

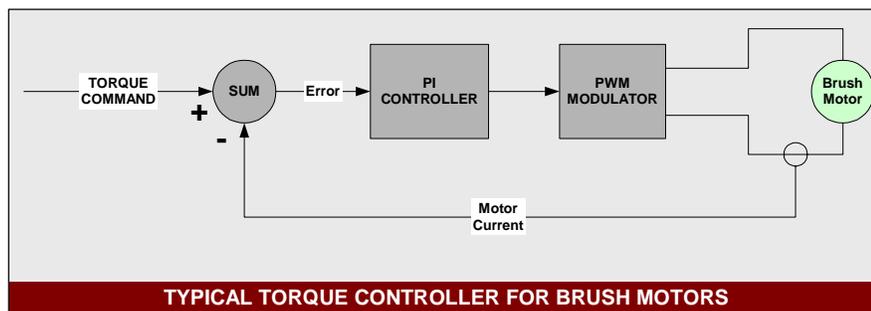
What is 'Field Oriented Control' and what good is it?

Using brushless servo motors and drives in your next new product? You have probably seen the buzzwords: 'Trapezoidal', 'Sinusoidal', and 'Field Oriented Control'. You will need to understand what they mean so that you can make the right choice for your design.

During the last decade or two, servomotors have evolved from largely brush types to brushless. This has been driven by lower maintenance and higher reliability of brushless motors. As brushless motors have become more prevalent during this period, the circuit and system techniques used to drive them have evolved as well. The variety of control schemes has led to a similar variety of buzzwords that describe them.

Most high performance servo systems employ an inner control loop that regulates torque. This inner torque loop will then be enclosed in outer velocity and position loops to attain the desired type of control. While the designs of the outer loops are largely independent of motor type, the design of the torque loop is inherently specific to the motor being controlled.

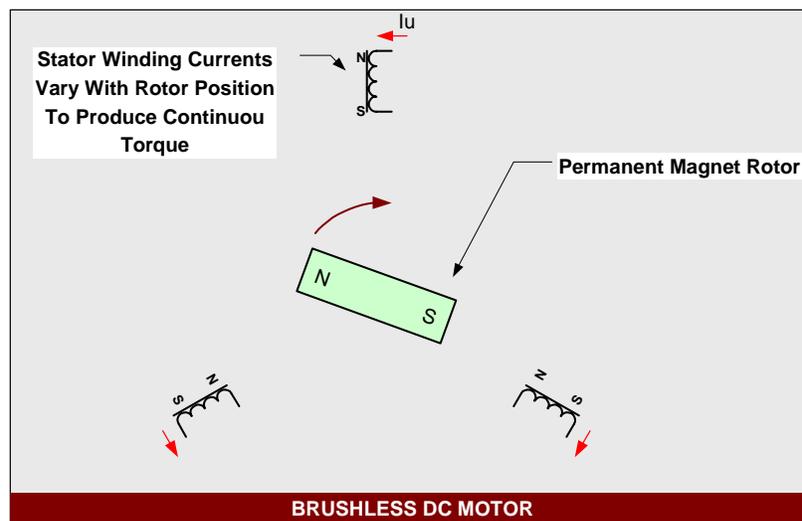
Torque produced by a brush motor is fairly easy to control because the motor commutates itself. Torque is proportional to the dc current into the two terminals of the motor, irrespective of speed. Torque control can therefore be implemented by a P-I feedback loop which adjusts the voltage applied to the motor in order to minimize the error between requested and measured motor currents.



Because brushless motors are not self-commutating, they are more complicated to control. Brushless motors have three windings, rather than two. The currents and voltages applied to the motor windings must be controlled independently and correctly as a function of rotor position in order to produce useful torque. The electronics required to drive brushless motors is therefore substantially more complex than that for brush motors.

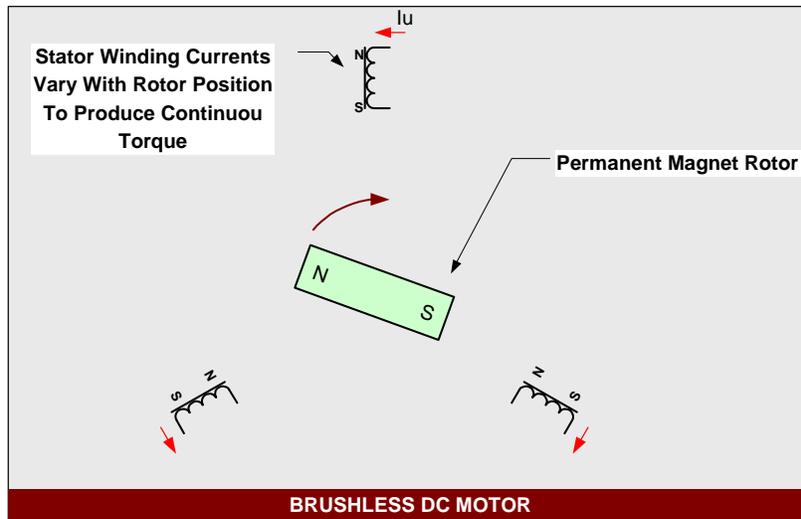
Brushless Motor Basics

In its simplest form, a brushless dc motor consists of a permanent magnet, which rotates (the rotor), surrounded by three equally spaced windings, which are fixed (the stator). Current flow in each winding produces a magnetic field vector, which sums with the fields from the other windings. By controlling currents in the three windings, a magnetic field of arbitrary direction and magnitude can be produced by the stator. Torque is then produced by the attraction or repulsion between this net stator field and the magnetic field of the rotor.



For any position of the rotor, there is an optimal direction of the net stator field, which maximizes torque; there is also a direction, which will produce no torque. If the permanent magnet rotor is in the same direction as the field produced by the net stator field, no torque is produced. The fields interact to produce a force, but because the force is in line with the axis of rotation of the rotor, it only serves to compress the motor bearings, not to cause rotation. On the other hand, if the stator field is orthogonal to the field produced by the rotor, the magnetic forces work to turn the rotor and torque is maximized.

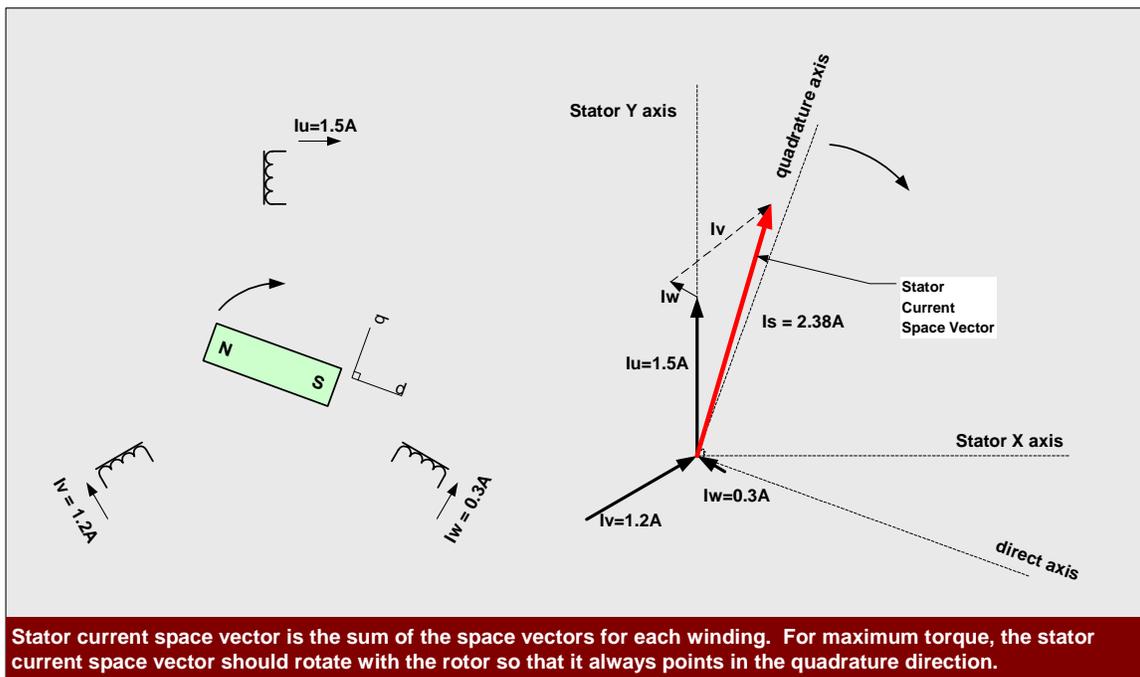
A stator field with arbitrary direction and magnitude can be decomposed into components parallel and orthogonal to the rotor field. In this case, only the orthogonal (quadrature) component produces torque, while the parallel (direct) component produces useless compression forces. For this reason, an efficient brushless motor drive will function so as to minimize the direct component of the stator field and maximize the quadrature component.



For the purposes of control system modeling and analysis, it is the convention to work in terms of winding currents rather than stator magnetic field. This is because motor currents are easily measured externally while fields (actually flux) are not.

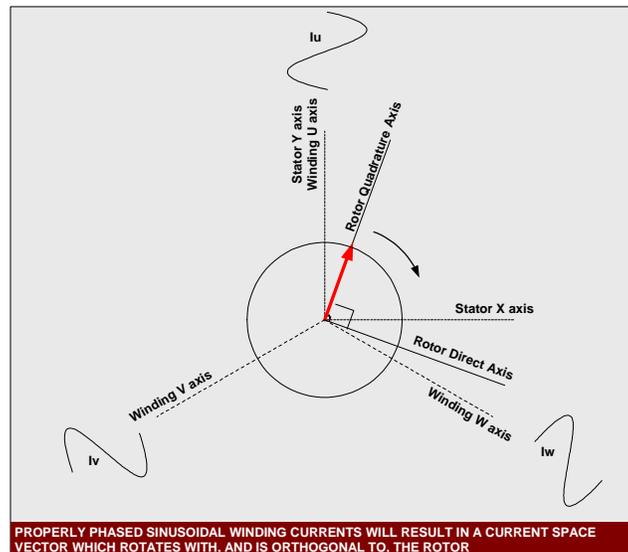
In a brushless motor, the stator field is produced by current flow in three equally spaced stator windings. Because these windings are mechanically located 120 degrees apart, they each produce a field vector component that is oriented 120 degrees from the other two. These three components sum to produce the net magnetic field of the stator.

In order to model the fields produced by the stator windings in terms of winding current, 'current space vectors' are used. The current space vector for a given winding has the direction of the field produced by that winding and a magnitude proportional to the current through the winding. This allows us to represent the total stator field as a current space vector that is the vector sum of three current space vector components, one for each of the stator windings. An intuitive way to view the stator current space vector is as a fictitious current that would flow in a single fictitious winding that rotates so as to produce the same stator field direction and magnitude as the combination of three real currents through real stator windings.



Just as with the stator field, the stator current space vector can be broken into orthogonal components in parallel with, and perpendicular to, the axis of the rotor magnet. The quadrature current component produces a field at right angles to the rotor magnet and therefore results in torque, while the direct current component produces a field that is aligned with the rotor magnet and therefore produces no torque. A good control algorithm will minimize the direct component of stator current since it only serves to produce waste heat and aggravate bearing wear. Winding currents will be adjusted so as to produce a current space vector that lies exclusively in the quadrature direction. Torque will then be proportional to the magnitude of the current space vector.

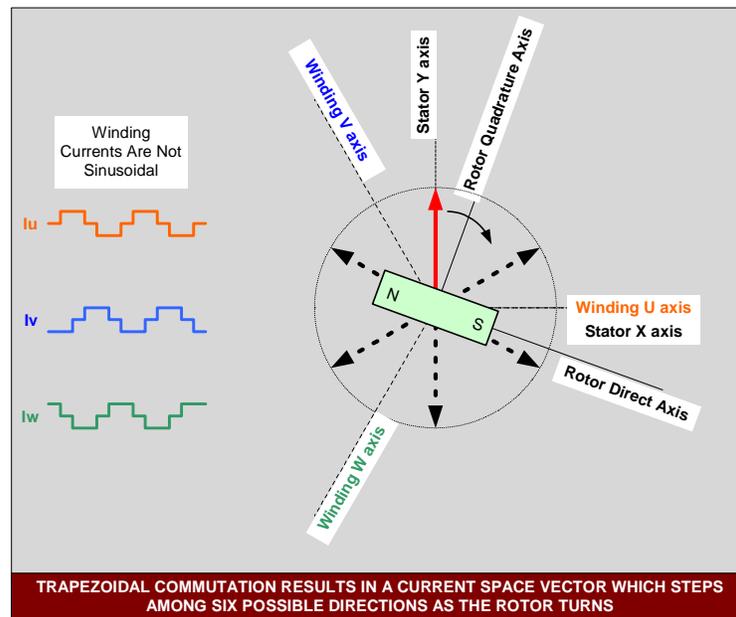
In order to efficiently produce constant smooth torque, the stator current space vector should ideally be constant in magnitude and should turn with the rotor so as to always be in the quadrature direction, irrespective of rotor angle and speed. While the stator current space vector may be constant in magnitude and direction if viewed from the rotating frame of reference of the rotor, from the fixed frame of the stator the current space vector describes a circle as the motor turns. Because the current space vector is produced by the vector sum of components from each of the motor windings, and because the three windings are physically oriented on axes that are 120 degrees apart from each other, the motor currents should ideally be three sinusoids, each phase shifted 120 degrees from the other two.



The sinusoidal winding currents should also be phased with respect to rotor angle so that the direct component of the stator current space vector is minimized (zero) and the quadrature component is maximized. This is the ideal case, and is achieved with varying degrees of success by different brushless motor control schemes.

Trapezoidal Commutation

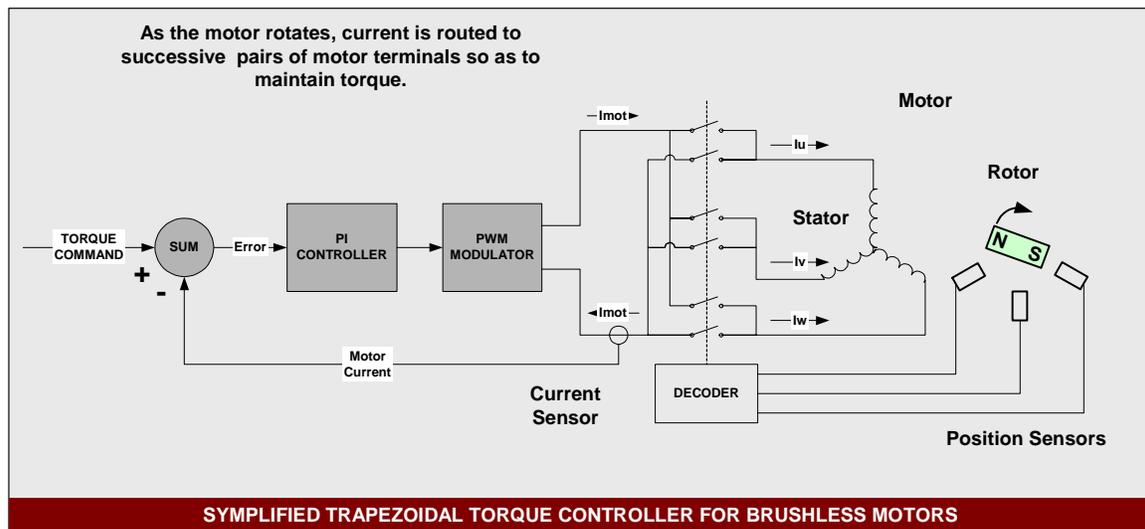
One of the simplest methods of control for dc brushless motors uses what is termed 'Trapezoidal' commutation. In this scheme, current is controlled through motor terminals one pair at a time, with the third motor terminal always electrically disconnected from the source of power. Three Hall devices embedded in the motor are usually used to provide digital signals which measure rotor position within 60 degree sectors and provide this information to the motor controller. Because at any time, the currents in two of the windings are equal in magnitude and the third is zero, this method can only produce current space vectors having one of six different directions. As the motor turns, the current to the motor terminals is electrically switched (commutated) every 60 degrees of rotation so that the current space vector is always within the nearest 30 degrees of the quadrature direction. The current waveform for each winding is therefore a staircase from zero, to positive current, to zero, and then to negative current. This produces a current space vector that approximates smooth rotation as it steps among six distinct directions as the rotor turns.



A block diagram of a trapezoidal brushless motor drive is shown in figure 1. A PI controller is used for current control. The desired torque is compared against the measured current to produce an error signal. The current error is then integrated (I) and amplified (P) to produce an output correction, which tends to reduce the error. The output of the P-I controller is subsequently pwm modulated and provided to the output bridge. This works to maintain a constant current in whatever windings are presently being driven.

Commutation is performed independently of the current control. Position signals from the Hall devices in the motor are used to select the appropriate pair of motor terminals to be driven by the output bridge. The remaining terminal is left disconnected.

Current sensing circuitry is designed so that current is always measured in the active winding pair and fed back to the current control loop.



Trapezoidal commutation performs adequately for many applications, but it has its shortcomings. Because the current space vector can only point in six discrete directions, it is misaligned from the optimal direction by anywhere from 0 to 30 degrees. This causes torque ripple of about 15% ($1 - \cos(30)$) at a frequency of six times the electrical rotational speed of the motor. The misalignment of the current space vector also represents a loss in efficiency, since some of the winding current produces no torque. Furthermore, the switching of active terminals introduces a transient to the current control loop six times per electrical revolution of the motor. This causes an audible 'click' and can make the motor difficult to control with precision at slow speeds.

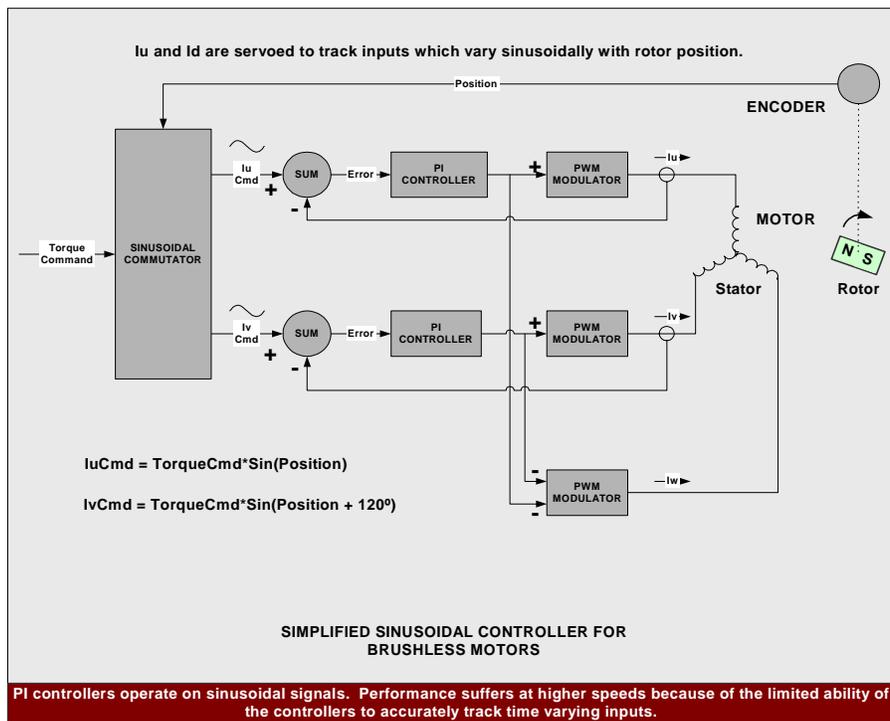
Sinusoidal Commutation

Trapezoidal commutation is inadequate to provide smooth and precise motor control of brushless dc motors, particularly at low speeds. Sinusoidal commutation solves this problem.

Sinusoidally commutated brushless motor controllers attempt to drive the three motor windings with three currents that vary smoothly and sinusoidally as the motor turns. The relative phases of these currents are chosen so that they should result in a smoothly rotating current space vector that is always in the quadrature direction with respect to the rotor and has constant magnitude. This eliminates the torque ripple and commutation spikes associated with trapezoidal commutation.

In order to generate smooth sinusoidal modulation of the motor currents as the motor turns, an accurate measurement of rotor position is required. The Hall devices provide only a coarse measure of rotor position and are inadequate for this purpose. For this reason, angle feedback from an encoder, or similar device, is required.

A block diagram of a sinusoidal brushless motor drive is shown in figure 2. This scheme uses a separate current loop for each of two motor winding currents. Since the motor is WYE wired, the current in the third motor winding is equal to the negative sum of the currents in the first two windings (Norton current law), and therefore cannot be separately controlled.

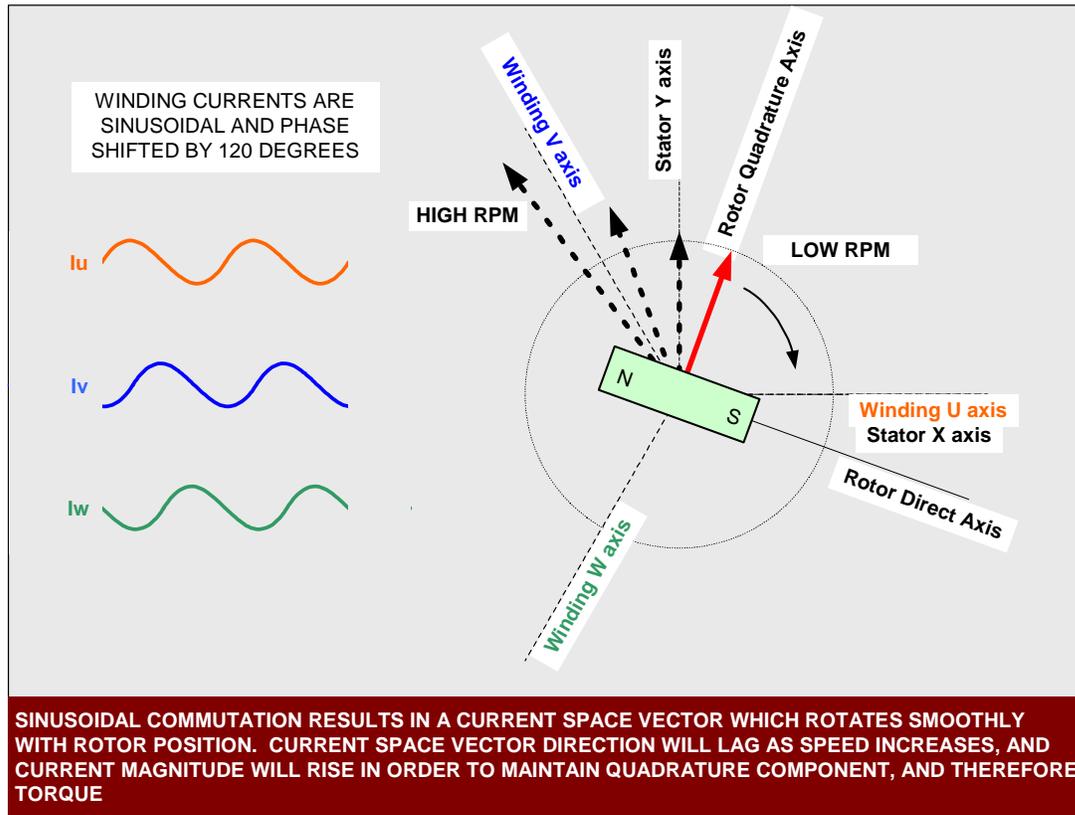


Since the winding currents must combine to produce a smoothly rotating current space vector of constant magnitude, and because the stator windings are oriented 120 degrees apart from each other, currents in each winding must be sinusoidal and phase shifted by 120 degrees. Position information from the encoder is used to synthesize two sinusoids, one 120 degrees phase shifted from the other. These signals are then multiplied by the torque command so that the amplitudes of the sinewaves are proportional to desired torque. The result is two sinusoidal current command signals appropriately phased to produce a rotating stator current space vector in the quadrature direction.

The sinusoidal current command signals are provided as inputs to a pair of P-I controllers that regulate current in the two appropriate motor windings. The current in the third motor winding is the negative sum of the currents in the controlled windings and therefore cannot be separately controlled. The output from each P-I controller is fed to a pwm modulator and then to the output bridge and two motor terminals. Voltage applied to the third motor terminal is derived as the negative sum of the signals applied to the first two windings, as appropriate for three sinusoidal voltages each separated by 120 degrees.

To the extent that the actual output current waveform accurately tracks the sinusoidal current command signals, the resulting current space vector is smoothly rotating, constant in magnitude and oriented in the quadrature direction, as desired.

Sinusoidal commutation results in smoothness of control that is generally unachievable with trapezoidal commutation. However, while it is very effective at low motor speeds, it tends to fall apart at high motor speeds. This is because as speed goes up the current loop controllers must track a sinusoidal signal of increasing frequency. At the same time they must overcome the motor back emf that also increases in amplitude and frequency as speed goes up.

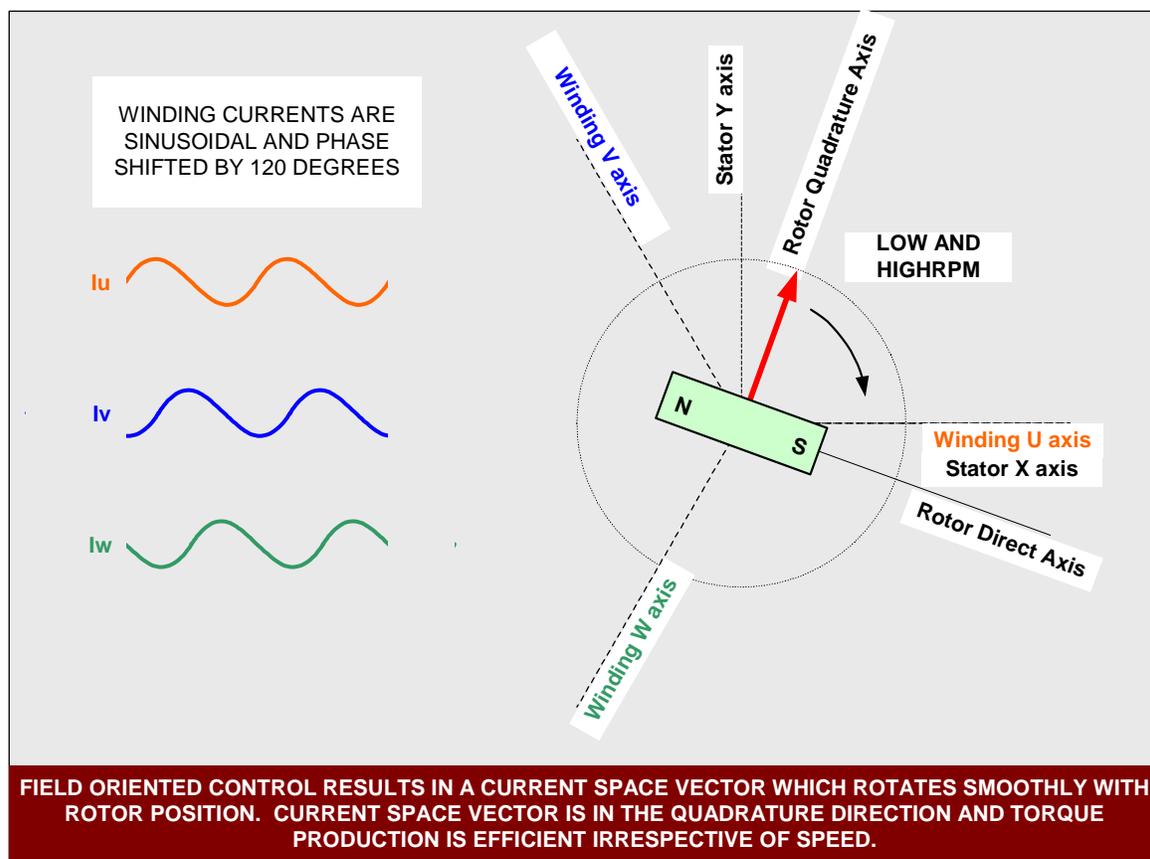


Because the P-I controllers have limited gain and frequency response, the time-variant perturbations to the current control loop cause phase lag and gain error in the motor currents. Higher speeds result in larger errors. This perturbs the direction of the current space vector relative to the rotor, causing it to shift away from the quadrature direction. When this happens, less torque is produced by a given amount of current and therefore more current is required to maintain torque. Efficiency deteriorates.

This degradation continues as speed increases. At some point motor current phase shift crosses through 90 degrees. When this happens torque is reduced to zero. With sinusoidal commutation, speeds above this point result in negative torque and are therefore not achievable.

Field Oriented Control

The fundamental weakness of sinusoidal commutation is that it attempts to control motor currents that are time variant in nature. This breaks down as speeds and frequencies go up due to the limited bandwidth of P-I controllers. Field Oriented Control solves this problem by controlling the current space vector directly in the d-q reference frame of the rotor. In the ideal case, the current space vector is fixed in magnitude and direction (quadrature) with respect to the rotor, irrespective of rotation. Because the current space vector in the d-q reference frame is static, the P-I controllers operate on dc, rather than sinusoidal signals. This isolates the controllers from the time variant winding currents and voltages, and therefore eliminates the limitation of controller frequency response and phase shift on motor torque and speed. Using Field Oriented Control, the quality of current control is largely unaffected by speed of rotation of the motor.

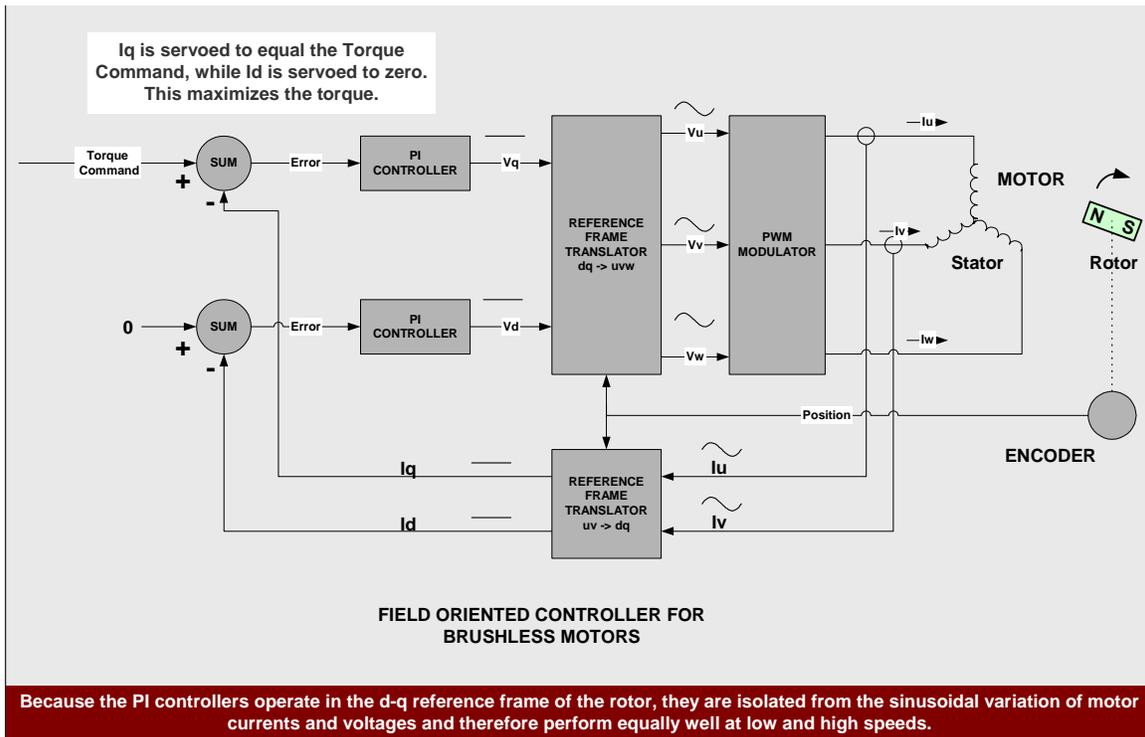


In Field Oriented Control, motor currents and voltages are manipulated in the d-q reference frame of the rotor. This means that measured motor currents must be mathematically transformed from the three-phase static reference frame of the stator windings to the two axis rotating d-q reference frame, prior to processing by the PI controllers. Similarly, the voltages to be applied to the motor are mathematically

transformed from the d-q frame of the rotor to the three phase reference frame of the stator before they can be used for pwm output. It is these transformations, which generally require the fast math capability of a DSP or high performance processor, that are the heart of Field Oriented Control.

Although the reference frame transformations can be performed in a single step, they are best described as a two step process. The motor currents are first translated from the 120 degree physical frame of the motor stator windings to a fixed orthogonal reference frame. They are then translated from the fixed frame of the stator to the rotating frame of the rotor. This must be done at the update rate of the P-I controllers in order to insure valid results. This process is reversed to transform voltage signals from the P-I controllers from the d-q frame of reference to the terminals of the stator windings.

Once the motor currents are transformed to the d-q reference frame, control becomes rather straightforward. Two P-I controllers are used; one for the direct current component, and one for quadrature current. The input to the controller for the direct current and has zero input. This drives the direct current component to zero and therefore forces the current space vector to be exclusively in the quadrature direction. Since only the quadrature current produces useful torque, this maximizes the torque efficiency of the system. The second P-I controller operates on quadrature current and takes the requested torque as input. This causes the quadrature current to track the requested torque, as desired.



The outputs from the two P-I controllers represent a voltage space vector with respect to the rotor. Mirroring the transformation performed on motor currents, these static signals are processed by a series of reference frame transformations to produce voltage control signals for the output bridge. They are first translated from the rotating d-q frame of the rotor to the fixed x-y frame of the stator. The voltage signals are then converted from an orthogonal frame to the 120 degree physical frame of the U,V and W motor windings. This results in three voltage signals appropriate for control of the pwm output modulator.

It is the reference frame transformations that do the work of converting between the sinusoidal time variant current and voltage signals at the motor windings into the dc signal representations in the d-q space.

The important architectural difference between sinusoidal commutation and Field Oriented Control is the sequence of the commutation and current control processes. In sinusoidal commutation, commutation is performed first and is followed by P-I control of the resulting sinusoidal current command signals. The P-I controllers in a sinusoidal system are therefore exposed to the time variant currents and voltages of the motor, and motor performance is limited by the bandwidth and phase shift of the controllers. In Field Oriented Control, P-I control of current is performed first and is followed by fast commutation processes. The P-I controllers are therefore isolated from the time varying currents and voltages, and the system is not limited by P-I control loop bandwidth and phase shift.

So Why Is Field Oriented Control Better?

Field Oriented Control provides the smooth motion at slow speeds as well as efficient operation at high speeds. Sinusoidal commutation produces smooth motion at slow speeds, but is inefficient at high speeds. Trapezoidal commutation can be relatively efficient at high speeds, but causes torque ripple at slow speeds. Field Oriented Control provides the best of both worlds.

