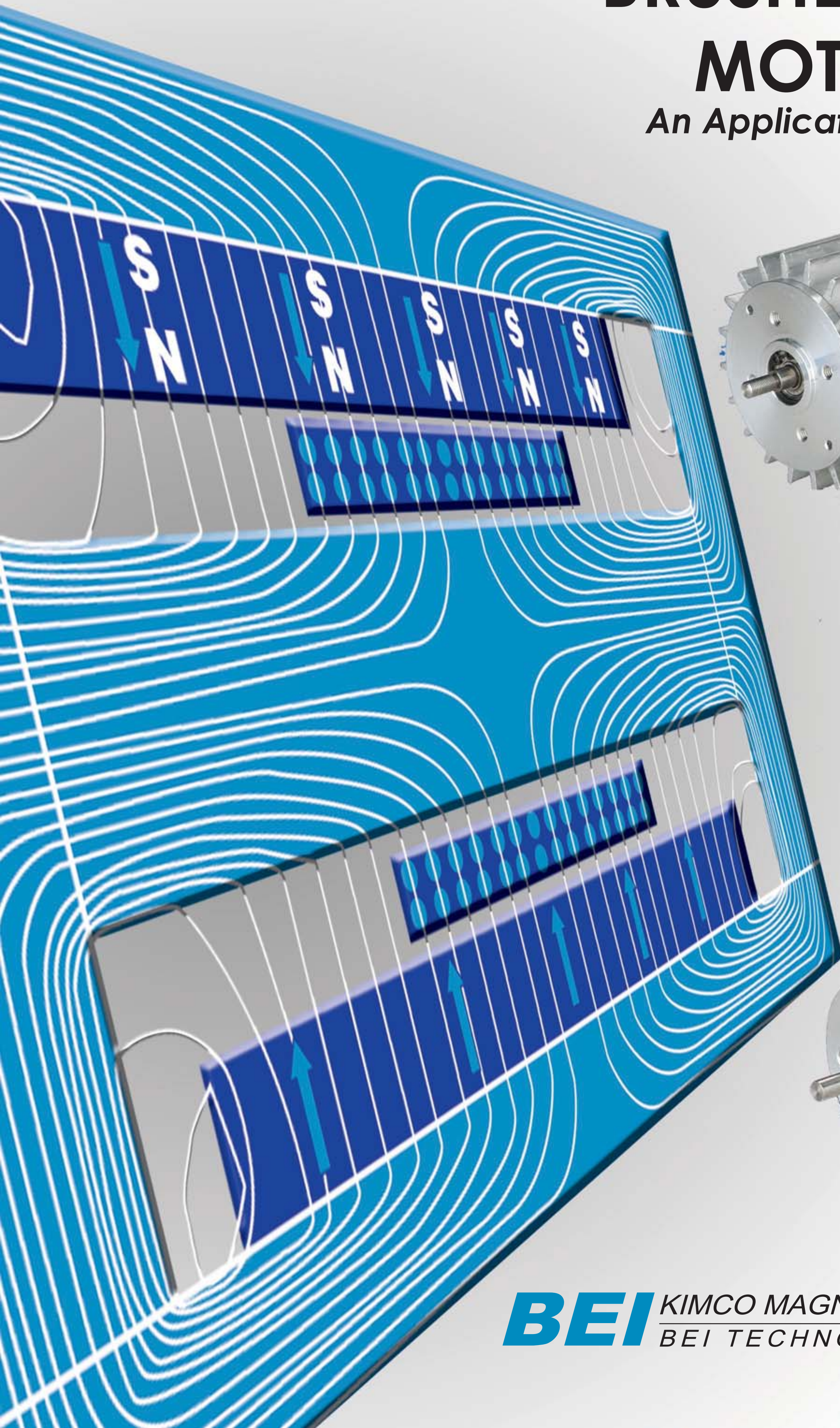
BRUSHLESS DC MOTORS

An Applications Guide



BEI KIMCO MAGNETICS DIVISION
BEI TECHNOLOGIES, INC.

BEI TECHNOLOGIES, INC.

BEI Technologies, Inc. is an internationally recognized leader of specialty products for producing, sensing and controlling motion in high accuracy machinery. Our particular specialties are brushless motors and voice coil actuators, control electronics, and position and speed recording encoders, which individually and together provide vital links between microcomputer logic and precision mechanisms.

Consider computer-age products such as computer-assisted respiratory equipment, medical devices, memory storage, printers, robot arms, CNC machines, computer controlled factories, CAD/CAM plotters, office automation machines, space satellite sensors, and optical scanners. All rely on BEI products to improve their performance, value, and market acceptance.

This guide is a tutorial on brushless motors designed and manufactured at BEI's Kimco Magnetics Division. Kimco Magnetics specializes in fractional and sub-fractional horsepower brushless motors and related electronics, as well as in linear and rotary actuators and specialty magnetics. Tutorial information pertaining to the actuators and specialty magnetics may be found in the "Actuator Applications Guide".

For further information on the products described in this Applications Guide contact:

Kimco Magnetics Division
BEI TECHNOLOGIES, INC.
804-A Rancheros Drive, San Marcos, CA 92069
Toll Free: (800) 572-7560 • Tel: (760) 744-5671
Fax: (760) 744-0425 • Internet: www.beikimco.com
E-Mail: sales@beikimco.com

BRUSHLESS DC MOTORS

MAGNETICS

A brushless motor is a hybrid permanent magnet DC motor. Figure 1 is a simplified illustration of how torque is generated in a permanent magnet DC motor:

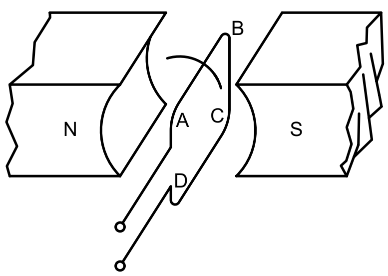


FIGURE 1

If current is caused to flow in the armature conductors, torque is produced. There is an application of a law of physics which is expressed as:

$$F = KBli, \qquad \textbf{(1)}$$

Where:
- F = force
- K = a constant
- B = air gap flux density
- l = length of conductor
- i = current in a conductor.

If more than one conductor is carrying the same current (multiple turns per coil), then

$$F = KBliz, \qquad \textbf{(2)}$$

where z = number of conductors in series. In a motor the conductors rotate about a central shaft (see Figure 1). Then torque, T, = FR, where R = radius at the air gap. So,

$$T = KRBliz \qquad \textbf{(3)}$$

Figure 1 shows the coil in the zero torque position. The maximum torque position is 90 electrical degrees from the position shown. As the conductors rotate from the maximum torque position, torque drops off in a sinusoidal fashion and becomes zero when the coil has moved 90 degrees.

A brush type motor has more than one coil. Each coil is angularly displaced from one another so that when the torque from one coil has dropped off, current is automatically switched to another coil which is properly located to produce maximum torque. The switching is accomplished mechanically with brushes and a commutator as shown in Figure 2.

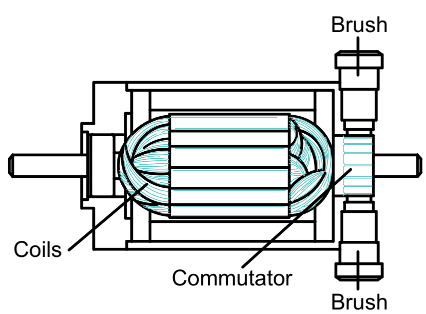


FIGURE 2

In a *brushless* motor, the position of the coils (phases), with respect to the permanent magnet field, is sensed electronically and the current is switched, or *commutated*, to the appropriate phases. The commutation is effected by means of transistor switches. A brush type motor may be converted into a brushless motor by bringing out all the leads that are attached to the mechanical commutator and providing switches for each lead; however, this approach would involve a large number of switches. Instead, a polyphase winding similar to that used in AC motors is utilized. In this design, the phases are "commutated" as a function of shaft position.

Two, three and four phase motor designs are common. BEI Technologies, Inc. provides 3 phase designs. This configuration optimizes performance even though it requires more electronic components. Three types of 3 phase windings are available: delta bi-polar, wye bi-polar, and wye uni-polar. These three winding configurations and their transistor orientation are shown in Figure 3.

3 PHASE, BI-POLAR COMMUTATION

Figure 4 illustrates the sequential steps in the commutation of a 3 phase, bi-polar system. Closing transistors (1) and (4) will enable current to flow through phase A and B. The permanent magnet rotor will then align itself in a zero torque, preferred position. If (1) is opened and (5) closed, current will flow through phases B and C, and the rotor will move 120 electrical degrees. Similarly, opening (4) and closing (2) will cause the rotor to move another 120 electrical degrees. (Note that the current through phase A is now flowing in the direction opposite the one at the start of this exercise.)

Obviously, there must be some logic in the order and rate the transistors are switched. Hall Effect sensors are typically used in the logic scheme. Graph 1 may help illustrate how this works. For instance, if one were to energize

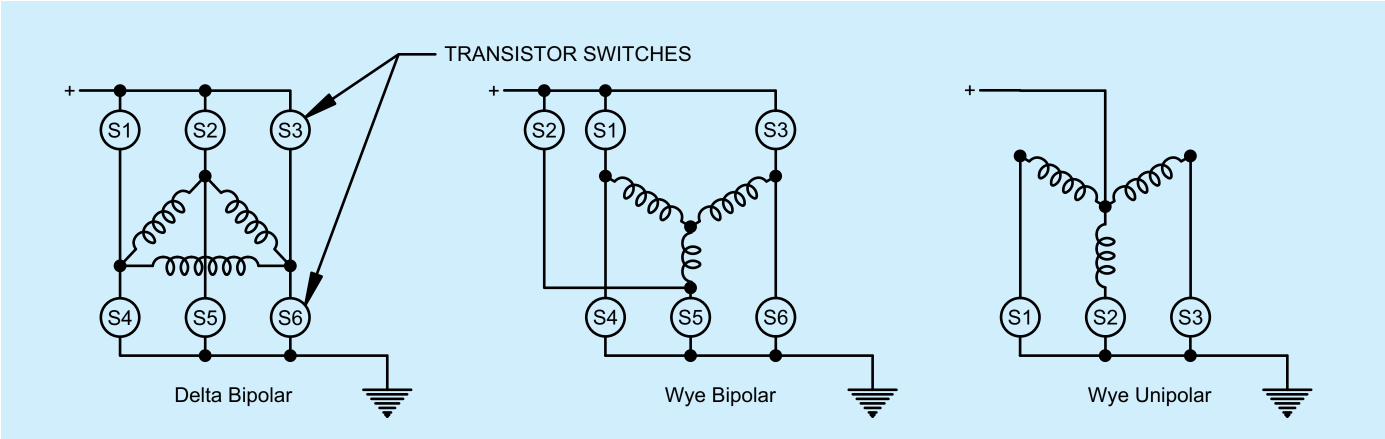
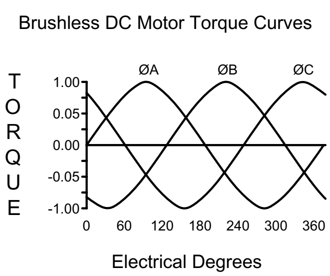


FIGURE 3

individual phases of a three phase brushless motor one would generate, as a function of electrical degrees of rotation, a torque curve as shown in Graph 1. Each phase would be 120 electrical degrees apart. (It should be noted that electrical degrees is simply mechanical degrees multiplied by the number of pole pairs of the motor.)



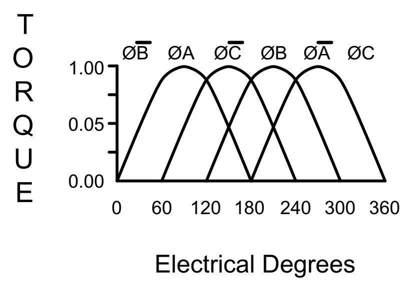
GRAPH 1

Now, imagine the rotor in Figure 4 resting in its zero torque position (i.e., the 180 electrical degree point on Graph 1), with current flowing through winding A. If the rotor is physically moved back from its rest position, torque will build up roughly sinusoidally and become peak at 90 electrical degrees. Since the objective is to have the motor run at its peak operating point, the position still another 30 degrees back from the peak torque point, or 60 degrees, is the point at which the winding must be switched on. A sensor is located to trigger from a rotor magnet at this specific event.

If the rotor is allowed to turn back towards its original rest, or zero torque point, but current is switched from winding A to winding B at 180 electrical degrees, the motor will operate on a new sine wave, or torque vs. angle, resulting in another point of peak performance. Again, a sensor is located in such a manner to mark this event. Similarly, the third sensor is set to trigger at 300 electrical degrees.

These Hall Effect sensor settings, 120 electrical degrees apart from sensor to sensor, automatically sequence the switching of currents from one phase to another, at the appropriate time.

Another important point to note from Graph 1 is the sign of the torque generated as a function of rotor position. If the currents in individual phases were switched at the proper electrical position, positive torque could always be generated, as illustrated in Graph 2.



GRAPH 2

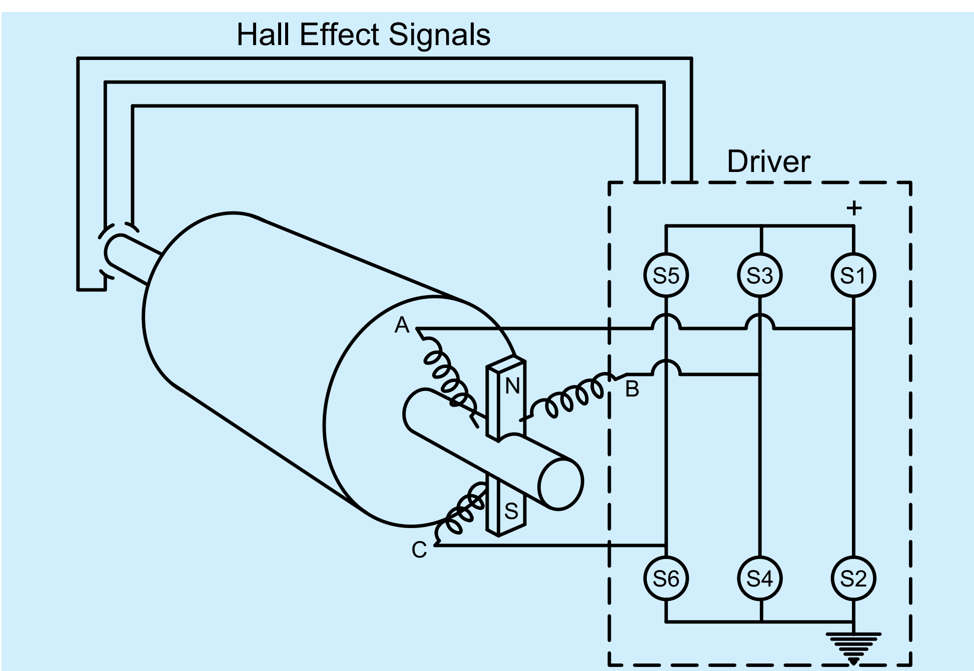
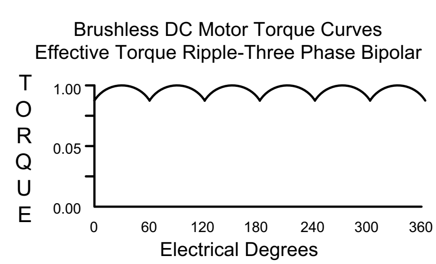
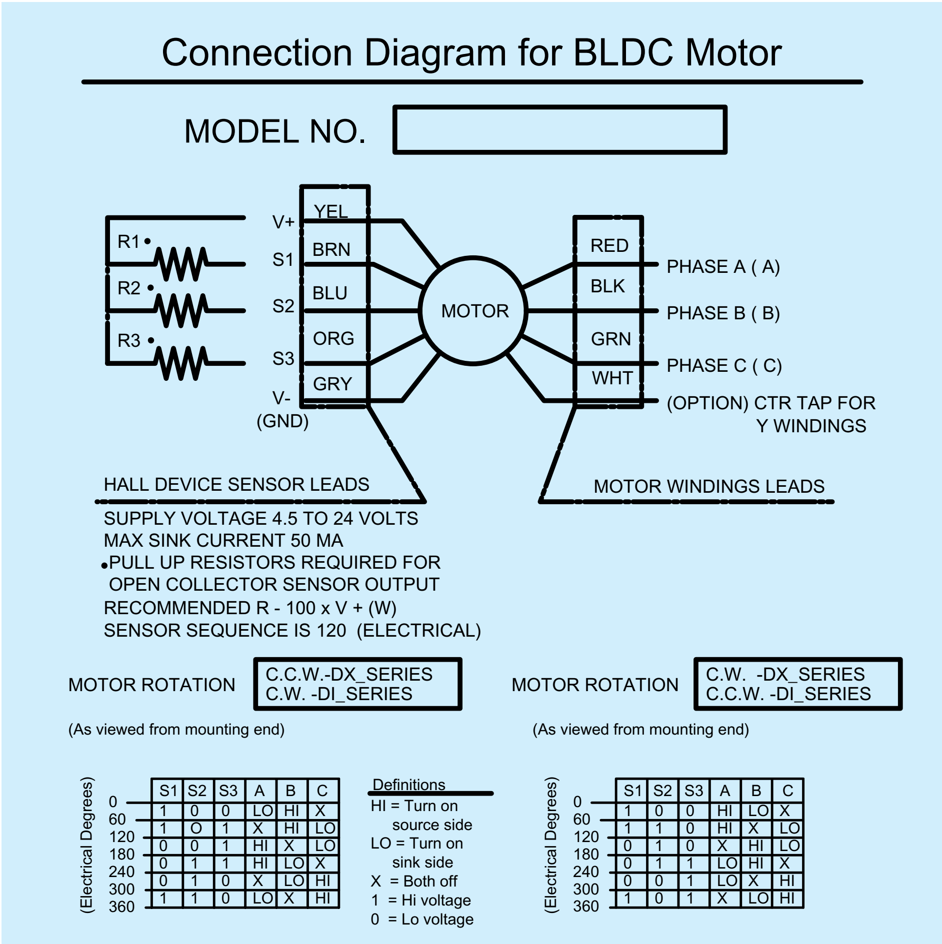


FIGURE 4

With the proper selection of phase energization (i.e., the proper commutation scheme) the resultant torque output of the motor is as illustrated in Graph 3. *The successful commutation of the brushless motor is knowing the rotor position in electrical degrees and having the proper commutation scheme.*



GRAPH 3



(Electrical Degrees) — C.C.W.-DX_SERIES / C.W. -DI_SERIES

Electrical Degrees	S1	S2	S3	A	B	C
0–60	1	0	0	LO	HI	X
60–120	1	O	1	X	HI	LO
120–180	0	0	1	HI	X	LO
180–240	0	1	1	HI	LO	X
240–300	0	1	0	X	LO	HI
300–360	1	1	0	LO	X	HI

(Electrical Degrees) — C.W. -DX_SERIES / C.C.W. -DI_SERIES

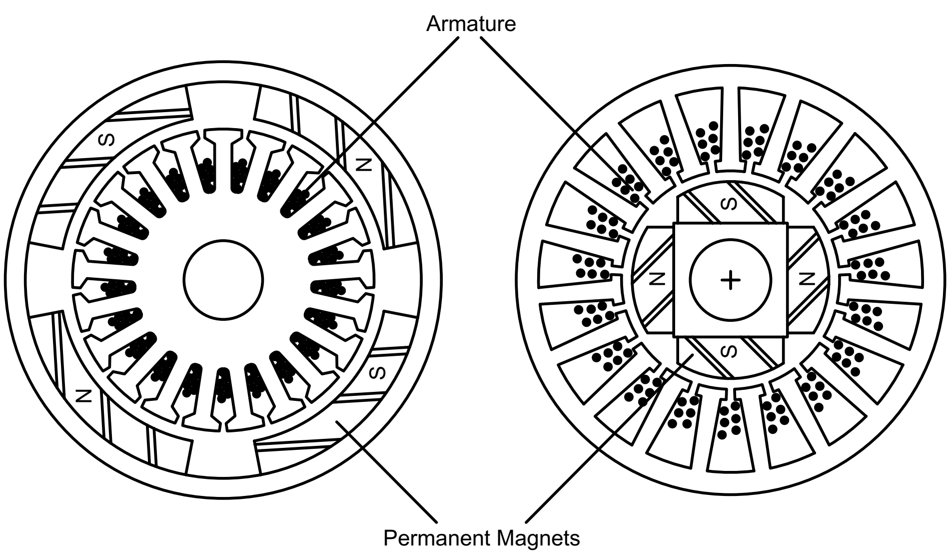
Electrical Degrees	S1	S2	S3	A	B	C
0–60	1	0	0	HI	LO	X
60–120	1	1	0	HI	X	LO
120–180	0	1	0	X	HI	LO
180–240	0	1	1	LO	HI	X
240–300	0	0	1	LO	X	HI
300–360	1	0	1	X	LO	HI

FIGURE 5

Figure 5 provides connection and color code information pertaining to motor and sensor leads in BEI brushless motors. The diagram also includes tables illustrating the proper sensor logic for clockwise and counter-clockwise shaft rotation.

"INSIDE-OUT" MECHANICAL DESIGN

A brush type motor has a permanent magnet stator and a wound rotor, as shown in Figure 2. The configuration of a brushless motor is reversed (i.e., a permanent magnet rotor and a wound stator). The wound member is referred to as the "armature". Furthermore, there are two types of brushless motors; the type that has an outer rotating magnet assembly, and the "inside out" type that has an inner rotating magnet assembly. Figures 6A and 6B depict the two motor types.



FIGURES 6A & 6B

The outer rotor and inner rotor features of a brushless motor design each have advantages and disadvantages. The ways in which the motor characteristics differ between the two designs are summarized in Table 1.

TABLE 1
Comparison of Motor Characteristics-
Inner Rotating vs Outer Rotating
Permanent Magnet Assemblies

Characteristic	Outer Rotating	Inner Rotating
Inertia	Higher	Lower
Torque/Power	Higher	Lower
Components	More	Fewer
Hall Effect Placement	Approx.	Precise

Inertia Considerations

One of the key elements of a proper motor selection exercise is an optimized load-inertia to rotor-inertia ratio. The recommended ratio is a maximum of 10 in rigid mechanical systems that utilize gear reducers or worm gears and a maximum of 3 for systems that include belt and pulley reductions. A motor with an outer rotor would therefore have an advantage of greater stability in a system with a very high reflected load inertia. On the other hand, a low rotor inertia enables attainment of higher acceleration rates, since the acceleration torque required in an application is the product of total inertia times acceleration rate, plus load/friction torque. The recommended load-to-rotor inertia maximums should not be exceeded whenever possible.

Another advantage of the lower inertia, inner rotor is the level of rotor balance attainable in the system. This advantage enables smooth operation at higher speeds (approximately 9,000 RPM to 12,000 RPM). Again, there is a trade off. The inner rotor has a a high speed limitation of about 15,000 RPM (without special mechanical sleeving of the rotor), whereas the outer rotor has a limitation of about 30,000 RPM. For very high speed operation, the outer rotor has the clear advantage.

Torque & Power Output

For a given motor volume, the outer rotor motor has higher torque and power output. This advantage is particularly important at high speeds of operation, where the back EMF of the motor winding eats away at the voltage source, leaving little voltage available to pull current. However, the inner rotor motor can be cooled more effectively than its outer rotor counterpart. This is so because the armature is external to the rotor, enabling direct heat dissipation through the motor outside diameter (O.D.). Addition of forced air cooling or heat sinking to the motor O.D. results in a dramatic increase in motor performance.

Number of Motor Components

In this category the inner rotor motor offers a couple of advantages over the outer rotor motor. The fewer number of parts in the inner rotor design means greater inherent reliability. It also puts money in the user's pocket, since design simplicity also results in lower costs to the motor manufacturer.

For the money, the inner rotor motor is the motor of choice where speeds of operation and inertia matching considerations allow.

TWO BEI OFFERINGS: HOUSED VS. FRAMELESS

BEI Technologies, Inc., offers motors in housed as well as unhoused, or frameless, configurations. Frameless motors are utilized by Original Equipment Manufacturers (OEM'S) interested in fully integrating motor part sets into the finished product. Frameless motors are also utilized in systems that require high servo bandwidth, where the use of a shaft coupling device could introduce unwanted mechanical resonances. They are also used as a result of economic considerations. Figure 7 depicts a frameless motor and its housed, brush motor counterpart.

Housed motors offer the convenience of a complete motor package, including bearings, shaft, enclosure, and mounting provisions. In addition, BEI Technologies, Inc. can provide housings that incorporate features of the customer's original equipment. For example, the motor mounting flange may be cast to include a mounting plate that would otherwise have been supplied as a separate component. The result is a savings in labor, book keeping, and inventory expenses.

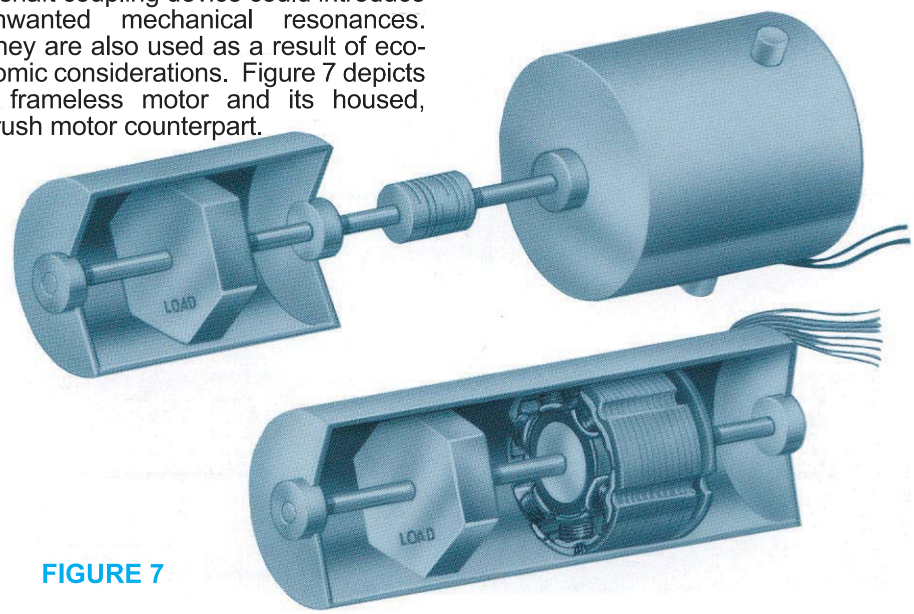


FIGURE 7

SIZING BRUSHLESS MOTORS

INFORMATION REQUIRED

The nature of the application under consideration dictates what information is required to properly select a motor candidate. For example, operating at a fixed speed will have a different demand than operation under servo conditions. In general, three parameters will determine motor selection: (1) peak torque requirement, (2) RMS torque requirement, and (3) speed of operation

Peak Torque Requirement

Peak torque, T_P is the sum of the torque due to acceleration of inertia, T_J, load, T_L, and friction, T_F^* :

$$T_P = T_J + T_L + T_F^* \quad \textbf{(4)}$$

**Other factors contribute to the overall torque requirement. The values of these factors are typically more difficult to asses. They are taken into consideration by employing a "rule-of-thumb" safety margin: 20% of the calculated torque value.*

Looking at the separate components, the torque due to inertia is the product of load (including motor rotor) inertia and load acceleration:

$$T_J = J_{L+M} \text{ X } \alpha. \quad (\alpha = \text{acceleration}) \quad \textbf{(5)}$$

The torque due to the load is defined by the configuration of the mechanical system coupled to the motor. The mechanical system also determines the amount of torque required to overcome friction in a given application. These systems will be described on pages 8 to 11.

RMS Torque Requirement

Root-Mean-Square or RMS torque is a value used to approximate the average continuous torque requirement of an application. It is a statistical approximation described by the following equation:

$$T_{RMS} = \sqrt{\frac{T_P{}^2 t_1 + (T_L + T_F)^2 t_2 + (T_J - T_L - T_F)^2 t_3}{t_1 + t_2 + t_3 + t_4}} \quad \textbf{(6)}$$

where t_1 is the acceleration time, t_2 is the run time, t_3 is the deceleration time, and t_4 is the dwell time in a move.

Speed of Operation

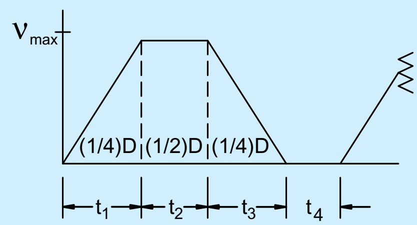
Speed of operation is also dictated by the configuration of the mechanical system that is coupled to the motor shaft, and by the type of move that is to be effected. For example, a single speed application would require a motor with a rated operating speed equal to the average move speed. A point-to-point positioning application would require a motor with a rated operating speed higher than the average move speed. (The higher operating speed would account for acceleration, deceleration, and run times of the motion profile, resulting in an average speed equal to the move speed.) Figures 8A and 8B relate rated operating speed to average move speed for point-to-point positioning move profiles.

ω_{max} = rated operating speed of motor, RPM.
ω_{TRAP} = average speed of motor required for a specified trapezoidal move, RPM

ω_{TRI} = average speed of motor required for a specified triangular move, RPM
D = total distance traveled, motor shaft revolutions.

t_1 = acceleration time, seconds
t_2 = run time, seconds
t_3 = deceleration time, seconds
t_4 = dwell time, seconds

Trapezoidal Move



i) For acceleration portion of curve:

$$\frac{\omega_{max} + 0}{2} = (1/4)D/t_1$$

$$\omega_{max} = D/2t_1$$

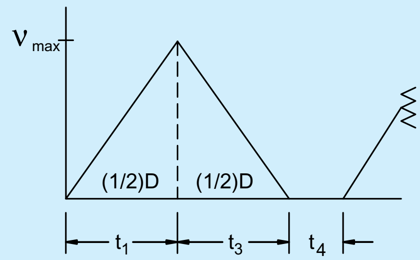
ii) For entire move:

$$\omega_{TRAP} = [(1/4)D+(1/2)D+(1/4)D]/(t_1+t_2+t_3) = D/3t_1$$

iii) $$\frac{\omega_{max}}{\omega_{TRAP}} = \frac{D/2t_1}{D/3t_1} = \frac{3}{2}$$

i.e., $\nu_{max} = 1.5\ \omega_{TRAP}$

Triangular Move



i) For acceleration portion of curve:

$$\frac{\omega_{max} + 0}{2} = (1/2)D/t_1$$

$$\omega_{max} = D/t_1$$

ii) For entire move:

$$\omega_{TRI} = [(1/2)D+(1/2)D]/(t_1+t_3) = D/2t_1$$

iii) $$\frac{\omega_{max}}{\omega_{TRI}} = \frac{D/t_1}{D/2t_1} = 2$$

i.e., $\omega_{max} = 2\ \omega_{TRI}$

FIGURES 8A & 8B

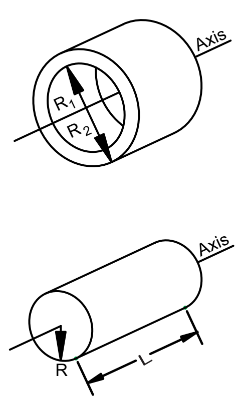
REFERENCE PHYSICS/PROPERTIES

This section presents conversion factors and physical characteristics of motion that are utilized in the sizing and selection of motors. The information provided is a technical basis for the calculations shown on pages 8 to 11.

Inertia Calculations

Inertia is a very important consideration during acceleration and deceleration of loads. Because belts, pulleys, gear sprockets, drive shafts, driven shafts, etc., are typically utilized in power transmissions applications, it is appropriate to review inertias of cylindrical objects.

Figure 9 illustrates two objects rotated about the cylinder axis and equations describing the corresponding rotational inertias.



Hollow Cylinder (or ring) about Cylinder Axis

$$J = \frac{m}{2}(R_1^2 + R_2^2)$$

Solid Cylinder about Cylinder Axis

$$J = \frac{mR^2}{2}$$

FIGURE 9

For objects of known weight, W, substituting W/g (g = acceleration of gravity) for m:

Solid Cylinder

$$J = \frac{(W/g)R^2}{2} = \frac{WR^2}{2g} = \frac{WR^2}{2(386 \text{ in Sec}^2)}$$

$$= (0.0013\ \text{Sec}^2/\text{in})R^2W \quad \textbf{(7)}$$

Hollow Cylinder

$$J = \frac{(W/g)(R_1^2 + R_2^2)}{2} = \frac{W(R_1^2 + R_2^2)}{2(386 \text{ in/Sec}^2)}$$

$$= (0.0013\ \text{Sec}^2/\text{in})(R_1^2 + R_2^2)W \quad \textbf{(8)}$$

If weight is unknown but volume, V, and material density, ρ, is known, substituting Vρ/g for m:

Solid Cylinder

$$J = \frac{(V\rho/g)R^2}{2} = \frac{(\pi R^2 L\rho)R^2}{2g}$$

$$= \frac{\pi L\rho R^4}{2(386 \text{in/Sec}^2)}$$

$$= (0.0041\ \text{Sec}^2/\text{in})R^4L\rho \quad \textbf{(9)}$$

Hollow Cylinder

$$J = \left(\frac{V\rho/g}{2}\right)(R_1^2 + R_2^2)$$

$$= \frac{\pi L\rho(R_2^2 - R_1^2)(R_2^2 + R_1^2)}{2(386 \text{ in/Sec}^2)}$$

$$= (0.0041\ \text{Sec}^2/\text{in})R_2^4 - R_1^4)L\rho \quad \textbf{(10)}$$

Material Densities

Table 2 shows the densities of commonly used materials. The values shown in the table should be substituted for ρ, in equations 9 and 10, when calculating inertias.

TABLE 2
Material Densities

Material	Density (oz/in^3)
Stainless Steel	4.48
Steel	4.51
Aluminum	1.54
Ceramic	2.83
Copper	5.12
Brass	4.94
Glass	1.50
Plastic	0.64

Coefficients of Friction

It also important to note the coefficients of friction for several types of surface-to-surface interfaces. This information is important in those instances where friction measurements are not possible, for one reason or another (eg: the system design is still at the paper stage). Table 3 is a listing of these values.

TABLE 3
Coefficients of Friction, μ

Contact Surface	Coefficient
Linear Ball Bearings	0.0001-0.004
Steel on steel (no lub)	0.57
Aluminum on steel	0.47
Teflon on steel	0.04
Teflon on Teflon	0.04
Glass on glass	0.4
Leadscrew	0.15
Rotary ball bearing	0.07

Conversion Factors

Table 4 is a collection of conversion factors often required in motor application exercises.

TABLE 4
Conversion Factors

Unit desired	Conversion
watts	**oz. in** X RPM / 1351
Radians/Sec	**RPM**/9.55
watts	**hp** X 746
oz. in.	(**hp** X 10^6)/RPM
oz. in.	(**watts** X 1351)/RPM
oz. in.	**lb in**/16
oz. in.	**lb ft**/192
oz. in.	**Nm** X 141.6
oz. in.	**g-cm**/72
oz. in. Sec^2	**oz in^2**/386
oz. in. Sec^2	**g-cm^2**/(7.09 X 10^4)
oz. in. Sec^2	**g-cm-Sec^2**/72
oz. in. Sec^2	**lb. in^2**/24.1
oz. in. Sec^2	**lb. in Sec^2** X 16

APPLYING BRUSHLESS MOTORS

THEORY

Permanent Magnet DC Motor Equivalent Circuit

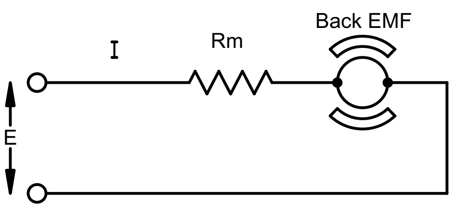


FIGURE 10

When a voltage is applied across the motor terminals, a current, I, circulates through windings of resistance, R_M, and the motor generates a back electromotive force (EMF). This back EMF is proportional to the speed of operation, w, by a constant, K_b,

$$\text{Back EMF} = \omega K_b \qquad \textbf{(11)}$$

and directly opposes the applied voltage. The equation that describes the circuit shown in Figure 10 is:

$$E = V_{source} = IR_M + \omega K_b \qquad \textbf{(12)}$$

At stall, $\omega = 0$ RPM and there is no back EMF. Then, $I = V_{source}/R_M$. As the speed builds up the back EMF increases. Then $V_{source} = \omega K_b + IR_M$ and, solving for I,

$$I = (V_{source} - \omega K_b)/R_M \qquad \textbf{(13)}$$

At some speed, and under no-load conditions, the magnitude of the back EMF will become equal to the magnitude of the voltage source. At this operating point, the numerator in Equation (13) becomes zero, leaving no voltage available to pull current. The motor speed observed at this point is referred to as the "no load" speed, ω_{NL}, of a motor with winding resistance, R_M.

Permanent Magnet DC Torque/ Speed Curve

A permanent magnet DC brushless motor behaves like any permanent magnet DC brush motor. All of the parameters discussed in this guide are based on the fact that an ideal P.M. motor has a linear torque/speed curve, as shown in Figure 11.

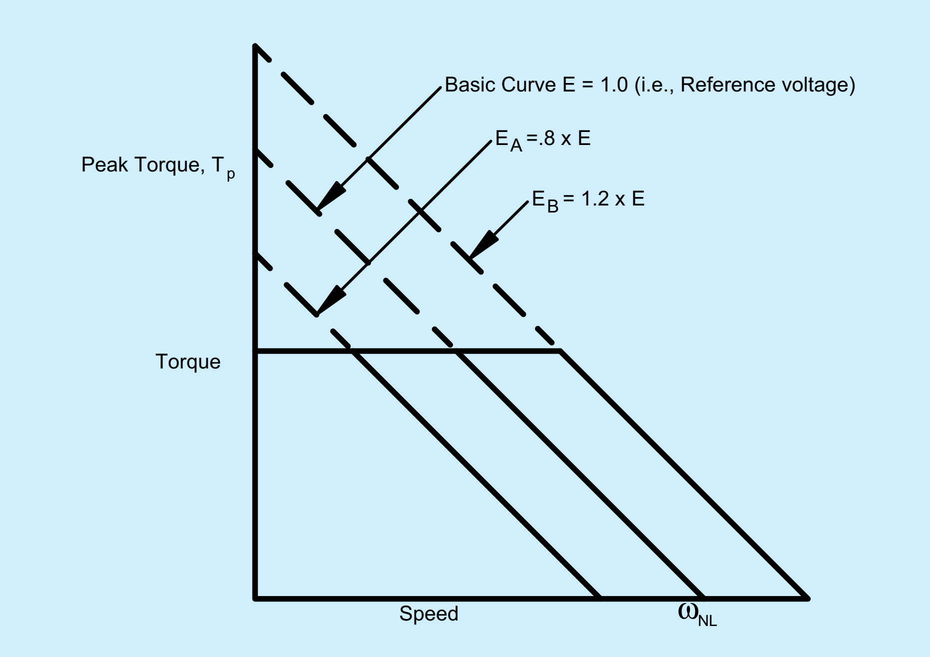


FIGURE 11

APPLICATION TYPES

A. Fixed Speed Operation

Brushless Blower, Brushless Pump, Optical Scanner, Respirator Blower, Surgical Drill, Metering Pump

Brushless motors are gaining popularity in many single-speed applications such as impeller drivers in blowers and pumps. The long-life characteristic of the “brushless” motor is becoming more and more attractive in applications that traditionally utilized brush motor technology. The typical fixed speed requirement is system power-up, followed by extended operation at one set speed. The acceleration time is not a critical parameter. In this case input voltage, continuous torque output, and speed of operation are the design parameters to be considered. (Inertia matching is not a consideration since the load is typically mounted directly to the motor shaft.)

Example:
Bus voltage - 70V DC
Operating speed - 6,000 RPM
Horsepower at 6,000 RPM - 1/3 H.P.

Step 1 - Peak Torque Calculation: none required.

Step 2 - RMS Torque Calculation: fixed speed applications do not require an RMS torque calculation. Instead, the average torque is calculated based on horsepower and operating speed requirements. From the values shown in Table 4, we have a 1/3 hp X 10^6/6,000 RPM, or 56 oz. in. continuos torque requirement.

Table 5 shows motor and winding parameters pertaining to the BEI Technologies DIN34 series (i.e., NEMA 34 flange) brushless motors. It appears that model DIN34-26 has a stall torque rating well above the 56 oz. in. calculated in the present example. Model DIN34-20 has a stall torque rating too small to meet the requirements. Table 5 lists one standard winding. For other windings, please consult our Applications Engineers.

Step 3 - Winding Selection: It was stated earlier that the back EMF voltage generated by the motor during operation subtracts directly from the available voltage supply. It is therefore imperative to allow enough voltage head-room to pull the current that will generate the desired torque at the speed of operation.

3.1 Calculation of generated back EMF:

The first step in selecting a winding is to start with a winding that has a back EMF constant low enough to produce the desired operating speed at the available input voltage. Winding A is appropriate (i.e., (70V/(0.092V/Rad/Sec))(9.55 RPM/Rad/Sec)) = 7,266 RPM; we need 6000 RPM). The back EMF voltage generated at the speed of operation is:

ωKb = (6 KRPM/(9.55RPM/Rad/Sec))(0.092V/Rad/Sec) = 58V

3.2 Calculation of torque-producing voltage:

$V_{torque} = V_{source} - 58V = 70V - 58V = 12V$ DC

TABLE 5

Standard Motor Parameters***	UNITS	SYMBOL	DIN34-20	DIN34-26	DIN34-32
Max. Recommended Speed	RPM	ω_{NL}	18,000	18,000	18,000
Peak Torque*	oz • in	T_P	120	250	350
Continuous Stall Torque**	oz • in	T_{CS}	50	100	135
Motor Constant	oz • in / √Watt	K_M	11.1	19.4	23.3
Electrical Time Constant	Milli-sec	τ_E	1.9	3.1	3.7
Mechanical Time Constant	Milli-sec	τ_M	8.8	5.7	5.4
Power I^2R @ Peak Torque	Watts	P_P	116.1	166.4	212.3
Damping Factor (Zero Impedance)	oz • in / rad/sec	F_O	0.88	2.65	4.07
Friction Torque	oz • in	T_F	3.0	6.0	7.0
Rotor Inertia	oz • in • sec^2	J_M	7.7×10^{-3}	1.5×10^{-2}	2.2×10^{-2}
Thermal Resistance	°C/Watt	θ_{th}	3.2	2.5	2.2
Max. Allowable Winding Temp.	°C		125	125	125
Phases/Winding Type			3/Y	3/Y	3/Y
Poles			6	6	6
Weight	oz.	W	32	48	66
Length	in.	ℓ	2.0	2.6	3.2

Standard Winding Constants***	Units	Tol	Symbol	DIN34-20			DIN-34-26			DIN34-32		
				A	B	C	A	B	C	A	B	C
DC Resistance	Ohms	±12.5%	R	0.30			0.45			0.36		
Voltage @ Peak Torque	Volts	Nominal	V_P	5.90			8.65			9.00		
Current @ Peak Torque	Amperes	Nominal	I_P	19.7			19.2			25		
Torque Sensitivity	oz•in/Amp	±10%	K_T	6.1			13.0			14.0		
Back EMF Constant	Volts/(rad/sec)	±10%	K_B	0.043			0.092			0.099		
Inductance	Milli-Henry	±30%	L	0.57			1.40			1.33		

* 10 Sec at 25 °C Ambient, 125 °C Winding Temperature
** 25 °C Ambient, 125 °C Winding Temperature and Heatsunk to 12” x 12” x ¼” Aluminum Plate.
*** Other operating speeds and torques are available to suit specific application requirements.

GENERAL CHARACTERISTICS
Ambient Operating Temperature: -55 °C to 65 °C
Insulation Resistance @ 500VDC: 1000 MΩ Min.
Bearings: Grease Packed, Double Shielded

3.3 Calculation current available to produce torque:

$12V/0.45\Omega$ = **27A**

3.4 Calculation of current required to drive load:

56 oz. in./Kt = (56 oz. in.)(13.0 oz. in./A) = **4.3A**

It appears that model DIN34-26, winding A, will provide the 56 oz. in. torque needed at 6,000 RPM operation.*

**In practice, the winding resistance increases as the motor temperature increases. The I^2R losses increase; and at high speed-core losses and eddy current losses affect the efficiency of the motor. Again, the 20% safety margin utilized in motor sizing exercises helps ensure proper selection.*

Step 4 - Controller Selection: The example shown above required a controller rated at least 70V DC output terminal voltage and 4.3A continuous output current. It should be noted that the voltage at the motor terminals is always lower than the input voltage to the controller due to losses in the electronic components. In addition, brushless motors are designed for efficiencies around 80%. A controller with a rated current about 20% greater than the calculated value should ultimately be selected.

Another consideration in controller selection is two-quadrant vs. four-quadrant control. A two-quadrant unit provides positive torque control in two directions (clockwise and counter-clockwise). The four-quadrant unit provides positive and negative torque in both directions. Fixed speed operation applications enable use of the less expensive two-quadrant technology.

B. High Acceleration Rate Application

Centrifuges, Mass Storage, Disk Certifiers/Burnishers, Wafer Spinners

In these applications the motor is selected to accelerate the load to a desired operating speed in a specified acceleration time. Once at speed, the motor needs to provide little torque to keep the load in motion. Input voltage, acceleration rate, load and motor inertia, and speed of operation are the parameters to be considered, as shown in the following disk certifier example.

Example:
Bus Voltage - 36V DC
Acceleration time - 2 seconds
Load - 8" diameter aluminum disk, 0.300" thick
Supporting chuck -5" diameter, ½" thick plastic, mounted directly to motor shaft.
Operating speed - 3,600 RPM
Duty Cycle: <10%

Step 1 - Load Inertia Calculation

1.1 Aluminum disk:

Equation (9) shows that the inertia of a solid cylinder of length L, radius R, and density ρ may be determined as follows:

$J = (0.0041\ Sec^2/in)R^4L\rho$ = $(0.0041\ Sec^2/in)(4")^4(0.300")(1.54\ oz/in.^3)$ = **0.4849 oz. in. Sec²**

1.2 Plastic chuck:

$J = (0.0041\ Sec^2/in)(2.5")^4(0.5")(0.64\ oz./in.^3)$= **0.051 oz. in. Sec²**

1.3 Motor rotor: To be included later.

Step 2 - Acceleration Calculation: Units of Radians/Sec² should always be used in acceleration rate calculations, since "Radian" is a unitless number. The product of acceleration and inertia will drop out to units of torque.

Acceleration rate = operating speed/acceleration time:

3,600 RPM/9.55=377 Rad/Sec, and Accel. rate = (377 Rad/Sec) / (2 Sec) = **188 Rad/Sec²**

Step 3 - Peak Torque Calculation: It was seen in Equation (4) that peak torque is the sum of the torque due to inertia, load, and friction. Since load (usually windage) and friction torque in applications such as disk certifiers are often negligible, the motor may be selected based on the product of inertia and acceleration alone:

T_p = (inertia) (acceleration rate) = (disk inertia + chuck inertia + rotor inertia) (acceleration) = (0.4849 + 0.051 + rotor, oz.in. Sec²) (188 Rad/Sec²)

Ignoring rotor inertia for now,

T_p = (0.5359 oz. in. Sec²) x (188 Rad/Sec²) = **100 oz. in.**

Step 4 - Motor Selection: A motor with a peak torque rating higher than the value calculated in Step 3 should be selected. Again, referring back to Table 5, model DIN34-20 has a peak torque rating of 120 oz. in. It also has a rotor inertia of 7.7×10^{-3} oz. in. Sec² ; a value that is negligible compared to the total load inertia. (If the rotor inertia was comparable to or greater than the load inertia, it would be necessary to proceed with motor selection iterations, plugging the rotor inertia value in the inertia-times-acceleration-rate equation to insure a proper peak torque requirement.)

Duty cycle check: (100 oz. in.)20% = 20 oz. in., well within the continuous stall rating of 50 oz. in.

Step 5 - Winding Selection: The winding should be selected in the same manner as shown in the single speed application example. In this case, the high peak torque requirement necessitates selection of a winding with a low resistance, so that enough current may be drawn to provide 100 oz. in. of torque. Winding A appears to be a suitable candidate.

Step 6 - Controller Selection: High acceleration rate applications require selection of a controller that has a peak current rating at least as high as the current dictated by motor winding parameters. The winding A selected in step 5 will result in a peak current magnitude of 100 oz. in./6.1 oz. in./A, or 16A. Again, considering motor efficiencies, a controller with a peak rating at least 20% higher than the calculation value, or about 20A, should be selected.

The high acceleration, single speed application also enables use of two-quadrant control.

C. Point-to-Point Positioning Application

The point-to-point positioning application is by far the most complex of all applications; not just from the standpoint of system integration and load compensation, but because of the difficulty in estimating an average velocity profile or duty cycle, in practice.

The remainder of this section describes five basic power transmission mechanical configurations. Equations specific to each configuration are provided to enable determination of the motor performance required to effect a point-to-point move. Once determined, move speed, reflected torque, and reflected inertia may be used to calculate the peak torque, RMS torque, and speed of operation motor selection parameters discussed on page 5 and 6. The section will conclude with an example of a chemical etching/plating process requiring point-to-point positioning capabilities.

General Parameters

J_L = Load inertia (oz. in. Sec^2)
J_M = Motor inertia (oz. in. Sec^2)
J_B = Belt inertia (oz. in. Sec^2)
W_L = Load weight (oz.)
F_G = Force due to gravity (oz.)
F_P = Push/Pull force (oz.)
W_B = Belt weight (oz.)
T_L = Load torque (oz. in.)
T_F = Friction torque (oz. in.)
E = Power transmission efficiency (%/100)
g = Acceleration of gravity (386 in./Sec^2)
P = Leadscrew pitch (Revolutions/inch)
μ = Coefficient of friction (%/100)
ω_M = Rotational velocity (RPM) at motor shaft
ω_L = Rotational velocity (RPM) at load shaft
ν = Average move velocity (inches/min)

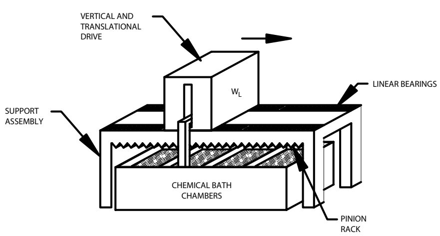


FIGURE 12

Example: Figure 12 illustrates equipment used in a chemical etching/plating process

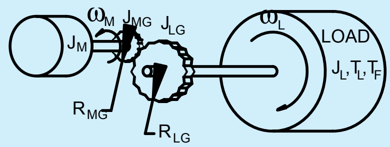
Drive = Motor with a 10:1 Reduction gear head (E=0.80), inertia, J_{GB} = 0.04 oz. in. Sec^2, pinion radius, R_p = 1.5", pinion material = stainless steel, 0.5" thick. (Rack and pinion efficiency = 0.90).

Weight = 4,000 oz., D = 24" move on linear bearings; move time = 1 Sec. Velocity Profile: Trapezoidal for controlled accel. and controlled decel. Duty cycle = 1 Sec move, 8 sec rest, repeated indefinitely. V_{Source} = 36V DC.

Step 1 - Break up the analysis into components - (1) Calculate values of parameters at the pinion, and (2) values reflected to the motor shaft, through the gear head.

Calculation of load parameters at the pinion: Figure 13D describes the equations pertaining to a rack and pinion system.

A. Configuration No. 1: Gear Reduction Mechanics

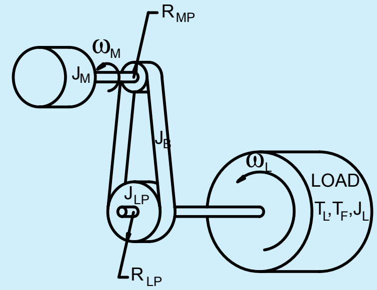


Additional application specific parameters

J_{GB} = Gear Box Inertia
J_{LG} = Load gear inertia (oz. in. Sec^2)
J_{MG} = Motor gear inertia (oz. in. Sec^2)
R_{LG} = Load gear radius (in.)
R_{MG} = Motor gear radius (in.)
G = Reduction ratio, R_{LG}/R_{MG} or rated gear box ratio

Parameter	At Motor Shaft	Reflected to Motor Shaft
Torque, T	N/A	$\frac{T_L + T_F}{G\,E}$
Speed, ω_M	N/A	$\omega_L G$
Inertia, J discrete gears	$J_M + J_{MG}$	$\frac{J_L + J_{LG}}{G^2 E}$
Inertia, gear box	$J_M + J_{GB}$	J_L/G^2E

B. Configuration No. 2: Timing Belt Mechanics



Additional application specific parameters

J_{LP} = Load pulley inertia (oz. in. Sec^2)
J_{MP} = Motor pulley inertia (oz. in. Sec^2)
R_{LP} = Load pulley radius (in.)
R_{MP} = Motor pulley radius (in.)
G = Reduction ratio, R_{LP}/R_{MP}

Parameter	At Motor Shaft	Reflected to Motor Shaft
Torque, T	N/A	$\frac{T_L + T_F}{G\,E}$
Speed, ω_M	N/A	$\omega_L G$
Inertia, J at motor shaft	$J_M + J_{MP} + J_B$	$\frac{J_L + J_{LP}}{G^2 E}$

FIGURE 13

$$T = \frac{\mu W_{LT} + F_P + F_g}{E} (R_P)$$

$$= \frac{(0.004)(4{,}000\text{ oz}) + 160\text{ oz} + 0}{0.90} 1.5" = 293\text{ oz in.}$$

$$\omega_L = \frac{\nu}{2\pi R_P} = \frac{(24"/1\text{ Sec})(60\text{ Sec/Min})}{(2\pi\text{Rad/Rev})(1.5\text{ in.})}$$

=153 RPM, but

for a trapezoidal move, ω_{max} = $3/2\omega_{TRAP}$ therefore, ω_{max} = **230 RPM**

$$J = \left(\frac{W_{LT}}{E \cdot g}\right) R_P^{\,2} + J_P$$

$$= \frac{4{,}000\text{ oz.}}{0.90(386\text{ in./Sec}^2)} (1.5")^2 + J_P$$

$$= 26\text{ oz. in. Sec}^2 + J_P$$

From page 6, J_p = (0.0041 Sec^2/in) $(1.5")^4$ (0.5") (4.48 oz./in^3) = **0.046 oz. in. Sec^2** - i.e., negligible.

Step 2 - Calculations of total parameters at motor shaft: The gear box equations shown in Figure 13B may be used for these calculations.

$$T = \frac{T_L + T_F}{G\,E} = \frac{293 + 0\text{ oz. in.}}{10\ (.9)} = 33\text{ oz. in.}$$

$$J = \frac{J_L}{G^2 E} + J_M + J_{GB}$$

$$= \frac{26\text{ oz. in. Sec}^2}{(10)^2 .9} + 0.04\text{ oz. in. Sec}^2 + J_M$$

= 0.33 oz. in. Sec^2 + J_M

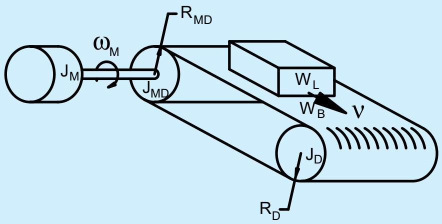
ω_M = (230 RPM) 10 = **2,300 RPM**

Step 3 - Calculation of peak torque requirement: From page 6 we have $T_P = T_J + T_L + T_F = (J_{L+M})\alpha + T_L + T_F$ = (0.33 oz. in. Sec^2 + J_M)α + T_L + T_F, but α = (2,300 RPM/9.55) / t_1 = (241 Rad/Sec)/0.333 Sec = 723 Rad/Sec^2, and T_P = (0.33 oz. in. Sec^2 + J) (723 Rad/Sec^2) + 33 oz. in. + 0 oz. in. ≈ 272 oz. in., assuming motor rotor inertia is small relative to reflected load inertia.

Step 4 - Calculation of RMS torque requirement: Equation (6) provides the desired value as follows:

$$T_{RMS} = \sqrt{\frac{T_P^{\,2} t_1 + (T_L + T_F)^2 t_2 + (T_J - T_L - T_F)^2 t_3}{t_1 + t_2 + t_3 + t_4}}$$

C. Configuration No. 3: Tangential Load Mechanics



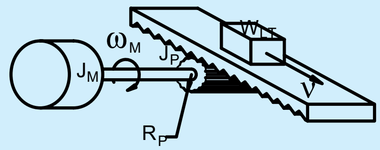
Additional application specific parameters

J_{MD} = Drive pulley (motor end) Inertia (oz. in. Sec^2)
J_D = Driven pulley inertia (oz. in. Sec^2)
R_{MD} = Drive pulley radius (in.)
R_D = Driven pulley radius (in.)

Parameter	At Motor Shaft	Reflected to Motor Shaft
Torque, T	N/A	$\frac{\mu(W_L + W_B) + F_P^* + F_g^{**}}{E} \cdot R_{MD}$
Speed, ω_M	N/A	$\frac{\nu}{2\pi R_{MD}}$
Inertia, J	$J_M + J_{MD} + J_D$	$\left(\frac{W_L + W_B}{E \cdot g}\right) R^2_{MD}$

* F_P may have a positive or negative value
**F_g applies only to vertical systems where gravity acts on a suspended load. This value will be negative if motion is with gravity; positive if motion is against gravity.

D. Configuration No. 4: Rack and Pinion Mechanics

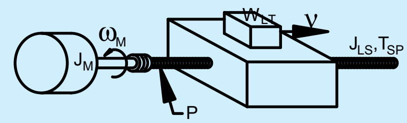


Additional application specific parameters

W_{LT} = Weight of Load plus track (oz.)
J_P = Pinion inertia (oz. in. Sec^2)
R_P = Pinion radius (in.)

Parameter	At Motor Shaft	Reflected to Motor Shaft
Torque, T	N/A	$\frac{\mu W_{LT} + F_P + F_g}{E} \cdot R_P$
Speed, ω_M	N/A	$\frac{\nu}{2\pi R_P}$
Inertia, J	$J_M + J_P$	$\left(\frac{W_{LT}}{E \cdot g}\right) R_P^2$

E. Configuration No. 5: Leadscrew Mechanics



Additional application specific parameters

W_{LT} = Weight of Load plus leadscrew table assembly (oz.)
P = Leadscrew Pitch (Rev/in.)
J_{LS} = Leadscrew Inertia (oz. in. Sec^2)
T_{SP} = Leadscrew preload torque (oz. in.)

Parameter	At Motor Shaft	Reflected to Motor Shaft
Torque, T	N/A	$\frac{\mu W_{LT} + F_P + F_g}{2\pi PE}$
Speed, ω_M	N/A	νP
Inertia, J	$J_{LS} + J_M$	$\frac{W_{LT}}{E \cdot g}\left(\frac{1}{2\pi P}\right)^2$

$$= \sqrt{\frac{(272 \text{ oz in})^2 (.33 \text{ Sec}) + (33 \text{ oz in})^2 (.33 \text{ Sec}) + (239 - 33 - 0 \text{ oz in})^2 (.33 \text{ Sec})}{.33 \text{ Sec} + .33 \text{ Sec} + .33 \text{ Sec} + 8 \text{ Sec}}} = \mathbf{66\ oz.\ in.}$$

Step 5 - Application of 20% safety margins:

1.2 X T_p = 1.2(272 oz.in.) = 326 oz. in.
1.2 X T_{RMS} = 66 oz. in. X 1.2
= 79 oz. in.

Step 6 - Motor and winding selection. Referring to Table 5, it appears model DIN34-36 meets the peak and RMS torque requirements. Looking at winding A,

V_{source} - $(K_b)(\omega)$ = 36V - (0.099 V/Rad/Sec)(241 Rad/Sec) = 12V

Current available to produce torque = V/R_M = 12V/0.36Ω = 33A

Current required to drive load:
peak=(326 oz. in.)/(14 oz. in./A)= 23A
RMS=(79 oz. in.)/(14 oz. in./A) = 6A

Conclusion: Winding A is a good match

Step 7 - Comparison of reflected load inertia to rotor inertia: We saw that the reflected load inertia was calculated at a value of 0.33 oz. in. Sec^2. The DIN34-36 has a rotor inertia of 0.022 oz. in. Sec^2. The ratio is therefore 0.33/0.022 = 15, which is slightly higher than the recommended value. The system may perform adequately under these conditions. If not, a solution may be utilization of a motor with a higher rotor inertia. Another solution may be direct coupling of the gear head to the motor shaft, thereby increasing the total shaft inertia almost to the level of the reflected load inertia. Electrical modifications to the control circuitry may also help reduce the effects of inertia mismatches. However, this is a solution usually employed "after the fact".

Step 8 - Controller Selection:

This application requires a 36V DC rated drive with continuous and peak current outputs of 6A and 23A, respectively.

In most of the equations provided above, friction was estimated from appropriate coefficients of friction. In practice, it is desirable to measure actual friction levels whenever possible. Friction is a parameter that is often under-estimated in value, but is paramount to proper motor selection. (Measured friction values would replace μW in all of the preceding equations.)

TWO-WIRE BRUSHLESS DC MOTORS

THE NEXT GENERATION

INTRODUCTION

Pound-for-pound, the typical "inside-out" brushless DC (BLDC) motor provides more output power, greater life and reliability, higher operating speeds, cleaner operation, ect., than its traditional, brush-type (PMDC motor) counterpart. High torque-to-inertia ratios; a stationary armature around a rotating permanent magnet assembly (instead of a stationary permanent magnet assembly around a rotating armature); and, of course, elimination of the brushes - make the BLDC motor the preferred choice when it comes to performance considerations. The BLDC motor is also the preferred choice from a cost consideration, when applications are evaluated on a total cost (i.e., over the life of the product) rather than up-front cost basis. For example, a brush-type motor which sells for around $40 to $45 may have a BLDC equivalent priced at about $100 - without electronics, or $150 - with electronics. Clearly, the $40 to $45 motor appears to cost less than the BLDC equivalent. However, this is the up-front cost of the motor - not the total cost. If the brushes only last 2,000 hours and the expected life of the product which uses the motor is 20,000 hours, then the motor has to be replaced ten times, for a total cost of $400 to $450 (not to mention down-time and maintenance costs). It is easy to see that the $100 BLDC motor, or even the $150 BLDC motor with electronics is, in fact, a much more cost effective solution, since it will last the entire life of the product.

The main technical issue of replacing a brush-type motor with its brushless counterpart is the commutation electronics consideration. The typical BLDC motor is an eight-wire device. Replacing the two-wire PMDC motor with its eight-wire counterpart requires additional electronic circuitry and additional considerations at the systems level. These and other related factors have led to the development of the two-wire BLDC motor - a BLDC motor that contains integral electronic commutation, or drive control circuitry. This type of motor has been manufactured at BEI, Kimco Magnetics Division for over a decade. The present tutorial is provided to familiarize the reader with the types of two-wire BLDC motors available in the market-place, variations thereof, and guidelines for applying these products.

TWO QUADRANT VS. FOUR QUADRANT CONTROL

In order to get a better appreciation of the two-wire BLDC motor application, it is first necessary to understand the different ways PMDC and/or BLDC motors may be controlled.

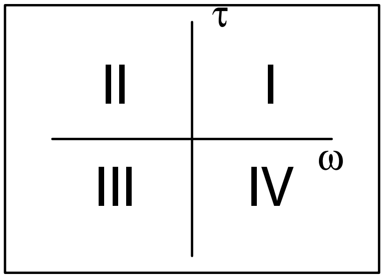


FIGURE 14:
Two-Coordinate
Torque Vs. Speed System

Figure 14 shows a two-coordinate system in which the horizontal axis represents motor shaft speed and the vertical axis represents the output torque. In DC motors, output torque is proportional to current, and output speed proportional to voltage. Motor drive electronics that can provide positive current and positive or negative voltage to the motor terminals are therefore called two-quadrant drives, since they operate in quadrants I and II. Drives that provide positive or negative current and positive or negative voltage to the motor terminals are called four-quadrant drives, since they operate in all four quadrants of the two-coordinate system.

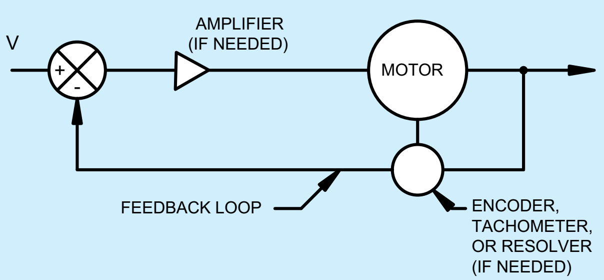


FIGURE 15A:
Block Diagram of a PMDC Motor

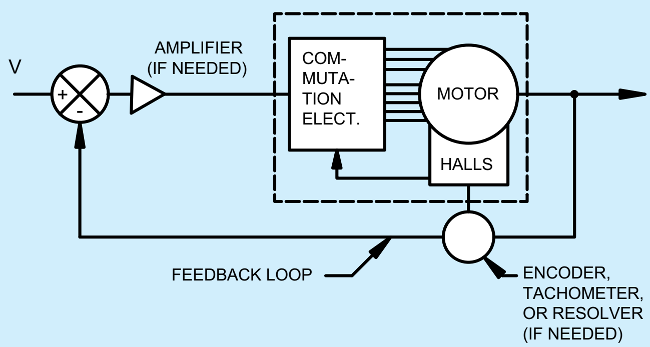


FIGURE 15B:
Block Diagram of a BLDC Motor

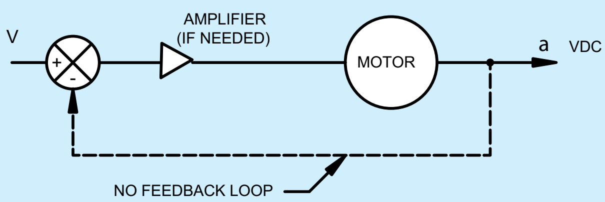


FIGURE 16A:
Block Diagram of a PMDC Motor Driven
in Open Loop Mode

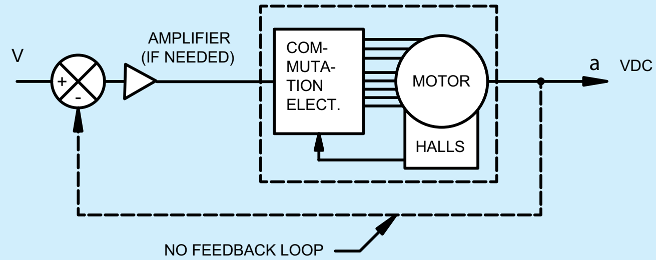


FIGURE 16B:
Block Diagram of a BLDC Motor Driven
in Open Loop Mode

Applications abound for two-quadrant and four-quadrant drives. For example, a turntable that needs to be rotated over a range of fixed speeds can be controlled with the two-quadrant system. The friction due to windage, bearings, etc., constantly applies a drag, or negative torque to the system, causing the table to slow down, and eventually stop, in the absence of a positive controlled torque. Positive torque is needed to keep the turntable rotating at the desired speed, in one or the other direction (i.e., clockwise or counter-clockwise). If, on the other hand, it is necessary to stop the turntable faster than frictional torque allows, or if the turntable must be stopped and held at a fixed angular position, then the four-quadrant drive is the proper solution. In this case, negative torque is used to decelerate the system, and positive and negative torque is used to hold the turntable in place (against disturbing forces).

OPEN-LOOP VS. CLOSED-LOOP CONTROL

As alluded to in the previous section, it is sometimes necessary to control the rotational speed and/or position of the motor shaft and attached load.

Figure 15 depicts a system in which there is control of the shaft output. This type of system requires a feedback device which senses the specific parameter that needs to be controlled. Referring to the turntable example previously described, the table that runs at a set speed would need a motor with a feedback device that measures the rotational velocity of the motor shaft. A table that also needs to be positioned would need a feedback-device that senses rotational velocity and angular position of the shaft. Either system is referred to as a “closed-loop” system, as illustrated in Figure 15.

Figure 16 depicts a system In which control of the motor shaft is not necessary. This type of system requires no feedback device (other than for commutation purposes). Since the feedback loop is not closed, this system is called “open-loop”.

TYPES OF TWO-WIRE BLDC MOTORS

The term “two-wire” refers to the two leads needed to operate a DC motor. These leads include a power supply Lead (typically 12V DC or 24V DC) and a power return lead. Two-wire BLDC motors are generally available in a variety of configurations, including the configurations described above - open-loop, closed-loop, two quadrant, and four-quadrant control -- and combinations thereof. Regardless of configuration, the main attribute of the two-wire BLDC motor is its elegantly simple two-wire hook-up. Figures 17A & B illustrate the difference between closed-loop BLDC motor systems that utilize standard eight-wire motors and those that use two-wire motors.

The primary differences between these two systems are the customer interface requirements and the location of the commutation electronics.

The eight-wire system shown in Figure 17A includes commutation electronics that are provided as a separate item -- sometimes in a separate enclosure and sometimes as a board that is to be mounted somewhere in the equipment. This type of system also includes a BLDC motor with eight leads. Three of the leads are for the power to the three windings (or phases). The other five leads are for the three Hall Effect device outputs, the Hall voltage supply, and the Hall voltage return. The Hall Effect devices sense rotor position. Their output is used to commutate the “brushless” motor through the use of commercially available commutation I.C.’s These chips decode the signals from the Halls and provide the logic with which the current-carrying transistors are switched on and off for proper phasing of the motor.

The two-wire system shown in Figure 17B has commutation electronics that are integral to the BLDC motor enclosure. In this system, two leads exit the motor -- one power supply lead and one power return lead. All of the motor/commutation electronics connections are performed at the motor manufacturing facility, making the customer interface aspect a snap.

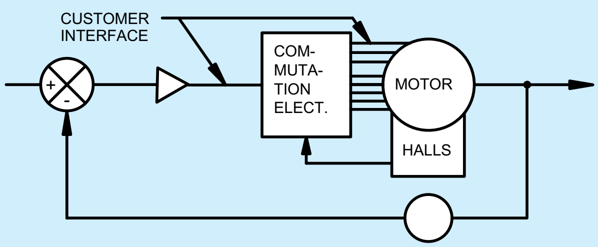


FIGURE 17A:
Block Diagram of an Eight-Wire BLDC System

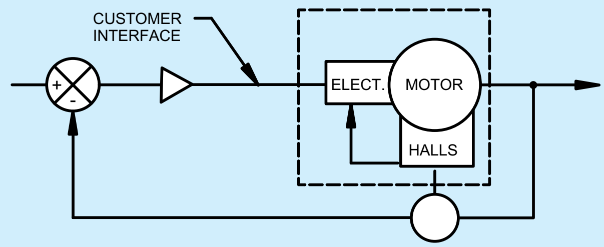


FIGURE 17B:
Block Diagram of a Two-Wire BLDC System

There are many variations of the "two-wire" BLDC motor presently available in the marketplace. However, the most popular and most widely used configuration is the two-quadrant, open- or closed-loop speed control package. Speed may be controlled with an on-board potentiometer or by bringing out a third wire for remote speed adjust. The third wire may accept a 0-5V analog input signal to set a speed which increases with the magnitude of the input signal. Additional wires or digital communication ports could also be provided to add features, resulting in what the industry has dubbed a "Smart" motor. Use of these options or configurations depends on the desired overall level of control. Of course, there are also the ever-present cost-vs.-performance trade-off considerations. The main point to bear in mind is that, with its integral electronics packaging, the two-wire BLDC motor accepts, and operates off of a straight DC supply, just like its two-wire brush-type DC counterpart.

APPLYING TWO-WIRE BLDC MOTORS

One of the major considerations in applying two-wire BLDC motors is heat generation. The three primary sources of heat are I^2R losses in the motor winding, eddy current losses in the motor stack (i.e., core losses) and switching losses in the electronics. The I^2R losses and core losses elevate the motor case temperature, as well as the temperature of the electronics. Consequently, there is a practical limitation on the size of BLDC motors that should be considered for two-wire control. For motors with commercial grade components, two-wire control works best in applications with performance requirements up to about 1/3 horsepower. Motors with military grade or high temperature, hybridized electronics packages will, of course, be suitable for use at higher horsepower ranges.

Another consideration in applying two-wire BLDC motors is the level of speed control needed in the application. In open-loop systems, there is no speed control requirement. Here, speed increases with decreasing load, and decreases with increasing load. In closed-loop speed control systems, however, it is desirable to maintain a set speed, regardless of load variation. In these systems, the two-wire motor can sometimes be designed to use the output from the Halls not only to commutate the motor, but as a feedback frequency for speed regulation. Halls provide a lower frequency output compared to other feedback devices such as shaft encoders and resolvers. As such, there is a practical low-end speed limit at which the two-wire motor should be used to control speed. This limit is about 500 RPM. There is also a percentage speed regulation limit to the hall based control. The Hall out-put can be used to regulate speed to about ±1 to 5% of set speed in systems with varying loads, or about ±0.5 to 1% of set speed in systems with very stable loads. The good news is that these types of applications are very common. The Hall-based speed control circuit is an inexpensive way to regulate speed. In fact, it comes free when other factors drive the change to brushless technology, and Hall-based speed regulation is an adequate solution.

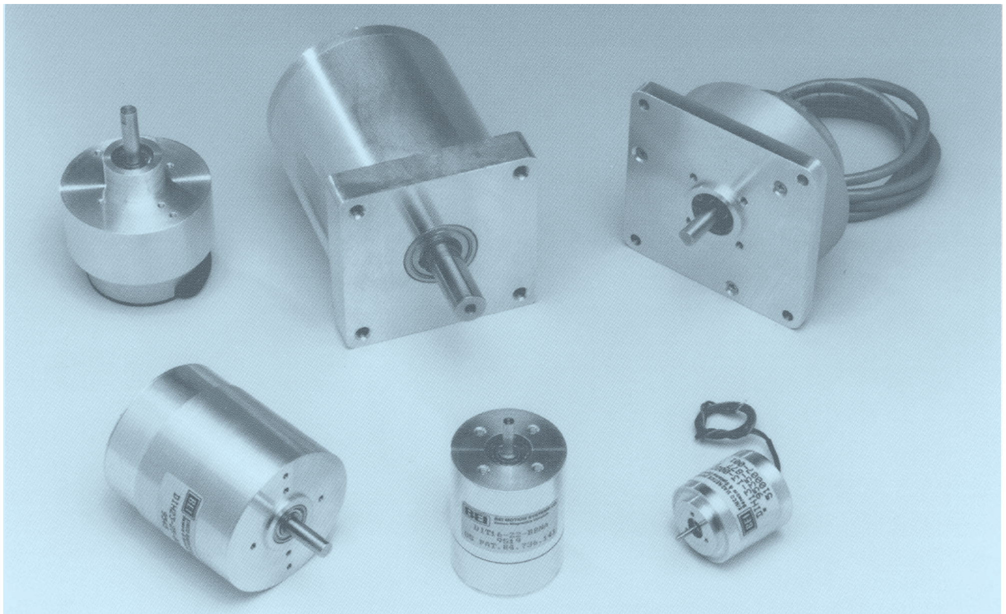


FIGURE 18:
Two-Wire Motors Available from BEI, Kimco Magnetics Division

BEI OFFERINGS

Figure 18 shows a sampling of the two-wire (and variations thereof) BLDC motors available from BEI, Kimco Magnetics Division. Sizes range from 1.1” diameter to 4” diameter, with shaft output power ratings ranging from sub-fractional to about 1/3 horsepower. Typical configurations include open-loop or closed-loop, two quadrant control. BEI also offers a patented configuration that, on some models, enables change of rotational direction simply by reversing polarity to the two motor leads - exactly as with the PMDC motor. This feature is especially important in product upgrade programs where space or resources are limited and an exact form, fit and function replacement is desired. In summary, two-wire BLDC motors offer a simple approach in converting from PMDC brush-type technology to BLDC technology. When it comes to product life, reliability, maintenance, controllability, user interface simplicity, and total cost, the two-wire BLDC motor is clearly the motor of choice.

GLOSSARY

MOTOR PARAMETERS

Peak Torque (T_P) - The torque that can be produced for 10 seconds without exceeding the maximum allowable winding temperature.

Continuous Stall Torque (T_{CS}) - This is the amount of torque that can safely be produced over an indefinite period of time under a stalled rotor condition. This value is measured with the motor mounted on an aluminum plate (6” x 6” x 1.8”) heat sink, to the maximum allowable temperature of the windings.

Moment of Inertia (J_m) - The moment of inertia of the rotating member, equal to Wk^2/g where W = weight (oz), k = radius of gyration (in.) and g = acceleration due to gravity (386 in/Sec^2).

Motor Constant (K_m) - A figure of merit of the motor. The higher the value for a given volume of motor, the more powerful the motor.

Electrical Time Constant (T_E) - This value is equal to L/R (inductance divided by resistance). It is also equal to the time it takes for the current to reach 63% of its steady state value when the winding is energized by a step input of voltage.

WINDING PARAMETERS

Windings may be changed to optimize parameters of a given motor model for a particular requirement. This may be accomplished without changing the basic motor constants. The winding constants are listed below:

Resistance (R_M) - The resistance between any two lines on a bi-polar motor or between line and neutral on a unipolar motor.

Torque Constant (K_t) - The torque that will be produced for a given current input.

Back EMF Constant (K_b) - The generated voltage as a function of speed.

ABOUT KIMCO MAGNETICS

WHERE MOTION TECHNOLOGY IS ON THE MOVE

Since its founding in 1974, the moving force of Kimco Magnetics has been its commitment to advancing motion technology by applying the latest magnetic concepts. The company's San Marcos, California, facility is dedicated to the design, development and production of high-performance motion devices. As part of BEI Technologies, Inc., Kimco Magnetics draws on a network of experts working in every facet of precision motion control.

Kimco Magnetics leads the industry in developing solutions to motion control through its development of specialty electromagnet devices for the most demanding applications. Our creative technical staff readily responds to all types of challenges, including those that can't be met by off-the-shelf equipment.

When you need the most advanced technology in brushless DC motors, voice coil actuators, or specialty electromagnetic devices, call BEI's Kimco Magnetics division.

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804-A Rancheros Drive, San Marcos, CA 92069 • Toll Free: (800) 572-7560 • Tel: (760) 744-5671 • Fax: (760) 744-0425 • Internet: www.beikimco.com • E-Mail: sales@beikimco.com

BEI Technologies, Inc. (Nasdaq: BEIQ) is an established manufacturer of electronic sensors and motion control products used for factory and office automation, medical and scientific equipment, military, aviation, and space systems, and transportation equipment including automobiles, trucks, and off-road equipment. The company's product portfolio includes optical encoders, brushless DC motors, voice coil actuators, potentiometric position sensors, silicon microelectromechanical (MEMS) devices, rotation rate sensors, pressure transducers, and servo systems.