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Brushless DC (BLDC) Motor Fundamentals

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INTRODUCTION

Brushless Direct Current (BLDC) motors are one of the motor types rapidly gaining popularity. BLDC motors are used in industries such as Appliances, Automotive, Aerospace, Consumer, Medical, Industrial Automation Equipment and Instrumentation.

As the name implies, BLDC motors do not use brushes for commutation; instead, they are electronically commutated. BLDC motors have many advantages over brushed DC motors and induction motors. A few of these are:

- Better speed versus torque characteristics
- High dynamic response
- High efficiency
- Long operating life
- Noiseless operation
- Higher speed ranges

In addition, the ratio of torque delivered to the size of the motor is higher, making it useful in applications where space and weight are critical factors.

In this application note, we will discuss in detail the construction, working principle, characteristics and typical applications of BLDC motors. Refer to **Appendix B: "Glossary"** for a glossary of terms commonly used when describing BLDC motors.

CONSTRUCTION AND OPERATING PRINCIPLE

BLDC motors are a type of synchronous motor. This means the magnetic field generated by the stator and the magnetic field generated by the rotor rotate at the same frequency. BLDC motors do not experience the "slip" that is normally seen in induction motors.

BLDC motors come in single-phase, 2-phase and 3-phase configurations. Corresponding to its type, the stator has the same number of windings. Out of these, 3-phase motors are the most popular and widely used. This application note focuses on 3-phase motors.

Stator

The stator of a BLDC motor consists of stacked steel laminations with windings placed in the slots that are axially cut along the inner periphery (as shown in Figure 3). Traditionally, the stator resembles that of an induction motor; however, the windings are distributed in a different manner. Most BLDC motors have three stator windings connected in star fashion. Each of these windings are constructed with numerous coils interconnected to form a winding. One or more coils are placed in the slots and they are interconnected to make a winding. Each of these windings are distributed over the stator periphery to form an even numbers of poles.

There are two types of stator windings variants: trapezoidal and sinusoidal motors. This differentiation is made on the basis of the interconnection of coils in the stator windings to give the different types of back Electromotive Force (EMF). Refer to the **"What is Back EMF?"** section for more information.

As their names indicate, the trapezoidal motor gives a back EMF in trapezoidal fashion and the sinusoidal motor's back EMF is sinusoidal, as shown in Figure 1 and Figure 2. In addition to the back EMF, the phase current also has trapezoidal and sinusoidal variations in the respective types of motor. This makes the torque output by a sinusoidal motor smoother than that of a trapezoidal motor. However, this comes with an extra cost, as the sinusoidal motors take extra winding interconnections because of the coils distribution on the stator periphery, thereby increasing the copper intake by the stator windings.

Depending upon the control power supply capability, the motor with the correct voltage rating of the stator can be chosen. Forty-eight volts, or less voltage rated motors are used in automotive, robotics, small arm movements and so on. Motors with 100 volts, or higher ratings, are used in appliances, automation and in industrial applications.

FIGURE 1: TRAPEZOIDAL BACK EMF

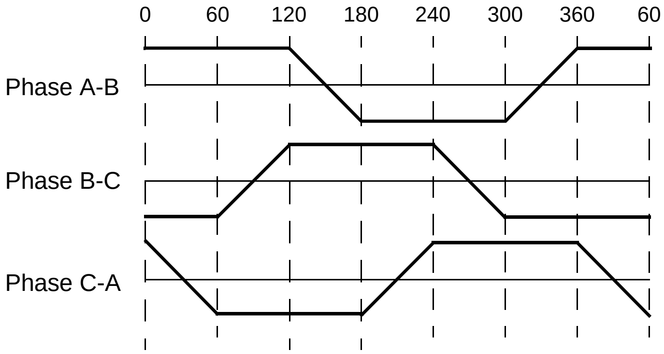


FIGURE 2: SINUSOIDAL BACK EMF

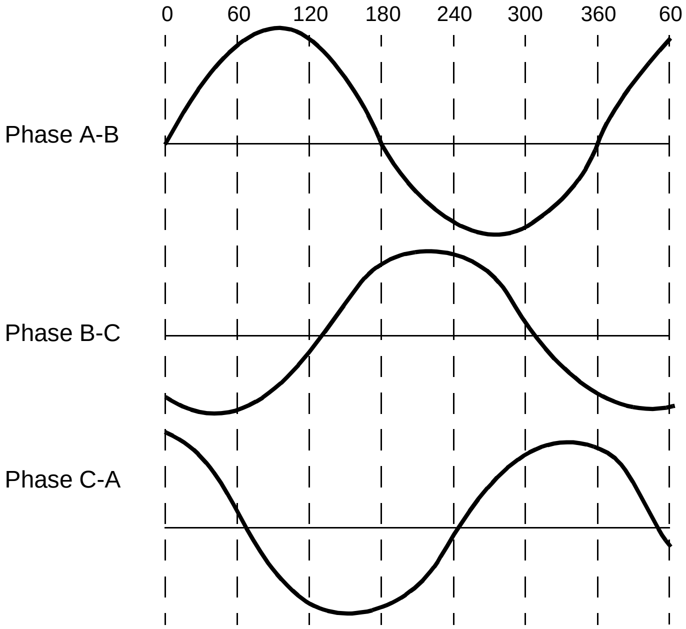
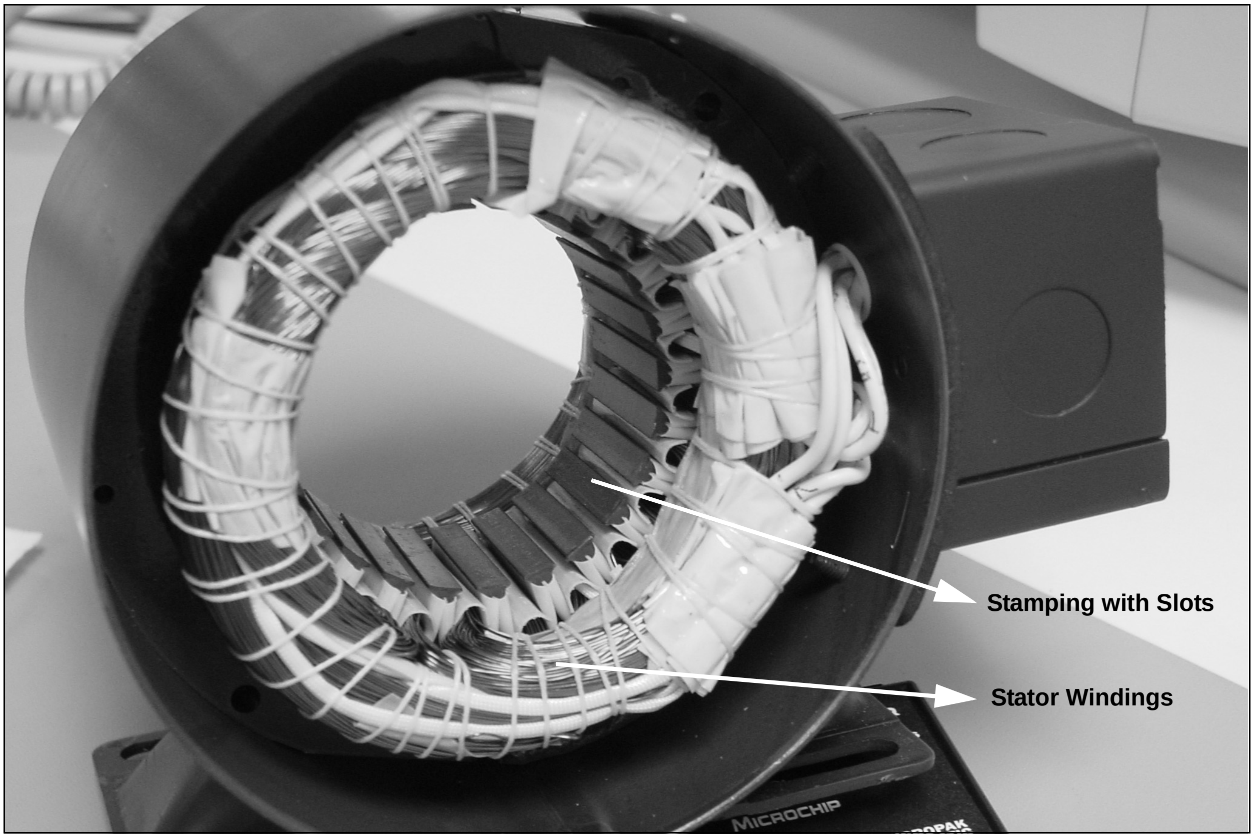


FIGURE 3: STATOR OF A BLDC MOTOR



Rotor

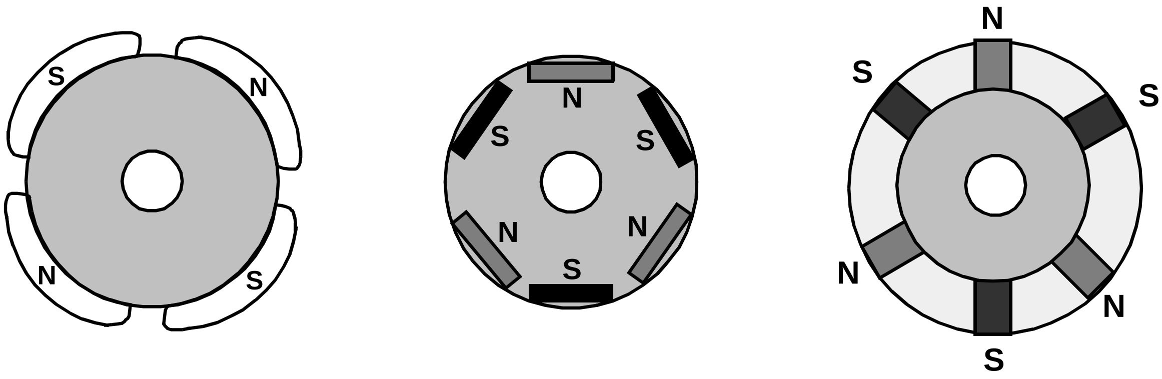
The rotor is made of permanent magnet and can vary from two to eight pole pairs with alternate North (N) and South (S) poles.

Based on the required magnetic field density in the rotor, the proper magnetic material is chosen to make the rotor. Ferrite magnets are traditionally used to make permanent magnets. As the technology advances, rare earth alloy magnets are gaining popularity. The ferrite magnets are less expensive but they have the disadvantage of low flux density for a given volume. In contrast, the alloy material has high magnetic density per volume and enables the rotor to compress further for the same torque. Also, these alloy magnets improve the size-to-weight ratio and give higher torque for the same size motor using ferrite magnets.

Neodymium (Nd), Samarium Cobalt (SmCo) and the alloy of Neodymium, Ferrite and Boron (NdFeB) are some examples of rare earth alloy magnets. Continuous research is going on to improve the flux density to compress the rotor further.

Figure 4 shows cross sections of different arrangements of magnets in a rotor.

FIGURE 4: ROTOR MAGNET CROSS SECTIONS



Circular core with magnets on the periphery

Circular core with rectangular magnets embedded in the rotor

Circular core with rectangular magnets inserted into the rotor core

Hall Sensors

Unlike a brushed DC motor, the commutation of a BLDC motor is controlled electronically. To rotate the BLDC motor, the stator windings should be energized in a sequence. It is important to know the rotor position in order to understand which winding will be energized following the energizing sequence. Rotor position is sensed using Hall effect sensors embedded into the stator.

Most BLDC motors have three Hall sensors embedded into the stator on the non-driving end of the motor.

Whenever the rotor magnetic poles pass near the Hall sensors, they give a high or low signal, indicating the N or S pole is passing near the sensors. Based on the combination of these three Hall sensor signals, the exact sequence of commutation can be determined.

Note: Hall Effect Theory: If an electric current carrying conductor is kept in a magnetic field, the magnetic field exerts a transverse force on the moving charge carriers which tends to push them to one side of the conductor. This is most evident in a thin flat conductor. A buildup of charge at the sides of the conductors will balance this magnetic influence, producing a measurable voltage between the two sides of the conductor. The presence of this measurable transverse voltage is called the Hall effect after E. H. Hall who discovered it in 1879.

FIGURE 5: BLDC MOTOR TRANSVERSE SECTION

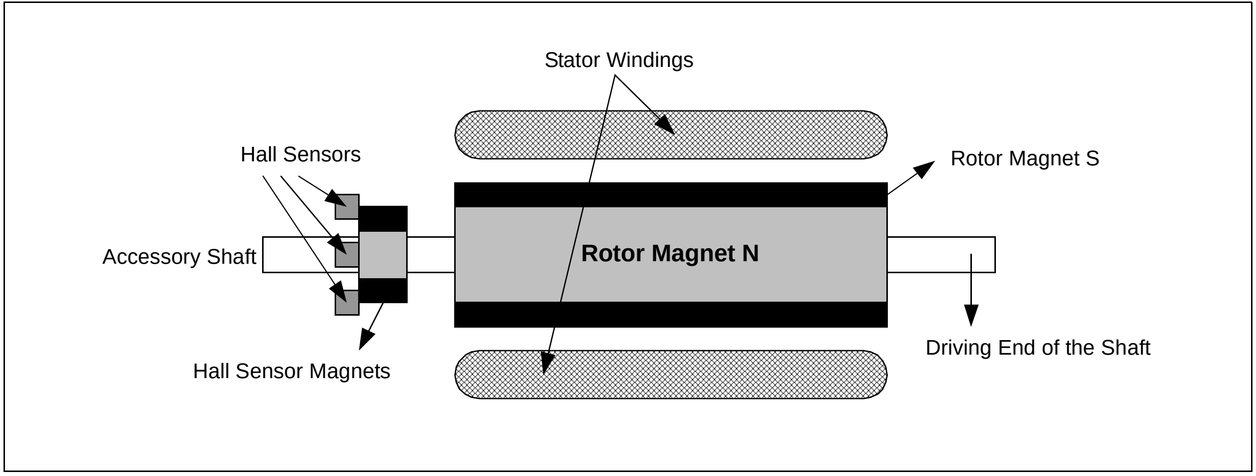


Figure 5 shows a transverse section of a BLDC motor with a rotor that has alternate N and S permanent magnets. Hall sensors are embedded into the stationary part of the motor. Embedding the Hall sensors into the stator is a complex process because any misalignment in these Hall sensors, with respect to the rotor magnets, will generate an error in determination of the rotor position. To simplify the process of mounting the Hall sensors onto the stator, some motors may have the Hall sensor magnets on the rotor, in addition to the main rotor magnets. These are a scaled down replica version of the rotor. Therefore, whenever the rotor rotates, the Hall sensor magnets give the same effect as the main magnets. The Hall sensors are normally mounted on a PC board and fixed to the enclosure cap on the non-driving end. This enables users to adjust the complete assembly of Hall sensors, to align with the rotor magnets, in order to achieve the best performance.

Based on the physical position of the Hall sensors, there are two versions of output. The Hall sensors may be at 60° or 120° phase shift to each other. Based on this, the motor manufacturer defines the commutation sequence, which should be followed when controlling the motor.

Note: The Hall sensors require a power supply. The voltage may range from 4 volts to 24 volts. Required current can range from 5 to 15 mAmps. While designing the controller, please refer to the respective motor technical specification for exact voltage and current ratings of the Hall sensors used. The Hall sensor output is normally an open-collector type. A pull-up resistor may be required on the controller side.

See the **“Commutation Sequence”** section for an example of Hall sensor signals and further details on the sequence of commutation.

Theory of Operation

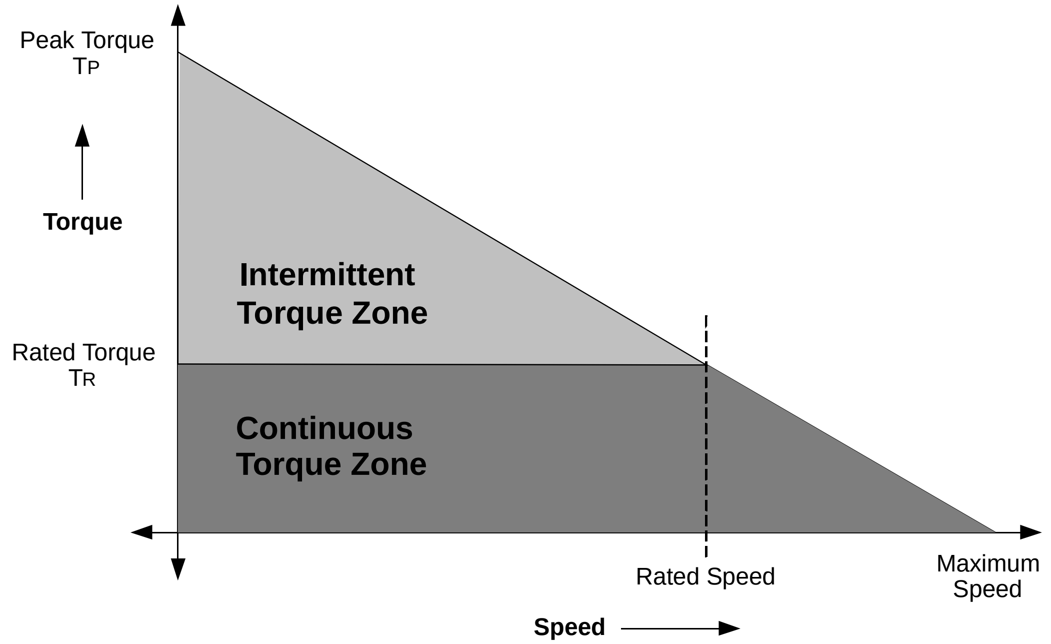
Each commutation sequence has one of the windings energized to positive power (current enters into the winding), the second winding is negative (current exits the winding) and the third is in a non-energized condition. Torque is produced because of the interaction between the magnetic field generated by the stator coils and the permanent magnets. Ideally, the peak torque occurs when these two fields are at 90° to each other and falls off as the fields move together. In order to keep the motor running, the magnetic field produced by the windings should shift position, as the rotor moves to catch up with the stator field. What is known as “Six-Step Commutation” defines the sequence of energizing the windings. See the **“Commutation Sequence”** section for detailed information and an example on six-step commutation.

TORQUE/SPEED CHARACTERISTICS

Figure 6 shows an example of torque/speed characteristics. There are two torque parameters used to define a BLDC motor, peak torque (TP) and rated torque (TR). (Refer to **Appendix A: "Typical Motor Technical Specification"** for a complete list of parameters.) During continuous operations, the motor can be loaded up to the rated torque. As discussed earlier, in a BLDC motor, the torque remains constant for a speed range up to the rated speed. The motor can be run up to the maximum speed, which can be up to 150% of the rated speed, but the torque starts dropping.

Applications that have frequent starts and stops and frequent reversals of rotation with load on the motor, demand more torque than the rated torque. This requirement comes for a brief period, especially when the motor starts from a standstill and during acceleration. During this period, extra torque is required to overcome the inertia of the load and the rotor itself. The motor can deliver a higher torque, maximum up to peak torque, as long as it follows the speed torque curve. Refer to the **"Selecting a Suitable Motor Rating for the Application"** section to understand how to select these parameters for an application.

FIGURE 6: TORQUE/SPEED CHARACTERISTICS



COMPARING BLDC MOTORS TO OTHER MOTOR TYPES

Compared to brushed DC motors and induction motors, BLDC motors have many advantages and few disadvantages. Brushless motors require less maintenance, so they have a longer life compared with brushed DC motors. BLDC motors produce more output power per frame size than brushed DC motors and induction motors. Because the rotor is made of permanent magnets, the rotor inertia is less, compared with other types of motors. This improves acceleration and deceleration characteristics, shortening operating cycles. Their linear speed/torque characteristics produce predictable speed regulation. With brushless motors, brush inspection is eliminated, making them ideal for limited access areas and applications where servicing is difficult. BLDC motors operate much more quietly than brushed DC motors, reducing Electromagnetic Interference (EMI). Low-voltage models are ideal for battery operation, portable equipment or medical applications.

Table 1 summarizes the comparison between a BLDC motor and a brushed DC motor. Table 2 compares a BLDC motor to an induction motor.

TABLE 1: COMPARING A BLDC MOTOR TO A BRUSHED DC MOTOR

Feature	BLDC Motor	Brushed DC Motor
Commutation	Electronic commutation based on Hall position sensors.	Brushed commutation.
Maintenance	Less required due to absence of brushes.	Periodic maintenance is required.
Life	Longer.	Shorter.
Speed/Torque Characteristics	Flat – Enables operation at all speeds with rated load.	Moderately flat – At higher speeds, brush friction increases, thus reducing useful torque.
Efficiency	High – No voltage drop across brushes.	Moderate.
Output Power/ Frame Size	High – Reduced size due to superior thermal characteristics. Because BLDC has the windings on the stator, which is connected to the case, the heat dissipation is better.	Moderate/Low – The heat produced by the armature is dissipated in the air gap, thus increasing the temperature in the air gap and limiting specs on the output power/frame size.
Rotor Inertia	Low, because it has permanent magnets on the rotor. This improves the dynamic response.	Higher rotor inertia which limits the dynamic characteristics.
Speed Range	Higher – No mechanical limitation imposed by brushes/commutator.	Lower – Mechanical limitations by the brushes.
Electric Noise Generation	Low.	Arcs in the brushes will generate noise causing EMI in the equipment nearby.
Cost of Building	Higher – Since it has permanent magnets, building costs are higher.	Low.
Control	Complex and expensive.	Simple and inexpensive.
Control Requirements	A controller is always required to keep the motor running. The same controller can be used for variable speed control.	No controller is required for fixed speed; a controller is required only if variable speed is desired.

TABLE 2: COMPARING A BLDC MOTOR TO AN INDUCTION MOTOR

Features	BLDC Motors	AC Induction Motors
Speed/Torque Characteristics	Flat – Enables operation at all speeds with rated load.	Nonlinear – Lower torque at lower speeds.
Output Power/ Frame Size	High – Since it has permanent magnets on the rotor, smaller size can be achieved for a given output power.	Moderate – Since both stator and rotor have windings, the output power to size is lower than BLDC.
Rotor Inertia	Low – Better dynamic characteristics.	High – Poor dynamic characteristics.
Starting Current	Rated – No special starter circuit required.	Approximately up to seven times of rated – Starter circuit rating should be carefully selected. Normally uses a Star-Delta starter.
Control Requirements	A controller is always required to keep the motor running. The same controller can be used for variable speed control.	No controller is required for fixed speed; a controller is required only if variable speed is desired.
Slip	No slip is experienced between stator and rotor frequencies.	The rotor runs at a lower frequency than stator by slip frequency and slip increases with load on the motor.

COMMUTATION SEQUENCE

Figure 7 shows an example of Hall sensor signals with respect to back EMF and the phase current. Figure 8 shows the switching sequence that should be followed with respect to the Hall sensors. The sequence numbers on Figure 7 correspond to the numbers given in Figure 8.

Every 60 electrical degrees of rotation, one of the Hall sensors changes the state. Given this, it takes six steps to complete an electrical cycle. In synchronous, with every 60 electrical degrees, the phase current switching should be updated. However, one electrical cycle may not correspond to a complete mechanical revolution of the rotor. The number of electrical cycles to be repeated to complete a mechanical rotation is determined by the rotor pole pairs. For each rotor pole pairs, one electrical cycle is completed. So, the number of electrical cycles/rotations equals the rotor pole pairs.

Figure 9 shows a block diagram of the controller used to control a BLDC motor. Q0 to Q5 are the power switches controlled by the PIC18FXX31 microcontroller. Based on the motor voltage and current ratings, these switches can be MOSFETs, or IGBTs, or simple bipolar transistors.

Table 3 and Table 4 show the sequence in which these power switches should be switched based on the Hall sensor inputs, A, B and C. Table 3 is for clockwise rotation of the motor and Table 4 is for counter clockwise motor rotation. This is an example of Hall sensor signals having a 60 degree phase shift with respect to each other. As we have previously discussed in the **“Hall Sensors”** section, the Hall sensors may be at 60° or 120° phase shift to each other. When deriving a controller for a particular motor, the sequence defined by the motor manufacturer should be followed.

Referring to Figure 9, if the signals marked by PWMx are switched ON or OFF according to the sequence, the motor will run at the rated speed. This is assuming that the DC bus voltage is equal to the motor rated voltage, plus any losses across the switches. To vary the speed, these signals should be Pulse Width Modulated (PWM) at a much higher frequency than the motor frequency. As a rule of thumb, the PWM frequency should be at least 10 times that of the maximum frequency of the motor. When the duty cycle of PWM is varied within the sequences, the average voltage supplied to the stator reduces, thus reducing the speed. Another advantage of having PWM is that, if the DC bus voltage is much higher than the motor rated voltage, the motor can be controlled by limiting the percentage of PWM duty cycle corresponding to that of the motor rated voltage. This adds flexibility to the controller to hook up motors with different rated voltages and match the average voltage output by the controller, to the motor rated voltage, by controlling the PWM duty cycle.

There are different approaches of controls. If the PWM signals are limited in the microcontroller, the upper switches can be turned on for the entire time during the corresponding sequence and the corresponding lower switch can be controlled by the required duty cycle on PWM.

The potentiometer, connected to the analog-to-digital converter channel in Figure 9, is for setting a speed reference. Based on this input voltage, the PWM duty cycle should be calculated.

Closed-Loop Control

The speed can be controlled in a closed loop by measuring the actual speed of the motor. The error in the set speed and actual speed is calculated. A Proportional plus Integral plus Derivative (P.I.D.) controller can be used to amplify the speed error and dynamically adjust the PWM duty cycle.

For low-cost, low-resolution speed requirements, the Hall signals can be used to measure the speed feedback. A timer from the PIC18FXX31 can be used to count between two Hall transitions. With this count, the actual speed of the motor can be calculated.

For high-resolution speed measurements, an optical encoder can be fitted onto the motor, which gives two signals with 90 degrees phase difference. Using these signals, both speed and direction of rotation can be determined. Also, most of the encoders give a third index signal, which is one pulse per revolution. This can be used for positioning applications. Optical encoders are available with different choices of Pulse Per Revolution (PPR), ranging from hundreds to thousands.

FIGURE 7: HALL SENSOR SIGNAL, BACK EMF, OUTPUT TORQUE AND PHASE CURRENT

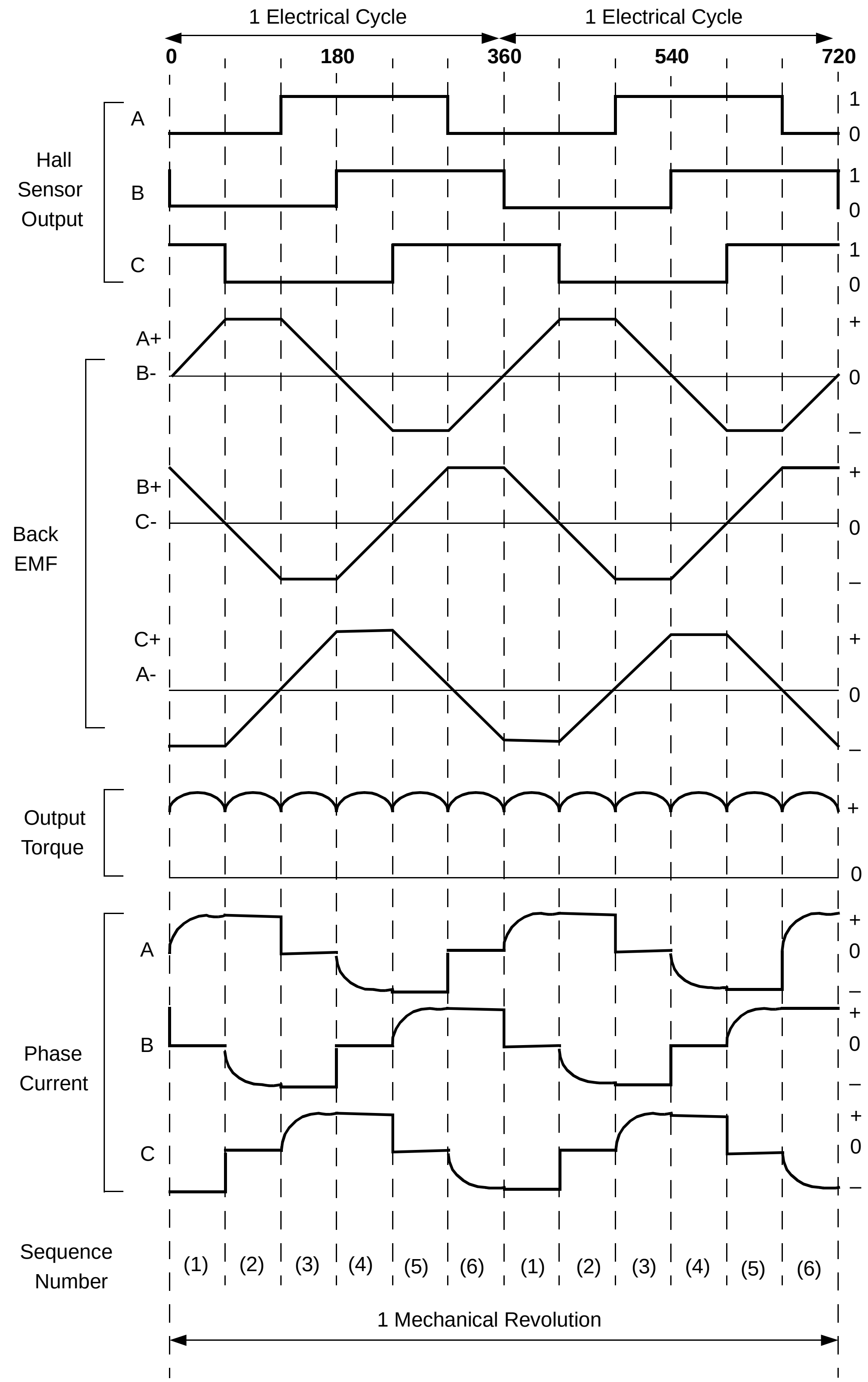


FIGURE 8: WINDING ENERGIZING SEQUENCE WITH RESPECT TO THE HALL SENSOR

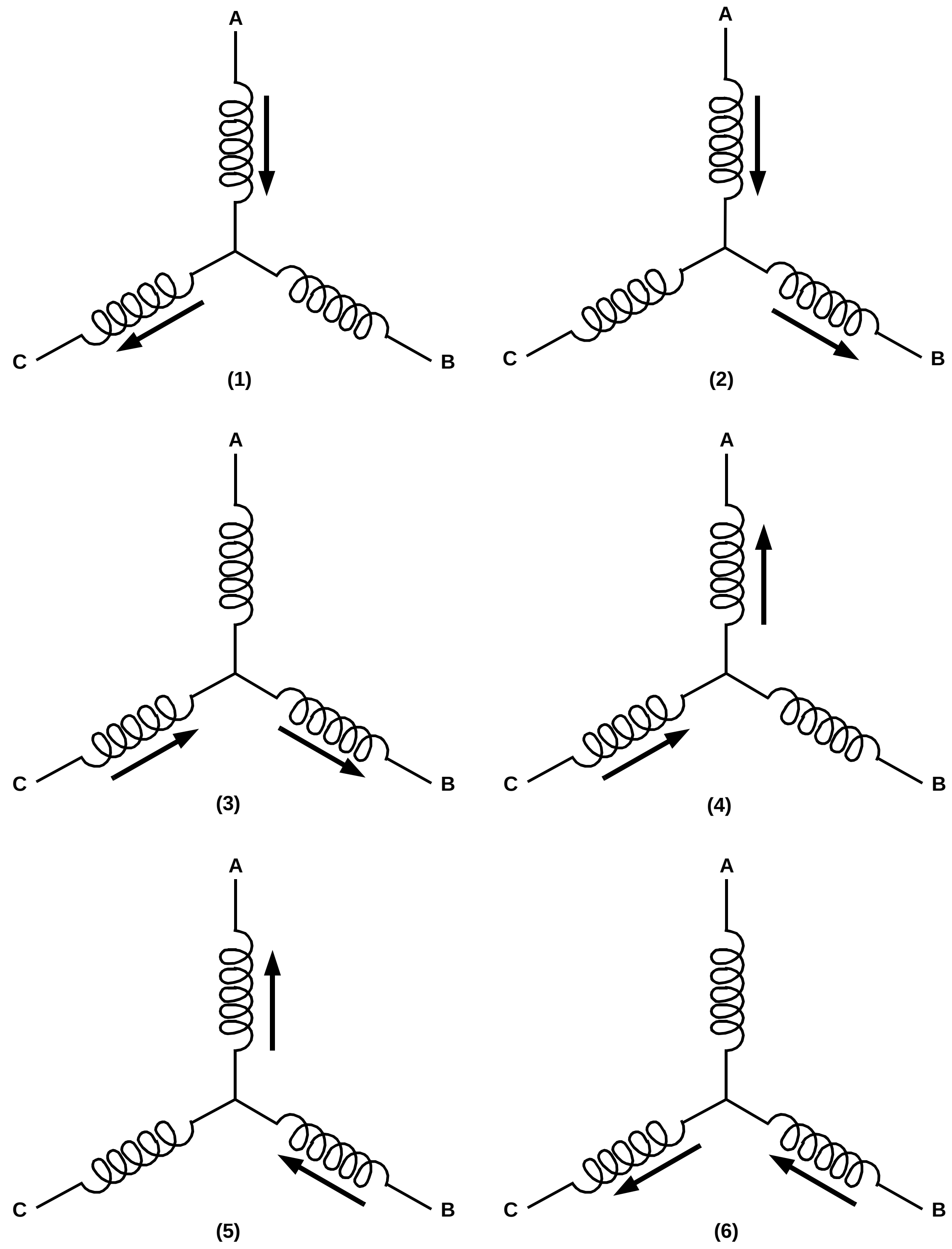


FIGURE 9: CONTROL BLOCK DIAGRAM

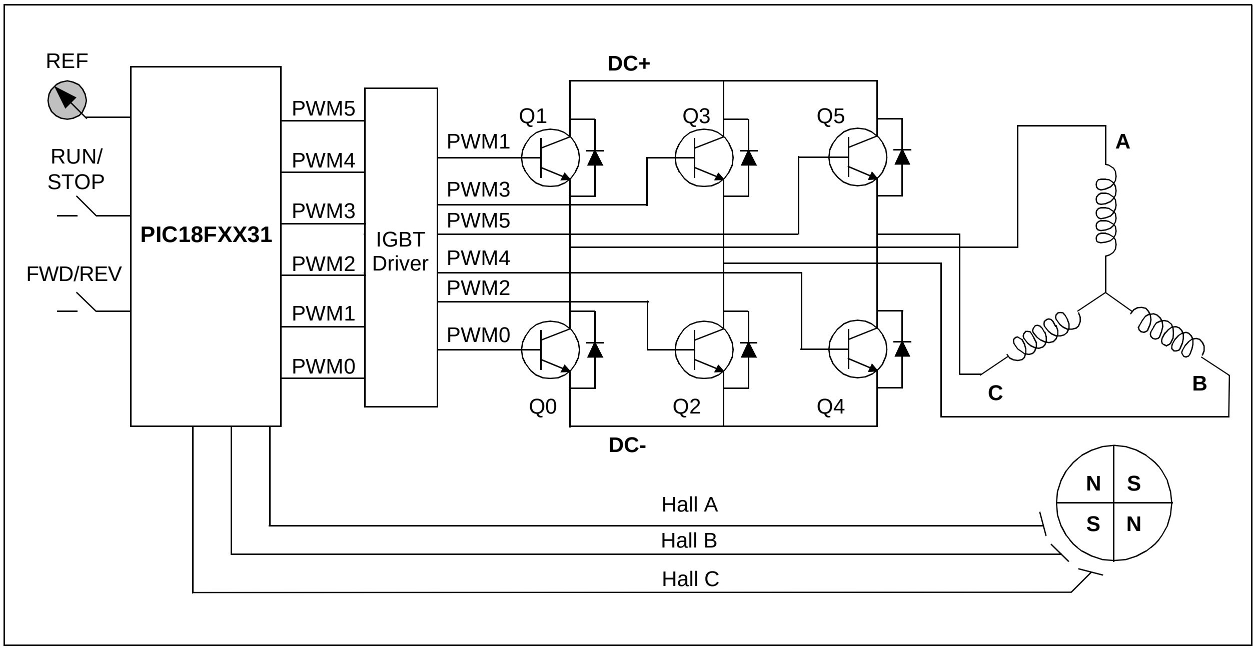


TABLE 3: SEQUENCE FOR ROTATING THE MOTOR IN CLOCKWISE DIRECTION WHEN VIEWED FROM NON-DRIVING END

Sequence #	Hall Sensor Input			Active PWMs		Phase Current		
	A	B	C			A	B	C
1	0	0	1	PWM1(Q1)	PWM4(Q4)	DC+	Off	DC-
2	0	0	0	PWM1(Q1)	PWM2(Q2)	DC+	DC-	Off
3	1	0	0	PWM5(Q5)	PWM2(Q2)	Off	DC-	DC+
4	1	1	0	PWM5(Q5)	PWM0(Q0)	DC-	Off	DC+
5	1	1	1	PWM3(Q3)	PWM0(Q0)	DC-	DC+	Off
6	0	1	1	PWM3(Q3)	PWM4(Q4)	Off	DC+	DC-

TABLE 4: SEQUENCE FOR ROTATING THE MOTOR IN COUNTER-CLOCKWISE DIRECTION WHEN VIEWED FROM NON-DRIVING END

Sequence #	Hall Sensor Input			Active PWMs		Phase Current		
	A	B	C			A	B	C
1	0	1	1	PWM5(Q5)	PWM2(Q2)	Off	DC-	DC+
2	1	1	1	PWM1(Q1)	PWM2(Q2)	DC+	DC-	Off
3	1	1	0	PWM1(Q1)	PWM4(Q4)	DC+	Off	DC-
4	1	0	0	PWM3(Q3)	PWM4(Q4)	Off	DC+	DC-
5	0	0	0	PWM3(Q3)	PWM0(Q0)	DC-	DC+	Off
6	0	0	1	PWM5(Q5)	PWM0(Q0)	DC-	Off	DC+

WHAT IS BACK EMF?

When a BLDC motor rotates, each winding generates a voltage known as back Electromotive Force or back EMF, which opposes the main voltage supplied to the windings according to Lenz's Law. The polarity of this back EMF is in opposite direction of the energized voltage. Back EMF depends mainly on three factors:

- Angular velocity of the rotor
- Magnetic field generated by rotor magnets
- The number of turns in the stator windings

EQUATION 1:

$$\text{Back EMF} = (E) \propto N l r B \omega$$

where:

N is the number of winding turns per phase,
l is the length of the rotor,
r is the internal radius of the rotor,
B is the rotor magnetic field density and
ω is the motor's angular velocity

Once the motor is designed, the rotor magnetic field and the number of turns in the stator windings remain constant. The only factor that governs back EMF is the angular velocity or speed of the rotor and as the speed increases, back EMF also increases. The motor technical specification gives a parameter called, back EMF constant (refer to **Appendix A: "Typical Motor Technical Specification"**), that can be used to estimate back EMF for a given speed.

The potential difference across a winding can be calculated by subtracting the back EMF value from the supply voltage. The motors are designed with a back EMF constant in such a way that when the motor is running at the rated speed, the potential difference between the back EMF and the supply voltage will be sufficient for the motor to draw the rated current and deliver the rated torque. If the motor is driven beyond the rated speed, back EMF may increase substantially, thus decreasing the potential difference across the winding, reducing the current drawn which results in a drooping torque curve. The last point on the speed curve would be when the supply voltage is equal to the sum of the back EMF and the losses in the motor, where the current and torque are equal to zero.

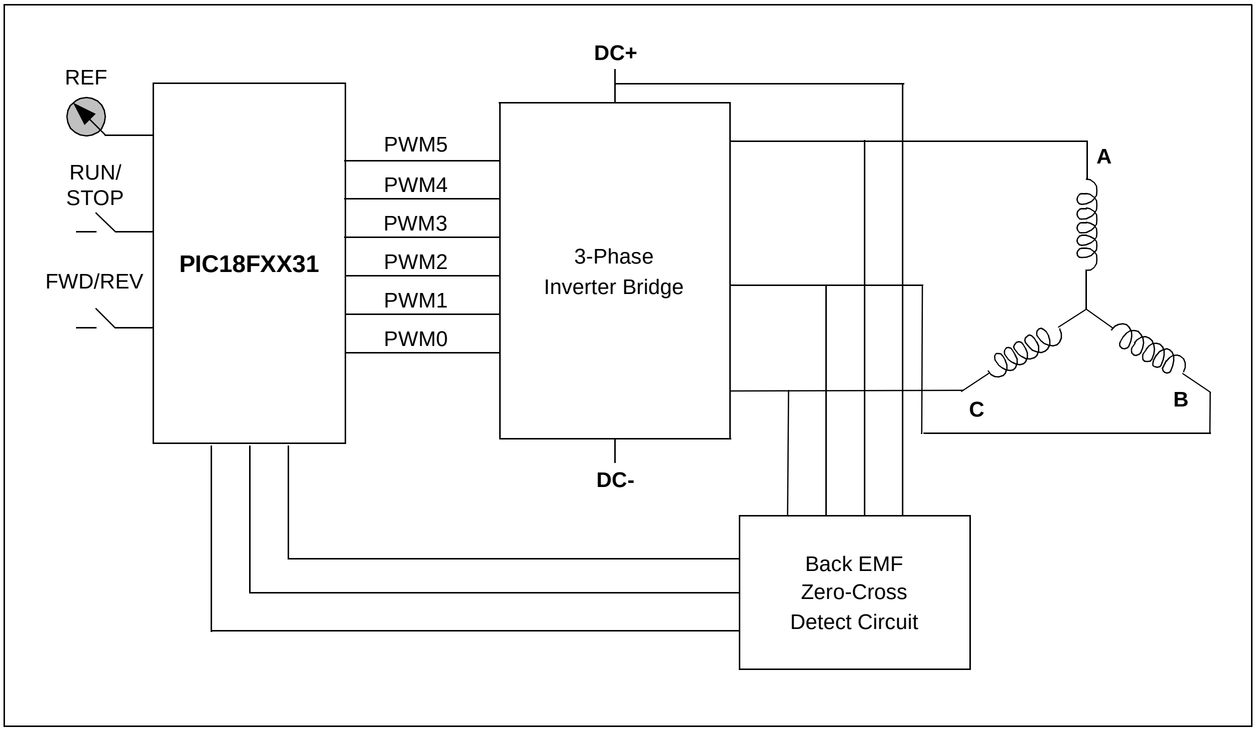
Sensorless Control of BLDC Motors

Until now we have seen commutation based on the rotor position given by the Hall sensor. BLDC motors can be commutated by monitoring the back EMF signals instead of the Hall sensors. The relationship between the Hall sensors and back EMF, with respect to the phase voltage, is shown in Figure 7. As we have seen in earlier sections, every commutation sequence has one of the windings energized positive, the second negative and the third left open. As shown in Figure 7, the Hall sensor signal changes the state when the voltage polarity of back EMF crosses from a positive to negative or from negative to positive. In ideal cases, this happens on zero-crossing of back EMF, but practically, there will be a delay due to the winding characteristics. This delay should be compensated by the microcontroller. Figure 10 shows a block diagram for sensorless control of a BLDC motor.

Another aspect to be considered is very low speeds. Because back EMF is proportional to the speed of rotation, at a very low speed, the back EMF would be at a very low amplitude to detect zero-crossing. The motor has to be started in open loop, from standstill and when sufficient back EMF is built to detect the zero-cross point, the control should be shifted to the back EMF sensing. The minimum speed at which back EMF can be sensed is calculated from the back EMF constant of the motor.

With this method of commutation, the Hall sensors can be eliminated and in some motors, the magnets for Hall sensors also can be eliminated. This simplifies the motor construction and reduces the cost as well. This is advantageous if the motor is operating in dusty or oily environments, where occasional cleaning is required in order for the Hall sensors to sense properly. The same thing applies if the motor is mounted in a less accessible location.

FIGURE 10: BLOCK DIAGRAM OF SENSORLESS CONTROL



SELECTING A SUITABLE MOTOR RATING FOR THE APPLICATION

Selecting the right type of motor for the given application is very important. Based on the load characteristics, the motor must be selected with the proper rating. Three parameters govern the motor selection for the given application. They are:

- Peak torque required for the application
- RMS torque required
- The operating speed range

Peak Torque (T_P) Requirement

The peak, or maximum torque required for the application, can be calculated by summing the load torque (T_L), torque due to inertia (T_J) and the torque required to overcome the friction (T_F).

There are other factors which will contribute to the overall peak torque requirements. For example, the windage loss which is contributed by the resistance offered by the air in the air gap. These factors are complicated to account for. Therefore, a 20% safety margin is given as a rule of thumb when calculating the torque.

EQUATION 2:

$$\therefore T_P = (T_L + T_J + T_F) * 1.2$$

The torque due to inertia (T_J) is the torque required to accelerate the load from standstill or from a lower speed to a higher speed. This can be calculated by taking the product of load inertia, including the rotor inertia and load acceleration.

EQUATION 3:

$$T_J = J_{L+M} * \alpha$$

where:

J_{L+M} is the sum of the load and rotor inertia and

α is the required acceleration

The mechanical system coupled to the motor shaft determines the load torque and the frictional torque.

RMS Torque Requirement (T_{RMS})

The Root Mean Square (RMS) torque can be roughly translated to the average continuous torque required for the application. This depends upon many factors. The peak torque (T_P), load torque (T_L), torque due to inertia (T_J), frictional torque (T_F) and acceleration, deceleration and run times.

The following equation gives the RMS torque required for a typical application where T_A is the acceleration time, T_R is the run time and T_D is the deceleration time.

EQUATION 4:

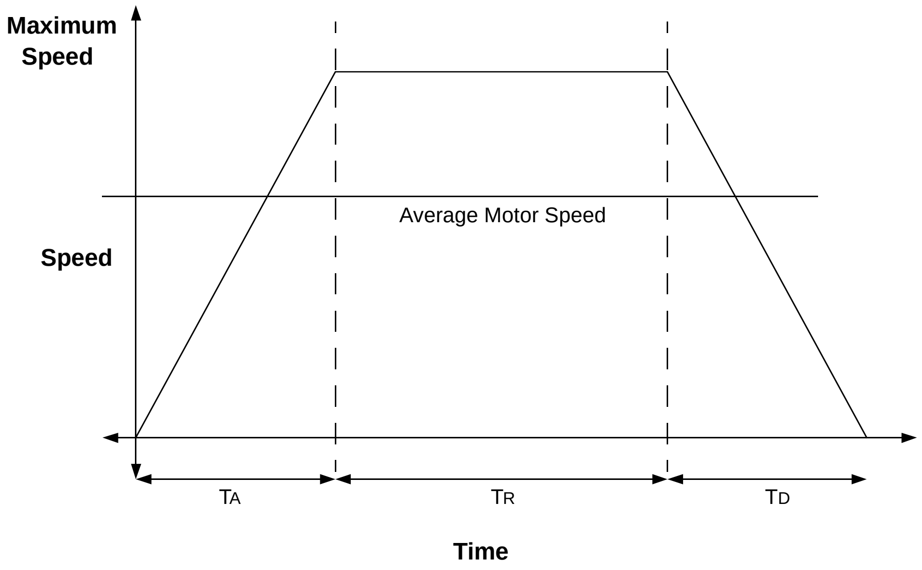
$$T_{RMS} = \sqrt{} [\{T_P^2 T_A + (T_L + T_F)^2 T_R + (T_J - T_L - T_F)^2 T_D\}/(T_A + T_R + T_D)]$$

Speed Range

This is the motor speed required to drive the application and is determined by the type of application. For example, an application like a blower where the speed variation is not very frequent and the maximum speed of the blower can be the average motor speed required. Whereas in the case of a point-to-point positioning system, like in a high-precision conveyer belt movement or robotic arm movements, this would require a motor with a rated operating speed higher than the average movement speed. The higher operating speed can be accounted for the components of the trapezoidal speed curve, resulting in an average speed equal to the movement speed. The trapezoidal curve is shown in Figure 11.

It is always suggested to allow a safety margin of 10%, as a rule of thumb, to account for miscellaneous factors which are beyond our calculations.

FIGURE 11: TRAPEZOIDAL SPEED CURVE



TYPICAL BLDC MOTOR APPLICATIONS

BLDC motors find applications in every segment of the market. Automotive, appliance, industrial controls, automation, aviation and so on, have applications for BLDC motors. Out of these, we can categorize the type of BLDC motor control into three major types:

- Constant load
- Varying loads
- Positioning applications

Applications With Constant Loads

These are the types of applications where a variable speed is more important than keeping the accuracy of the speed at a set speed. In addition, the acceleration and deceleration rates are not dynamically changing. In these types of applications, the load is directly coupled to the motor shaft. For example, fans, pumps and blowers come under these types of applications. These applications demand low-cost controllers, mostly operating in open-loop.

Applications With Varying Loads

These are the types of applications where the load on the motor varies over a speed range. These applications may demand a high-speed control accuracy and good dynamic responses. In home appliances, washers, dryers and compressors are good examples. In automotive, fuel pump control, electronic steering control, engine control and electric vehicle control are good examples of these. In aerospace, there are a number of applications, like centrifuges, pumps, robotic arm controls, gyroscope controls and so on. These applications may use speed feedback devices and may run in semi-closed loop or in total closed loop. These applications use advanced control algorithms, thus complicating the controller. Also, this increases the price of the complete system.

Positioning Applications

Most of the industrial and automation types of application come under this category. The applications in this category have some kind of power transmission, which could be mechanical gears or timer belts, or a simple belt driven system. In these applications, the dynamic response of speed and torque are important. Also, these applications may have frequent reversal of rotation direction. A typical cycle will have an accelerating phase, a constant speed phase and a deceleration and positioning phase, as shown in Figure 11. The load on the motor may vary during all of these phases, causing the controller to be complex. These systems mostly operate in closed loop. There could be three control loops functioning simultaneously: Torque Control Loop, Speed Control Loop and Position Control Loop. Optical encoder or synchronous resolvers are used for measuring the actual speed of the motor. In some cases, the same sensors are used to get relative position information. Otherwise, separate position sensors may be used to get absolute positions. Computer Numeric Controlled (CNC) machines are a good example of this. Process controls, machinery controls and conveyer controls have plenty of applications in this category.

SUMMARY

In conclusion, BLDC motors have advantages over brushed DC motors and induction motors. They have better speed versus torque characteristics, high dynamic response, high efficiency, long operating life, noiseless operation, higher speed ranges, rugged construction and so on. Also, torque delivered to the motor size is higher, making it useful in applications where space and weight are critical factors. With these advantages, BLDC motors find wide spread applications in automotive, appliance, aerospace, consumer, medical, instrumentation and automation industries.

APPENDIX A: TYPICAL MOTOR TECHNICAL SPECIFICATION

The following table shows a few of the parameters that can be found in the technical specification of a motor and explains how each parameter is useful to the application. In addition, a physical name plate can usually be found on a motor that lists many of the same parameters.

TABLE A-1: TYPICAL MOTOR TECHNICAL SPECIFICATION PARAMETERS

Electrical Parameter	Typical Symbol	Unit	Definition
Reference Voltage	V	Volts	This is the rated terminal voltage.
Rated Current	Ir	Amps	Current drawn by the motor when it delivers the rated torque.
Peak Current (stall)	Ipk	Amps	This is the maximum current allowed to be drawn by the motor.
No Load Current	I_{NL}	Amps	Current drawn by the motor when there is no load on the motor shaft.
Back EMF Constant	K_E	V/RPM or V/rad/s	Using this parameter, back EMF can be estimated for a given speed.
Resistance	R	Ohms	Resistance of each stator winding.
Inductance	L	mH	Winding inductance. This, along with resistance, can be used to determine the total impedance of the winding to calculate the electrical time constant of the motor.
Motor Constant	K_M	Oz-in/√W or NM//√W	This gives the ratio of torque to the power.
Electrical Time Constant	τE	ms	Calculated based on the R and L of the windings.

Mechanical Parameter	Typical Symbol	Unit	Definition
Speed	N	RPM or rad/s	Rated speed of the motor.
Continuous Torque	T_C	Oz-in or N-M	This is the torque available on the shaft for the given speed range.
Peak Torque or Stall Torque	Tpk	Oz-in or N-M	This is the maximum torque that motor can deliver for a short duration of time. This torque may not be available for all the speed ranges.
Torque Constant	Kt	Oz-in/A or N-M/A	This is the torque produced for every ampere of current drawn by the motor. Since the torque varies linear with current, this parameter can be used to interpolate the torque delivered for a given current and vice versa.
Friction Torque	T_F	Oz-in or N-M	This is the torque loss due to friction which includes mainly the bearing friction.
Rotor Inertia	J_M	Oz-in-s^2/N-M-s^2	Rotor moment of inertia. This is useful to determine the acceleration and deceleration rates, the dynamic response of the system and to calculate the mechanical time constant of the rotor.
Viscous Damping	D	Oz-in/RPM or N-M-s	
Damping Constant	K_D	Oz-in/RPM or N-M-s	
Temperature	T	°F or °C	Operating ambient temperature.
Maximum Winding Temperature	θmax	°F or °C	Maximum allowed winding temperature. If the winding temperature exceeds this limit, winding leakage current may increase or there are chances of winding breakdown.
Thermal Impedance	R_{TH}	°F/W or °C/W	This is the thermal impedance posed by the motor to the ambient.
Thermal Time Constant	τTH	min	Time constant based on the thermal impedance. A motor with a heat sink will have a higher time constant than a motor without a heat sink.

APPENDIX B: GLOSSARY

Air Gap

Uniform gap between the stator and rotor.

Angular Velocity

Velocity in radians (2π x frequency).

Asynchronous Motor

Type of motor in which the flux, generated by the stator and rotor, have different frequencies.

EMF

Electromotive Force. The potential generated by a current carrying conductor when it is exposed to magnetic field. EMF is measured in volts.

IGBT

Insulated Gate Bipolar Transistor.

Lenz's Law

The Electromotive Force (EMF), induced in a conductor moving perpendicular to a magnetic field, tends to oppose that motion.

MOSFET

Metal Oxide Silicon Field Effect Transistor.

Rated Speed

Speed specified on the name plate of a motor.

Rotor

Rotating part of the motor.

Slip Speed

Defined by the corresponding frequency difference between the stator and rotor magnetic fields (applies only to induction motors).

Stator

Stationary part of the motor.

Synchronous Motor

Type of motor in which the flux generated by the stator and rotor have the same frequencies. The phase may be shifted.

Synchronous Speed

Speed of the motor corresponding to the rated frequency.

Torque

Rotating force in Newton-Meters or Pound-Inches.

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