AC vs DC Brushless Servo Motor

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Brushless motors are similar to AC motors since a moving magnet field causes rotor movement. Brushless motors are also similar to PM DC motors since they have predicable linear characteristics.

Is this why the brushless is sometimes called AC brushless and sometimes called DC brushless? It is the method of driving or powering the motor from which the name AC or DC is derived. The method of driving the motor will result in different effects (i.e. different torque delivered even from the same motor!).

Torque developed

Torque developed by a brushless motor depends on the control technology used. A simplified way to determine the type of control is to look at the feedback scheme. DC uses Hall sensors for feedback, whereas AC uses resolver or encoder for feedback. Each of these control methods has its strong points and advantages, which have to be reviewed to determine which is best for an application.

By applying a constant current to one winding of a three phase motor, a torque is generated. Since the winding distribution is sinusoidal, torque is not distributed evenly as the shaft is rotated through 360 degrees. As shown in Figure 1, the resulting torque generated is a function of the shaft angular position. Thus, current into a single winding generates a torque that is described by:

(1) $T = T' \times \sin(\text{electrical angle}) = T' \times \sin\phi$

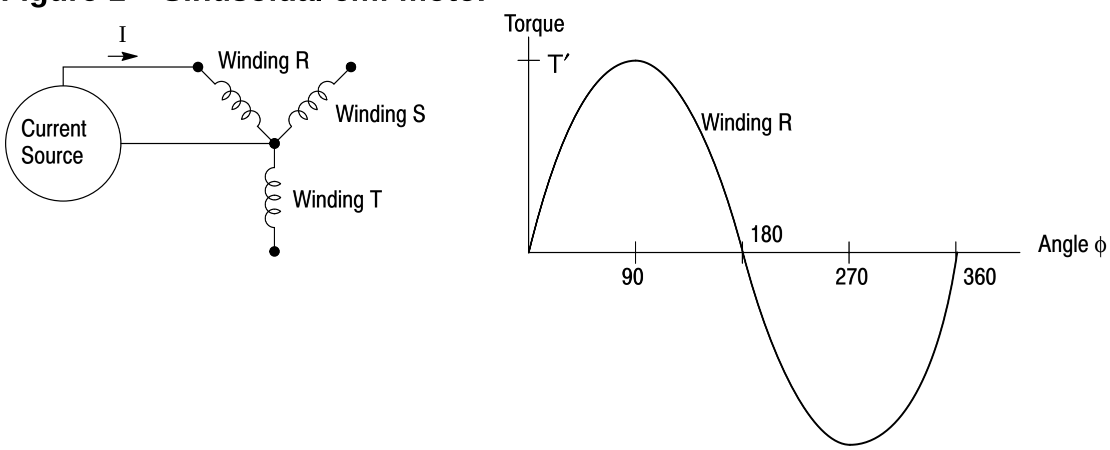
where:
T = instantaneous torque
T' = peak value of torque
ϕ is the electrical angle of the shaft

The electrical angle is different from the mechanical angle, and these are related by:

(2) $\text{electrical angle} = \frac{N}{2} \times \text{mechanical angle}$

where N is the number of poles.

Figure 1 – Sinusoidal emf motor



Equation (1) showed the torque generated by only one winding. In a three phase system, the windings are shifted by 120 electrical degrees, and the equations describing torque per winding are:

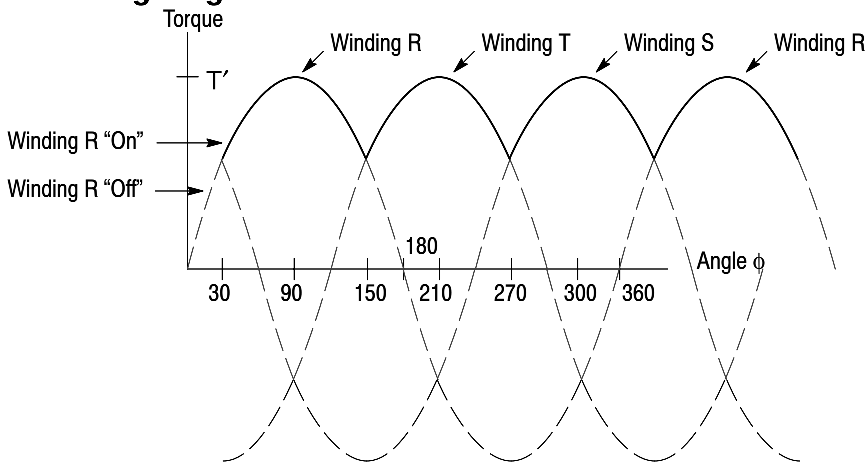
(3) $T_R = T'_{peak} \times \sin\phi$

(4) $T_S = T'_{peak} \times \sin\phi + 120°$

(5) $T_T = T'_{peak} \times \sin\phi + 240°$

Energizing winding R while the rotor is at a position of 30 electrical degrees (see Figure 2) will result in a torque being developed, forcing the shaft to rotate. The shaft will rotate to the 180 electrical degree position and stop. However, if when the shaft is at the 150 electrical degree position, the current is removed from winding R and applied to winding T, the shaft will continue to rotate. If this process is repeated (i.e., current is removed from winding T at 270 degrees and applied to winding S), the shaft will continue to rotate. By continuation of this scheme, rotation is continued.

Figure 2 – Energizing sinusoidal emf motor



This illustrates one method of controlling (commutating) the brushless motor, and, of course, other methods exist. But the control scheme, or method of commutating the sinusoidal back emf brushless motor, will affect the back emf and torque constant values, i.e., the values measured versus apparent application results may appear different. The following will cover the sine emf motor, when driven by various methods, and the results attained.

DC control/phase–neutral connected motor

A sinusoidal emf winding configuration with the neutral grounded, as shown in Figure 3, and a DC current applied to the individual coils conducting for 120 degrees would yield an effective or average back emf of:

$$(6)\quad K_E = \int_{\frac{\pi}{6}}^{\frac{5\pi}{6}} \left(\frac{K'_{E\phi} \sin\phi}{\frac{5\pi}{6} - \frac{\pi}{6}} \right)$$

where $K'_{E\phi}$ is measured phase to neutral (ϕ–N) and represents the peak value of the sinusoidal and therefore K_E is the average over the waveform.

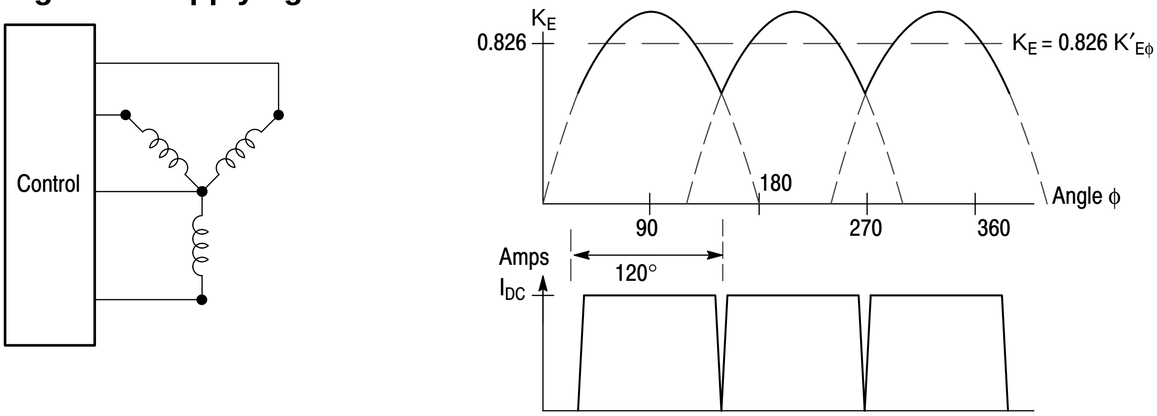
$$(7)\quad K_E = \frac{-3}{2\pi} K'_{E\phi} \left(\cos\frac{5\pi}{6} - \cos\frac{\pi}{6} \right)$$

$$(8)\quad K_E = \frac{-3}{2\pi} K'_{E\phi}\,(1.73)$$

$$(9)\quad K_E = \frac{2.59}{\pi} K'_{E\phi}$$

$$(10)\quad K_E = 0.826\, K'_{E\phi}$$

Figure 3 – Applying a DC current to a sinusoidal emf motor



The relationship between voltage constant and torque constant are related through:

(11) Metric $K_{T\phi} = K_{E\phi}$ (N–m/Amps, v/r/s)　　v/r/s = volts/radians/second

(12) English $K_{T\phi} = 1.35\ K_{E\phi}$ (oz–in/Amp, V/kRPM)　　V/kRPM = volts/1000 revolutions/minute

Thus the expression for torque becomes:

(13) $T = K_T\ I$

(14) Metric $T = 0.826\ K'_{E\phi}\ I$ (torque in N–m, $K_{E\phi}$ in v/r/s)

or

(15) English $T = 1.35\ K_{E\phi}\ I$

(16) $T = 1.35 \times 0.826\ K'_{E\phi}\ I$

(17) $T = 1.11\ K'_{E\phi}\ I$ (torque in oz–in, K_E in V/kRPM)

Keep in mind that K_E is easy to measure and verify, whereas the torque constant is more difficult to measure. The back emf or voltage constant is measured on a phase to neutral basis, and current is the DC level when the winding is "On".

With the commutation scheme as explained above, the torque will fluctuate between a high point and a low point, thus giving rise to torque ripple. Figure 4 reveals that the minimum amount of torque will be:

(18) $T_{min} = T' \times \sin(30) = 0.5T'$

The maximum torque is:

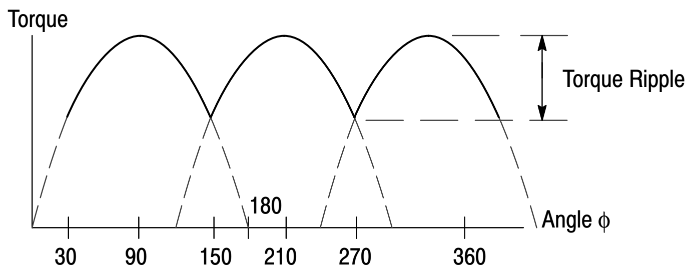
(19) $T_{max} = T' \times \sin(90) = T'$

The torque ripple percent is:

(20) $\% = \frac{Max - Min}{Max} = \frac{1 - 0.5}{1} = 50\%$

Note that the control should be designed to reduce this torque ripple to an acceptable level for the given application.

Figure 4 – Torque ripple from the motor shown in Figure 2



DC control/phase–phase connected motor

In the above discussion, only current in one winding was allowed. If positive and negative currents are applied (that is, applying power across two motor windings), a different picture emerges. As can be seen in Figure 5, with winding R energized (in the 30 electrical degree position), a positive torque is developed. If at the same time a negative current of equal magnitude is applied to winding T, then a positive torque is also developed. The sum of these two torques will be:

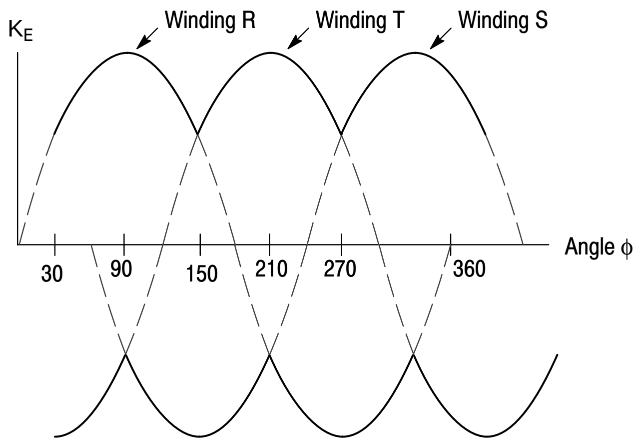
(21) $T = T_R + (-T_T)$

(22) $T = T' \sin\phi - T' \sin(\phi + 240^\circ)$

(23) $T = T' \times 0.5 - T' (-1.0)$

(24) $T = T' \times 1.5$

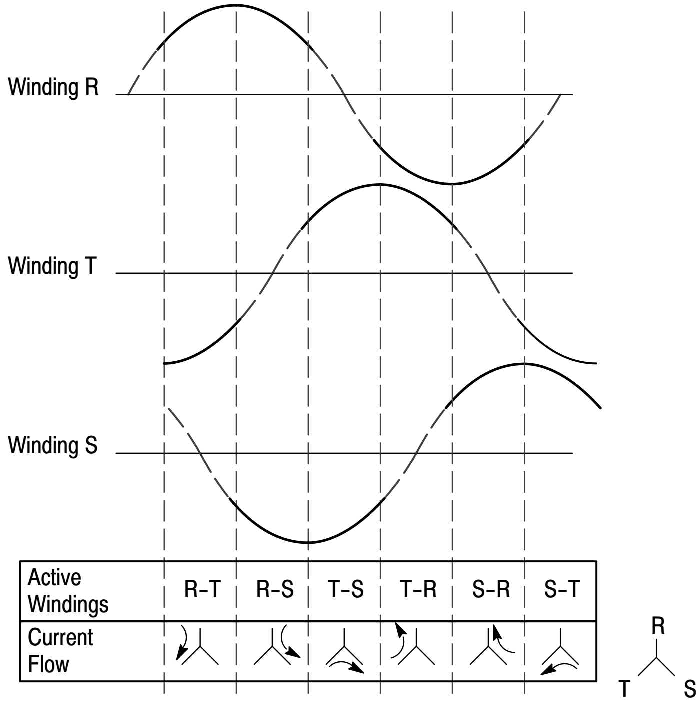
Figure 5 – Energizing a sinusoidal emf motor to produce torque



This shows that the torque developed by energizing two windings simultaneously is 50% greater than energizing only one winding. This torque results in shaft rotation, and when the shaft reaches the 90 electrical degrees position, current is removed from winding T and applied to winding S (negative current). Again positive torque is developed and rotation continues. An illustration of timing involved when switching (or commutation) from winding to winding is shown in the timing diagram of Figure 6. Since there are six different commutation sections for 360 degrees of rotation, this commutation scheme is referred to as six–step, or DC brushless, control.

Figure 6 – Applying a DC current to two windings of a sinusoidal emf motor

Solid lines indicate when the windings are energized.



This commutation scheme, i.e., a sinusoidal emf with floating neutral, and the DC control as shown in Figure 7 could have the winding conducting for 60 degrees. This yields an average back emf of:

$$(25)\quad K_E = \int_{\frac{\pi}{3}}^{\frac{2\pi}{3}} \left(\frac{K'_{E\phi\phi} \sin\phi}{\frac{2\pi}{3} - \frac{\pi}{3}} \right)$$

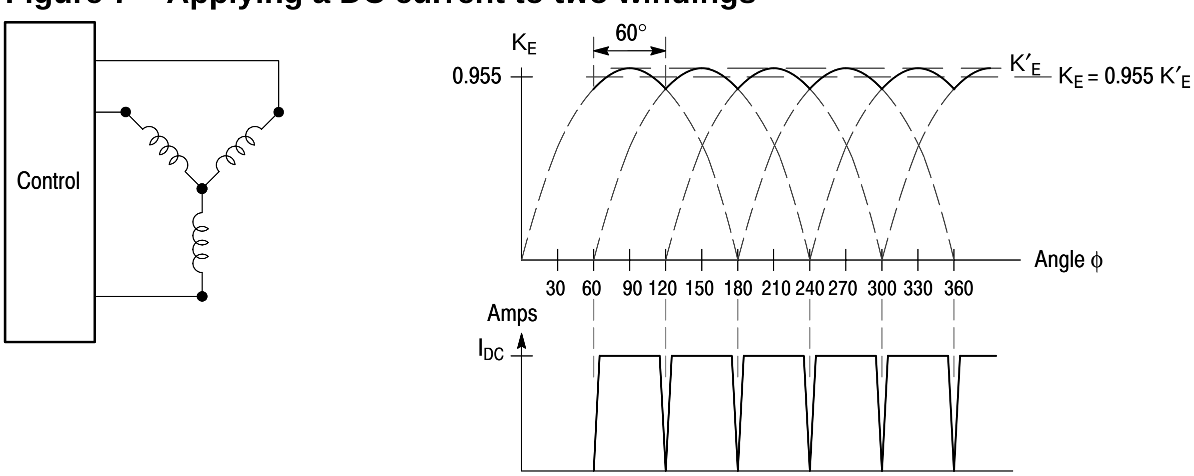
where K'_E is measured phase to phase (ϕ–ϕ) and represents the peak value of the sinusoidal, and K_E is therefore the average over the waveform.

$$(26)\quad K_E = \frac{-3}{\pi} K'_{E\phi\phi} \left(\cos \frac{2\pi}{3} - \cos \frac{\pi}{3} \right)$$

$$(27)\quad K_E = \frac{-3}{\pi} K'_{E\phi\phi}$$

$$(28)\quad K_E = 0.955\, K'_{E\phi\phi}$$

Figure 7 – Applying a DC current to two windings



Equations (11) and (12) state the relationship between voltage constant and torque constant.

Thus, the expression for torque, with a floating neutral, becomes:

(29) $T = K_T I$

(30) Metric $T = 0.955 K'_{E\phi\phi} I$ (torque in N–m, K_E in v/r/s)

or

(31) English $T = 1.35 K_{E\phi\phi} I$

(32) $T = 1.35 \times 0.955 K'_{E\phi\phi} I$

(33) $T = 1.289 K'_{E\phi\phi} I$ (torque in oz–in, K_E in V/kRPM)

The back emf or voltage constant is measured on a phase to phase basis, and current is the DC level through the winding, i.e., the DC level when the winding is “On.” Note that Equations (13) through (17) cannot be directly compared to Equations (29) through (33) due to the different “average” values of energized windings, i.e., measuring and energizing phase neutral vs. phase phase.

With the commutation scheme above, the maximum torque developed occurs at 60 degrees and is:

(34) $T_{max} = T' (\sin(60) - \sin(300))$

(35) $T_{max} = T' \times 1.73$

The maximum torque is:

(36) $T_{min} = T' \times 1.5$

The torque ripple percent is:

(37) $\% = \frac{Max - Min}{Max} = \frac{1.73 - 1.5}{1.73} = 13.2\%$

This represents lower ripple than the situation presented by Equation (20), but comes with the addition of bidirectional current flow. Torque ripple depends on the control scheme. Again the control must be designed to reduce ripple to acceptable application tolerances.

AC control/sine motor

Suppose that the application of a current whose amplitude is a function of angular position, Equation (38), is applied simultaneously to all three windings (see Figure 8). Since there are feedback devices to generated sinusoidal position information, this approach is possible. When using this approach, the control is often referred to as a sine controller. When energizing all three windings, the output torque developed by the brushless motor is then equal to the sum of the torques in all three phases:

(38) $I = I' \times (\sin\phi + \phi phase)$

(39) $T_M = T_R + T_S + T_T$

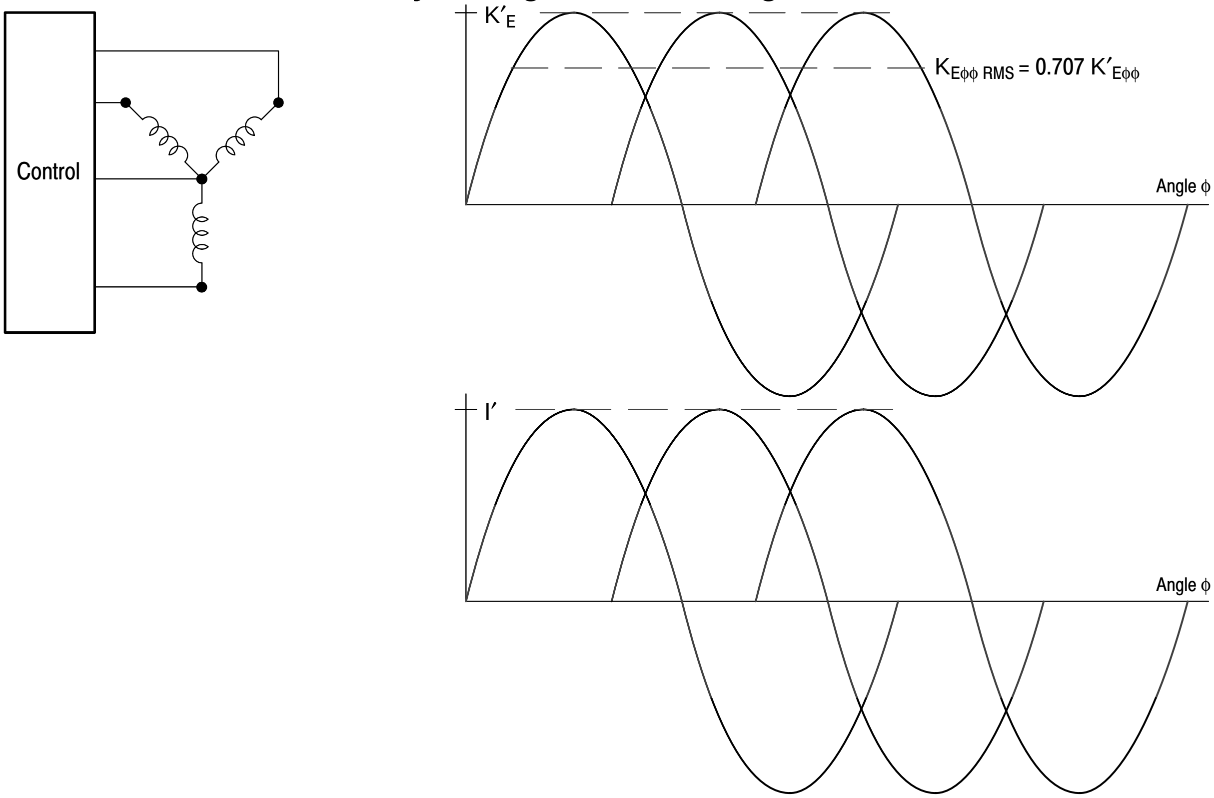
The individual phase torques are:

(40) $T_R = K_T (R) I' (\sin \phi)$

(41) $T_S = K_T (S) I' (\sin \phi) + 120^\circ$

(42) $T_T = K_T (T) I' (\sin \phi) + 240^\circ$

Figure 8 – Driving the sinusoidal emf motor with sinusoidal current simultaneously through three windings.



Note that since the windings are also sinusoidal, previously explained, the individual torque constants are:

(43) $K_T(R) = K'_{T\phi}\,(\sin\ \phi)$

(41) $K_T(S) = K'_{T\phi}\,(\sin\ \phi) + 120^\circ$

(42) $K_T(T) = K'_{T\phi}\,(\sin\ \phi) + 240^\circ$

where peak values for windings R, S, and T are equal and K'_{TO} is the phase to neutral value. Thus, combining Equations (40), (41), and (42) with Equations (43), (44), and (45) results in:

(46) $T_R = K'_{T\phi}\,\sin(\phi) \times I' \sin\phi$

(47) $T_S = K'_{T\phi}\,\sin(\phi + 120^\circ) \times I' \sin(\phi + 120^\circ)$

(48) $T_T = K'_{T\phi}\,\sin(\phi + 240^\circ) \times I' \sin(\phi + 240^\circ)$

Using these equations with substitutions into Equation (39), we arrive at:

(49) $T_M = K'_{T\phi}\,I'[\sin^2\phi + \sin^2(\phi + 120^\circ) + \sin^2(\phi + 240^\circ)]$

An important note to remember here is $K'_{T\phi}$ is the peak value of the phase to neutral torque constant and I' is the peak value of the sinusoidal current (not the RMS). Equation (49) can be reduced to:

(50) $T_M = K'_{T\phi}\,I' \times 1.5$

With this commutation scheme, there is no difference between the maximum and minimum torque developed. Therefore, there is no torque ripple (ideal) when employing a sine controller with a sine emf motor. Equation (50) provides an expression for torque developed in terms of torque constant as measured from phase to neutral. However, with most motors the neutral is not accessible. Therefore, an equivalent phase to phase expression is desired. The equation is developed as follows:

(51) $K_{T\phi} \times 2 = K_{T\phi\phi}$

(52) $I' = \dfrac{I_{RMS}}{.707}$

(53) $K'_T = \dfrac{K_{T\,RMS}}{.707}$

These can be substituted into Equation (50), with the result:

(54) $T = \left(\dfrac{1.5\,K'_{T\phi\phi}}{2}\right) \times \left(\dfrac{I_{RMS}}{.707}\right) = 1.0608K'_{T\phi\phi}\,I_{RMS}$

(55) $T = \left(\dfrac{1.0608\,K_{T\phi\phi\,RMS}}{.707}\right) \times \left(I_{RMS}\right)$

(56) $T = \left(1.5\,K_{T\phi\phi\,RMS}\right) \times \left(I_{RMS}\right)$

This equation provides a relationship between torque developed, the RMS current (which can be measured), and the phase to phase torque constant of the motor. However, K_T cannot be easily measured. The saving factor is the K_E on a phase to phase basis is very easy to measure. Simply by observing the motor's back emf waveform on a scope (when driving the motor by some external means) and measuring that waveform, the value for K_E can be determined. K_E is simply volts divided by kRPM. Then, by using the appropriate conversion factor to convert from K_E to K_T, Equation (56) may be used.

K_E and K_T Relationship

The relationship between the torque constant and voltage constant can most easily be derived by analyzing the system using the metric approach. The phase to neutral analysis provides:

(57) $K_{T\phi} = K_{E\phi}$

where K_T is in N–m/amp and K_E is v/r/s.

Since in a three phase Wye connected system:

(58) $2 \times K_{T\phi} = K_{T\phi\phi}$

(59) $\sqrt{3} \times K_{E\phi} = K_{E\phi\phi}$

Therefore:

(60) $K_{T\phi\phi} = \dfrac{2}{\sqrt{3}} K_{E\phi\phi}$

(61) $K_{T\phi\phi} = 1.15473\,K_{E\phi\phi}$

$(N - m/amp) \quad (v/r/s)$

This is the basic equation (in metric) for the relationship of torque constant versus voltage constant for a three phase motor when driven with a three phase excitation. From this the other dimension systems can be derived:

(62) $K_{T\phi\phi} = 11.039 \times 10^{-3}\,K_{E\phi\phi}$

$(N - m/amp) \quad (v/r/s)$

(63) $K_{T\phi\phi} = 97.698 \times 10^{-3}\,K_{E\phi\phi}$

$(lb - in/amp) \quad (V/KRPM)$

(64) $K_{T\phi\phi} = 1.563\,K_{E\phi\phi}$

$(oz - in/amp) \quad (V/KRPM)$

Substituting Equation (60) into Equation (56) provides:

(65) $T = 1.5 \frac{2}{\sqrt{3}} K_{E\phi\phi\ RMS}\, I_{RMS}$

(66) $T = \sqrt{3}\, K_{E\phi\phi\ RMS}\, I_{RMS}$ (with K_E in v/r/s)

or:

(67) $T = K_{T\phi\phi\ RMS}\, I_{RMS}$

with:

(68) $K_{T\phi\phi\ RMS} = \sqrt{3}\, K_{E\phi\phi\ RMS}$
(N–m/amp) (v/r/s)

This provides the relationship between torque developed, the RMS current, and the measurable voltage constant of the motor. Note that current and voltage constant are expressed in RMS terms, i.e., RMS of a sinusoidal waveform. By simply measuring the motor's peak value of K_E, using a scope, the developed torque may now be easily calculated.

Table 1 summarizes the relationship of a sinusoidal emf motor when driven with either a DC drive or an AC drive. By multiplying the peak value of the sine back emf times the factor in the table, the equivalent, or RMS, value is determined. This RMS value can then be used in calculations, and the sine emf motor is treated as an ordinary PMDC motor.

Table 1

		English	**Metric**
For DC drive	K_E	0.95 V/kRPM	0.009076 v/r/s
	K_T	1.285 oz–in/amp	0.009076 N–m/amp
For AC drive	K_E	0.707 V/kRPM	0.006754 v/r/s
	K_T	1.656 oz–in/amp	0.011698 N–m/amp

Table 2 shows and example calculation for the RMS values for a motor driven as a generator at 1,000 RPM with back emf (peak value) measured as 75 V/kRPM peak phase to phase.

If the example load were 400 oz–in (2.82 N–m) and the motor were powered by a six–step control (vs. a sine control) the currents would be 4.1 Amps instead of 3.2 Amps respectively.

Table 2

		English	**Metric**
For six–step Drive	K_E	71.2 V/kRPM	0.680 v/r/s
	K_T	96.3 oz–in/amp	0.680 N–m/amp
	I	4.1 Amps	4.1 Amps
For sine Drive	K_E	53.0 V/kRPM	0.506 v/r/s
	K_T	124.2 oz–in/amp	0.877 N–m/amp
	I	3.2 Amps	3.2 Amps
Current required is calculated from the relationship where K_T is the torque current from Table 1.	$T = K_T I$		