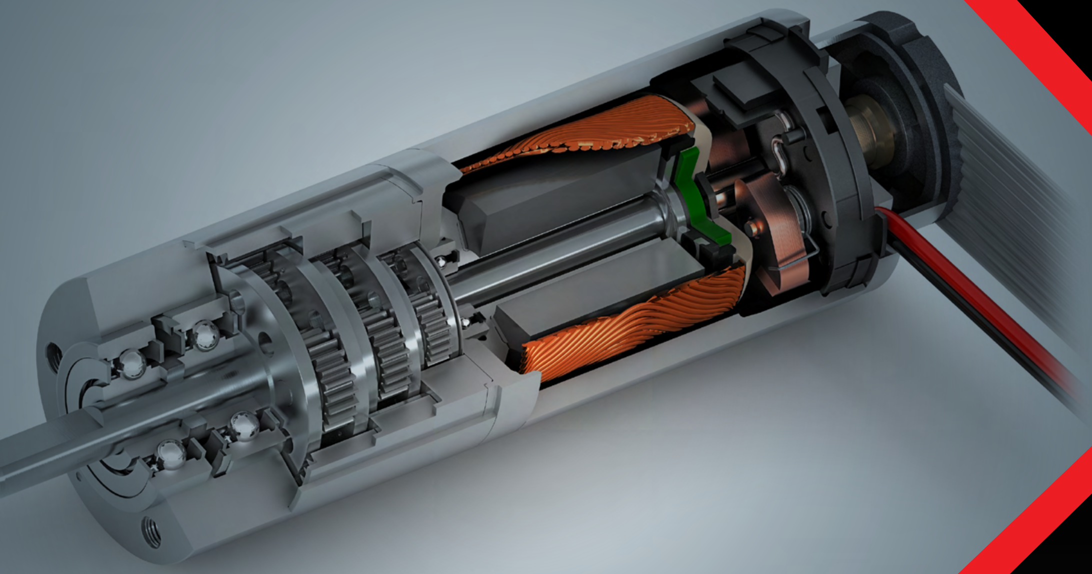
BROUGHT TO YOU BY:

MOTION CONTROL TIPS
A Design World Resource



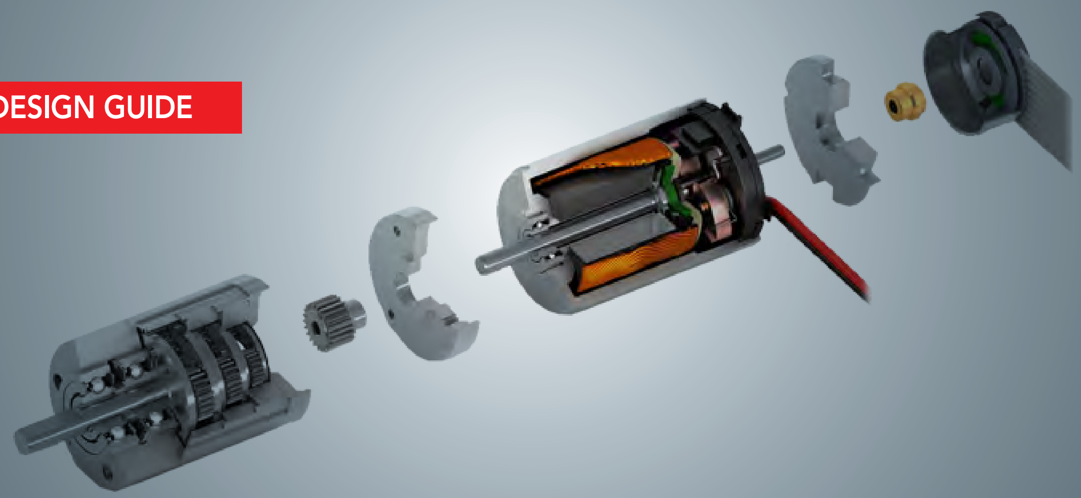
DC MOTORS

DESIGN GUIDE

SPONSORED BY:

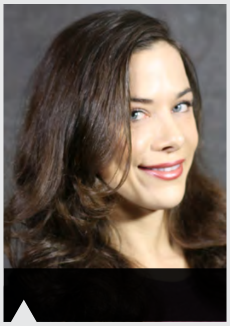
maxon

maxon Drives & Systems | maxon group



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.



LISA EITEL
Executive editor

TABLE OF CONTENTS

DC MOTOR
CONSTRUCTION AND OPERATION

All dc electric 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, regularly during the motor rotation, the commutator must reverse the current. The arcing and friction from that reversing causes mechanical wear. So at some interval, the current-carrying spring and brush require replacement ... and the commutator requires cleaning. 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 nix mechanical commutation for electronic commutation. That eliminates the mechanical wear and tear involved with brushed dc motors. In BLDC motors, the rotor contains permanent magnets and the stator contains the coils. The coil windings are electrically separated so can be seperately turned on and off. In this way, they can (upon electrification in sequence) produce a rotating magnetic field. The BLDC's commutator doesn't bring the current to the rotor. Instead, the rotor's permanent magnet field trails the rotating stator field. Successful commutation relies on precise rotor-position data, often from magnetic sensing with Hall-effect sensors that also allow for tracking of speed and torque.

While the focus of this Design Guide is BLDC motors, let's quickly consider other dc motor types to understand competitive solutions.

QUICK COMPARISON: WHERE BRUSH MOTORS EXCEL

In contrast with brushless dc motors, brush 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?

Brushes in dc brush motors wear and shed particles that render the motors unsuitable for cleanrooms.

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.

Common industry naming conventions of today differentiate three dc motor subtypes — dc brush motors, dc permanent-magnet (PM) motors, and dc universal motors. However, caveats and sub-classifications abound. Many large dc motors employ brushes and wound fields though PM motors dominate fractional and integral-horsepower applications below 18 hp.

(continued)

DC MOTOR CONSTRUCTION AND OPERATION

Some engineers call dc brush motors ***wound-field motors*** because it's wound and lacquered coils of copper wire that makes the electromagnetic field. Others also argue that all dc motors are brush dc motors, and that the term ***brushless dc motor*** is a misnomer. In any case, 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 interact with a stator magnetic field (for output of mechanical rotation) and
2. Current through stator windings make the magnetic field in question.

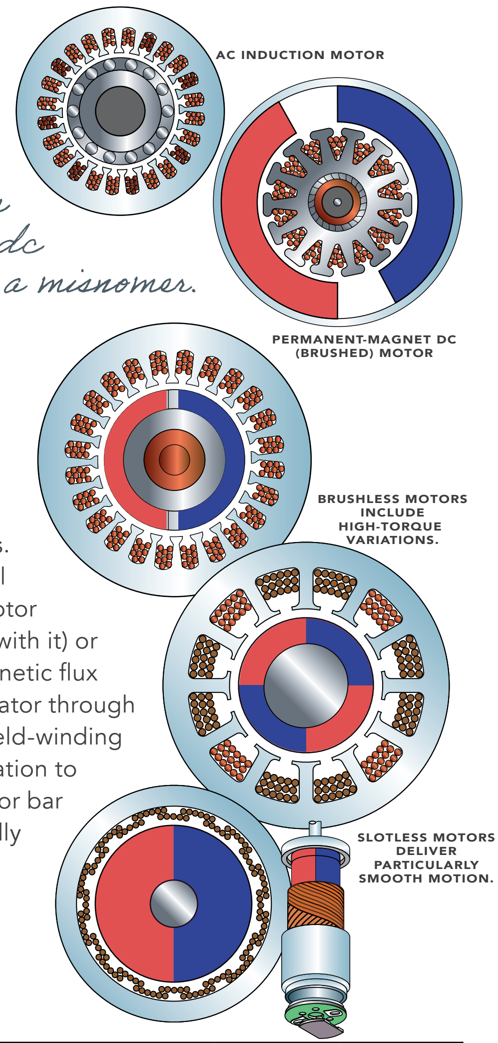
In contrast, permanent-magnet brush dc motors use:

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 ***shunt-wound motors*** connect in parallel so field current is proportional to the load on the motor. The armature and field coils in ***series-wound motors*** connect in series so current passes only through field coils. The armature and field coils in ***compound-wound motors*** include both series and shunt windings.

Some argue that the term brushless dc motor is a misnomer.

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.



	BRUSHLESS DC MOTOR	BRUSH DC MOTOR	SERVOMOTOR DC	SERVOMOTOR AC	STEPPER MOTOR	THREE-PHASE INDUCTION AC MOTOR	THREE-PHASE SYNCHRONOUS MOTOR	UNIVERSAL MOTOR	SINGLE-PHASE AC MOTOR
COMPARABLE SIZE	small	small	small	small to medium	intermediate	medium to large	medium to large	large	large
POWER	dc power converted from ac by a drive	dc power	drive supply	drive supply	drive supply	ac power	ac power	ac or dc power	ac power
EFFICIENCY	82% or better	58 to 86%	56 to 86%	50 to 84%	60 to 70%	60 to 70%	70 to 80%	50 to 60%	40 to 60%
DESIGN TRADEOFFS	moderate to high cost • versatile	low cost	high cost • high performance	high cost • high performance	moderate cost • versatile	low cost • versatile	moderate cost • versatile	low cost	low cost
NOISE	quiet	noisy	noisy	quiet	moderately noisy	quiet	quiet	noisy	quiet
DYNAMICS	moderate responsiveness • wide speed range	moderate responsiveness • wide speed range	highly responsive • narrow speed range	highly responsive • average speed range	moderate responsiveness • wide speed range	sluggish response • wide speed range	sluggish response • wide speed range	sluggish response • average speed range	sluggish response • narrow speed range
SERVICE LIFE	long	short	short	long	long	long	long	short	long
USES	motion-control applications • air conditioners • dishwashers • washing machines, consumer appliances • Mobile robots, medical & lab equipment, pumps, power tools, semiconductor processing, electronics manufacturing	power tools • electric toys • motorized automotive elements • home appliances	motion-control applications • office automation • equipment for manufacturing	robotic arms • pick-and-place arrangements • precision machine-tool axes • conveyors	robots • consumer-grade appliances • HVAC systems	bulk material handling • cranes and conveyors • process control • HVAC systems • heavy industrial equipment	process control • compressors • washers	larger power tools • commercial kitchen appliances • vacuum cleaners	pumps • industrial washing machines • blowers • vacuum cleaners

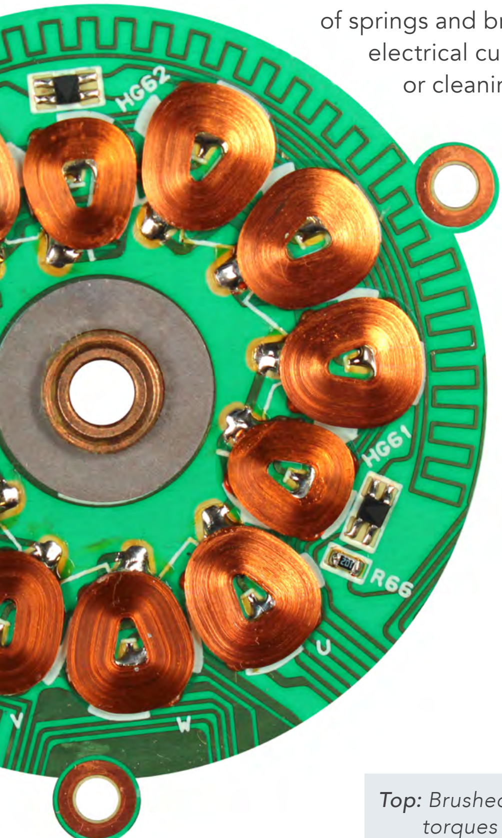
(continued)

DC MOTOR CONSTRUCTION AND OPERATION

In fact, the way dc brush motors let designers customize field and rotor windings means they're suitable for applications needing 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.



Friction from brush-commutator engagement make for long position-settling times—rendering brush dc motors unsuitable for certain high-precision designs.

Top: *Brushed dc motors output high peak torques and can run off simple speed controllers to move myriad applications.*

Middle: *Though beyond the focus of this Design Guide, dc motors can also take the form of ultra-miniature dc pancake motors.*

Bottom: *BLDC motors are so ubiquitous because compared to brushed dc motors, BLDC motors are more efficient. They're also more reliable and typically have longer life spans.*

(continued)

DC MOTOR CONSTRUCTION AND OPERATION

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.

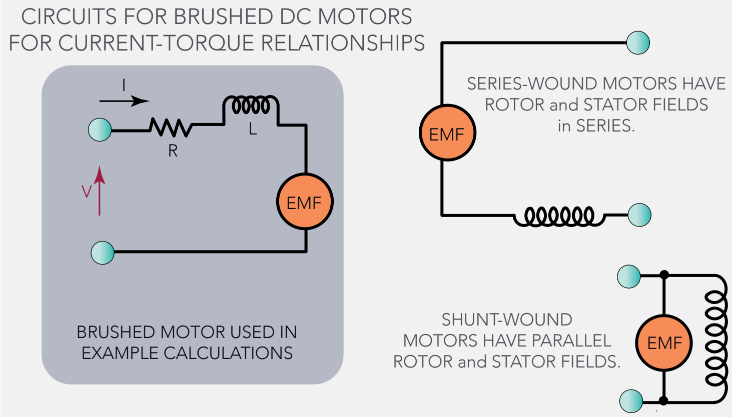
In shunt-wound motors, the field (stator) winding connects in parallel with the armature (rotor) winding.

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.

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

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* B_{emf}.



reversal. That necessitates reversing contactors. So for reversing motion, sometimes manufactures just design shunt-would motors with higher stability and omit stabilizing windings.

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 (also 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 and rail-train applications.

BRUSHLESS DC MOTOR SPECIFICS

Brushless dc (BLDC) motors do away with mechanical commutation in favor of electronic commutation, which avoids mechanical wear as exhibited by brushed dc motors. In most BLDC motors, permanent magnets are on the rotor and coils in the stator. The coil windings produce a rotating magnetic field because they're electrically separated so can be independently turned on and off.

In a BLDC motor, contacting brush-and-copper commutation doesn't bring current to the rotor. Instead, the rotor's permanent magnet field trails the rotating stator field with its rotor field.

Brushless dc (BLDC) motors use magnets for commutation.

In this way, 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 magnetic fields.

Note some naming-convention caveats: Permanent-magnet (PM) dc motors with brushes (for mechanical commutation) are often called PMDC motors. But motors commonly 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). That's why some manufacturers avoid the use of BLDC and instead call these motors electronically commutated or *EC* motors.

The BLDC naming convention merely indicates that:

- These motors don't run directly from ac lines and
- These 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.

BLDC motors don't wear but need electronic current-phase commutation.

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. Getting rid of the brushes also means a decrease in electromagnetic interference (EMI) noise and no sparking from the brushes making contact with the commutator.

BLDC COMMUTATION SPECIFICS

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

Although the back EMF or B_{emf} waveform of a BLDC motor is theoretically trapezoidal, motor inductance smooths B_{emf} into a more sinusoidal shape. This is why BLDC motors can use either trapezoidal or sinusoidal commutation methods. Trapezoidal commutation is the simpler of the two approaches but produces significant torque ripple every 60° *at each commutation step*. Sinusoidal commutation avoids torque-ripple generation for smooth motion and precise motor control.

Sinusoidal commutation avoids torque ripple that occurs with trapezoidal and six-step (modified trapezoidal) methods.

The basic premise behind sinusoidal commutation is to provide each of the motor windings with currents that vary sinusoidally as the motor turns. The currents are phase shifted by 120° to match the orientation of the stator windings. The current space vector has constant magnitude and is always orthogonal to the rotor.

(continued)

BLDC MOTORS

Recall that maximum torque is produced when the stator and rotor magnetic fields are orthogonal or at 90° to each other.

A key to achieving sinusoidal commutation is the ability to accurately determine the rotor position. Because Hall devices provide only a rough measurement of rotor position, an encoder is typically used to provide rotor position information.

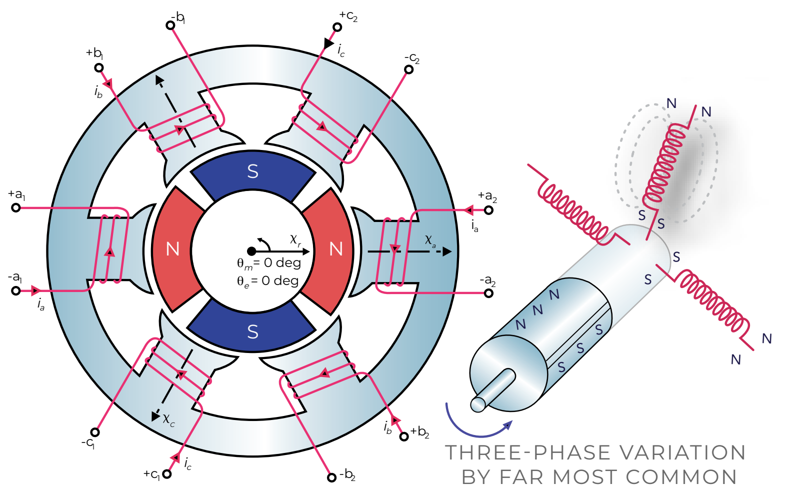
Based on the rotor position, two sinusoidal waveforms are created, 120° phase shifted from each other. Multiplying these signals by the torque command produces amplitudes that are proportional to the desired torque. These commands are fed to the controller, which regulates the current in the motor windings.

According to Kirchhoff's current law, the sum of the three currents must equal zero, so the current in the third motor winding is the negative sum of the first two (to maintain a zero sum of the three) ... and so cannot be directly controlled.

The downside of sinusoidal commutation is that it becomes inefficient at high speeds. The faster the motor turns, the higher the frequency of the sinusoidal signals, and controllers have difficulty tracking these high-frequency signals. Higher motor speeds also cause back-EMF to increase in both amplitude and frequency, making it more difficult for the motor to overcome.

Both conditions result in disturbances to the current control loop and cause phase lag and errors in the currents. The result is that the current space vector moves away from the ideal (orthogonal) position relative to the rotor, and less torque is produced by a given amount of current.

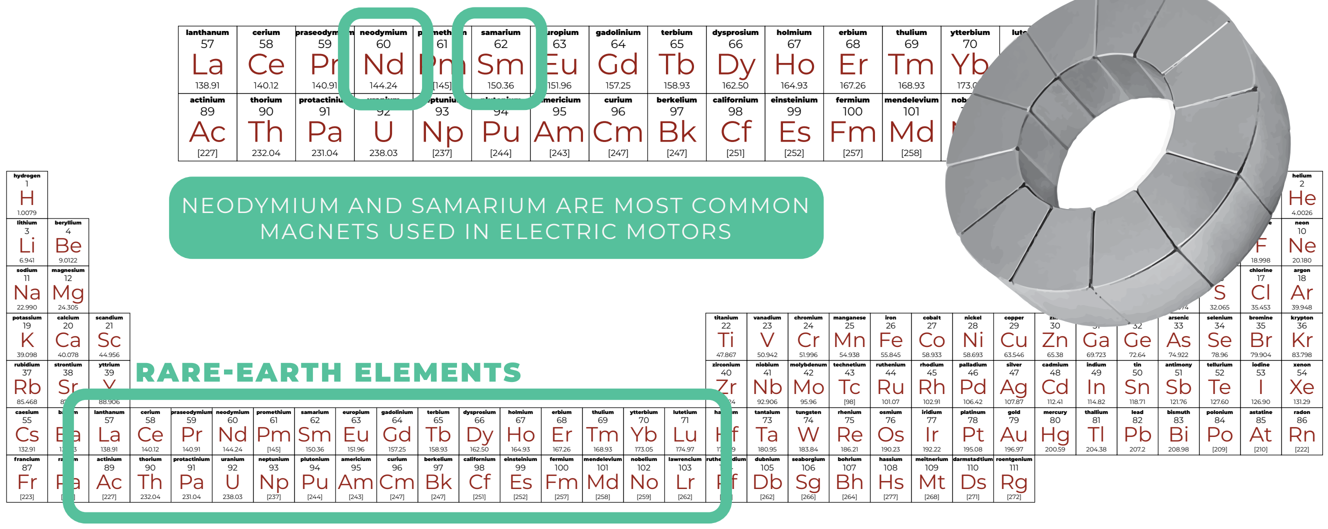
The most common brushless-motor variations have stator windings and rotors with permanent magnets. Power on a winding sets an electromagnetic field that interacts with the magnets to turn the rotor. Electronics determine the sequence for commutation (the energizing of the stator windings) based on the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



THREE-PHASE VARIATION
BY FAR MOST COMMON

BRUSHLESS MOTORS OMIT BRUSHES AND USUALLY (THOUGH NOT ALWAYS) **INCORPORATE PERMANENT MAGNETS** FOR FIELD FLUX.

THE PERMANENT MAGNETS ARE MADE OF RARE-EARTH ELEMENTS.



CONSIDERING DC MOTORS' **HALL SENSORS**

Recall from basic engineering training that the Hall effect was discovered in the late 1800s by physicist Edwin Hall. In short, the Hall effect is the tendency of current flowing on a conductor to deflect as it passes through a magnetic field.

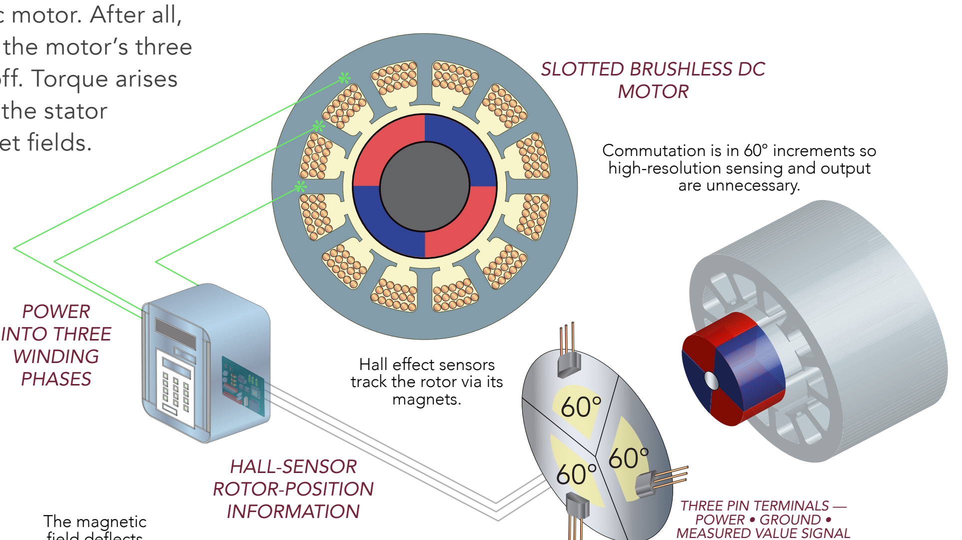
More precisely, any external magnetic field induces a transverse (sideways) force on the material's charge carriers (electrons, ions, and holes) that segregates them to the conductor sides — negative to one side and positive to the other. This deflection appears as a lopsided charge or voltage in the conductor.

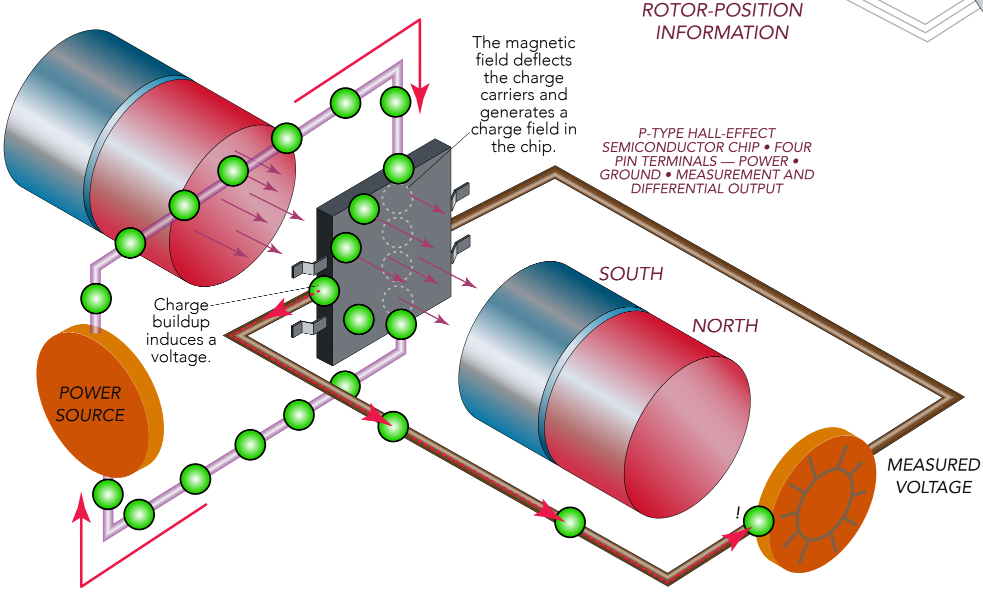
Hall-effect sensors work by detecting this voltage.

Most design engineers are most familiar with Hall-effect sensors (solid-state semiconductor chips sometimes called *Hall chips*) as they're used in brushless dc (BLDC) motors. Here, Hall-effect sensors perform the duty of what the brushes and mechanical commutator do in a brushed dc motor. After all, commutation is sequenced energization of the motor's three stator windings — positive, negative, and off. Torque arises from the attraction and repulsion between the stator fields and PMDC motor's permanent-magnet fields. Torque crests when these two fields are at 90° and wanes as the fields align.

Hall effect sensors track the rotor position to let the motor drive energize the correct stator winding for maximum torque.

Hall-effect sensors are useful for linear-position sensing too. Some linear encoders contain Hall chips in their read heads to track magnetic-field strength from a magnetically banded (coded) encoder scale. Another design actually flips this arrangement around so that the long linear scale is studded with an array of Hall chips, and a magnet (traversing the axis stroke with the payload, cylinder piston, or electric-actuator carriage) is the moving sensor element.





(continued)

CONSIDERING BLDC MOTORS' HALL SENSORS

MORE ON SENSOR AND MOTOR INTERACTIONS

DC motors can be brushed type (so mechanically commutated) or brushless and electrically commutated. In BLDC motors, Hall effect sensors are used in place of the mechanical commutator and brushes.

Hall-effect sensors are solid-state magnetic field sensors. They work on the principle that when a conductor with current flowing through it is placed in a magnetic field, the magnetic field induces a transverse (or sideways) force on the charge carriers, which pushes them to the sides of the conductor — negative to one side and positive to the other side. This buildup of charge on the sides of the conductor induces a voltage. This phenomenon is known as the Hall effect.

The purpose of commutation (whether by mechanical or by electrical means) is to energize the stator windings in a certain sequence — with one winding positive, one negative, and the third one powered off.

Torque production is caused by the attraction and repulsion between the stator field and the permanent magnets of the rotor. Maximum torque is achieved when these two fields are oriented at 90° to each other, and torque diminishes as the fields align. So to keep the motor turning, the stator's magnetic field should change position as the rotor field "catches up" with it.

To energize the correct stator winding, rotor position must be known. This is the job of the Hall effect sensors — to monitor the rotor's position.

BLDC motors typically have three Hall-effect sensors mounted either to the stator or to the rotor and use what is known as six-step commutation.

60° multiplied by six steps equals 360° or one full rotation — hence the term six-step commutation.

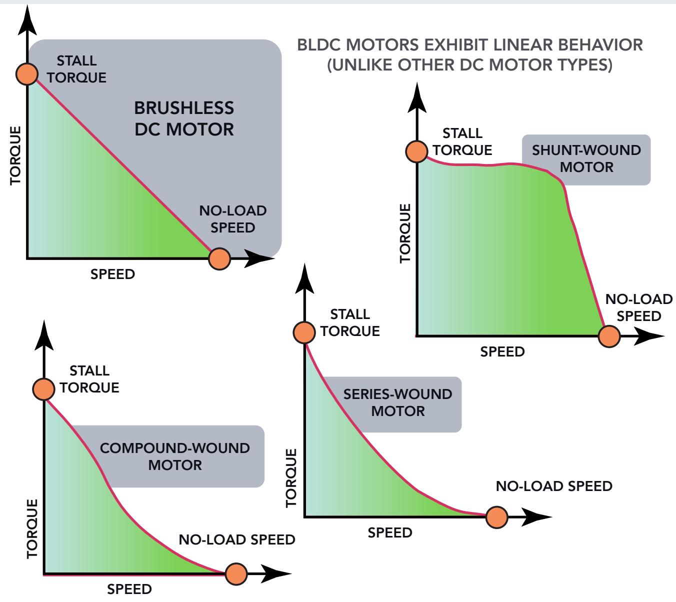
When the rotor passes a sensor, it produces either a high or a low signal to indicate which rotor pole (N or S) has passed. Every 60° this switching of the three Hall-effect sensors (from high to low or from low to high) provides rotor-position information.

In six-step commutation, each of the three windings (U, V, W) is either energized positive, negative, or off depending on whether each of the three Hall effect sensors has a high or a low state.

Hall-effect sensors are the most common method of determining rotor position in BLDC motors due to their low cost and ease of use with the permanent magnets of the rotor. Because commutation happens in 60° increments, high-resolution sensing and output are unnecessary.

DEEPER DIVE ON **LINEAR BEHAVIOR**

BLDC motors find copious use in consumer and professional-grade power tools. Image: Dreamstime



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 including brushed PMDC and brushless BLDC exhibit the linear behavior characteristics described here.

Despite their similar speed and torque behavior, there are significant differences between PMDC and BLDC motors as described earlier in this Design Guide.

DIFFERENCE BETWEEN **SLOTTED AND SLOTLESS MOTORS**

Image: Dreamstime

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 can in some cases make it difficult to achieve smooth motion — especially at slow speeds. To eliminate this effect, a new slotless-motor design was developed sans slots in the stator (which are the root cause of cogging torque).

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 called ***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 airgap 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.

Side note about linear-motor varations: The term iron core is commonly used when discussing slotted linear motors. This originates from the fact that the stator-windings assembly is encased in steel. No wonder linear motors with slotted stators are sometimes called iron-core motors. In contrast, slotless linear motors are often called air-core motors.

OTHER SLOTLESS-MOTOR BENEFITS

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.

Slotted motors still maintain some advantages. For example, the airgap in a slotted motor is smaller than the airgap in a slotless design … which must accommodate the self-supported winding assembly.

(continued)

SLOTTED AND SLOTLESS MOTORS

This means that the flux density is higher in a slotted motor, and torque production is more effective and efficient.

One way that manufacturers of slotless motors overcome the effects of the bigger airgap is to use larger, stronger permanent magnets in the rotor. But this increases cost.

What's more, 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 noncritical.

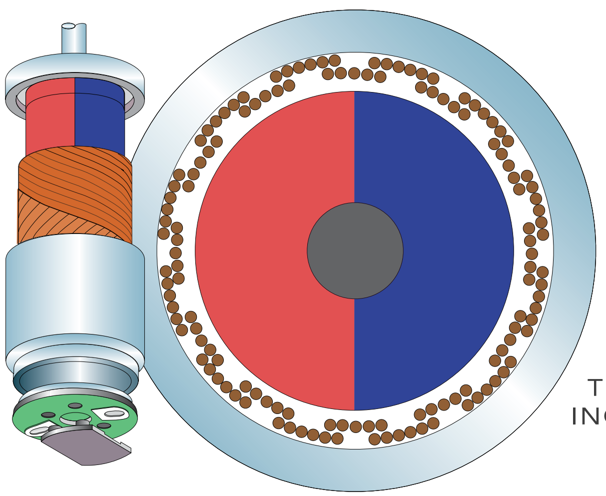
ENDURING SLOTTED-MOTOR BENEFITS

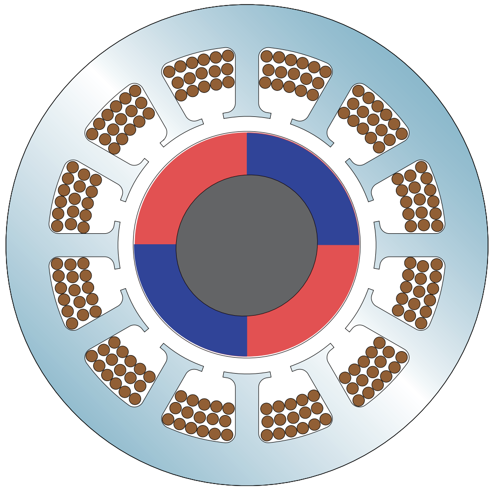
Traditional small-frame BLDC motors deliver peak performance at high rpm. The catch is that such high rotational speeds are usually too high to make efficient use of a gearbox. In fact, even when a traditional small-frame BLDC motor is paired with a custom high-rpm gearbox, there are typically noise and heat issues that make them unsuitable for critical applications. Why? Well, consider how a traditional coreless BLDC design is based on tooling-intensive winding technology developed for brush motors. Representative offerings here include slotless stators and encapsulated connections and sintered ring magnets — with two poles and no skew. Unfortunately, peak performance for such designs is usually at about 20,000 rpm … yet the gearboxes that usually get paired with such motors require far lower speed — usually of about 6,000 to 8,000 rpm.

In contrast, some BLDC motors readily pair with tailored planetary gearboxes in holistically developed designs. These are targeted to applications needing high torque from a small form factor with low power consumption. Peak performance at low rpm is another design objective for such BLDC motors.

Pre-integrated BLDC gearmotors are often optimized for gear input limitations. Higher pole counts can make for higher torque density and peak motor efficiency within gearbox speed ranges … for torque capabilities within the gearbox's speed range that far exceed those of traditional setups.

SLOTLESS MOTORS DELIVER SMOOTH MOTION.





TRADITIONAL BRUSHLESS MOTORS INCLUDE HIGH-TORQUE VARIATIONS.

Image: Dreamstime

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; E = B_{emf} and *L* = inductance.

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

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

The B_{emf} 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:

$$E = k_E \bullet \omega$$

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:

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

(continued)

VOLTAGE AND SPEED RELATIONSHIP

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

$$T = I \cdot k_T$$

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 angular velocity:

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

For dc motors, the torque and electrical constants, k_T and k_E 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. When the voltage remains constant, an increase in the load (torque) on the motor results in a decrease in speed.

BLDC and other dc motor uses abound in automotive designs. More specifically, electronically adjusted windows, mirrors, and seat adjusters often employ permanent-magnet and other dc motors pre-integrated with gearsets to deliver high torque. Such miniature motors must also be ruggedized to withstand the normal vibrations a vehicle experiences over thousands of miles of driving. Plastic encapsulation and reinforced metal housings help address this issue and concurrently protect the dc motors from water and dust ingress. Images: Dreamstime

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 k_T = 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:

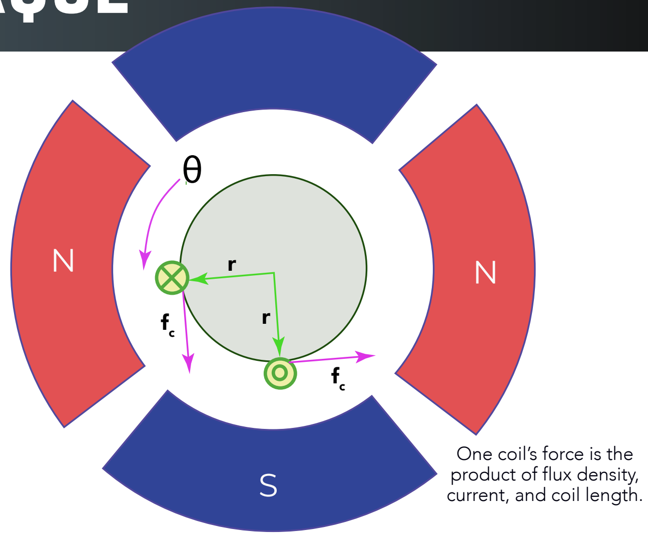
$$B = \frac{\phi}{A}$$

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

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

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

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



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

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 $2\pi A$ can be combined to form the torque constant k_T which is specific to the motor. This simplifies the torque equation to:

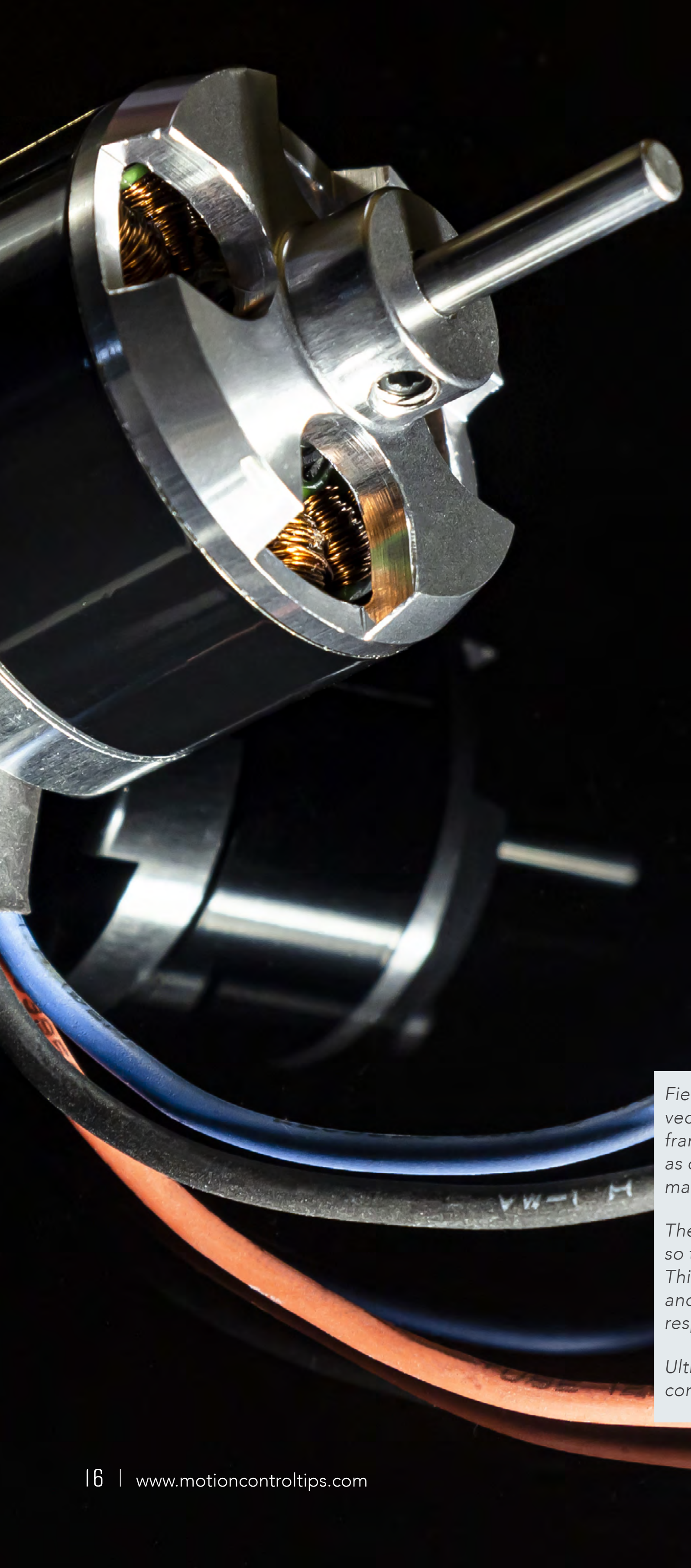
$$T = I_a \cdot k_T$$

For most dc motor cases, we can assume the flux ϕ 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.

WAYS TO AVOID TORQUE RIPPLE IN **DC MOTORS**

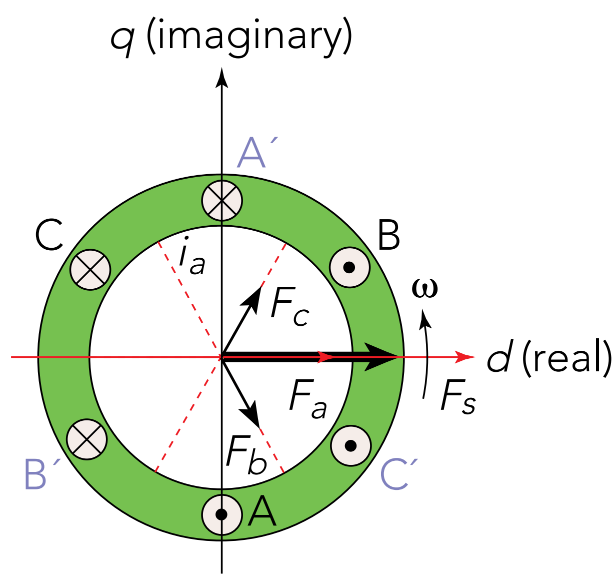


Torque ripple — variations in torque production during shaft revolution — is an undesirable effect that occurs in permanent-magnet motors that prevents smooth motor rotation. Torque ripple is generally defined as non-linear torque production of an energized motor. Cogging torque (a phenomenon similar 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 comparable permanent-magnet ac (PMAC) motors is that the windings in a BLDC motor are trapezoidally wound for trapezoidal B_{emf} waveform output.

Because their back EMF is trapezoidal, BLDC motors often use trapezoidal commutation.

In contrast, PMAC motors are sinusoidally wound and use sinusoidal commutation.



Field-oriented control directly controls the current-space vector in the ***d-q*** *or* ***direct*** *and* ***quadrature*** *rotor reference frame. Ideally that's a vector fixed in direction (also known as quadrature) relative to the rotor's magnetic poles … no matter the rotation.*

The current-space vector in the ***d-q*** *reference frame is static so the PI controls run off dc instead of sinusoidal signals. This isolates them from time-variable winding voltages and currents — which in turn avoids controller frequency-response limitations among other things.*

Ultimately, the arrangement renders the quality of current control immune to the effects of motor rpm.

(continued)

CONSIDERING BLDC MOTORS' HALL SENSORS

In trapezoidal commutation, the rotor is monitored by three Hall sensors that 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.

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:

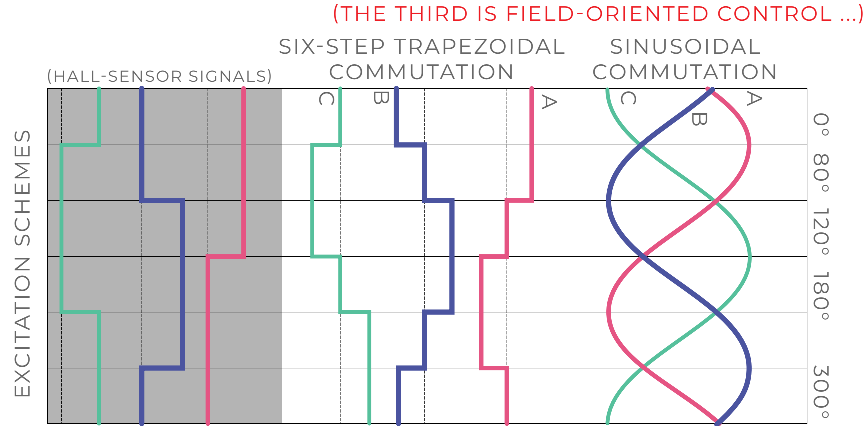
- Increase the number of windings in the stator or
- Increase the number of poles in the rotor.

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. What's more, because sinusoidal commutation is continuous, torque ripple is greatly reduced.

Another commutation method called ***field-oriented control*** or ***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.

TWO COMMON BRUSHLESS-MOTOR CONTROLS



FIELD-ORIENTED CONTROL OF BRUSHLESS MOTORS