Celera MOTION
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Sinusoidal Drive Operation with Brushless PM Motors

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OVERVIEW

The permanent magnet brushless motor, also known as; brushless DC, brushless AC, brushless servo, and synchronous motor, can be driven by two motor control configurations. Historically, motor controllers used DC square waves of current switched in six different states based on signals from hall devices spaced at 120 electrical degrees, (the six state drive). Today, most brushless motors of this type are driven by motor controllers using sinusoidal current control with space vector modulation.

Sinusoidal current control offers the most advantages in smooth motion from a smoothly rotating torque vector. Running a synchronous motor with sine waves is natural and effective because the motor generates torque proportional to angle sinusoidally. In this configuration, all three phases of the motor are used at all times and the optimum commutation angle set for maximum torque production at all times making torque proportional to current.

The challenge with selecting a motor and predicting performance using sinusoidal control comes in relating published motor data sheet parameters to actual motor operation.

This technical note explores the theory behind motor and drive interaction and more specifically provides focus on parameter conversions and torque production.

Please refer to TN-2001 for examples of motor torque production, i.e. the torque versus angle curve. Also refer to TN-2002 for more details on matching motor inductance between the motor controller and the motor.

THE 3 PHASE BRUSHLESS PM MOTOR

Most brushless motors, whether linear or rotary, have three electrical phases. It is common practice to connect the center tap of each phase together inside the motor, in a "wye" configuration, then bring out three power leads.

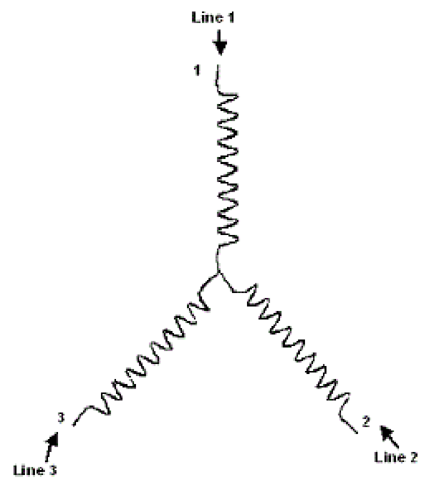


Figure 1 above is a resistor network representing a "wye" configuration. This represents three power input wires and the return of each phase connected together in a center tap inside the motor.

Based on this industry standard wye configuration, the measured parameters of the motor tend to be line-line readings. This is actually measuring a two phase on condition. When you see a datasheet for a motor you will notice the following electrical parameters, (line to line values).

Parameter	Units	Description
Kt	NM/amp	Torque Constant. It is a 1st order approximation of torque sensitivity with current for the motor. This parameter is not measured. It is calculated from the Ke below. Given the proper units, the two are equal for a Brushless PM motor (see notes below)
Ke	Volts/rad/sec	Back EMF constant. This is a measurement of the generated voltage output of a motor when being back driven. The waveform is generally sinusoidal with amplitude and frequency varying as speed changes.
R	Ohm	Electrical Resistance. This value depends on the temperature at the time of measurement.
L	Milli-Henry	Electrical Inductance. This is small signal inductance measurement using an industry standard 1khz LCR bridge/meter.
Poles		The motor pole count. The number of magnetic poles on the rotor. This includes both north and south magnet poles and it not to be confused with

		"pole pairs" a designation that some manufacturers use which is related to the electrical frequency of the motor.

Important Notes:

1. Measurements are for two phase on (or line-line) conditions. Because the motor is connected internally in a wye configuration, there is only access to one leg from each phase.
2. Kt is an approximation for a non-linear phenomenon. If a motor has saturation or high cogging torque, the actual torque versus current plot may not be linear, therefore Kt is not always a constant.
3. Ke and Kt are equal in first order approximation as long as you are in the Metric set of units. 1 volt/rad/sec = 1 NM/amp. This is, of course, considering only the two phase on driving condition traditionally associated with Six State trapezoidal drives.
4. The back emf wave form and the torque angle curve of the motor are not equivalent, because the torque angle curve includes saturation and cogging torque.
5. There are motors that use a Delta connection. They are more prevalent in AC motors and brushless motors used with traditional six state DC switching motor controllers. They are not discussed in this technical memo.

The Torque versus Angle Curve

In all electromagnetic synchronous rotary devices, torque is a function of both current applied to the winding and the position of the rotor w.r.t. the stator phase. Measurement of this typically yields a torque versus angle curve. It is the true representation of a motor's ability to create torque at any specific angle. It is also a map of how torque changes with angle and current, including the effects of phase balance, cogging torque, and saturation within the motor.

As a motor is driven by a sinusoidal motor controller, current is applied to all three phases of the motor in a sinusoidal pattern with angle. While this method approaches an ideal system, i.e. sinusoidal current and sinusoidal torque versus angle, it can also be impacted from items like cogging torque or a mismatch between the control sine waves and the motor's torque angle characteristics.

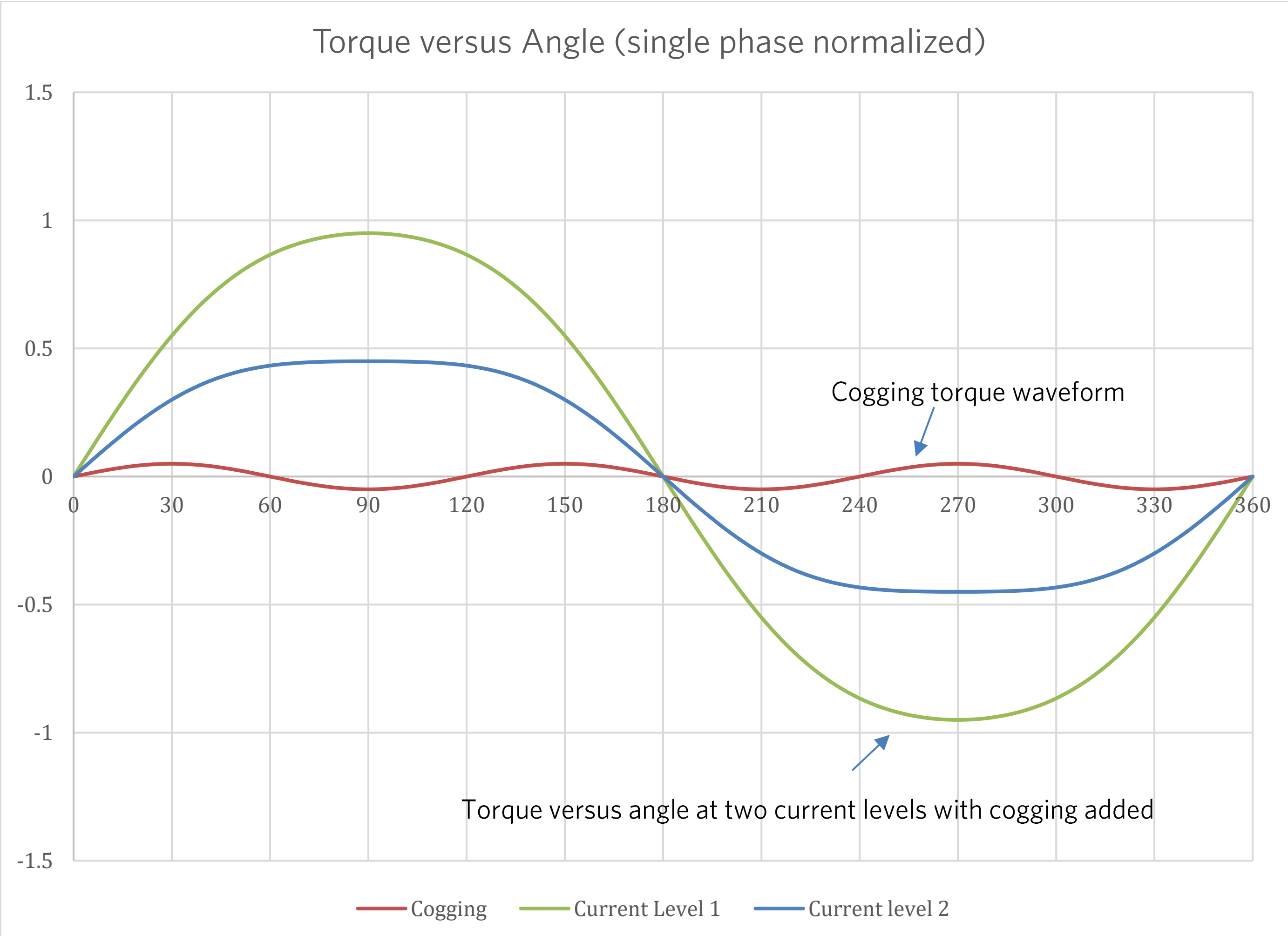


Figure 2 above shows a typical torque versus angle curve for a rotary motor. It is depicting only one of the three phases of the motor. Two levels of current have been selected to show how torque changes with current. Cogging torque at 5% of the rated torque value is shown. Notice how the cogging torque impacts the total torque by reshaping the total torque output, especially at lower current levels.

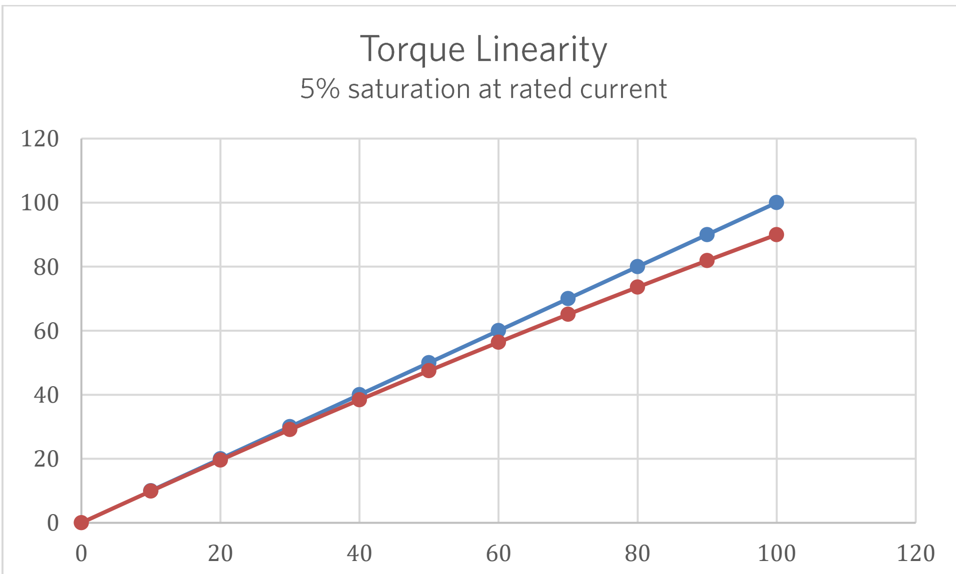
The torque angle curve is critical to the performance of the motor. From Figure 2 above it is clear that at current level 2, essentially 50% of the motor's rated current, the cogging torque plays a role to reduce the torque output at the peak torque position. This adds to the non-linear attributes of the torque versus current curve eventually causing torque ripple when all three phases are considered. There is not a constant rotating flux or torque vector.

It also causes the torque versus angle curve to deviate from the back emf curve in shape and amplitude. Therefore, the torque constant being equal to the back emf constant is a first order approximation.

Torque Linearity

Many motors are designed to optimize torque and minimize weight. This can force the designer to make compromises in copper volume versus steel volume. Magnetic steel has high Ni content for reduced losses and high efficiency, but also saturates prematurely when flux density is high.

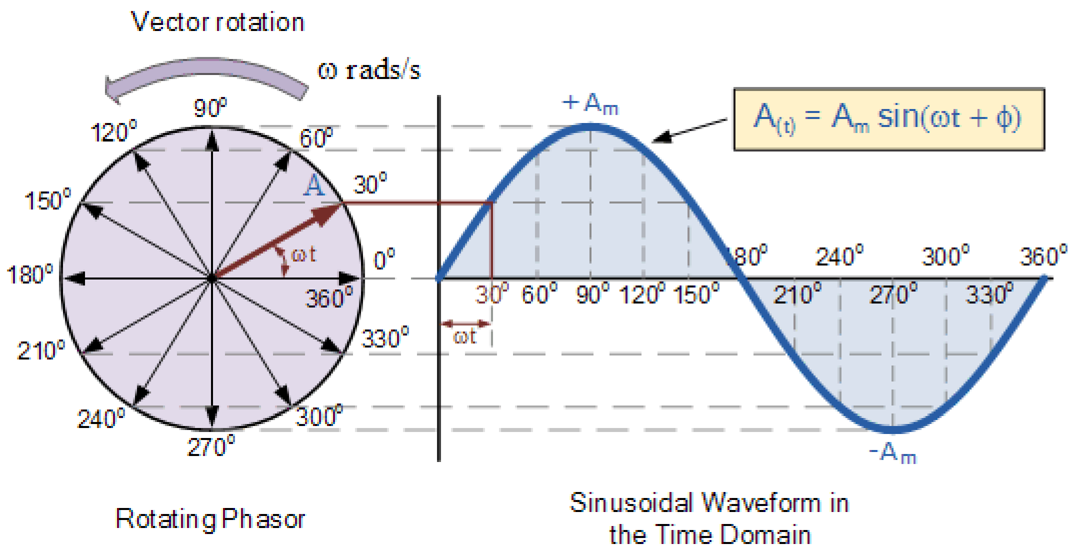
When current is increased in the motor winding it is not uncommon to find that steel someplace in the magnetic circuit saturates. It is common to find that even at their thermal rating, many motors exhibit 5% saturation. This saturation value gets worse as current is increased into the intermittent torque range of the motor.



This is more evidence to debunk the theoretical notion that Kt = Ke in brushless permanent magnet motors. Every motor is different, a designer may have optimized Km and weight knowing that there would be saturation.

The Sinusoidal Current Control Drive

Applying sinusoidal current to all three motor phases with amplitude that is function of angle can produce a constantly rotating current or torque vector, (sans the above sections limitation). The resulting motor torque being equal to the vector sum of the torques of all three phases.



The equations are as follows;

Tphase a = Kt phase a * sin Φ
Tphase b = Kt phase b * sin (Φ + 120)
Tphase c = Kt phase c * sin (Φ + 240)

Since the phases of the motor are also sinusoidal, (sans issues with cogging torque and saturation), the phase torque constants are as follows, (Kt values are per phase, not line-line measured values);

Kt phase a = Kt a * sin Φ
Kt phase b = Kt b * sin (Φ + 120)
Kt phase c = Kt c * sin (Φ + 240)

Kt a, Kt b, and Kt c are the single phase torque constants. Note: when measured per above we are measuring a two phase on condition.

Assuming that the amplitude of phase a, b, and c are the same and the torque versus angle for each phase is sinusoidal, combining the input current wave forms and the motor torque wave forms provide the following;

Tphase a = Kt a * sin Φ * sin Φ
Tphase b = Kt b * sin (Φ+120) * sin (Φ+120)
Tphase c = Kt c * sin (Φ+240) * sin (Φ + 240)

Combining these equations with substitutions from above we come to;

$$T_{motor} = K_t * i\,[\sin^2 \Phi + \sin^2 (\Phi+120) + \sin^2 (\Phi+240)]$$

$$T_{motor} = K_{t\,phase} * i * 1.5$$

Where: Kt = peak value of the per phase torque angle curve
i = peak value of the per phase current sinusoid (not the RMS value).

Important Notes:
1. Both torque angle curves and current input curves are assumed to be pure sinusoids
2. Assumes all three the sinusoids for both motor and controller have the same amplitude

In real world cases torque ripple results from non-linear aspects of cogging torque, phase balance in the motor, and phase balance in the motor controller.

Kt and Ke Measured versus Actual for Sinusoidal Control

As stated above, the three phase permanent magnet brushless motor is normally connected in a "wye" connection where the center tap for each phase is internally connected. Only three wires are accessible external. All measurements are for a line-line or a two phase on condition.

All of the theory above assumes a per-phase torque constant Kt and assumes that input current is supplied to the neutral (center tap) connection. In order to reconcile this with datasheet measured values, a conversion to single phase is required.

Kt = Ke in metric units for PM synchronous motors.

$$K_{t\,line\text{-}line} = 2 * K_{t\,phase}$$

$$Sqrt(3) * K_{e\,phase} = K_{e\,line\text{-}line}$$

$$K_{t\,sine} = Sqrt(3) * K_{e\,line\text{-}line} / 2$$

$$K_{t\,sine} = .866 * K_{e\,line\text{-}line}$$

Where Kt sine uses the peak of the driving sinewave, not the RMS value. In most motor data sheets you will find both Kt and Kt sine values. They are both line to line values.

MOTOR CONSTANT K_m

A widely used figure of merit to compare motors and size motors is the motor constant Km. A motor's Km is a measure of its ability to create torque as a function of how much heat is dissipated.

This figure of merit can also be used to measure a motors ability to generate torque under a voltage limited case. For example, in low voltage applications, motor resistance becomes a limiting factor in attaining current, therefore, limiting the torque production. A motor with a high Km will allow more current into the winding for a given voltage, (assuming Kt is fixed in both motors). This is directly related to the amount of usable area for copper the motor has.

Km = Kt/ SQRT(R), the units are in NM/watt$^{1/2}$

When making this calculation, it is critical to understand the parameters. For example, Kt and R must both be line to line value for accuracy. If you use Kt sine you must use the proper R per phase.

Km = Kt^2/R is another method of this calculation. It is important to compare units when comparing motor Km value.

CONCLUSION

Modern servo motor controllers, (also called drivers), all use sinusoidal current control. This is the preferred method of driving a three phase brushless synchronous motor with sinusoidal torque versus angle curves. Six state control arrived early in the technology cycle shift from DC to Brushless DC motors when microcontrollers and DSP based controllers were not available. Today it is rare to find a six state motor controller in a precision servo control application.

There are many factors to be considered in selecting a motor. Assuming smooth motion is desired, sinusoidal control is paramount. Other factors like cogging torque and torque linearity must also be considered. For example, slotless motors have excellent torque linearity and zero cogging. Their absolute torque output for their size is lower than a slotted motor, but it really depends on how the slotted motor is going to be utilized and will all of the extra torque be available.