

# Field Oriented Control Using Polar Coordinates for ACIM Motors

AN037405-0117

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## Abstract

This application note discusses the field-oriented control of three-phase alternating current induction motors (ACIM). In this document, *field-oriented control (FOC)* is also referred to as *space vector control*.

Three-phase AC induction motors are mechanically simple, rugged, and highly reliable. These types of motors are lower in cost per horsepower than DC motors, and are capable of more torque and efficiency than single-phase AC motors. A three-phase AC induction motor can be controlled by varying its inputs according to a mathematical model of the rotor flux field in a complex vector space, known as *vector control*. Vector control provides efficient and accurate control of a motor's speed and torque. Usually, vector control is the domain of digital signal processors (DSPs), digital signal controllers (DSCs), and some 32-bit and 16-bit microcontrollers.

Constant cost pressure and increased consumer expectations have driven design engineers to seek minimal hardware solutions that extract maximum performance from motors used in consumer goods. This application note describes how Zilog's Z16FMC 16-bit microcontroller is used to implement vector control of an AC induction motor.

The Z16FMC Series of Flash MCUs used to produce this application is based on Zilog's advanced 16-bit ZNEO CPU core, which is tailored to motor control applications.

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- **Note:** The source code file associated with this application note, [AN0374-SC01](#), was tested with version 5.0.0 of ZDSII for Z8 Encore! MCUs. Subsequent releases of ZDSII may require you to modify the code supplied with this application.
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## Discussion

It is known that a current flow through an inductor causes a flux and torque that are orthogonal to each other. The orthogonal components, flux and current (torque), are referred to as *d* and *q* components. The physical relationship between flux and current is utilized in electromagnetic machines, such as an electromotor, to convert electrical energy into kinetic energy. However, there are situations in which the orthogonal relationship between these *d* and *q* vectors becomes distorted. Therefore, it is necessary to perform certain actions to compensate for the nonorthogonal effects. High speeds can disturb the orthogonal relationship in a motor due to the effects of increased back-EMF (BEMF). In this situation, the *q* component could conceivably be lagging. To compensate for this non-orthogonal effect, a sophisticated control called *field-oriented control* (a.k.a. space vector control), is implemented. Additional advantages include direct torque control and

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improved steady and transient-state performances of an ACIM using field-oriented control.

The Z16FMC Series Flash MCU is optimized to support control of single-phase and multiphase variable-speed motors. Target applications include consumer appliances, HVAC, factory automation, refrigeration, and automotive applications.

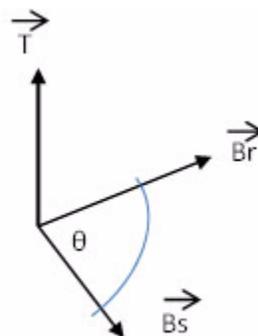
To rotate a three-phase motor, three AC voltage signals must be supplied and phase-shifted 120° from each other. To perform this phase shifting, the Z16FMC MCU features a flexible PWM module with three complementary pairs, or six independent PWM outputs, supporting deadband operation and fault-protection trip inputs. These features provide multiphase control capability for multiple motor types, and ensure safe operation of the motor by providing immediate shutdown of the PWM pins during a fault condition. The duty cycle of each microcontroller PWM output is varied to control the period and amplitude of its generated AC signal, which in turn determines the speed and torque of the motor.

An AC induction motor consists of a stator, which is a stationary frame with a rotating component; a rotor, which is mounted on a shaft; and ball bearings. In a three-phase AC induction motor, the stator is laced with three sets of inductor windings energized by three AC voltage inputs that are phase-offset 120° from each other, producing a rotating field of magnetic flux inside the stator. The rotor flux field is controlled to be orthogonal to the stator flux field to obtain optimal torque production. The stator field interacts with the rotor flux field and exerts a magnetic force on it, resulting in torque on the output shaft which is highest when the rotor and stator fields are at an angle of 90° to each other. This electromagnetic interaction is expressed mathematically in Equation 1.

**Equation 1**

$$\vec{T} = \vec{B}_s \times \vec{B}_r$$

Equation 1 states that the resulting torque vector from the cross-product of the rotor flux vector  $\vec{B}_s$  and stator flux vector  $\vec{B}_r$  is greatest when they are at an angle of 90° to each other, as shown in Figure 1.



**Figure 1. Torque as a Measure of Rotor and Stator Vectors**

► **Note:** In this document, vector quantities are indicated in bold notation (for example,  $\mathbf{V}_s$ ) or are displayed with an arrow over the quantity (for example,  $\vec{V}_s$ ).

Observe the following sequence to operate an AC induction motor with field-oriented control.

1. The AC from the mains is rectified.
2. The resulting DC power is applied to the logic and power circuits.
3. The Z16FMC microcontroller generates the motor control signals to the inverter bridge.
4. The control signals are fed into the inverter bridge so that the sinusoidal waveforms are reconstructed 120° from each other.

This sequence is illustrated in Figure 2.

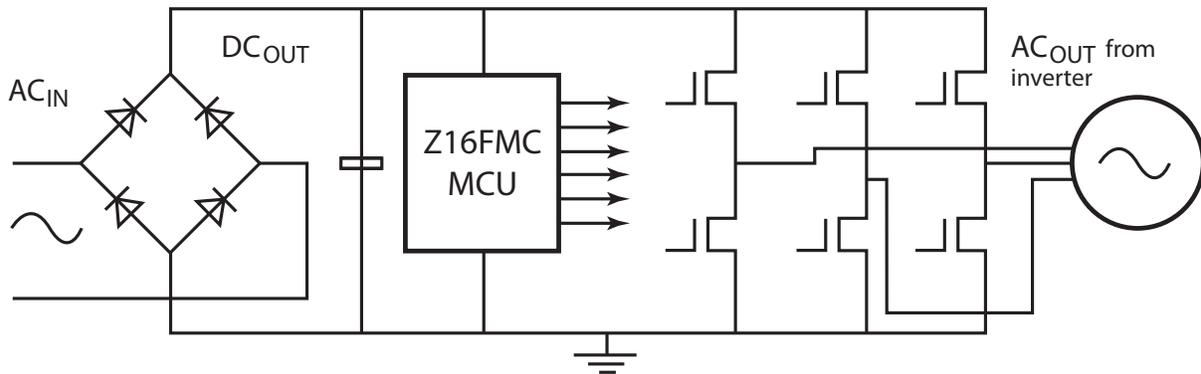


Figure 2. The Process of Operating ACIM with Field Oriented Control

## General Field Oriented Control Theory of Operation

Reading and controlling stator currents is a fundamental part of field-oriented control toward achieving an orthogonal relationship between stator and rotor fields. Most FOC applications use the *single current shunt, rectangular FOC* method, with implementation of the forward and reverse Clarke and Park transforms. However, rather than employ the reverse Clarke and Park transforms, this FOC application proposes dual current shunt resistors with a *rectangular-to-polar coordinate transformation* implementation, which will be explained in subsequent sections.

FOC consists of both space vector control and space vector modulation. *Space vector control* refers to the independent control of flux and torque currents; namely, the d and q components, plus a necessary 90° alignment between rotor flux and stator flux. *Space vector modulation*



refers to a sinusoidal pulse-width modulation pattern to rotate reference vector  $\vec{V}_s$  within a hexagon, with a magnitude and angle adjustment based on FOC corrections.

The difference between using single current and dual current shunt resistors to control currents with FOC – and the perceived advantage of using dual current shunt resistors with polar coordinates – is highlighted in the next section.

### **Advantages and Disadvantages of Single Current Shunt and Dual Current Shunt Implementation**

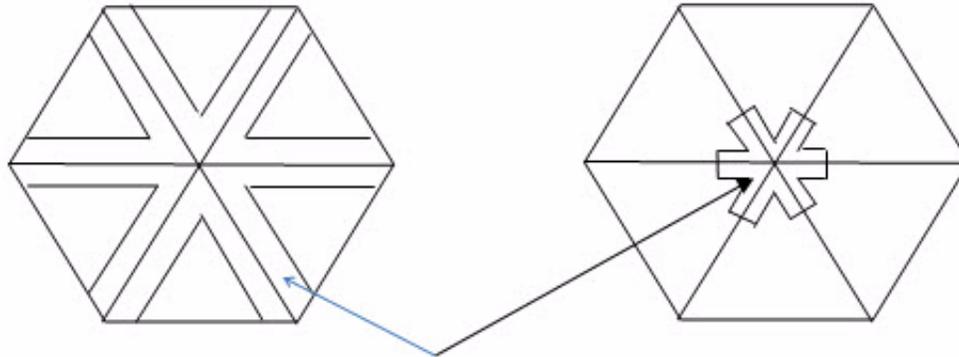
Single Current Shunt and Dual Current Shunt implementation each has certain advantages and disadvantages, which are listed below.

<b>Single Shunt Implementation</b>		<b>Dual Shunt Implementation</b>	
<b>Advantage</b>	<b>Disadvantage</b>	<b>Advantage</b>	<b>Disadvantage</b>
Cost savings	Depending on the PWM peripheral features, special Space Vector Modulation (SVM) pattern may have to be applied so that current measurements take place at a certain combination of duty cycles that energize the phases	Because the currents are physically flowing independently in each sense resistor, special SVM techniques are not necessary. Currents can be measured independently at any time	Additional cost for a second current sense resistor

However, current readings can be inaccurate for both types of implementations:

- When the motor is running at or near full speed, at which the duty cycles are nearly the same, as indicated at the left side of Figure 3
- When the motor is running at or near its lowest speed, in which the duty cycles are nearly the same, as indicated at the right side of Figure 3
- The phase currents must be read when the lower device of either of the three phase current paths is conducting

Current measurement errors may occur during these conditions at any PWM period. However, the average on-time for each duty cycle on the lower switching devices will have been 50% within an electrical commutation period at which proper currents are obtained.



The length of the bars indicates the magnitude of the duty cycles

Figure 3. Operating Conditions

In Figure 4, the duty cycles are shown at lower speeds; the vertical red and yellow bars indicate the time duration or space in between duty cycles for which an ADC measurement must occur.

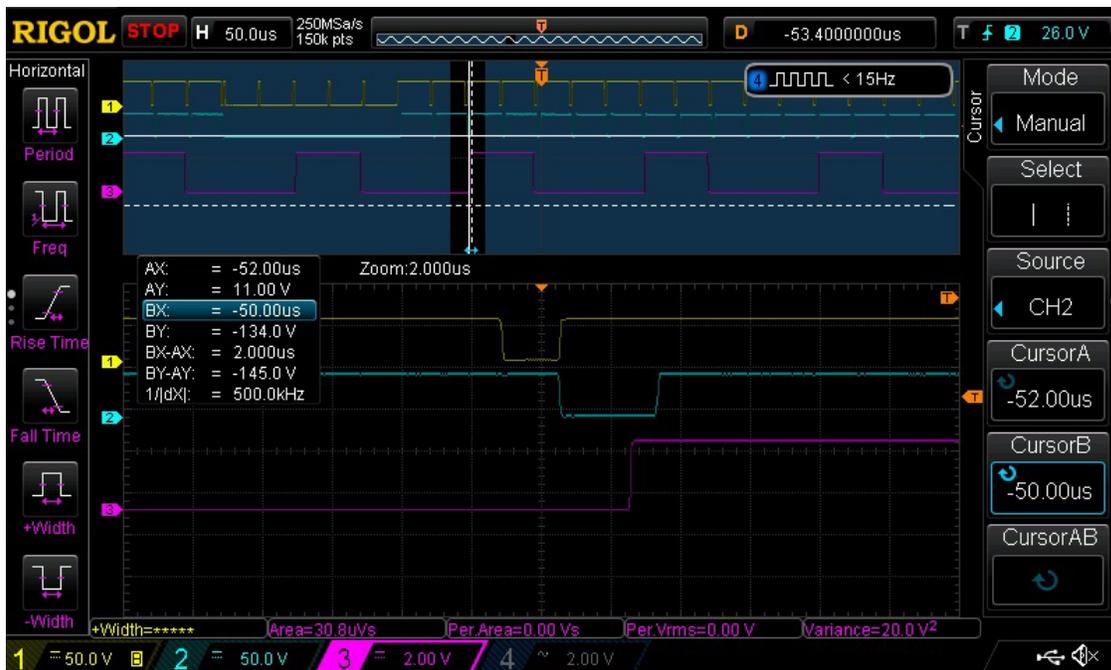


Figure 4. Low-Speed ADC Measurement Timing

In Figure 5, the duty cycles are shown at higher speeds; the vertical red and yellow bars indicate the time duration or space in between duty cycles for which an ADC measurement must occur.

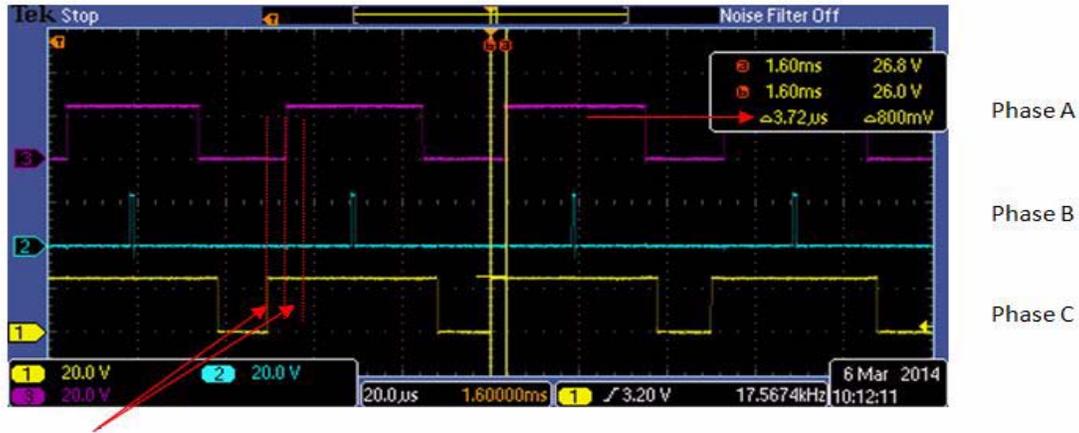


Figure 5. High-Speed ADC Measurement Timing

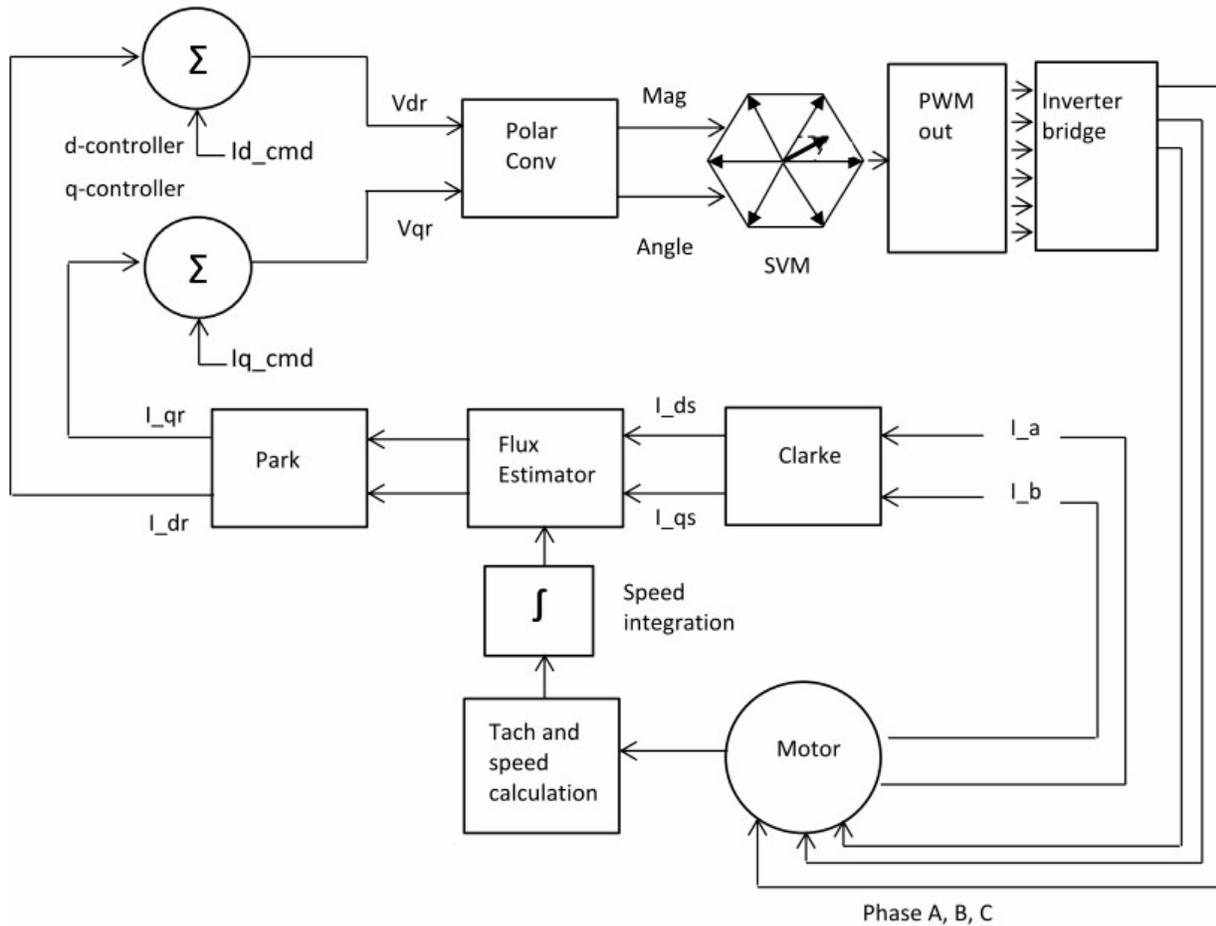
Since only two currents are measured, the third current is derived from Kirchoff's current law.

## Field Oriented Control Using Polar Coordinates

Generally, all FOC algorithms are contained within the PWM service interrupt routine. These algorithms include the following components:

- Phase current measurements
- Clarke transform
- Flux estimator (flux speed integrator)
- Park transform
- PI current controllers
- Polar coordinates or rectangular coordinates implementation
- Application of the angle and magnitude to the three-phase voltages with the inverter bridge

Figure 6 illustrates the Polar FOC control sequence.



**Figure 6. The Polar FOC Control Sequence**

## Clarke Transform

The vector addition of three stator phase currents forms a reference current,  $\vec{I}_s$ , which is governed by Equation 2.

### Equation 2

$$\vec{I}_s = \vec{I}_a(t) \times e^{j\theta} + \vec{I}_b(t) \times e^{j\left(\theta - \frac{2\pi}{3}\right)} + \vec{I}_c(t) \times e^{j\left(\theta + \frac{2\pi}{3}\right)}$$

The formation of the stator current,  $\vec{I}_s$ , can be simplified to map three current vectors to a stationary two-axis coordinate system called *d-q vector coordinates*, or a *Clarke transform*, as shown in Equation 3.

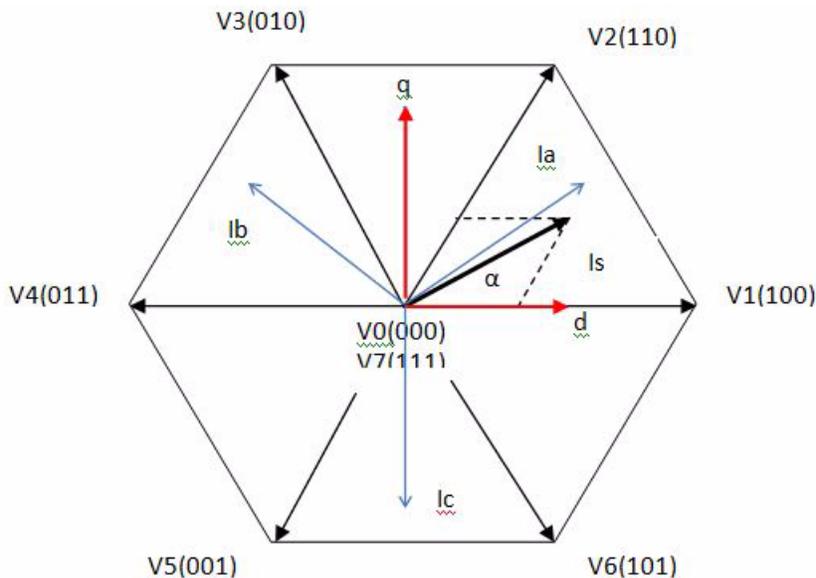
**Equation 3**

$$\vec{i}_{s-\alpha} = i_a$$

$$\vec{i}_{s-\beta} = \frac{1}{\sqrt{3}} \times i_a + \frac{2}{\sqrt{3}} \times i_b$$

In these two equations, a and b are the subscripts referring to the stator currents.

The d and q currents are the flux- and torque-producing currents which are orthogonal to each other and are controlled independently by the FOC algorithms, as shown in Figure 7.



**Figure 7. d and q Currents**

In Figure 7, the d current is the flux-producing vector, and the q current is the torque-producing vector.

**Rotor Flux Estimator and Sine Wave Table Lookup**

For field-oriented control, it is crucial to correctly obtain the rotor flux speed and its angular position. To obtain this information, the rotor’s angular periods are captured with the Z16FMC MCU’s Timer 0 peripheral and are provided by a tachometer to calculate the speed of the rotor. The integral of the rotor speed becomes the rotor flux angle to provide the rotor’s angular position.

These frequency and speed calculations are shown in the following equations. In Equation 4, the angular speed is the time derivative of angular displacement; in Equation 6, the synchronous speed of the stator field is derived.

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**Equation 4**

$$\omega = \frac{d\phi}{dt}$$

**Equation 5**

$$\text{Freq} = \frac{1}{\text{period}}$$

**Equation 6**

from Equation 6.

$$\text{Speed} = 120 \times \frac{\text{Freq}}{p}$$

In Equations 5 and 6, Freq is the applied frequency and p is the number of pole pairs.

The number of pole pairs determines the mechanical revolutions, which is a multiple of the electrical revolution of the rotor. In praxis, the code in the PWM service interrupt is computed by adding the frequency information to a variable used to store the rotor angle, and then to determine the rotor flux angle, as indicated in the following code fragment.

```
RotorAngle.word += foc.Rotorfreq;
```

The information in the RotorAngle variable is then used to determine the sine and cosine values for the vector rotation and the space vector modulation sectors.

The angles required for the sine and cosine values – and to perform the space vector modulation timing – are provided in a 90° look-up table containing 256 values. Because only partial sine information is available, the following software algorithms must be implemented to reconstruct this sine wave based on the speed integrator information provided.

```
Theta += Speed + Slip;  
SVMsector = Theta;  
if(Theta > 0x1FFFu)  
{  
  Theta = Theta - 0x1FFFu;  
}  
Angle = (Theta & 0x07FFu) >> 3;  
Sin_theta = Sine_table[Angle];  
Cos_theta = Sine_table[256-Angle];
```

If a 360° sine table is implemented, an interpolating index variable can be used in which the high byte becomes the nonfractional index to the look-up table. Only one look-up table is required because the cosine is using an offset to the same values.

The values obtained from the sine table look-up table become the sine theta and cosine theta values, which are required to maintain the 90° relationship of the d and q vectors, and for the forward and reverse vector rotation of these d and q vectors.

## Park Transform

The angular information from the flux estimator and the outputs of the Clarke transform become the inputs to the Park transformation with which to rotate the d and q vectors, and thus to align the stator currents with the rotor position. This transformation is also referred to as the *two-axis stationary coordinates to two-axis rotational coordinates transformation*. This transformation is implemented using Equation 7 and illustrated in Figure 8.

### Equation 7

$$I_{ds} = I_{s\_α} \times \cos(\theta) + I_{s\_β} \times \sin(\theta)$$

$$I_{qs} = -I_{s\_α} \times \sin(\theta) + I_{s\_β} \times \cos(\theta)$$

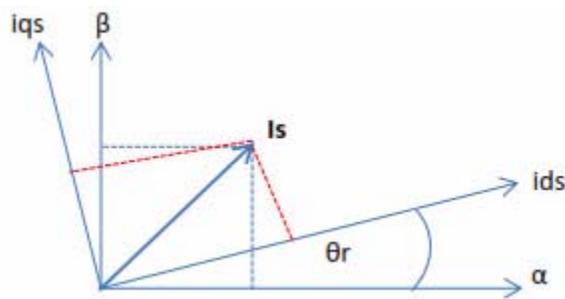


Figure 8. The Park Transformation

In Figure 8,  $\alpha$  represents the Phase A reference axis to which the rotor angle ( $\theta$ ) is referenced. Vector rotation and alignment with the rotor is required to communicate the appropriate position of the new adjusted reference vector  $I_s$  to the stator current so that a  $90^\circ$  relationship between rotor and stator can be established. As seen from the stator, controlling the d and q currents is difficult because they change in AC-like (i.e., sinusoidal) patterns. However, by projecting the orthogonal d-q vector stationary reference frame onto the rotational vector reference frame via the Park transform, the d and q currents are more easily controlled as they rotate with the rotor, and therefore function more like DC values similar to those of a DC motor.

## PI Regulators

The DC-like outputs of the Park transform become the inputs to the d (flux) and q (torque) current regulators, along with demand torque and demand flux. The purpose of the PI current controllers is to separately control the d and q magnitude components according to the demand flux and torque. Because the  $90^\circ$  relationship was already established in the Park transform and should not be altered further, only the d and q magnitudes are controlled.

After the currents are adjusted to the demanded values, the PI controllers output the control values  $V_d$  and  $V_q$ . This process is illustrated in Figure 9.

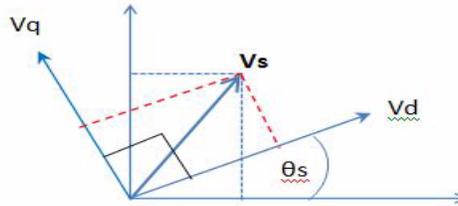


Figure 9. PI Controllers Output Values Vd and Vq

- **Note:** The PI controller outputs are in terms of voltage instead of current so that they can be used later for the stator voltages to produce the current vector,  $\vec{I}_s$ .

A potentiometer and ADC conversion is used to calculate the demand currents  $I_{d\_cmd}$  and  $I_{q\_cmd}$  to form the demand stator current, as shown in Equation 8. The  $I_{q\_cmd}$  values are then used as an index to access the demand values located in a 128-value square root table.

#### Equation 8

$$I_s = \sqrt{I_d^2 + I_q^2}$$

### Rectangular-to-Polar Coordinates

At this point, the FOC process can implement rectangular coordinates using either the reverse Park and Clarke transforms method, or the rectangular-to-polar coordinate method. If the inverse Park and Clarke transforms are used, the reverse Park transform rotates the d and q values on the two-axis rotational coordinate plane back to the two-axis static coordinate plane to align the vectors with the a-axis of the stator reference frame.

The reverse Clarke transform translates the information from the two-coordinate system back to a three-coordinate system to form the stator voltages  $V_a$ ,  $V_b$ , and  $V_c$ . However, the rectangular-to-polar coordinate system does not implement these transforms; instead, the PI outputs Vd and Vq are input to the rectangular-to-polar conversion, as shown in Figure 10.

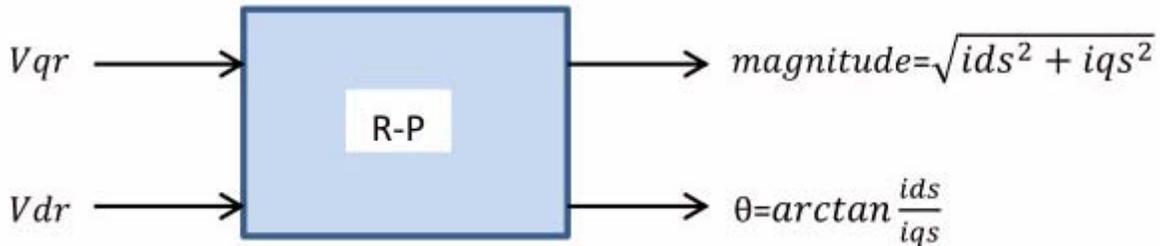


Figure 10. Angle and Magnitude Resolver, Rectangular-to-Polar Method

The mathematical concept of this rectangular-to-polar coordinate system is shown in Figure 11.

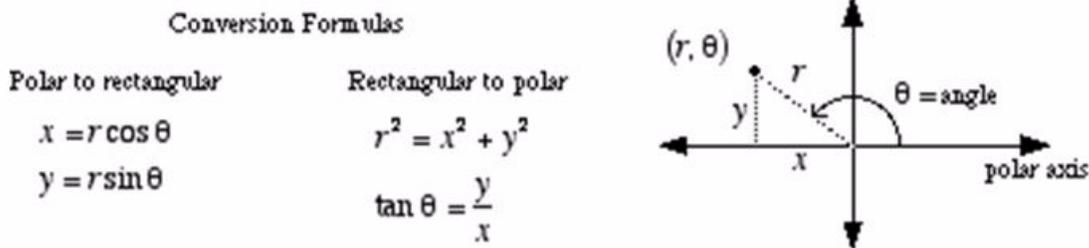
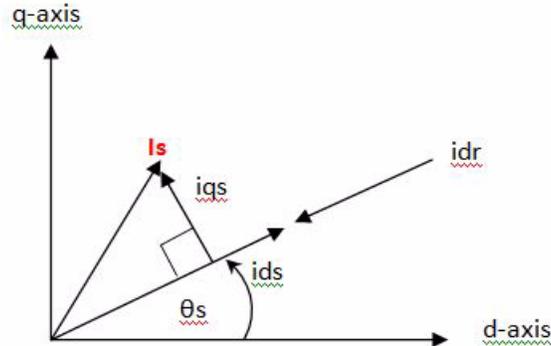


Figure 11. Mathematical Concept of Rectangular-to-Polar Coordinate System

As seen in Figure 11,  $x$  represents the d (flux) component,  $y$  represents the q (torque) component, and the  $\vec{V}_s$  reference vector is represented by the hypotenuse  $r$ . As can be seen, the magnitude of  $r$  is represented by the length of  $r$ , with an angle of  $\theta$ .

The outputs of the rectangular-to-polar coordinates represent the corrected angle and magnitude, which become the input to the PWM block and space vector modulation block, essentially converting the angle and magnitude from the two-coordinate d and q plane to form the three-phase voltage to be applied to the three stator windings.

In this control process, the stator flux field vector,  $I_{ds}$ , is aligned with the rotor flux field vector,  $I_{dr}$ . An  $I_{qs}$  vector is positioned at a right angle to the  $I_{dr}$  vector, thereby aligning the rotor flux field  $90^\circ$  with the stator flux field to produce the current vector,  $I_s$ . The  $I_{ds}$  and  $I_{dr}$  components are the flux vectors, and the  $I_{qs}$  components are the torque vectors, as shown in Figure 12.



**Figure 12. Flux Vector Alignments**

At this point, field-oriented control is completed, and repeated every time the PWM service routine interrupts. Therefore, the accuracy and response of the FOC mechanisms greatly depends on the PWM interrupt frequency and the time at which these algorithms are processed.

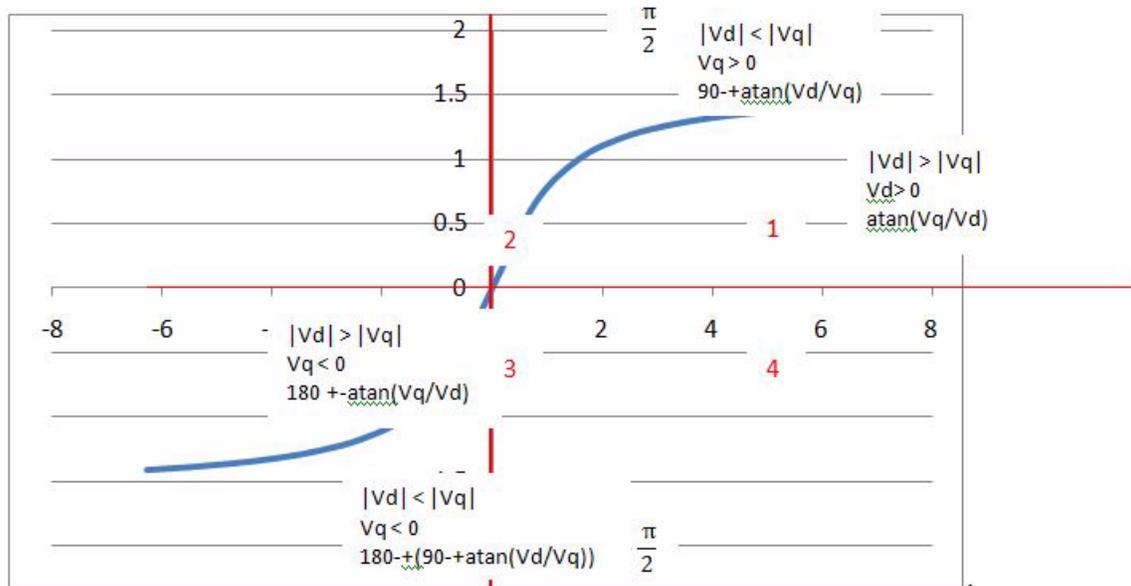
In essence, with field-oriented control, the flux and torque currents required to rotate the motor are controlled through the stator current vector, which, in turn, is controlled by the motor voltages and angle.

### Rectangular-to-Polar Coordinate Adjustment

To implement the rectangular-to-polar coordinate method, two look-up tables are implemented: one for the square root values, and another for the arctangent values. Each of these look-up tables contains 128 values, thereby representing a range of 0°–45°. The values from either table are selected based on the PI controller output values  $V_{dr}$  and  $V_{qr}$ .

To access the arctangent look-up table values, the result of either  $V_{dr} \div V_{qr}$  or  $V_{qr} \div V_{dr}$  is used as the index. If  $V_{dr}$  is greater than  $V_{qr}$ , the angle is between 0° to 45°, and  $V_{qr}$  is divided by  $V_{dr}$ . If  $V_{qr}$  is greater than  $V_{dr}$ , the angle is between 45° to 90° and  $V_{dr}$  is divided by  $V_{qr}$ . If  $V_{qr}$  is positive, the angle is located in quadrant one or two, depending on the sign of  $V_{dr}$ . If  $V_{qr}$  is negative, then the angle is located in quadrant three or four depending on the sign of  $V_{dr}$  and a  $180^\circ \pm 45^\circ$  angle with respect to  $\frac{\pi}{2}$  is executed.

This process is illustrated in Figure 13.



**Figure 13. Rectangular-to-Polar Coordinate Adjustment**

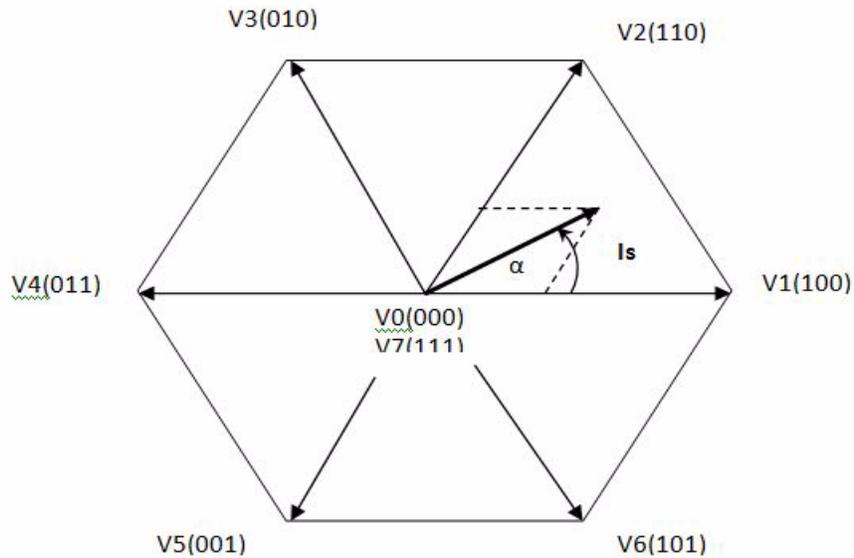
## Space Vector Modulation

The output of the rectangular-to-polar conversion provides the angle and magnitude information for the flux and torque respectively. This information is fed into the space vector modulation block to generate the reference vector  $\vec{V}_s$ , and ultimately, the vector  $\vec{I}_s$ . Any position of the reference vector  $\vec{V}_s$  can be created within the hexagon by using any two adjacent base vectors V1 through V6, in combination with a zero vector. The resulting space vector modulation PWM pattern is applied to the inverter bridge to form three-phase voltages to generate the reference current  $\vec{I}_s$  with magnitude *mag*. The complex representation of this reference vector  $\vec{I}_s$  is expressed in Equation 9.

### Equation 9

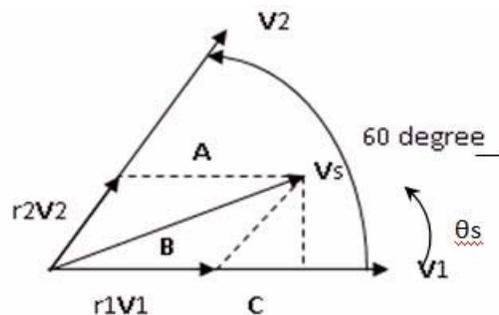
$$\vec{I}_s = \text{mag} \cdot e^{j\theta} = (i_{d_s} + j i_{q_s})$$

The rotating reference vector within the hexagon,  $\vec{I}_s$ , is shown in Figure 14.



**Figure 14. Rotating Reference Vector  $I_s$**

Using the rotor angle and the adjacent base vectors within the hexagon of Figure 14, the scalar coefficients for the adjacent base vectors,  $r_1$  and  $r_2$ , must be calculated using Equation 10 to time-modulate the base vectors,  $V_1$  and  $V_2$ , and thereby to generate the resulting voltage reference vector,  $\vec{V}_s$ , as shown in Figure 15.



**Figure 15. Resulting Voltage Reference Vector  $V_s$**

**Equation 10**

$$\vec{V}_s = r_1 \times v_1 + r_2 \times v_2$$

After the angular information of the rotor from the rectangular-to-polar coordinates is obtained, the scalar quantities  $r_1$  and  $r_2$  are calculated, as shown in Equations 11 and 12.

**Equation 11**

$$r_1 = m \times \sqrt{3} \times \sin(60 - \Delta\theta)$$

**Equation 12**

$$r_2 = m \times \sqrt{3} \times \sin(\Delta\theta)$$

In the above equations,  $m$  is the magnitude and  $\theta$  is the angle of difference between the rotor angle and any of the adjacent base vector angles.

The time values for which the adjacent base vectors are modulated to obtain the reference vector,  $\vec{V}_s$ , are calculated using Equations 13 through 15.

**Equation 13**

$$t_0 = (1 - t_1 - t_2) \times T$$

**Equation 14**

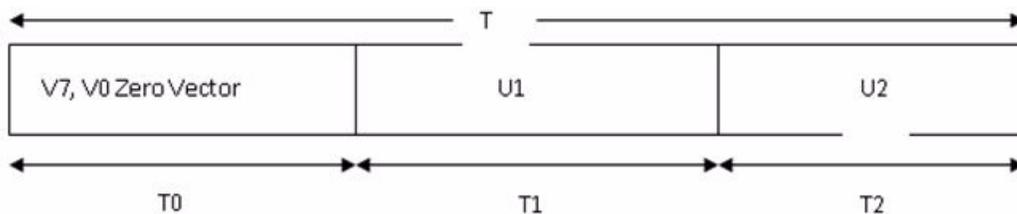
$$t_1 = r_1 \times T$$

**Equation 15**

$$t_2 = r_2 \times T$$

In the above equations,  $T$  is the PWM time period, and the sum of  $t_0$ ,  $t_1$ , and  $t_2$  cannot be greater than the time period of the PWM.

$t_0$  becomes the time period for which either or both zero vectors are applied in combination with  $t_1$  and  $T$  to form the reference vector,  $\vec{V}_s$ , as shown in Figure 16.



**Figure 16. Switching Times for Base Vectors V1, V2, and Zero Vectors**

To find the time values  $t_0$ ,  $t_1$ , and  $t_2$ , the angles are determined by using V1 as the reference axis going counterclockwise to find the base vector angle to be subtracted from the angle of the rotor.

For example, using Equations 13 through 15, if the command magnitude is 12V at a bus voltage of 24V and the commanded  $\vec{V}_s$  angle is  $190^\circ$ , this vector is expressed mathematically as shown in Equation 16.

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**Equation 16**

$$\vec{V}_s = 12 \times e^{j190}$$

The angle is 190° and the adjacent base vector is V4, which is 180°. The coefficients  $r_1$  and  $r_2$  are calculated using Equations 17 and 18.

**Equation 17**

$$r_1 = \sqrt{3} \times \frac{12V}{24V} \times \sin(60\text{deg} - (190\text{deg} - 180\text{deg}))$$

**Equation 18**

$$r_2 = \sqrt{3} \times \frac{12V}{24V} \times \sin(190\text{deg} - 180\text{deg})$$

If the PWM period is 50  $\mu\text{s}$ , the time duration for  $t_0$  using either zero vector V0 or V7 is:

$$t_0 = (1 - r_1 - r_2) \times T$$

The time duration for  $t_1$  is:

$$t_1 = r_1 \times T$$

The time duration for  $t_2$  is:

$$t_2 = r_2 \times T$$

## Space Vector Modulation Pattern

The FOC application described in this document uses the equations discussed in the previous section to form the reference vector,  $\vec{V}_s$ , and thus to implement patterns with the V0 and V7 null vectors in an alternate-reverse manner. As a result, only one inverter leg is switching at any given time to minimize linear switching power losses in the inverter bridge. The switching sequence is  $t_1-t_2-t_0$ ,  $t_0-t_2-t_1$ , and is illustrated in Figure 17.

However, using the dual current shunt method, it is easier to deploy different modulation schemes so that other space vector modulation methods can be applied by using the zero vectors and the  $t_1$  and  $t_2$  time values in different sequences. This method is useful for other aspects of a design, such as reduced harmonic losses and fewer ripple currents.



Figure 17. Alternate-Reverse PWM Switching Pattern

## Slip Frequency

*Slip frequency* is an intrinsic part of AC induction motors. In an AC induction motor, the stator flux field rotates at a synchronous speed according to the sinusoidal frequencies of the currents that produce this stator flux field. The resulting induced flux field in the rotor interacts with this stator flux field and causes a torque to rotate the motor at the synchronous speed, minus a frequency that is referred to as *slip frequency*. The rotor frequency is always less than the stator field frequency, because the rotating stator flux field establishes a rotating flux field in the rotor. Therefore, the rotor flux field tries to follow the stator flux field but cannot catch up with it. As a result, these two fields are not in sync with each other.

Using Equation 19, the slip frequency can be calculated and applied to produce the correct field orientation of torque and flux currents in the AC induction machine.

### Equation 19

$$\int s = \frac{1}{2\pi T_r} \times \frac{I_q}{I_d}$$

In the above equation,  $T_r$  is the rotor time constant and is computed as  $\frac{L_r}{R_r}$ , which is the rotor winding inductance divided by the rotor winding resistance.

$I_q$  is the torque producing component and  $I_d$  is the magnetizing component of the  $d$ - $q$  coordinates.

## Z16FMC MCU Phase Current Reading

Figure 18 illustrates the current-reading implementation using the Z16FMC MCU's operational amplifier circuit.

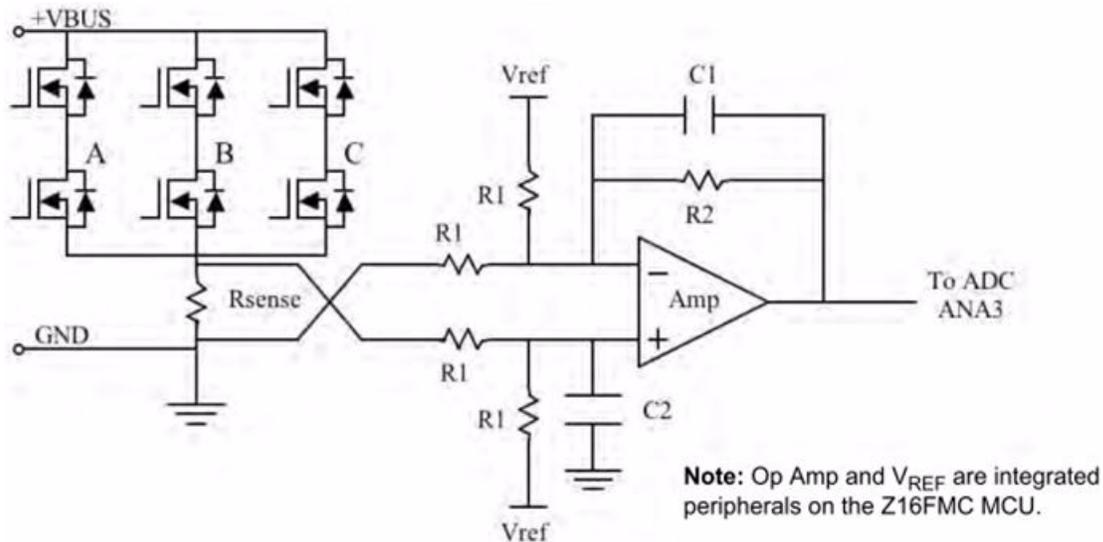


Figure 18. Current Sense Operational Amplifier

For current sensing using a single current-sense resistor, the operational amplifier is used to offset the ground-referenced current sense signal to 1 V (half of the 2 V reference); the voltage gain increases by a factor of 5. For a sense resistor value of 20 m $\Omega$  and a current of  $\pm 4$  A with a gain of 5, a 1 V signal can have a swing of  $\pm 0.4$  V.

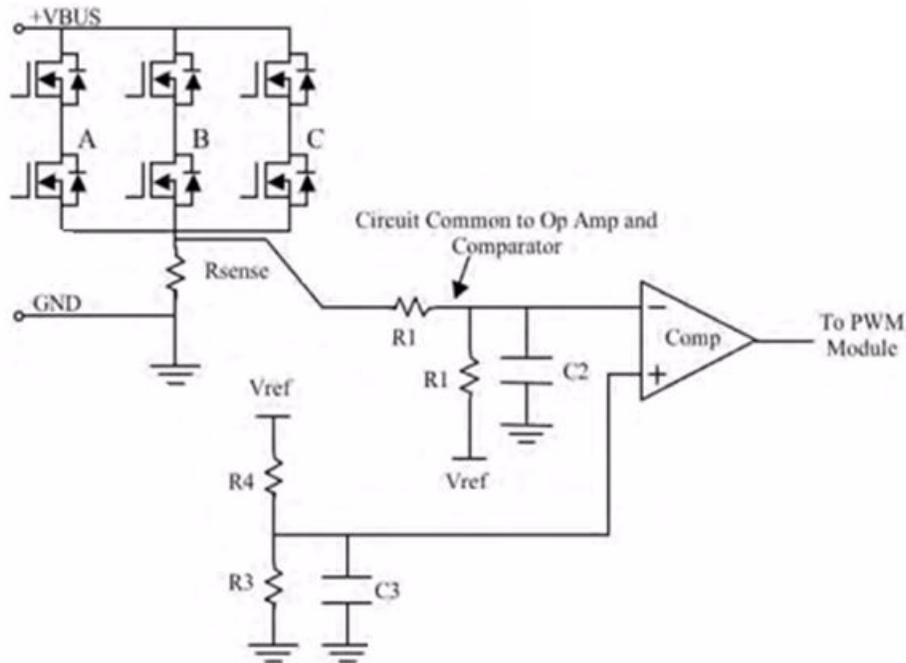
At zero current across the current sense resistor, the output of the amplifier is 1 V, which centers around the 2 V reference voltage for the ADC module.

A current normalization is then performed to generate the offset to be subtracted from the actual current readings. This offset should be at  $V_{REF} \div 2$ , or  $ADC \text{ range} \div 2$ , to convert the unsigned quantities of the currents to signed quantities.

For example, if the ADC current reading has a value of 90, then the current value obtained will be  $90 - 127 = -37$ . If the ADC current reading is 220, then the current value obtained will be  $220 - 127 = 93$ .

## Overcurrent Protection Circuit with the Z16FMC Internal Comparator

As shown in Figure 19, with an overcurrent event, the output of the comparator provides a shut-down signal for the PWM module to disable the motor operation in near-real time.



**Figure 19. Overcurrent Sense Circuit**

► **Note:** Comparator and  $V_{REF}$  are integrated peripherals on the Z16FMC MCU.

In Figure 19, R3 and R4 set the overcurrent trip threshold. Because it is a DC value, a bypass capacitor (C3) of 0.1  $\mu$ F is used.

For an R4 value of 10, R3 can be calculated as shown in Equation 20.

**Equation 20**

$$R3 = R4 \times \left( \frac{V_{REF} + I_{max} \times R_{sense}}{V_{REF} - I_{max} \times R_{sense}} \right) = 10k\Omega \times \left( \frac{2V + 10A \times 0.02\Omega}{2V - 10A \times 0.02\Omega} \right) = 12.2k\Omega \approx 12.4k\Omega$$

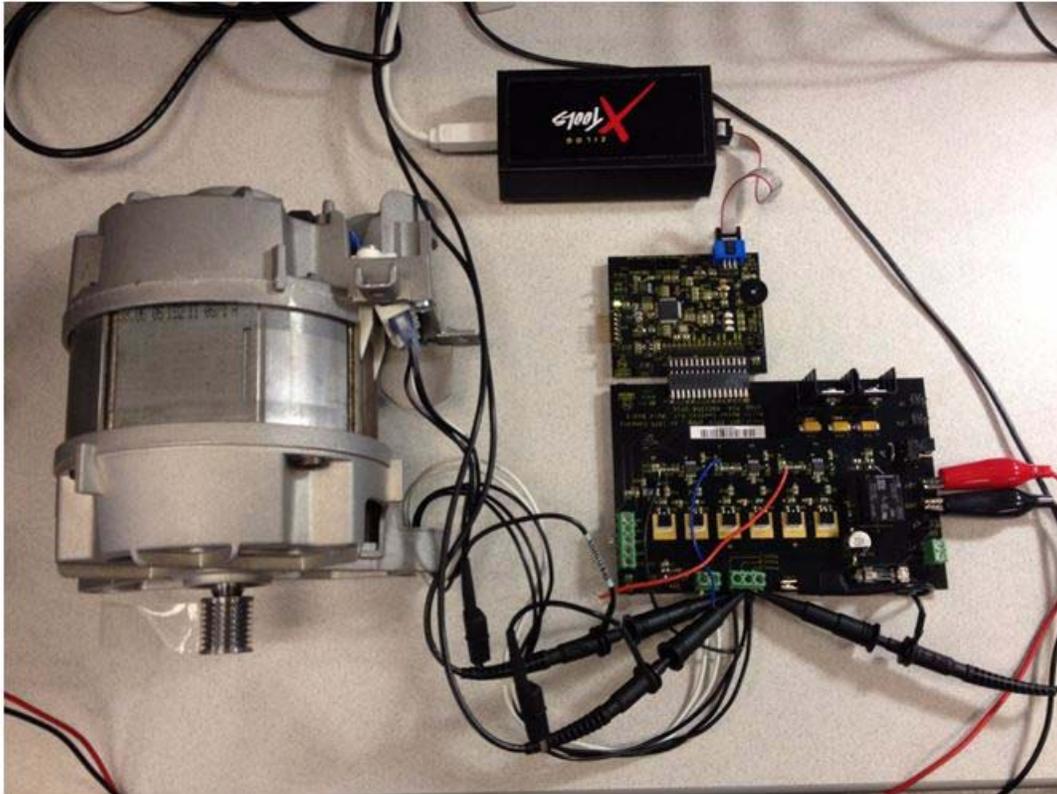
**Equipment Used**

- MultiMotor Series Development Kit (ZMULTIMC100ZCOG)
- Tektronix 2014B digital phosphor oscilloscope
- BK Precision 1667 power supply

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## Hardware Setup

Figure 20 shows the hardware used in the testing procedure. It includes an AC induction motor, an opto-isolated smart cable, and Zilog's MultiMotor Series Development Kit.



**Figure 20. The MultiMotor Development Kit with AC Inductor Motor**

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- **Note:** This testing hardware is tailored to a single-shunt resistor. However, to correctly implement the dual-shunt software, the hardware must be configured for a dual-shunt current resistor; the [AN0374-SC01](#) software provides this option for the dual current shunt resistor method. If using dual-shunt resistors, a two- input MUX can be implemented to select either of the dual current sensors.
- 

## Testing Procedure

The MultiMotor Series Development Kit is operated with a 24 V DC power supply. Using the test setup shown in Figure 20, three oscilloscope probes are connected to the MultiMotor Series Development Board's Phase A, Phase B, and Phase C BEMF voltage dividers to show the three-phase voltage waveforms of a dual-shunt current resistor polar coordi-

nate FOC and a single current shunt rectangular coordinate FOC. A current probe is clamped onto one of these three phases to show the resulting current waveforms.

## Results

Using signed integer variables, the [AN0374-SC01](#) software can be controlled so that the code processing is executed in a reasonable amount of time. The subroutine times are:

- FOC and space vector modulation in the PWM interrupt service routine: 39 $\mu$ s
- Hall sensor interrupt service routine: 7.6 $\mu$ s
- ADC sampling for speed control: 4.5 $\mu$ s

Due to the use of signed variables, quadrant information is automatically provided, making quadrant determinations unnecessary.

Using the dual current shunt polar coordinate FOC method, Figure 21 shows the alternating-reverse PWM switching patterns generated by the space vector modulation block to generate the phase voltages shown in Figure 22.



Figure 21. Alternate-Reverse Space Vector Modulation PWM Pattern

Using the dual current shunt polar coordinate FOC method, Figure 22 shows the resulting three-phase voltages and a single-phase current.

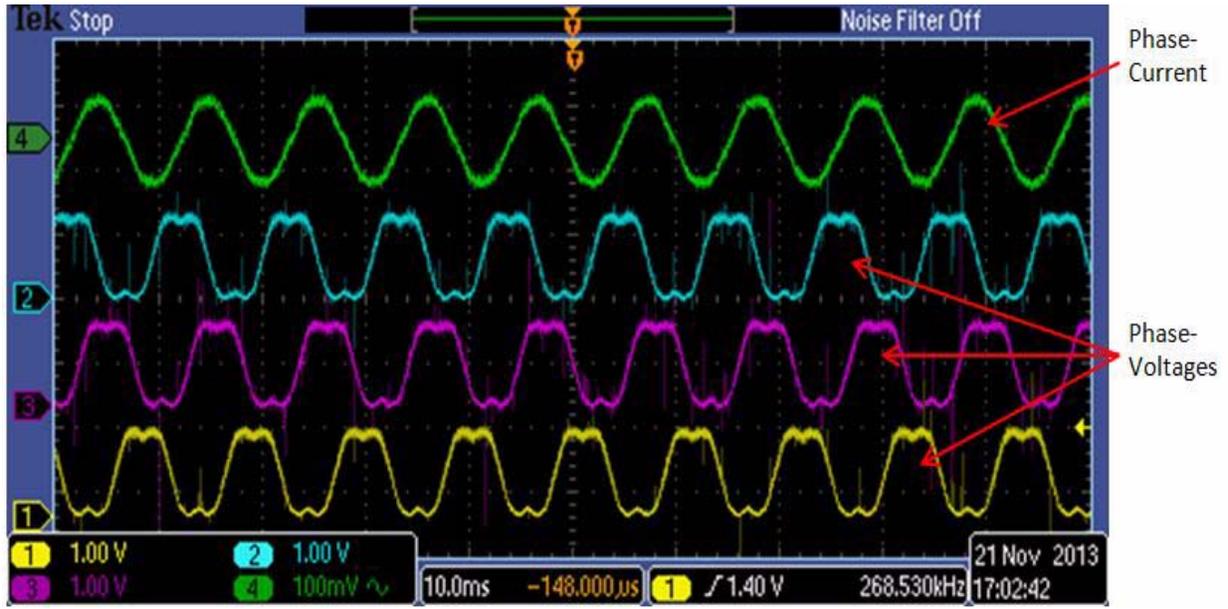


Figure 22. Dual Current Shunt Phase Voltages and Single Current Signal

Figures 23 through 25 show the space vector modulation pattern and the three-phase voltages with a single-phase current using the single current shunt rectangular coordinate FOC method. In Figure 23, current A is flowing; however, currents B and C are not flowing.

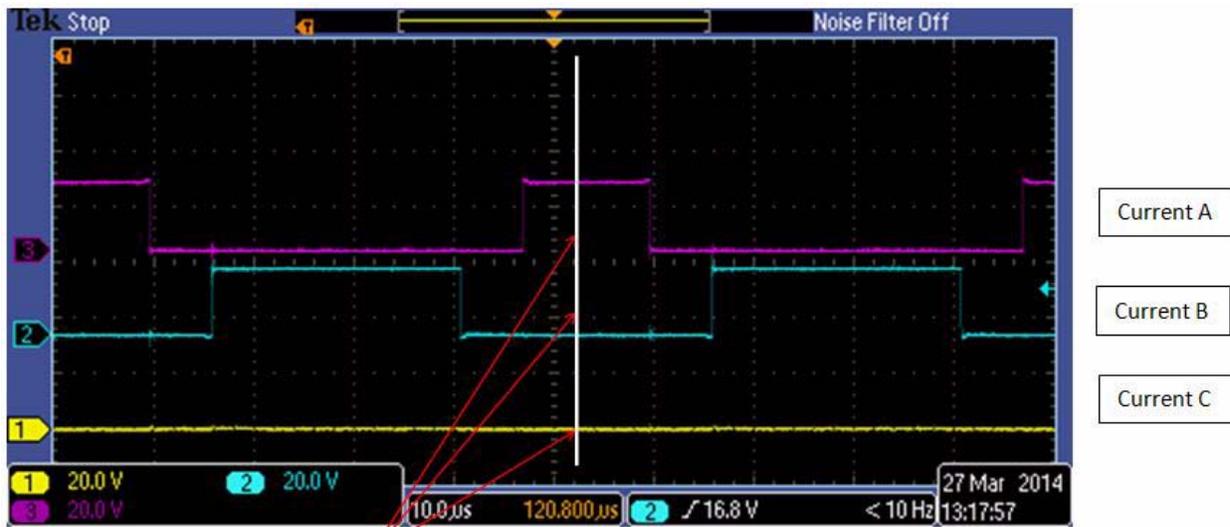


Figure 23. Current A is Flowing

In Figure 24, current B is flowing, and currents A and C are not flowing.



Figure 24. Current B is Flowing

After obtaining the first and second current samples, the missing currents are found using Kirchhoff's current law. As shown in Figure 25, the three phases are energized with PWM patterns so that currents can be obtained in between energized phase windings, thereby adding more time and complexity to the software.

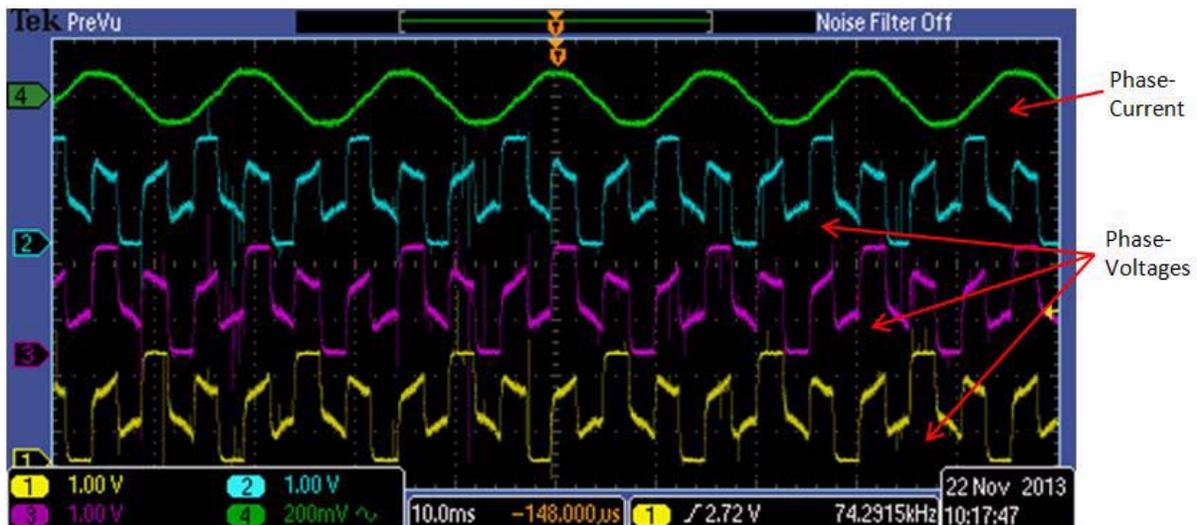


Figure 25. Single-Shunt Phase Voltages and Single Current Signal

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## Summary

This application note discusses the implementation of a field-oriented control scheme using polar coordinates with dual current-sense shunt resistors instead of the commonly used rectangular coordinate field-oriented control using a single current-sense resistor.

The dual current shunt resistor approach has advantages in terms of current-reading accuracy due to the single current shunt resistor method's timing limitations at low speeds and near full speed. Additionally, the dual current shunt resistor approach allows for a greater choice of space vector modulation schemes, which has benefits such as reduced linear switching power losses, fewer harmonic losses, and reductions in ripple currents. The single-shunt approach is limited in these choices because individual currents must be obtained from the sum of the stator currents. As a result, PWM switching patterns must be set so that only one phase winding is energized at a time to differentiate between stator currents.

Using the Clarke transform, the current readings are transformed from a three-current coordinate to a two-axis stationary coordinate  $d$ - $q$  vector frame. The output of this Clarke transform is fed into the Park transform which will rotate the two-coordinate stator  $d$  and  $q$  vectors to align them with the rotor position of the motor. Next, the output currents of the Park transform are fed into the two PI current controllers, one for the direct current or flux-producing component referred to as the  $d$  component, and one for the quadrature current or torque-producing component, referred to as the  $q$  component. These two controllers implement a proportional and integral control, referred to as a *PI loop*, to control these  $d$  and  $q$  current vectors separately. The voltage outputs of these two PI controllers provide inputs to the rectangular-to-polar conversion block, which then feeds directly into the space vector modulation block to provide phase voltage switching signals.

In essence, the control of an AC machine consists of two parts: field-oriented control of the currents, and a space vector modulation scheme to apply control voltages to the phases of the motor. The polar coordinate field-oriented control scheme is advocated here to emphasize its advantage: the ability to apply different space vector modulation schemes without sacrificing accuracy in current measurements. This ability is essential to the FOC mechanism.

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