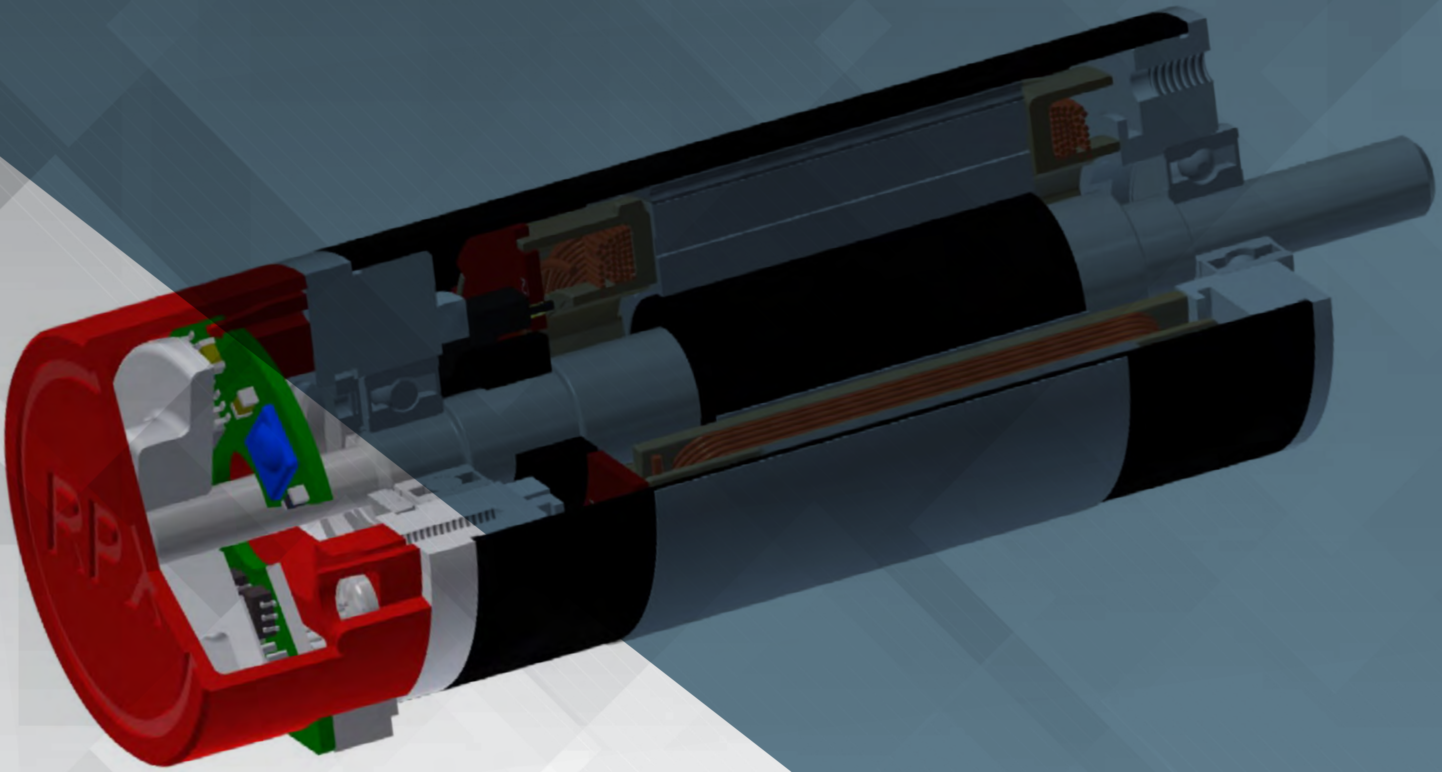
DESIGN GUIDE ON DC MOTORS



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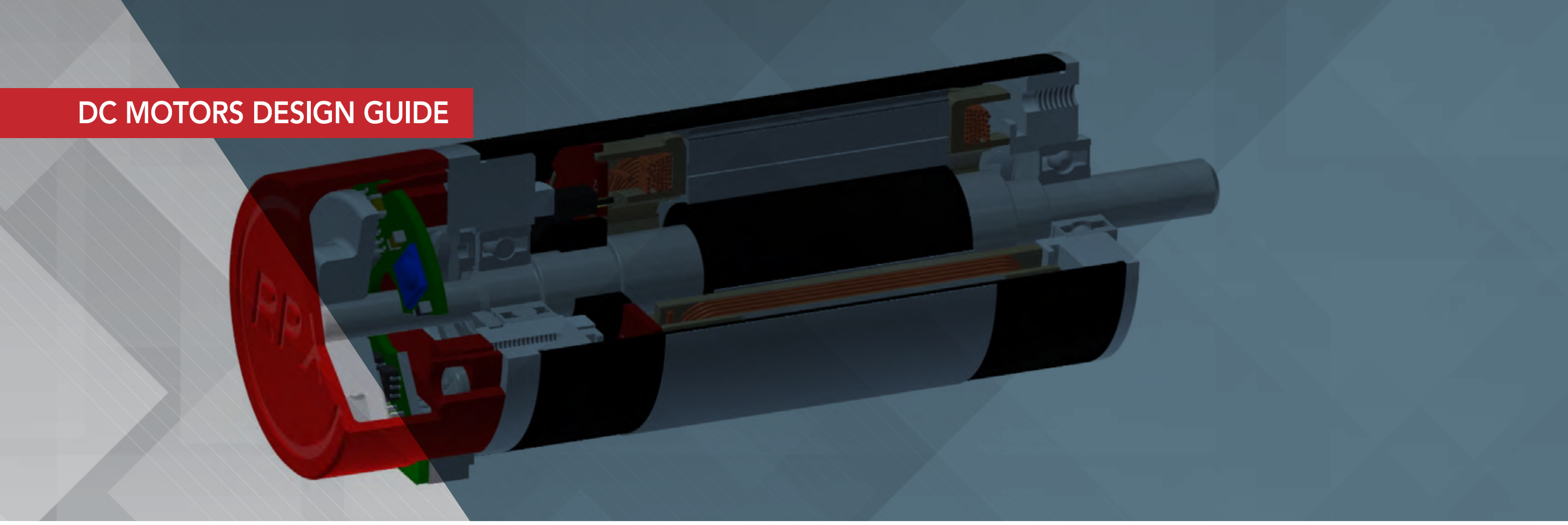

DC motors are motion components that take electrical power in the form of direct current (or some manipulated form of direct current) and convert it into mechanical rotation. The motors do this through the use of magnetic fields that arise from the electric currents to spur rotation of a rotor fixed with an output shaft. Output torque and speed depends on the electrical input and motor design.

In this Design Guide, the editors of Design World detail the most common dc motor types as well common ways to quantify their output during the design-engineering process.

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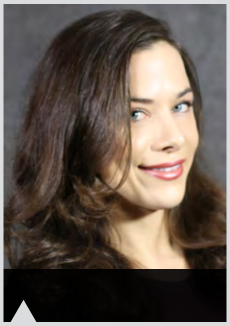

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TABLE OF CONTENTS

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BRUSHED MOTOR CONSTRUCTION AND OPERATION

Let's begin our overview of dc motors with a primer on brush dc motors. These motors are a mature technology that's been around for more than a century. So with brushless motors and an ever-increasing array of controls for all motor types, why do engineers still use brush motors? After all, it's common knowledge that brush motors exhibit wear at their brush-and-commutator interface. The truth is that brush dc motors output high peak torques and can run off simple speed controllers to move myriad applications. They often cost less than other options, especially in large volumes. Plus they can have a linear torque-speed relationship, which makes controls easier.

According to the most common industry naming conventions of today, there are three dc motor subtypes here — dc brush motors, dc permanent-magnet (PM) motors, and dc universal motors. As we'll see, there are some caveats and sub-classifications. Many larger dc motors still employ brushes and wound fields … though PM motors dominate fractional and integral-horsepower applications below 18 hp, and PM motors are increasingly common for myriad designs.

Some engineers call dc brush motors wound-field motors, because it's a wound and lacquered coil of copper wire that makes the electromagnetic field. Some engineers also argue that all dc motors are brush dc motors, and that the term "brushless dc motor" is a misnomer. No matter the term, there are permanent magnet, shunt, series, and compound-wound brush dc motors. All except the former use two currents:

1. Current through armature (rotor) windings to interact with a stator magnetic field (for output of mechanical rotation) and
2. Current through stator windings to make the magnetic field in question.

In contrast, permanent-magnet brush dc motors use:

1. Current through armature (rotor) windings to interact with a stator magnetic field (for output of mechanical rotation) and
2. Permanent magnets on the stator to make the magnetic field in question.

The armature and field coils in a shunt-wound motor connect in parallel so the field current is proportional to the load on the motor.

The armature and field coils in series-wound motor connect in series so current passes only through the field coils.

The armature and field coils in compound-wound motors include both series and shunt windings.

No matter the setup, brush dc motors have commutators and brush contacts to pass current to the rotating rotor's copper-wire windings. Designers can control speed by changing rotor voltage (and current with it) or by changing the magnetic flux between rotor and stator through adjustments of the field-winding current. Brush orientation to the rotor's commutator bar segments mechanically controls the phase commutation.

In fact, the way dc brush motors let designers control field and rotor windings means they're suitable for applications that need simple and cost-effective torque and speed control.

That said, increased functionality from electronics for PM motors means that this advantage in less pronounced than it once was. What's worse, current on both rotor and stator generate heat that limits the motors' continuous-current ratings. The motors also present a spark hazard, so can't go in explosive settings. At certain periods during the dc motor rotation, the commutator must reverse the current, reducing motor life with arcing and friction. So, brushed dc motors require more maintenance in the form of replacement of springs and brushes that carry the electrical current, and replacement or cleaning of the commutator. These components are important for transferring electrical power from outside the motor to the spinning coil windings of the rotor inside the motor.

Note: The brushes in dc brush motors wear and need replacing, and brush-wear particles mean that designers shouldn't use dc brush motors in cleanrooms. Same goes for applications that need high precision, as friction from brush-commutator engagement make for long position-settling times.

SHUNT, SERIES, AND COMPOUND-WOUND DC MOTOR VARIATIONS

Series-wound dc motors: As mentioned, the armature (rotor) and field coils in series-wound motors connect in series. That means the entire armature (rotor) current passes to the field winding. So, these motors only need one input voltage supply. Torque equals current squared. Increasing armature (rotor) current induces a field-current increase. Regenerative braking isn't possible; field current collapses when rotor current passes through zero and reverses.

Torque is highest when the motor stops because the armature (rotor) generates no back electromotive force (B*emf*) when at rest. When the armature (rotor) accelerates, B*emf* increases. That in turn reduces effective current, voltage and torque. Without loading, the motor accelerates to dangerous speeds. In contrast, increased load slows the motor but lowers B*emf* … and increases torque to turn the load.

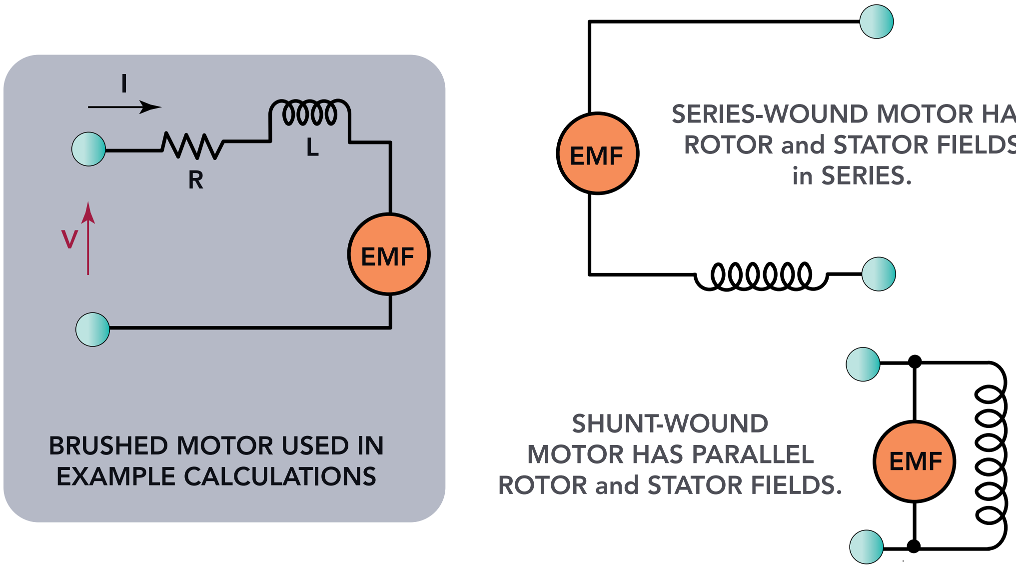
Series-wound motors can't regulate speed well, as speed control depends on adjustments to the supply voltage. Even so, they're inexpensive and can drive designs that need high starting torque. For example, designers use series-wound motors in low and high-power automotive mechanisms, consumer products such as power tools, toys, and sewing machines, and industrial traction drives with fixed and variable speed. Designers can reverse series-wound motors by reversing field or armature (rotor) winding connections.

Shunt-wound dc motors: As mentioned, armature and field coils in shunt-wounds motor connect in parallel … so field current is proportional to the load on the motor. Variable-voltage input allows for speed adjustment. Supply fixed voltage to a shunt-wound motor to make it run at constant speed. Then supply increasing motor current to a shunt-wound motor to increase torque without significant slowing.

With these motors, a technique called field weakening can control speed without forcing the controls to change input voltage. A field-winding rheostat reduces field (stator) current and with it the magnetic flux between armature and field — across the airgap that separates them. Speed is inversely proportional to flux, so this accelerates the motor. One caveat: Torque is directly proportional to flux, so the acceleration comes with diminished torque output.

IN SHUNT-WOUND MOTORS, THE FIELD (STATOR) WINDING CONNECTS IN PARALLEL WITH THE ARMATURE (ROTOR) WINDING.

CIRCUITS FOR BRUSHED DC MOTORS FOR CURRENT-TORQUE RELATIONSHIPS



Shown here are typical brushed dc motor circuits. The one to the left is used to calculate the relationship between voltage and dc motor output speed. Applied voltage equals the voltage drop across the coil resistance R and the inductor L plus the back electromotive force Bemf.

(continued)

SHUNT, SERIES, AND COMPOUND-WOUND DC MOTOR VARIATIONS

Stabilizing windings prevent acceleration as load increases at weak field settings. The only catch is that reversing applications need reversal of this winding to go with armature (rotor) voltage reversal. That necessitates reversing contactors. So for reversing motion, sometimes manufactures just design shunt-would motors with higher stability and omit stabilizing windings.

Note: The operation of a permanent-magnet brush dc motor is much like that of a shunt-wound motor, save for the mode of field-flux production.

Reversing a shunt-wound motor's connections on either rotor windings or field reverses the motor's direction of rotation; self-excitation maintains the field when the rotor current reverses, which means the motors can regeneratively brake.

Shunt-wound motors drive machine tools and automotive fan and wiper applications.

Compound-wound motors: Separately excited motors (sometimes called compound-wound motors) are dc brush motors with independent voltage supplies to the field (stator) and armature (rotor) … for better control over motor output. Input voltage on either winding can control motor output speed and torque. Most manufacturers build compound-wound motors with series and shunt-wound field (rotor) windings. The direction and strength and direction of two windings dictates the motor's speed-torque curves.

Compound-wound motors work well for traction in automotive or rail-train applications.

QUICK DC AND BLDC MOTOR REVIEW

All dc motors generate a magnetic field, either via electromagnetic windings or permanent magnets. An armature, which is often a coil of wires, is placed between the north and south poles of a magnet. When current flows through the armature, the field produced by the armature interacts with the magnetic field from the magnets and eventually generates a torque and thereby motion. For motion-control applications, the most common dc motor types are brushed dc motors and brushless motors … permanent-magnet motors.

In a brushed dc motor, the magnet acts as the stator. The armature is integrated onto the rotor and a commutator switches the current flow. The commutator's function is to transfer current from a fixed point to the rotating shaft. Brushed dc motors generate torque straight from the dc power supplied to the motor by using internal commutation, fixed permanent magnets, and rotating electromagnets.

Brushed dc motors have the advantage of generally low initial cost and simple control of motor speed. However, there are some drawbacks. At certain periods during the dc motor rotation, the commutator must reverse the current, causing reduced motor life due to arcing and friction. Consequently, brushed dc motors require more maintenance such as frequently replacing the springs and brushes which carry the electrical current, as well as replacing or cleaning the commutator. These components are important for transferring electrical power from outside the motor to the spinning coil windings of the rotor inside the motor.

BLDC motors, on the other hand, do away with mechanical commutation in favor of electronic commutation. That eliminates the mechanical wear and tear involved with brushed dc motors. In BLDC motors, the permanent magnet is housed in the rotor and the coils are placed in the stator. The coil windings produce a rotating magnetic field because they're separated from each other electrically, which enables them to be turned on and off. The BLDC's commutator doesn't bring the current to the rotor. Instead, the rotor's permanent magnet field trails the rotating stator field, producing the rotor field. Successful commutation relies on precise rotor-position data, often from magnetic sensing with a Hall Effect sensor, which also allows for tracking of speed and torque.

BRUSHLESS DC MOTOR DESIGNS

Brushless dc (BLDC) motors do away with mechanical commutation in favor of electronic commutation, which eliminates the mechanical wear and tear involved with brushed dc motors. In BLDC motors, the permanent magnet is housed in the rotor and the coils are placed in the stator. The coil windings produce a rotating magnetic field because they're separated from each other electrically, which enables them to be turned on and off. The BLDC's commutator does not bring the current to the rotor. Instead, the rotor's permanent magnet field trails the rotating stator field, producing the rotor field. Read the related article: What are brushless dc motors? Technical summary for engineers.

BRUSHLESS DC (BLDC) MOTORS ARE DC MOTORS THAT USE MAGNETS INSTEAD OF BRUSHES AND A COMMUTATOR FOR COMMUTATION. THE BENEFIT TO THAT IS THEY DON'T SUFFER FROM BRUSH WEAR … BUT THE DRAWBACK IS THAT THEY NEED ELECTRONIC CURRENT-PHASE COMMUTATION.

In short, brushless dc motors work like shunt-wound motors, but field flux comes from magnets instead of current through a winding. The permanent magnets are made of rare-earth elements such as high-energy neodymium that generate a magnetic field.

Note that there are some naming-convention caveats: There exist permanent-magnet (PM) dc motors with brushes (for mechanical commutation) and some references call these motors PMDC motors. Furthermore, some motors called brushless dc motors have permanent magnets (PMs) so they are technically PM synchronous motors that run on ac (though through a dc bus and electronic inverter circuitry). In other words, this naming convention merely indicates that 1) these motors don't run directly from ac lines and 2) the motors (with the proper drives) can replace dc brush motors (paired with drives) in closed-loop applications.

Most permanent-magnet dc motors drive fractional-horsepower applications though other uses are on the rise. Output torque is proportional to armature (rotor) current over the motor's speed range.

Though brushless dc motors with armature (stator) magnets exist (powered by current to the rotor through a commutator) PM motors with rotor magnets are far more common. These have rotor PMs that form a magnetic field to act much like shunt-wound motors. With the ever-falling cost of electronics, today's permanent-magnet motor-drive systems are often less costly than comparable brush-motor-drive systems.

BLDC motors have quite a few advantages over their brushed counterparts. Compared to brushed dc motors, BLDC motors are more efficient due mainly to the elimination of the friction from the brushes. They're also more reliable and typically have longer life spans as well. Getting rid of the brushes also means a decrease in EMI (electromagnetic interference) noise and no sparking from the brushes making contact with the commutator.

BLDC motors excel in everything from low-power applications such as consumer products to high power applications in electric vehicles and industrial equipment.

DEEP DIVE ON LINEAR BLDC BEHAVIOR

When the term "linear behavior" is used to describe a system, it implies that the system's output is directly proportional to the input. Unlike their wound-field counterparts, permanent magnet dc (PMDC) motors exhibit linear behavior. The use of permanent magnets means PMDC motors don't need separate field excitation, and therefore, don't experience the electrical losses that often occur in field windings of other dc motor designs.

In permanent magnet motors, linear behavior is evident in several performance characteristics. First, the motor's angular velocity (or speed) is directly proportional to the applied voltage, as shown by the equation:

$$\omega = \frac{V}{k} - \frac{T}{k^2} \cdot R$$

Where ω = angular velocity; V = voltage; k = motor constant; T = torque; and R = resistance.

Second, the motor's output torque is directly proportional to the current through the armature. The relationship between torque and current is shown by the equation:

$$T = I \cdot k_T$$

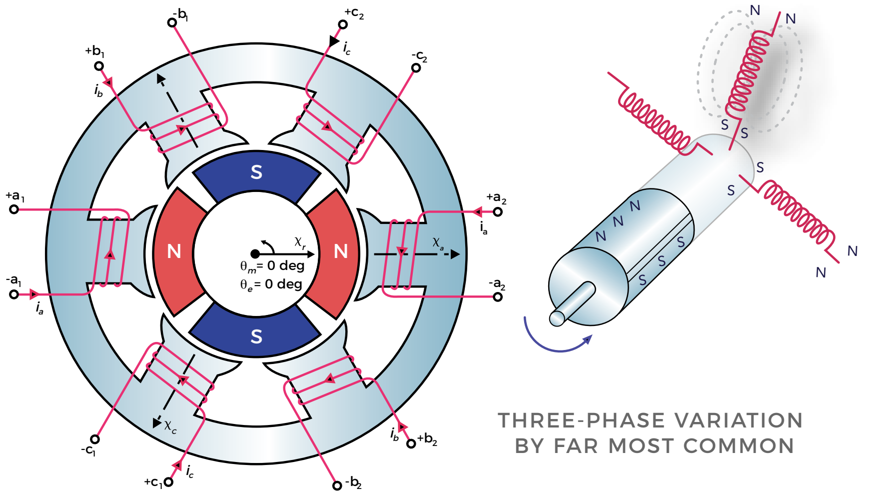
Where T = torque; I = current through the armature; and k_T = torque constant of the motor.

The linear characteristics of PMDC motors also extend to their torque-speed curves. The linearity of the relationship between speed and torque makes permanent magnet motors ideal for adjustable speed uses and for servo applications.

DC motors with permanent magnets can be either brushed or brushless types. As noted earlier, brushed permanent magnet dc motors are often called PMDC motors while brushless permanent magnet dc motors are referred to as BLDC motors. Both motor types — PMDC and BLDC — exhibit the linear behavior characteristics described above.

Despite their similar speed and torque behavior, there are two significant differences between PMDC and BLDC motors. First, PMDC motors are commutated mechanically, via brushes and a commutator, whereas BLDC motors are commutated electronically, typically via Hall effect sensors on the stator. Second, PMDC motors have a stator made of permanent magnets, while BLDC motors have permanent magnet rotors.

TYPICAL BRUSHLESS DC MOTOR DESIGN: PERMANENT MAGNETS ON ROTOR



THREE-PHASE VARIATION BY FAR MOST COMMON

Brushless motors have stator windings and rotors with permanent magnets. Power on a winding sets an electromagnetic field that interacts with the magnets to turn the rotor. Electronics determine the sequence for commutation (or energizing of the stator windings) in brushless motors. This sequence is based on the rotor position, which is most often provided by either three Hall sensors or a rotary encoder … although there are methods of determining rotor position without additional feedback devices.

DIFFERENCE BETWEEN SLOTTED AND SLOTLESS MOTORS

The original brushless dc (BLDC) motors were designed with slotted stators, and the majority of BLDC motors are still made this way. But this design produces cogging torque, which makes it difficult to achieve smooth motion, especially at slow speeds. To eliminate this effect, a new design was developed, eliminating the slots in the stator (which are the root cause of cogging torque), and slotless motors were born.

In a slotted motor design, the stator is made of slotted steel laminations that are stacked together, and copper windings are inserted into these slots. (The design of the stator is sometimes referred to as having teeth.) The slotted motor design is simple and inexpensive to manufacture, but it has a major drawback — cogging torque.

Cogging torque (also referred to as detent torque) is a result of the permanent magnets in the rotor attempting to line up with the slots, or teeth, of the stator. The primary effect of cogging torque is that it causes motor rotation to be jerky and not smooth … especially at low motor speeds.

In a slotless motor, there are no iron teeth to support the windings. Instead, the stator lamination is constructed of steel rings that are stacked together, and the windings are encapsulated in an epoxy resin, which gives the winding structure shape and rigidity. This self-supporting winding is placed in the air gap between the stator lamination and the rotor.

The primary benefit of a slotless motor design is that the lack of teeth in the lamination eliminates cogging torque and results in a motor with very smooth running characteristics. Torque production is predictable and highly controllable because in the absence of these uncontrolled disturbances (such as that from cogging torque) motor torque production is directly related to the current supplied to the winding.

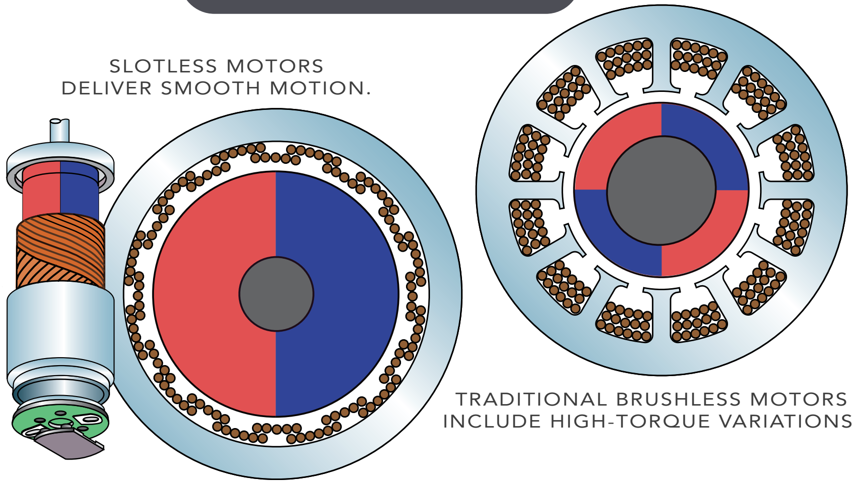
There are other benefits to the slotless design. First, the elimination of cogging also significantly reduces audible noise. And since there's no iron core, inductance is very low and current can get into the stator windings very quickly, making slotless motors good for applications that require high acceleration and dynamic response.

But slotted motors still hold some advantages. For example, the air gap in a slotted motor is smaller than the air gap in a slotless design (which must accommodate the self-supported winding assembly). This means that the flux density is higher in a slotted motor, and torque production is more effective and efficient.

> THE TERM *IRON CORE* IS COMMONLY USED WHEN DISCUSSING SLOTTED LINEAR MOTORS. THIS ORIGINATES FROM THE FACT THAT THE ASSEMBLY OF STATOR WINDINGS ENCASED IN A STEEL, SLOTTED STATOR IS SOMETIMES REFERRED TO AS AN IRON CORE. IN CONTRAST, SLOTLESS LINEAR MOTORS ARE OFTEN CALLED AIR CORE MOTORS.

One way that manufacturers of slotless motors overcome the effects of the bigger air gap is to use larger, stronger permanent magnets in the rotor. But this increases cost. And, the cost to manufacturer the self-supporting winding structure is typically higher than a conventional slotted design. For this reason, the traditional slotted motor design is still the first choice for applications in which smooth running and the elimination of cogging are not critical.

SLOTLESS VERSUS SLOTTED BRUSHLESS DC MOTOR



SLOTLESS MOTORS DELIVER SMOOTH MOTION.

TRADITIONAL BRUSHLESS MOTORS INCLUDE HIGH-TORQUE VARIATIONS.

Notice how the construction of a traditional brushless motor with a slotted design differs from that of a slotless build.

DETAILS ON VOLTAGE AND DC MOTOR OUTPUT SPEED

During operation of a dc motor, a coil is placed in a magnetic field — and when an electric current passes through the coil a torque is produced to make the motor turn. The entire process is driven by applying electrical power to the coil, with the source voltage having a direct relationship to the motor's output speed. To understand this relationship between voltage and speed, consider a typical dc motor circuit.

Applied voltage equals the voltage drop across the coil resistance R and the inductor L plus the back electromotive force B*emf* …

$$V = I \cdot R + L\frac{dk}{dt} + E$$

Where V = applied voltage; I = current; R = resistance; L = inductance; and E = B*emf*

The voltage equation can be simplified by assuming that the current is constant, in which case inductance can be disregarded:

$$V = I \cdot R + E$$

The Bemf is a voltage that is generated by the rotation of the coil. It opposes the applied voltage, reducing the voltage flowing through the motor. B*emf* is calculated as:

$$E = k_E \cdot \omega$$

Where: k_E = electrical constant inherent to the motor and ω = angular velocity of the motor

Substituting for E in the voltage equation, we get:

$$V = I \cdot R + k_E \cdot \omega$$

Current I through the motor coil is directly related to the motor's torque:

$$T = k_T \cdot I$$

Which can be rearranged as:

$$I = \frac{T}{k_T}$$

Where: T = torque and k_T = Torque constant inherent to the motor

Substituting for I, the voltage equation now becomes:

$$V = \frac{T}{k_T} \cdot R + k_E \cdot \omega$$

This shows the direct relationship between the applied voltage and the motor's angular velocity. Rearranging to solve for the angular velocity:

$$\omega = \frac{\left(V - \frac{T}{k_T} \cdot R\right)}{k_E}$$

For dc motors, the torque and electrical constants, kT and kE are equal so the angular velocity equation can be simplified to:

$$\omega = \frac{V}{k} - \frac{T}{k^2} \cdot R$$

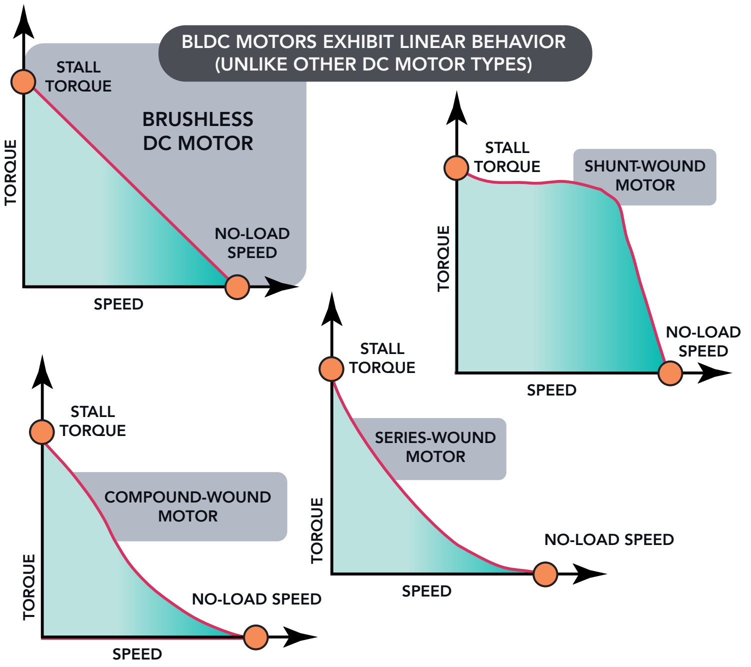
From this we can see that the motor's maximum speed occurs when there's no load (torque) on the motor. Rearranging for torque:

$$T = \frac{(V - \omega \cdot k)}{R} \cdot k$$

Similarly, maximum torque occurs when angular velocity is zero.

These two relationships can be seen in a typical dc motor's torque-speed curve.

Back to the original question: how does voltage affect speed? From the analysis above, we can see that when the load (torque) on the motor is constant, speed is directly proportional to supply voltage. And, when the voltage remains constant, an increase in the load (torque) on the motor results in a decrease in speed.



Unlike dc motors with wound fields, permanent magnet dc motors exhibit linear behavior without electrical losses associated with dc motors with other types of construction.

THE RELATIONSHIP BETWEEN CURRENT AND OUTPUT TORQUE

Torque is a rotational force produced when a vertical force is applied at some distance from the center axis of the rotating body. The familiar equation for torque is:

$$T = F \cdot d$$

Where T = Torque; F = Applied vertical force; and d = Distance from axis of rotation.

In a dc motor, the output torque is directly proportional to the current through the windings, and is given as:

$$T = I \cdot k_T$$

Where I = current through the windings an kT = torque constant (specific to the motor)

To see how this relationship is developed, consider the geometry of a four-pole dc motor as illustrated in this Design Guide. The force on one coil is the product of flux density, current through the coil, and the length of the coil:

$$F_c = B \cdot I_c \cdot L$$

Where:
F_c = force on one coil; B = flux density; I_c = current through one coil and L = length of the coil. Current through one coil is calculated as:

$$I_c = \frac{I_a}{A}$$

Where I_a = total current through the armature and A = area of the coil.

Substituting for I_c in the force equation, we get:

$$F_c = \frac{B \cdot I_a \cdot L}{A}$$

Because torque equals force times distance, the torque equation can be shown as:

$$T_c = \frac{B \cdot I_a \cdot L \cdot r}{A}$$

Where T_c = torque on one coil and r = distance from center of armature. The flux density B equals the total flux divided by area:

$$B = \frac{\phi}{A}$$

Where ϕ= total flux. Because the motor is essentially a cylinder, area is calculated:

$$A = \frac{2 \cdot \pi \cdot r \cdot L}{P}$$

Where P = number of poles. Substituting into the flux density equation, we get:

$$B = \frac{\phi \cdot P}{2 \cdot \pi \cdot r \cdot L}$$

Substituting this into the torque equation, we get:

$$T_c = \frac{\phi \cdot P \cdot I_a \cdot L \cdot r}{2 \cdot \pi \cdot L \cdot r \cdot A}$$

Which simplifies to:

$$T_c = \frac{\phi \cdot P \cdot I_a}{2 \cdot \pi \cdot A}$$

T_c is the torque on just one coil. Total torque equals T_c multiplied by the number of coils:

$$T_c = \frac{\phi \cdot P \cdot I_a}{2 \cdot \pi \cdot A}$$

Where T = total torque and Z = Number of coils

To further simplify the torque equation, the number of poles P, the number of coils Z, and the geometric factors 2πA can be combined to form the torque constant kT which is specific to the motor. This simplifies the torque equation to:

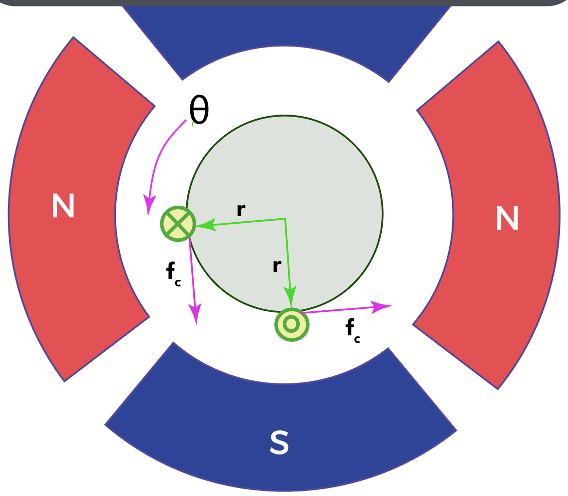
$$T = \phi \cdot I_a \cdot k_T$$

For most dc motor cases, we can assume the flux ⍰ is constant, making torque directly proportional to the current:

$$T = I_a \cdot k_T$$

When examining the torque-current curve for a dc motor, notice that the no-load (stall) current is greater than zero. This is because some current is needed to overcome the internal friction of the motor.

FORCE ON ONE COIL IS THE PRODUCT OF FLUX DENSITY, CURRENT, AND COIL LENGTH



We use this four-pole motor in our example calculations on the relationship between current and dc motor output torque.

WAYS TO AVOID TORQUE RIPPLE IN DC MOTORS

Torque ripple — variations in torque production during shaft revolution — is an undesirable effect that occurs in permanent-magnet motors that prevents smooth motor rotation. Torque ripple is generally defined as non-linear torque production of an energized motor. Cogging torque (a phenomenon similar to torque ripple) is torque produced by the attraction between the permanent magnets of the rotor and the slots of the stator in an un-energized motor.

Consider a BLDC motor with a rotor having permanent magnets and a stator with windings. Torque is produced by the repulsive forces between the magnetic fields of the stator and the rotor. An important distinction between BLDC motors and their counterpart permanent-magnet ac (PMAC) motors is that the windings in a BLDC motor are trapezoidally wound for trapezoidal B*emf* waveform output. Because their B*emf* is trapezoidal, BLDC motors typically use trapezoidal commutation, whereas PMAC motors are sinusoidally wound and use sinusoidal commutation.

In trapezoidal commutation, the rotor is monitored by three Hall sensors, which provide rotor position information every 60° (rather than continuously, as with sinusoidal commutation). This produces six torque ripples per electrical cycle of the motor, or 12 torque ripples for every full mechanical revolution of the motor shaft.

The frequency of the torque ripple is proportional to the motor's shaft speed. At high motor speeds, the inertia of the motor and the load can smooth out the effects of torque ripple. And at low motor speeds, high-frequency torque ripple can be filtered out using feedback and parameters in the motor controller. But if the frequency of the torque ripple is near the bandwidth of the controller's speed loop, it can cause detrimental variations in motor speed.

The primary methods for reducing torque ripple in BLDC motors with regard to design are to increase the number of windings in the stator or to increase the number of poles in the rotor. Torque ripple can also be reduced through various control methods, taking a page from the PMAC motor playbook and using sinusoidal (rather than trapezoidal) commutation.

Although in theory the B*emf* of a BLDC motor is trapezoidal, in reality, it is more sinusoidal in nature. With sinusoidal B*emf* and the addition of a resolver or encoder to accurately track rotor position, it is feasible to use sinusoidal commutation for BLDC motors. And because sinusoidal commutation is continuous, torque ripple is greatly reduced.

Another commutation method known as field oriented control (FOC) can also be used for BLDC motors. FOC provides higher efficiency and surpasses the speed limitations inherent in sinusoidal commutation, although it is more complex and can be more costly to implement.

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