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setting a new standard for efficiency:

Brushless DC Motors

The basic function of an electric motor is to convert electrical energy into mechanical energy. Considering the ready availability of electricity and the myriad uses for mechanical energy, it's no surprise that electric motors are widely used.

In the HVAC realm, electric motors drive fans and compressors, which makes these components largely responsible for the electrical energy that's consumed by an HVAC system. So, when a new motor technology is introduced—one that promises remarkably better efficiency—it's worth a closer look.

Such is the case with brushless DC, or "electronically commutated," motors (ECMs). Proponents of brushless technology claim that the design results in quieter operation, more efficient performance, greater output power, higher operating speeds, and longer service life.

To help you assess the science behind the promises, this *EN* provides a refresher on basic motor operation. Along the way, it explains what makes a brushless DC motor different and considers their appropriateness for HVAC applications.

AC, DC … and something in-between

The most basic way to classify electric motors is by *power supply* and *size*. As for power supply, motors either use alternating current (AC) or direct current (DC). AC power is readily available from the distribution grid, while DC power requires a battery or, more commonly, a converter that changes AC to DC. In the size category, motors are either *fractional* (smaller than 1 hp) or *integral* (1 hp or larger).*

More than 80 percent of the motor energy used in commercial HVAC applications is consumed by integral horsepower AC motors.[2] Under the Energy Policy Act, many of these motors already meet or exceed the minimum efficiency requirements in ASHRAE Standard 90.1–1989.

So, why are fractional horsepower DC motors garnering the attention of HVAC manufacturers and building owners alike when the opportunity for savings seems so limited?

* An instruction manual authored by the U.S. Census Bureau uses output ratings to define three motor categories: *integral hp* ≥ 1 hp; *fractional hp* ≥ 1/10 hp but < 1 hp; and *subfractional hp* ≥ 1/1000 hp but < 1/10 hp.[1]

Basic "anatomy" of a motor …

stator. The supports and stationary portions of the magnetic circuit, associated winding, and leads of a motor.

rotor. Sometimes called an armature. It is the motor's rotating member, including the shaft.

commutator. A cylindrical ring or disc assembly of conducting members … with an exposed surface for contact with a current-collecting device.

brush. A conductor, usually composed (in part) of some form of carbon, serving to maintain an electric connection between stationary and moving parts of a motor or generator. [1]

Quest for single-phase efficiency

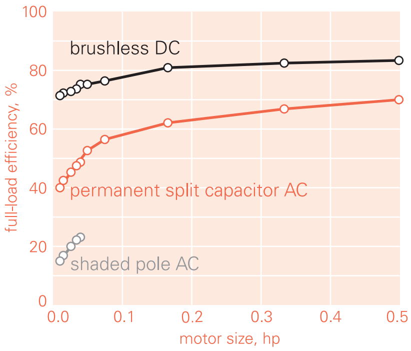
When it comes to energy use, small (fractional horsepower) single-phase AC motors leave considerable room for improvement.

AC motors are designed to run most efficiently at the rated voltage and speed. When an application requires multiple speeds, the conventional solution is either to use a motor with multiple taps (the least expensive option) or to add an SCR (silicon-controlled rectifier).

Each of these adaptations causes the motor to run less efficiently. The performance degradation can be significant: The typical full-load efficiency of 55 to 65 percent at the rated voltage can drop to as little as 15 to 20 percent at part load and reduced voltage.

When compared with more common motor technologies, such as shaded pole and permanent split capacitor, the brushless design's full-load efficiency of 75 percent or better offers substantial energy savings for motors

Figure 1. Typical full-load efficiencies for subfractional motors



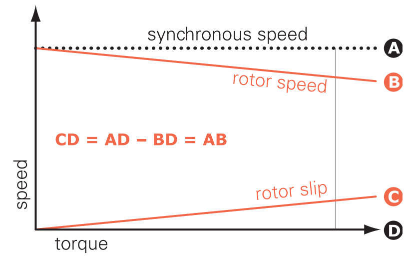
with subfractional horsepower ratings (Figure 1). But the *real* advantage of a brushless DC motor becomes evident at part load, where its performance edge doubles or triples.

All electric motors rely on the attraction and repulsion of magnetic fields to operate, so what's responsible for this dramatic difference in performance? The answer requires review of a few motor fundamentals.

AC induction motors

In AC motors, the magnetic field in the stator is created by passing alternating current through coils of wire. The rise and fall of this magnetic field causes current to flow in the bars of the squirrel-cage rotor, which in turn creates another magnetic field. (It's the interaction of these magnetic fields that produces torque.) Induction motors are so-named because the stator's fluctuating magnetic field "induces" current in the rotor.

Figure 2. Typical speed–torque relationship for AC induction motors



"Slip" (CD) is the difference in rotor speed relative to that of synchronous speed.

In a three-phase motor,† the stator coils energize and de-energize sequentially, creating a rotating magnetic field. Torque results when the induced magnetic field of the rotor "chases" the rotating stator fields; when the fields align, torque disappears. AC induction motors depend on the rotor turning slower than the rotation of the stator fields. As the speed of the rotor approaches that of the stator fields, the force (torque) on the rotor diminishes. The difference between these speeds is called *slip.*

Figure 2 illustrates the relationship between torque and speed. Notice that rotor speed (and, therefore, shaft speed) decreases as load is applied to the motor. In HVAC terms, a fan connected to this motor will require higher torque to maintain airflow as the system static pressure increases (for example, a damper closes), resulting in slower shaft rotation and (therefore) less airflow.

† The three-phase motor is used to simplify the explanation of rotating fields; but small, single-phase motors are typically the frame of reference for comparisons of AC and BLDC performance.

DC motors

As in AC motors, the driving force provided by a DC motor results from the interaction of rotating magnetic fields in the rotor and stator. But because direct current doesn't oscillate, the polarity fluctuations needed to keep the rotor turning must be created mechanically. There are several ways to do this, as evidenced by the types of DC motors available; *shunt-wound*, *series-wound*, *compound-wound*, and *permanent-magnet* are just a few. To understand the principles of DC motor operation, let's look at how a permanent-magnet motor works.

When current passes through a coil of wire placed between the north and south poles of a permanent magnet (Figure 3), the magnetic field generated by the coil interacts with the field from the permanent magnet and applies rotational force (torque).

If the coil is allowed to rotate (from the position in Figure 3A), the fields eventually align such that the plane of the armature coil is perpendicular to the field of the permanent magnet

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Figure 3. Forces created by interaction of a magnetic field and armature flux

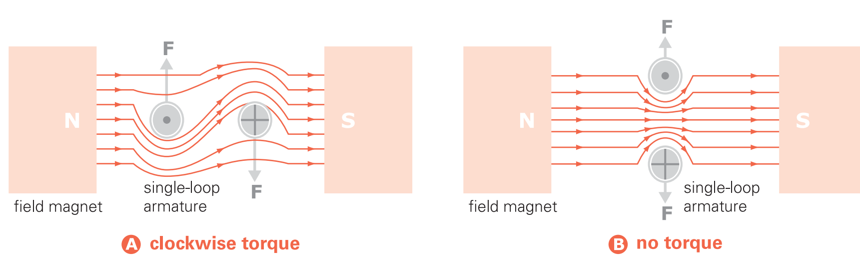
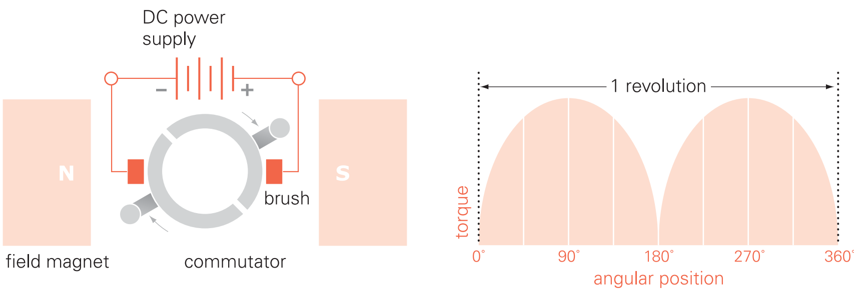


Figure 4. Two-segment commutator configuration and resulting torque curve for a DC motor



(Figure 3B) and torque disappears. Rotation can be maintained by reversing the direction of current flow in the coil of wire as it reaches the position shown in Figure 3B.

In a permanent-magnet DC motor, the permanent magnet forms the stator, the loops of wire (armature coil) are placed on the rotating shaft (rotor), and a *commutator* switches the current flow from one coil to the other (Figure 4) at exactly the right moment. The commutator provides a means for connecting a stationary power source to the rotating coils, typically via conductive rods (brushes) that ride on smooth conductive plates. The uneven torque that results from a single-coil armature can be smoothed by adding additional coils and commutator segments (Figure 5).

Motor fact. A motor will draw only as much power and consume only as much energy as it takes to satisfy the load:

$$energy = \frac{motor\ load \times operating\ time}{motor\ efficiency}$$

To save energy:

- Reduce the load
- Reduce the operating time
- Increase efficiency [3]

Unlike AC motors, in which a certain amount of slip is unavoidable, the *synchronous* nature of DC motors means that they operate at a fixed speed for a fixed voltage, providing a significant advantage in applications where knowing motor speed is important. Changing the voltage produces a predictable change in speed. Adding load to the motor (that is, increasing the torque on the shaft) increases the current draw without slowing shaft rotation.

The Achilles' heel for a DC motor is its commutator. Consistently transferring current from a stationary point to the rotating shaft requires materials that can carry current, yet withstand friction and arcing. Commutators require periodic maintenance, decrease motor life, and limit the maximum speed at which the motor can turn.

Motor fact. According to a U.S. Department of Energy Fact Sheet (DOE/GO-10096-314), electric motors are responsible for consuming more than half of all of the electrical energy used in the United States.

Best of both: Brushless DC motors

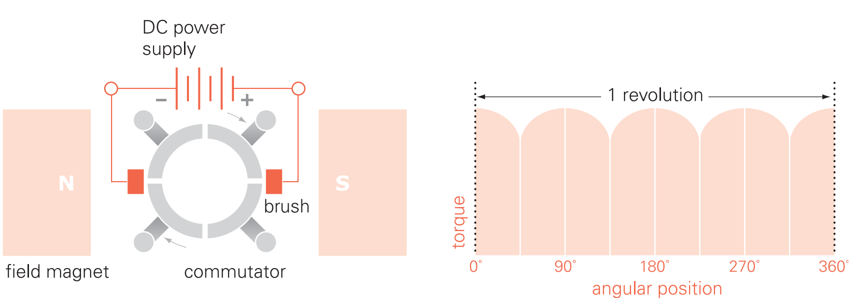
A brushless DC (BLDC) motor implements the basic operating principles of DC motor operation a bit differently by placing the permanent magnet in the rotor and the coil(s) in the stator. The coil windings are electrically separate from each other, which allows them to be turned on and off in a sequence that creates a rotating magnetic field. In this case, it's the field of the rotor's permanent magnet ("chasing" the rotating stator field) that makes the rotor turn.

One significant advantage of this arrangement is that the commutator doesn't carry current to the rotor—which eliminates the brushes and their wear-related drawbacks.

It's still necessary to know the rotor position so that excitation of the stator field always leads the permanent-magnet field to produce torque. In a BLDC motor, this function is provided by a commutation assembly consisting of electronic circuitry and a series of sensors (usually photo sensors, Hall effect devices, or magneto resistors). The circuitry decodes the sensor signals to determine the position of the shaft and energize the appropriate stator windings.

It's the combination of permanent-magnet rotor, wound-field stator, and electronic commutation that defines the brushless DC motor and gives rise

Figure 5. Four-segment commutator configuration and resulting torque curve for a DC motor



to its other aliases (electronically commutated motor or ECM, and electronically commutated permanent magnet or ECPM motor).

Benefits of "brushless" technology

Broad operating range. Eliminating the brushes is a definite plus: It not only extends the motor's service life and reduces maintenance, but also eliminates the speed restrictions inherent to "brushed" DC motors. (BLDC motors can attain speeds of more than 60,000 rpm.) More importantly, the power circuit components that are required to convert from alternating to direct current provide the basis for variable-speed drive, making BLDC motors well-suited for applications that require speed control over a wide operating range.

From the standpoint of direct replacement, a simple DIP switch setting at the factory will allow a BLDC motor to handle any multispeed requirements. In fact, the motor's wide operating range *could* allow one motor size to cover a wide array of products and product sizes. (Manufacturers benefit most from this possibility, but owners who stock replacement parts on site also could benefit.)

Motor fact. *Annual energy savings* estimates the energy dollars saved based on motor efficiency, rated horsepower, and operational loading:

$$\$ = hp \times L \times 0.746 \times hr \times C \times \left[\frac{100}{E_{std}} - \frac{100}{E_{ee}}\right]$$

where:

hp = Rated horsepower of the motor
L = Load factor (percentage of full load/100)
hr = Annual operating hours
C = Average energy costs, \$/kWh
E_{std} = Efficiency rating of the "standard" (baseline) motor, %
E_{ee} = Efficiency rating of the "energy-efficient" motor, %

(The 0.746 factor converts horsepower to kilowatts.) [4]

Table 1. Simple payback for replacing three-speed permanent split-capacitor AC (PSC-AC) induction motors with brushless DC (BLDC) motors in fan–coils[a,b]

Nominal airflow, cfm	First cost (est), \$ USD PSC-AC (std)	First cost (est), \$ USD BLDC (opt)	Motor efficiency, % PSC-AC	Motor efficiency, % BLDC	Energy input, watts PSC-AC	Energy input, watts BLDC	Energy input, watts Energy saved	Annual energy cost savings, \$ USD	Simple payback, yr
200			35	65	55.5	30.0	25.5	16.29	8.6
300			35	70	80.2	39.0	41.2	26.35	5.4
400	—	+70	35	70	96.4	49.1	47.3	30.29	4.6
600			50	70	115.2	79.1	36.1	23.12	6.0
800			50	70	124.3	93.2	31.2	19.95	7.0

[a] This comparison isn't exactly "apples to apples": The PSC-AC motors varied in size, with the smallest fan–coil using a 1/20 hp motor; but in each case, the replacement was a 1/3 hp BLDC motor.

[b] Saving calculations are based on annual operation of 4,000 hours and an energy cost of \$0.08/kWh.

Higher efficiency. Using permanent magnets in the rotor helps keep rotors small and inertias low. Without current flow (and the associated losses) in the rotor, the motor generates less heat. And what heat *is* produced dissipates more efficiently from the brushless motor's wound stator to the outer metallic housing than through the "brushed" motor's shaft or rotor–stator air gap.

Flexible design. The DC power supply permits a motor design with any number of phases in the stator. Although three-phase configurations are most common, two- and four-phase configurations also are used.

How the coils are energized is flexible, too. As an example, two windings can be energized with the third off at any instant in a three-phase BLDC configuration. Energizing the coils in pairs simplifies control design, which lowers first cost, and provides more torque—about 10 percent more than energizing the windings sinusoidally.

Where "brushless" technology falls short

Higher first cost. BLDC technology requires power transistors to drive the stator windings at a specified motor current and voltage level. This addition, coupled with electronic commutation controls, makes brushless DC motors more expensive to purchase than their AC counterparts. While it's true that the gap is narrowing, thanks to advances in "brushless" technology and increased volume, BLDC motors still carry a first-cost penalty.

Disruptive harmonics. Although the *displacement* power factor for BLDC motors is 1, the *true* power factor (ratio of total watts consumed to volt-amps supplied) *is less than 1*. The difference results from the harmonic currents that nonlinear loads (such as variable-speed devices, computers, office machines, and certain lighting systems) create when converting from AC to DC power.

Harmonic currents do no useful work; worse still, they burden

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system components—overheating conductors and connectors, and in severe cases, burning out transformers and motors. The distorted waveform of harmonic currents also can interfere with the operation of sensitive equipment.

Determining whether harmonic currents will cause a problem in a particular building requires review of several contributing factors, including the power conversion method, the number of nonlinear loads, and the electrical system in which the BLDC motors are applied. Where necessary, it's possible to alter the design of the electrical system (by oversizing the neutral wire, for example) and/or reduce motor-generated harmonics (perhaps by adding a harmonic filter). Not all systems will require such measures, but it's important to make that determination by reviewing the electrical system *before* it's installed so that appropriate steps can be taken.

Make the most of brushless DC motors

With simple paybacks often exceeding six years (Table 1, p. 4), justifying the extra cost to replace a fractional horsepower AC motor, based solely on improved full-load efficiency, can be difficult. Since most fractional horsepower motors in HVAC applications drive fans, let's consider brushless DC motors in that context.

Applications that are best suited for BLDC technology can take full advantage of its unique operating characteristics—*synchronous speed–torque performance* and *variable-speed drive capability*. VAV boxes are a logical candidate because they deliver widely varying amounts of airflow.

Figure 6. Comparison of motor efficiencies in series fan-powered VAV boxes

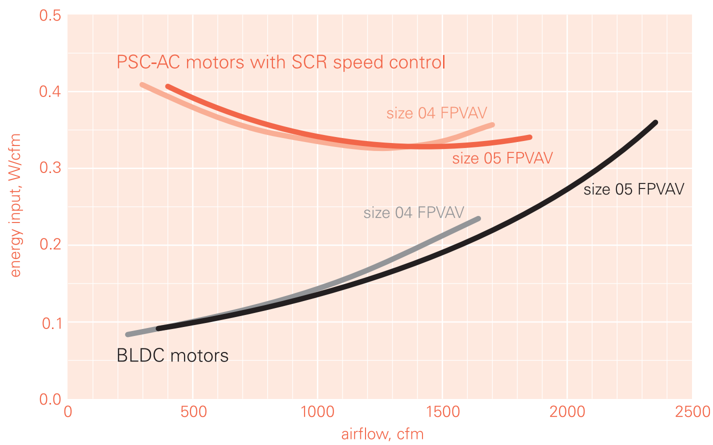


Figure 6 compares the performance of a standard AC motor with that of a BLDC motor at various airflows in two series fan-powered VAV boxes. Although the advantage is only slight at full load, the performance of the BLDC motor really shines at low flow conditions.

Another benefit of BLDC technology is the ability to accurately control connected loads. Motor speed, applied voltage, and torque share a linear relationship (Figure 7).This attribute—combined with the electronic commutator's precise measurement of speed—makes it possible to control a BLDC motor such that it delivers a known torque output. In VAV boxes, this means that fan flow rates can be preset in the factory, eliminating much of the expense of balancing the air distribution system.

Motor fact. *Simple payback* (SP) describes the time, in years, required to recoup an initial investment or incremental cost. When comparing new motors, use the cost difference:

$$\frac{\textit{price premium} - \textit{utility rebate}}{\textit{annual dollar savings}}$$

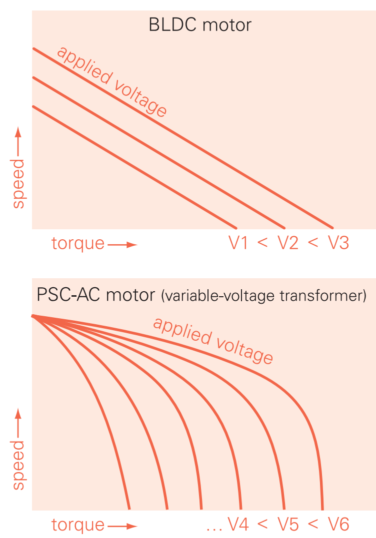
For replacement motors, use the full purchase price of the replacement motor plus any installation costs:

$$\frac{\textit{price} + \textit{installation} - \textit{utility rebate}}{\textit{annual dollar savings}}$$

As a rule of thumb, a simple payback of less than two to three years is regarded as "economically feasible."

Precise speed–torque control also may mean less time spent air-balancing. With AC motors, fan output is pressure-dependent: Any change in static pressure (modulating the damper position, for example) alters the fan's discharge airflow (sometimes by as much as 25 percent) … and usually necessitates several trips to the unit to obtain proper diffuser flow.

Figure 7. Typical speed–torque curves for BLDC vs. PSC-AC motors



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Closing thoughts

Widespread use and acceptance of brushless DC motors in residential products (where motors are small and the efficiency advantage is most significant) has prompted greater competition in the market. With market interest comes further research and development, ultimately reducing first cost and increasing application flexibility.

Given the existing availability and first-cost penalty, BLDC technology will find greatest acceptance wherever its performance advantage over a wide speed range can be combined with its excellent variable-speed capabilities. You can expect this combination to yield an efficiency improvement of at least 30 percent over single-speed AC induction motors. ●

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Endnotes

[1] U.S. Census Bureau. 2003. *MA335H: Motors and Generators*. Available at http://www.census.gov/cir/www/instructions/ma335h.pdf; accessed November 2004.

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