Baldor Basics: Motors

Edward Cowern, P.E.

Beginning with this initial installment — and with the gracious permission of ABB/Baldor Electric — we are pleased to announce the beginning of a new series — *Baldor Basics: Motors*. This is a collection of basics-driven, motor-intensive articles authored by former Baldor engineer Edward Cowern, PE — a respected name by many in the electric motor industry. During his tenure at Baldor, Cowern — now enjoying his retirement — was tasked with producing a number of motor- and basics-related tutorials, primarily in response to a steady flow of customer questions regarding motors. Today's customers continue to ask questions and seek answers to address their various motor-related issues. As with Cowern's original introduction to the series, we hope you find these articles useful and would appreciate any comments or thoughts you might have for future improvements, corrections or topics.

— The Editors

Types of Motors

The most reliable piece of electrical equipment in service today is a transformer. The second most reliable is the 3-phase induction motor. Properly applied and maintained, 3-phase motors will last many years. One key element of motor longevity is proper cooling. Motors are generally classified by the method used to dissipate the internal heat.

Several standard motor enclosures are available to handle the range of applications — from "clean-and-dry" (indoor air handlers) to the "wet-or-worse" — as found on roofs and wet cooling towers.

Open drip-proof (ODP) motors are good for clean and dry environments. As the name implies, drip-proof motors can handle some dripping water provided it falls from overhead or no more than 15 degrees off vertical. These motors usually have ventilating openings that face down. The end housings can frequently be rotated to maintain "drip-proof" integrity when the motor is mounted in a different orientation. These motors are cooled by a continuous flow of the surrounding air through the internal parts of the motor.

Totally enclosed fan-cooled (TEFC) motors are cooled by an external fan mounted on the end opposite the shaft. The fan blows ambient air across the outside surface of the motor to carry heat away. Air does not move through the inside of the motor, so TEFC motors are suited for dirty, dusty, and outdoor applications. There are many special types of TEFC motors, including corrosion-protected and washdown styles. These motors have special features to handle difficult environments. TEFC motors generally have "weep holes" at their lowest points to prevent condensation from puddling inside the motor. As in open drip-proof motors, if the TEFC motor is mounted in a position other than horizontal, the end housings can generally be repositioned to keep the weep holes at the lowest point.

Totally enclosed air over (TEAO) motors are applied in the air-stream on machines such as vane axial fans where the air moved by a direct connected fan passes over the motor and cools it. TEAO motors frequently have dual HP ratings, depending on the speed and temperature of the cooling air. Typical ratings for a motor might be: 10 HP with 750 feet-per-minute of 104 °F air, 10 HP with 400 FPM of 70 °F air, or 12.5 HP with 3,000 FPM of 70 °F air. TEAO motors are usually confined to original equipment manufacturer (OEM) applications because the air temperature and flows need to be predetermined.

Totally enclosed non-ventilated (TENV) motors are generally confined to small sizes (usually under 5 HP) where the motor surface area is large enough to radiate and convect the heat to the outside air without an external fan or air flow. They have been popular in textile applications because lint cannot obstruct cooling.

Hazardous location motors are a special form of totally enclosed motor. They fall into different categories depending upon the application and environment, as defined in Article 500 of the National Electrical Code.

The two most common hazardous location motors are ***Class I — explosion-proof***, and ***Class II — dust ignition-resistant***. The term explosion-proof is commonly — but *erroneously* — used to refer to all categories of hazardous location motors. Explosion-proof applies only to Class I environments — i.e., those that involve potentially explosive liquids, vapors, and gases. Class II is termed dust ignition-resistant; these motors are used in environments that contain combustible dusts such as coal, grain, flour, etc.

Single-phase motors. Three-phase motors start and run in a direction based on the "phase rotation" of the incoming power. Single-phase motors are different — they require an auxiliary starting means. Once started in a direction, they continue to run in that direction. Single-phase motors are categorized by the method used to start the motor and establish the direction of rotation.

Table 1 The three categories generally found in HVAC applications

Category	Approximate HP Range	Relative Efficiency
Shaded pole	1⁄100–1⁄6 HP	Low
Split Phase	1⁄25–1⁄2 HP	Medium
Capacitor	1⁄25–15 HP	Medium to High

Three Categories Generally Found in HVAC Applications

Shaded pole is the simplest of all single-phase starting methods. These motors are used only for small, simple applications such as bathroom exhaust fans. In the shaded pole motor, the motor field poles are notched and a copper shorting ring is installed around a small section of the poles (Fig. 1).

The ***altered pole*** configuration delays the magnetic field build-up in the portion of the poles surrounded by the cop-

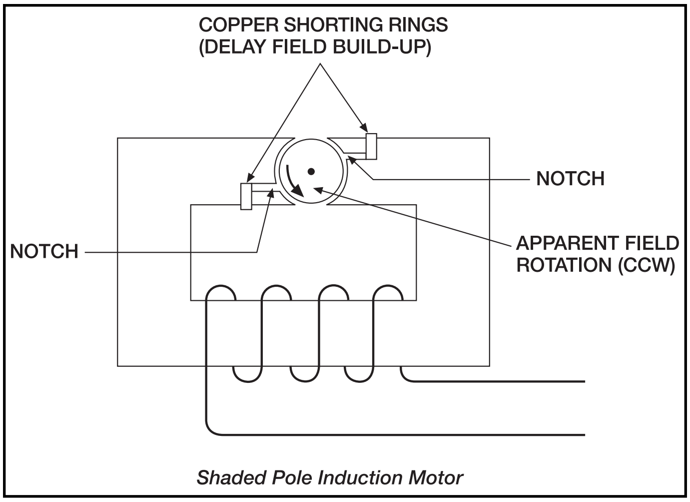

Figure 1 Shaded pole is the simplest of all single phase starting methods.

per shorting rings. This arrangement makes the magnetic field around the rotor seem to rotate from the main pole toward the shaded pole. This appearance of field rotation starts the rotor moving. Once started, the motor accelerates to full speed.

The ***split-phase*** motor has two separate windings in the stator (stationary portion of the motor) (Fig. 2). The winding shown in black is only for starting. It uses a smaller wire size and has higher electrical resistance than the main winding. The difference in the start winding location and its altered electrical characteristics causes a delay in current flow between the two windings. This time delay, coupled with the physical location of the starting winding, causes the field around the rotor to move and start the motor. A centrifugal switch or other device disconnects the starting winding when the motor reaches approximately 75% of rated speed. The motor continues to run on normal induction motor principles.

Split-phase motors are generally available from 1/25 to ½ HP. Their main advantage is low cost. Their disadvantages are low starting torque and high starting current. These disadvantages generally limit split-phase motors to applications where the load needs only low starting torque and starts are infrequent.

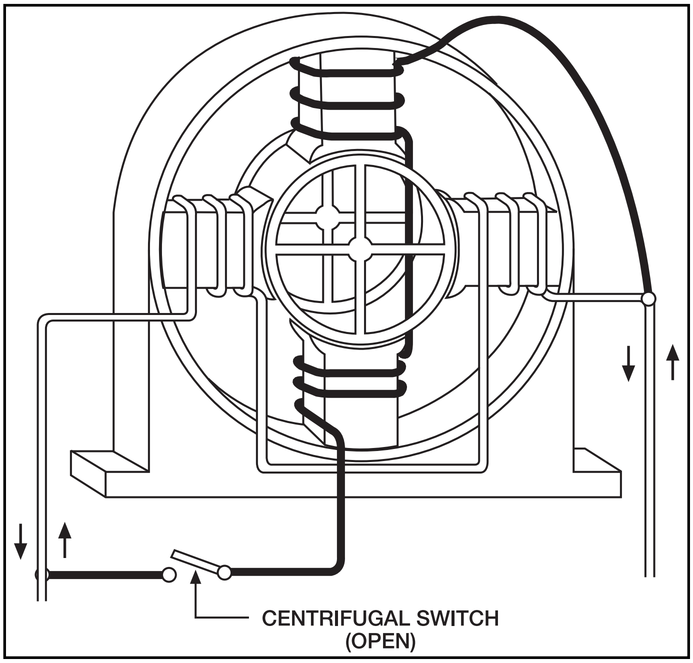

Figure 2 The split-phase motor has two separate windings in the stator.

Capacitor motors are the most popular single-phase motors. They are used in many agricultural, commercial and industrial applications where 3-phase power is not available. Capacitor motors are available in sizes from sub-fractional to 15 HP.

Table 2 Capacitor motors categories

Category	Usual HP Range
Capacitor start — induction run	1/8–3 HP
Single value capacitor (also called permanent split capacitor or PSC)	1/50–1 HP
Two-value capacitor (also referred to as capacitor start capacitor run)	2–15 HP

Capacitor motors fall into three categories:

Capacitor start induction run motors form the largest group of general purpose single-phase motors. The winding and centrifugal switch arrangement is similar to that in a split-phase motor. However, a capacitor start motor has a capacitor in series with the starting winding. Figure 3 shows the capacitor start motor. The starting capacitor produces a time delay between the magnetization of the starting poles and the running poles, creating the appearance of a rotating field. The rotor starts moving in the same direction. As the rotor approaches running speed, the starting switch opens and the motor continues to run in the normal induction motor mode.

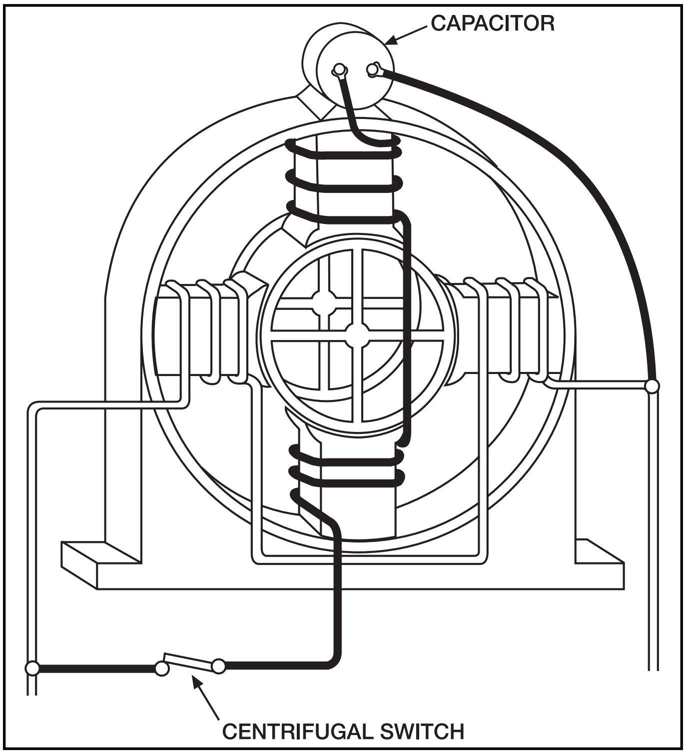

Figure 3 A capacitor start motor has a capacitor in series with the starter winding.

This moderately priced motor produces relatively high starting torque (225 to 400% of full-load torque) with moderate inrush current. Capacitor start motors are ideal for hard to start loads such as refrigeration compressors. Due to its other desirable characteristics, it is also used in applications where high starting torque may not be required. The capacitor start motor can usually be recognized by the bulbous protrusion on the frame that houses the starting capacitor.

In some applications it is not practical to install a centrifugal switch within the motor, as these motors have a relay operated by motor inrush current. The relay switches the starting capacitor into the circuit during the starting period. When the motor approaches full speed the inrush current decreases and the relay opens to disconnect the starting capacitor.

Single-value capacitor motors, also called permanent split capacitor (PSC) motors, utilize a capacitor connected in series with one of the two windings. This type of motor is generally used on small sizes (less than 1 HP). It is ideally suited for small fans, blowers, and pumps. Starting torque on this type of motor is generally 100%, or less, of full load torque.

Two-value capacitor motors. The two-value capacitor motor is utilized in large horsepower (5-15 HP) single-phase motors (Fig. 4).

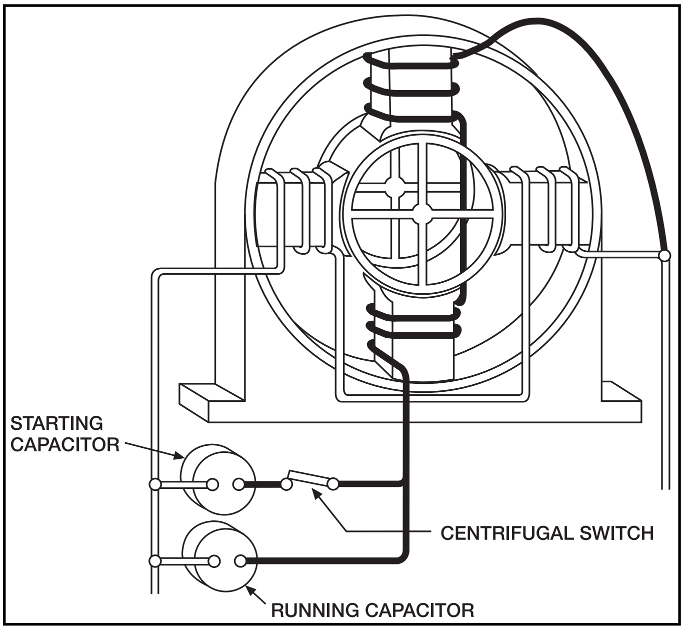

Figure 4 **The two valve capacitor motor is used in large horsepower single phase motors.**

The running winding, shown in white, is energized directly from the line. A second winding, shown in black, serves as a combined starting and running winding. The black winding is energized through two parallel capacitors. Once the motor has started, a switch disconnects one of the capacitors, thus letting the motor operate with the remaining capacitor in series with this winding of the motor.

The two-value capacitor motor starts as a capacitor start motor but runs as a form of a two-phase or PSC motor. Using this combination, it is possible to build large single-phase motors having high starting torques and moderate starting currents at reasonable prices. The two-value capacitor motor frequently uses an oversize conduit box to house both the starting and running capacitors.

Motors Operating on Adjustable Frequency Drives (AFDs)

In the infancy of adjustable frequency drives (AFDs), a major selling point was that AFDs could adjust the speed of "standard" 3-phase induction motors. This claim was quite true when the adjustable frequency drives were "6-step" designs. The claim is still somewhat true, although ***pulse width modulated (PWM)*** AFDs have somewhat changed the rules, PWM drives are electrically more punishing on motor windings — especially for 460 and 575 volt drives.

Standard motors can still be used on many AFDs, especially on HVAC fan, blower, and pump applications, as long as the motors are high-quality, conservative designs that use ***inverter spike resistant (ISR)*** magnet wire. On these variable torque loads a relatively small speed reduction results in a dramatic reduction in the torque required from the motor. For example, a 15% reduction in speed reduces the torque requirement by over 25%, so these motors are not stressed from a thermal point of view. Also, variable torque loads rarely need a wide speed range. Since the performance of pumps, fans, and blowers falls off dramatically as speed is reduced, speed reduction below 40% of base speed is rarely required.

This naturally leads to the question — "What is meant by high-quality, conservative designs?"

Basically, this means that the motor must have phase insulation, should operate at a relatively low temperature rise (as in the case with most premium efficiency motors), and should use a high class of insulation (either F or H).

In addition, it is frequently desirable to have a winding thermostat in the motor that will detect any motor overheat conditions that may occur. Overheating could result from overload, high ambient temperature, or loss of ventilation.

Inverter duty motors being offered in the marketplace today incorporate "premium efficiency" designs along with oversized frames or external blowers to cool the motor, regardless of its speed. These motors are primarily designed for constant torque loads where the affinity laws do not apply. Inverter duty motors usually have winding thermostats that shut the motor down through the AFD control circuit in case of elevated temperature inside the motor. Inverter duty motors also have high-temperature insulating materials operated at lower temperatures. This reduces the stress on the insulation system. Although some of the design features of inverter duty motors are desirable for HVAC applications, HVAC applications usually do not require inverter duty motors.

Note that some cautions should be observed. Generally speaking, the power coming out of an AFD is somewhat rougher on the motor than power from a pure 60 cycle source. Thus it is not a good idea to operate motors on AFDs into their service factors.

In addition, when an old motor (one that has been in service for some time) is to be repowered from an adjustable frequency drive, it may be desirable to add a load reactor between the AFD and the motor. The reactor reduces the stress on the motor windings by smoothing out current variations, thereby prolonging motor life.

Reactors are similar to transformers with copper coils wound around a magnetic core. Load reactors increase in importance when the AFDs are going to run in the "quiet" mode. In this mode the very high carrier frequency can create standing waves that potentially double the voltage peaks applied to the motor. The higher voltage can stress the motor insulation enough to cause premature failure.

Service factor. Some motors carry a service factor other than 1.0. This means the motor can handle loads above the rated HP. A motor with a 1.15 service factor can handle a 15% overload, so a 10 HP motor with a 1.15 service factor can handle 11.5 HP of load. Standard open drip-proof motors have a 1.15 service factor. Standard TEFC motors have a 1.0 service factor, but most major motor manufacturers now provide TEFC motors with a 1.15 service factor.

The question often arises whether to use service factor in motor load calculations. In general, the best answer is that for good motor longevity, service factor should not be used for basic load calculations. By not loading the motor into the service factor, the motor can better withstand adverse conditions that occur. Adverse conditions include higher than normal ambient temperatures, low or high voltage, voltage imbalances, and occasional overload. These conditions are less likely to damage the motor or shorten its life if the motor is not loaded into its service factor in normal operation.

NEMA locked rotor code. The "NEMA code letter" is an additional piece of information on the motor nameplate. These letters indicate a range of inrush (starting or "locked rotor") currents that occur when a motor starts across the line with a standard magnetic or manual starter. Most motors draw 5 to 7 times rated full-load (nameplate) amps during the time it takes to go from standstill up to about 80% of full-load speed. The length of time the inrush current lasts depends on the amount of inertia (flywheel effect) in the load. On centrifugal pumps with very low inertia, the inrush current lasts only a few seconds. On large, squirrel cage blowers the inrush current can last considerably longer.

The locked rotor code letter quantifies the value of the inrush current for a specific motor. The lower the code letter, the lower the inrush current. Higher code letters indicate higher inrush currents.

The table lists the NEMA locked rotor code letters and their parameters:

Table 3 Code letters usually applied to common motors

NEMA Code Letter	Locked Rotor KVA/HP	NEMA Code Letter	Locked Rotor KVA/HP
A	0–3.15	L	9.0–10.0
B	3.15–3.55	M	10.0–11.2
C	3.55–4.0	N	11.2–12.5
D	4.0–4.5	0	not used
E	4.5–5.0	P	12.5–14.0
F	5.0–5.6	Q	not used
G	5.6–6.3	R	14.0–16.0.
H	6.3–7.1	S	16.0–18.0
I	not used	T	18.0–20.0
J	7.1–8.0	U	20.0–22.4
K	8.0–9.0	V	22.4 and up

	F	G	H	J	K	L
3 phase HP	15 up	10–7½	5	3	2–1½	1
1 phase HP		5	3	2–1½	1, ¾	½

The code letters usually applied to common motors are:

The proposed design E motors, which will have very high efficiencies, will have higher inrush currents than the motors currently available. These motors will require special considerations when sizing circuit breakers and starters for these motors when they become available. The 1998 National Electrical Code incorporated some special provisions for these proposed Design E motors.

Insulation Classes

The electrical portions of every motor must be insulated from contact with other wires and with the magnetic portion of the motor. The insulation system consists of the varnish that jackets the magnet wire in the windings along with the slot liners that insulate the wire from the steel laminations. The insulation system also includes tapes, sleeving, tie-strings, a final dipping varnish, and the leads that bring the electrical circuits out to the junction box.

Insulation systems are rated by their resistance to thermal degradation. The four basic insulation systems normally encountered are Class A, B, F, and H. Class A has a temperature rating of 105 °C (221 °F), and each step from A to B, B to F, and F to H involves a 25 °C (45 °F) jump. The insulation class in any motor must be able to withstand at least the maximum ambient temperature plus the temperature rise that occurs as a result of continuous full-load operation. Selecting an insulation class higher than necessary to meet this minimum can help extend motor life or make a motor more tolerant of overloads, high ambient temperatures, and other problems that normally shorten motor life.

A widely used rule of thumb states that every 10 °C (18 °F) increase in operating temperature cuts insulation life in half. Conversely, a 10 °C decrease doubles insulation life. Choosing a one-step higher insulation class than required to meet the basic performance specifications of a motor provides 25 °C of extra temperature capability. The rule of thumb predicts that this better insulation system increases the motor's thermal life expectancy by approximately 500%.

Motor Design Letters

The National Electrical Manufacturers Association (NEMA) has defined four standard motor designs using the letters A, B, C and D. These letters refer to the shape of the motors' torque and inrush current vs. speed curves. Design B is the most popular motor. It has a relatively high starting torque with reasonable starting currents. The other designs are only used on fairly specialized applications. Design A is frequently used on injection molding machines that require high pull-out torques. Design C is a high-starting torque motor that is usually confined to hard-to-start loads, such as conveyors that are going to operate under difficult conditions.

Design D is a so-called "high-slip" motor and is normally limited to applications such as cranes, hoists, and low-speed punch presses where high starting torque with low starting current is desirable. Design B motors do very well on most HVAC applications. **PTE**