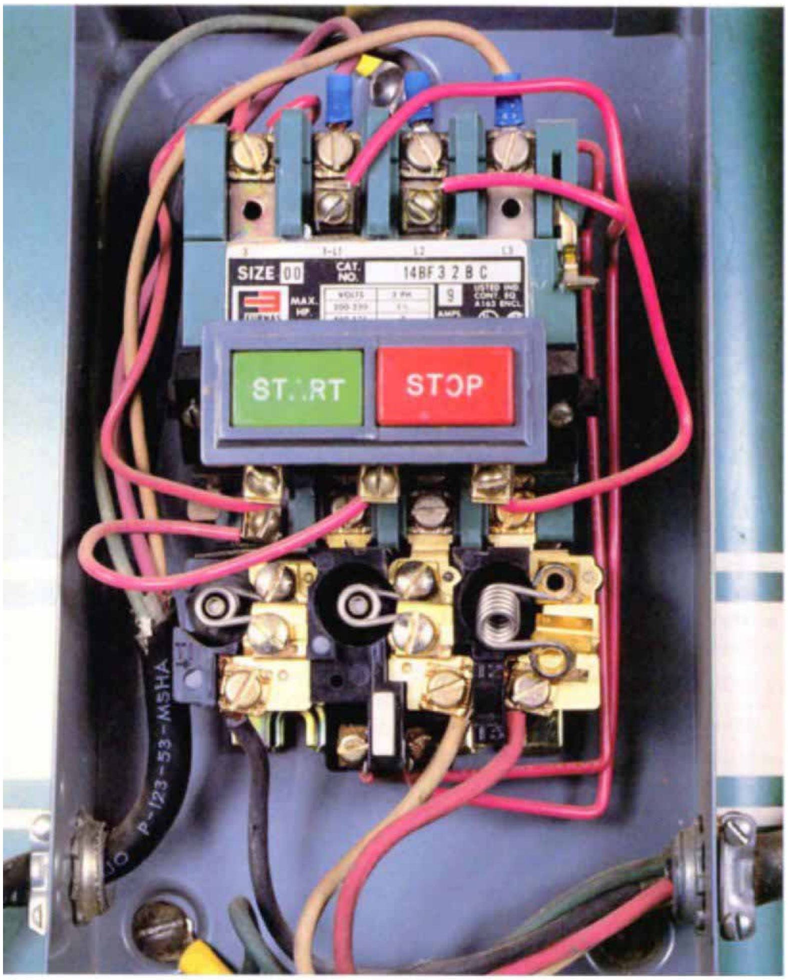
NEMA's standards for induction motor horsepower are based on a motor's ability to deliver its nameplate rated power continuously, 24 hours a day, under full load. But these standards can also be qualified by time-duty ratings of 15 minutes, 30 minutes and 1 hour, each representing the period of time the motor can deliver its rated horsepower without overheating. A duty-limited motor will always be marked accordingly on its nameplate. Continuous-duty motors are commonly used on stationary woodworking machinery. This capability, however, is rarely needed for machines, such as saws, jointers, or planers, which are seldom operated at continuous full load.

Machinery manufacturers aren't compelled to comply with NEMA's rating standards; they may devise their own methods for measuring the output of their motors. It's not unheard of for a tool manufacturer to take liberties with claimed horsepower ratings: the *same* motor design could be rated at its *continuous-duty horsepower* by one manufacturer and *peak power output* by another.

Any electric motor is capable of producing far greater than its continuous-rated power, if temperature rise is ignored. A 3-HP motor, for example, can generate up to 7 HP for short time periods. Beyond that, it reaches its pullout or breakdown point and stalls, just like an airplane attempting an overly steep climb. If you don't cut the power or reduce the load, the motor will overheat and burn up.

On inexpensive tools that have induction motors of questionable pedigree, watch out for the words "maximum developed horsepower," which is advertising talk for a motor whose claimed output is right up near its pullout point. You can't operate the motor for very long at its maximum output without thermally damaging the motor. Some small induction motors rated at 2⅞ maximum developed horsepower perform more like 1-HP continuous-duty motors. Furthermore, never mix apples with oranges and attempt to compare a machine rated in continuous-duty horsepower to a machine rated in maximum developed horsepower. *E.H. C.*

Proper alignment of pulleys, essential to good machine performance, can be checked with a straightedge. Multiple belts are used on this resaw bandsaw to handle high torque.



With the power off and cover plate removed, you can see the three coil-like heating elements inside this three-phase magnetic motor starter, located below the start and stop buttons. The element on the right has been partially removed to afford a better view.

Fig. 4: Table of wire gauges

		Length of circuit wiring or extension cord			
		25 ft.	50 ft.	100 ft.	150 ft.
Amperage rating of single-phase motor, 110v or 220v	5	14 ga.	14 ga.	12 ga.	10 ga.
	8	14 ga.	14 ga.	12 ga.	10 ga.
	10	14 ga.	14 ga.	12 ga.	10 ga.
	15	14 ga.	12 ga.	12 ga.	10 ga.
	20	12 ga.	10 ga.	8 ga.	8 ga.
	30	8 ga.	8 ga.	8 ga.	6 ga.

your shop power system. If the machine is a considerable distance from the power panel or plug, use heavier-gauge wire (see figure 4) to avoid voltage drop. This applies to extension cords for portable power tools as well.

Maintenance—Thanks to modern ball bearings, most electric motors require little maintenance. In fact, sealed bearings usually need to be replaced by the time they need lubrication. Too much well-intended maintenance can be damaging; motor bearings are more likely to fail from too much (or incompatible) lubrication than they are from lack of lubrication. If you're in doubt about whether or not to lubricate, *don't.* However, this advice doesn't apply to older motors with bronze sleeve bearings. The oil cups on these motors should be filled with high-grade SAE 10 to 20 non-detergent machine oil (don't substitute plain motor oil), always with the motor shut off. Over-lubrication won't hurt these bearings.

One regular maintenance habit will extend a motor's life: vacuuming the sawdust out of cooling passageways in the motor housing. To reduce the hazard of fire, clean out electrical junction boxes and switchboxes occasionally, cutting off the power first.

Troubleshooting—Unfortunately, there are no simple tests to determine the internal condition of a motor. In capacitor-start motors, centrifugal switch or capacitor failures are common faults. Switches wear out, burn or stick in one position. Capacitors can open, short out or change value. Whether a starter switch or capacitor fails, the result is the same: the motor hums but won't start. You can sometimes temporarily get the motor going with a quick hand turn of the pulley. But use extreme caution in doing so, and keep your hands clear of blades or cutters. When the starter switch fails to open, the motor will come up to speed but will draw excessive current (amperes) and overheat quickly. If the starting capacitor changes value as it becomes weak, the motor will be slow in starting and won't come up to speed as quickly as it should. Low line voltage caused by wire that's too small can produce the same symptoms.

Failure to react to any of these indications can lead to a complete motor meltdown, where the heat that builds up from an overload or component failure causes windings to overheat, burn off their insulation and short out. Do *not continue* to operate any motor on a machine or power tool when erratic performance or unusual noise is evident. Things will only get worse—and repairs more expensive—if problems are ignored, since capacitor or centrifugal switches can be replaced at a fraction of the cost of rebuilding or replacing the motor.

If you do burn out a standard-size single-phase or three-phase induction motor, it's usually quicker—and cheaper—to replace rather than rebuild it. But if the motor has a special mounting or isn't of a frame size or type carried by your local distributor, you may have no choice but to pay for a rebuild by a local motor repair shop. ☐

Ed Cowern is an electrical engineer and president of a company that distributes electric motors. For information on how electric motors are rated, contact the National Electrical Manufacturers Association, 2121 L St. N.W, Washington, D.C. 20037.

Further reading

***How Electric Motors Start and Run* by Harold Parady and Howard Turner and *Electric Motors* by James Allison are available from the American Association for Vocational Instructional Materials, 120 Engineering Center, Athens, GA 30602.**