"How to Turn an AC Induction Motor Into a DC Motor (A Matter of Perspective)"

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The territory of high-performance motor control has been dominated by synchronous DC motors. This group of motors includes brushed, brushless, wound-field and permanent-magnet varieties. The simple reason for this domination is that DC motors are easier to control. This is especially true if the application requires good control of motor torque, velocity, or position. The electromechanical model of a DC motor shows that motor torque, within limits, is an approximately linear function of the input current. So, it is a relatively easy task to derive solid performance out of a DC motor with proportional-integral-derivative (PID) controllers.

In the "real design world", the selection process for a type of motor to use in an application can be complex. A particular motor can't be chosen based solely on how easy it is to control. There are many other system-related variables to juggle, such as:

- How easy is it to maintain the motor?
- What happens to the system when the motor fails? (i.e. a shorted winding)
- What will be the operating environment?
- How will the motor be cooled?
- What is the cost of the motor?

The list of considerations can go on and on….

AC induction motors (ACIM) have distinct advantages over other types of motors, and have typically been used when a robust, fixed-speed solution is desired. The evolution of microcontroller (MCU) and power electronic devices has made inexpensive variable-speed control of an ACIM possible. However, the performance of a DC motor cannot be matched using basic control methods. This article will explore the topic of field-oriented control (FOC) and how it can be used to improve the control of an ACIM using a Digital Signal Controller (DSC). FOC lets you use DC control techniques for an AC motor, and can remove one of the variables in the motor-selection process for your next design.

How a Motor Works
An electric motor produces a mechanical force, when current flows in proximity to a magnetic field.   A synchronous motor has a source of magnetic field. This field can be provided by permanent magnets or by windings that are energized with a source of current. Within limits, the torque response of the motor is a linear function of the current and the magnetic field strength. The linear response makes these motors easy to control in high-performance applications. A PID controller can be used to control the motor current and resulting motor torque. If needed, secondary PID controllers can be used to control position or velocity.

So, it looks like we've got the problem solved! We'll just use a synchronous motor with field windings or permanent magnets to get good control performance. Well, "Wait a minute," you might say. "I need a high-power motor in my application. I could use a motor with rotor and stator windings. But, I'll have to worry about replacing brushes and keeping the rotor cool. I could use a brushless motor with permanent magnets, but the cost of the magnets would make the cost of the motor too high."

The AC Induction Motor
An ACIM can really help out in this situation. The ACIM has windings on the outside of the motor, which makes it easy to provide cooling. The rotor is a simple steel cage, so it is durable and can withstand high temperatures. The ACIM has no brushes to wear out. OK then – so far, so good. Now, take a look at how the motor operates.

Since AC power is widely available, the ACIM is usually designed with a specific line voltage and frequency in mind. For this discussion, let's take a look at the nameplate of a typical ACIM. The parameters shown in our example nameplate are shown below:

Voltage: 230 VAC
Frequency: 60 Hz
FLA: 1.4A
HP: 1/3
RPM: 3450

Among other things, the nameplate specifies a rated power for the motor, operating voltage, operating frequency and operating RPM. The stator windings of the motor are arranged so that a rotating magnetic field is created when energized with AC currents.

The rotor of an ACIM must turn at a lower speed than the rotating field. The difference between the field speed and the rotor speed is called slip. Slip can be expressed as a ratio or a frequency, but it is helpful to consider the slip frequency. For this example motor, the rotating field speed would be 60 rev/s, or 3,600 RPM. But, you'll notice that the nameplate RPM under load is only 3,450 RPM, or 57.5 rev/s. So the slip frequency is 60 Hz – 57.5 Hz, or 2.5 Hz.

In this example, you can consider the 2.5 Hz slip frequency as a source of AC power that supplies energy to the rotor via transformer coupling. The rotor becomes energized with AC currents that produce a rotor magnetic field, allowing the motor to produce torque. The ACIM slip gives the motor the ability to self-regulate its own speed, to a certain extent. As the motor load is increased, the rotor speed will decrease. The slip frequency will then increase, which increases the rotor currents and the motor torque.

Variable-Speed ACIM Control

An ACIM can be operated at different speeds and torque levels by varying the frequency and voltage supplied to the motor. Let's suppose that you want to operate our example motor at ½ the rated speed. To accomplish this, you would reduce the frequency input to the motor by a factor of 1/2, or 30 Hz. If we wanted to operate the motor at ¼ speed, then the frequency would be reduced to 15 Hz.

You'll also want to keep the stator field relatively constant by keeping the stator currents constant. The ACIM motor is inductive and the stator currents will increase as the input frequency is decreased. Therefore, you also need to reduce the input voltage by a proportionate amount when the frequency is decreased. A constant V/Hz profile is often used to provide variable-speed operation of an ACIM. The V/Hz constant for our example motor can be calculated by dividing the operating frequency into the operating voltage.

$K = V/Hz = 230/60 = 3.83$

Now, for a given choice of input frequency we can compute the desired drive voltage for that input frequency:

Voltage = K* Frequency

The result is called the 'Volts-Hertz' profile and can be plotted as shown in Figure 1. There is no fixed rule that says the drive voltage has to maintain a fixed linear relationship to frequency. In fact, the shape of the V/Hz profile is often altered in specific frequency ranges to optimize the drive performance in a particular speed range. For example, the shape of the profile shown in Figure 1 has been adjusted to provide higher voltages in the low frequency range. This modification provides a boost to the motor torque when the motor starts from rest to help overcome load friction and inertia. Within the mechanical limits of the motor, you can also increase the drive frequency beyond the nameplate value to achieve a higher speed. However, the available voltage may be limited, so motor torque will also be lower.

Figure 1: Typical V/Hz Profile for a Variable Speed ACIM Application
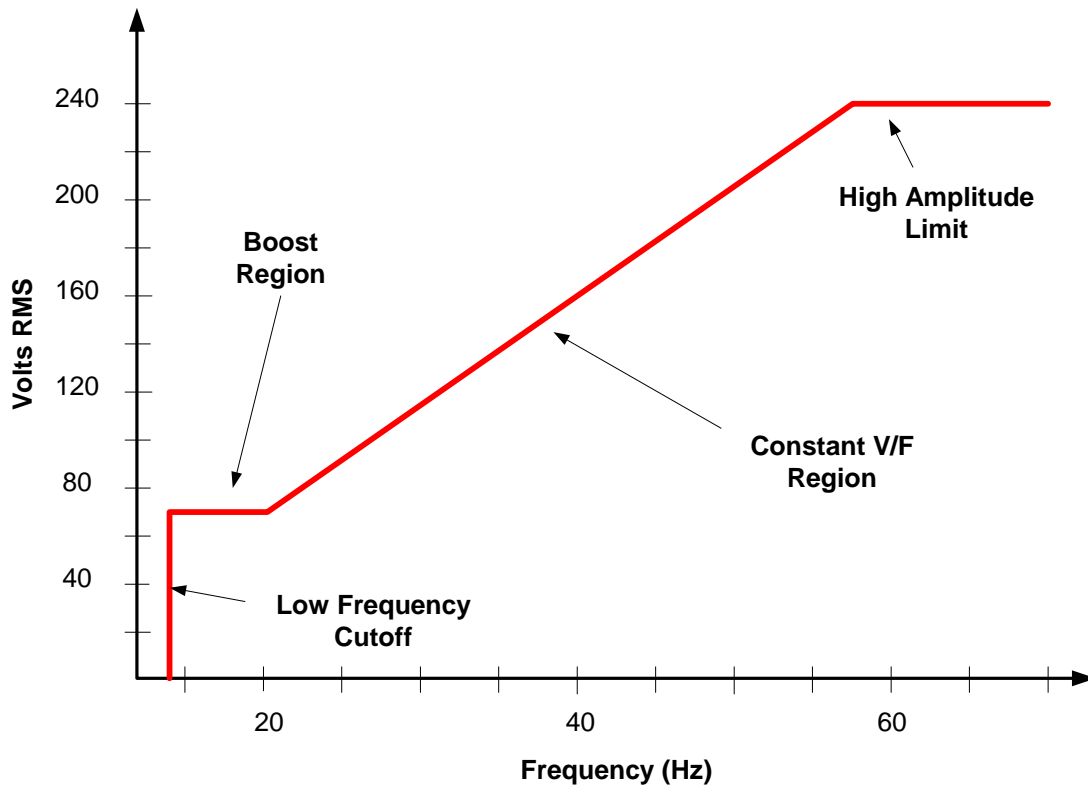
For applications that do not require frequent speed or load variations, the V/Hz method for controlling an ACIM works well. This is especially true when control loops are used to regulate speed or motor current. A typical system block diagram that you can use for a V/Hz application is shown in Figure 2. The MCU has a specialized PWM peripheral to drive a 6-transistor inverter circuit. The MCU measures the frequency of the motor tachometer, calculates the speed error, and generates a drive demand using a PID control loop. The drive demand is translated into a required voltage and frequency using the V/Hz profile. Finally, the PWM modulation code varies the duty cycle over time to generate sinusoidal drive signals with the proper amplitude and frequency.

Figure 2: Typical System Block Diagram Used for Variable Speed ACIM Control
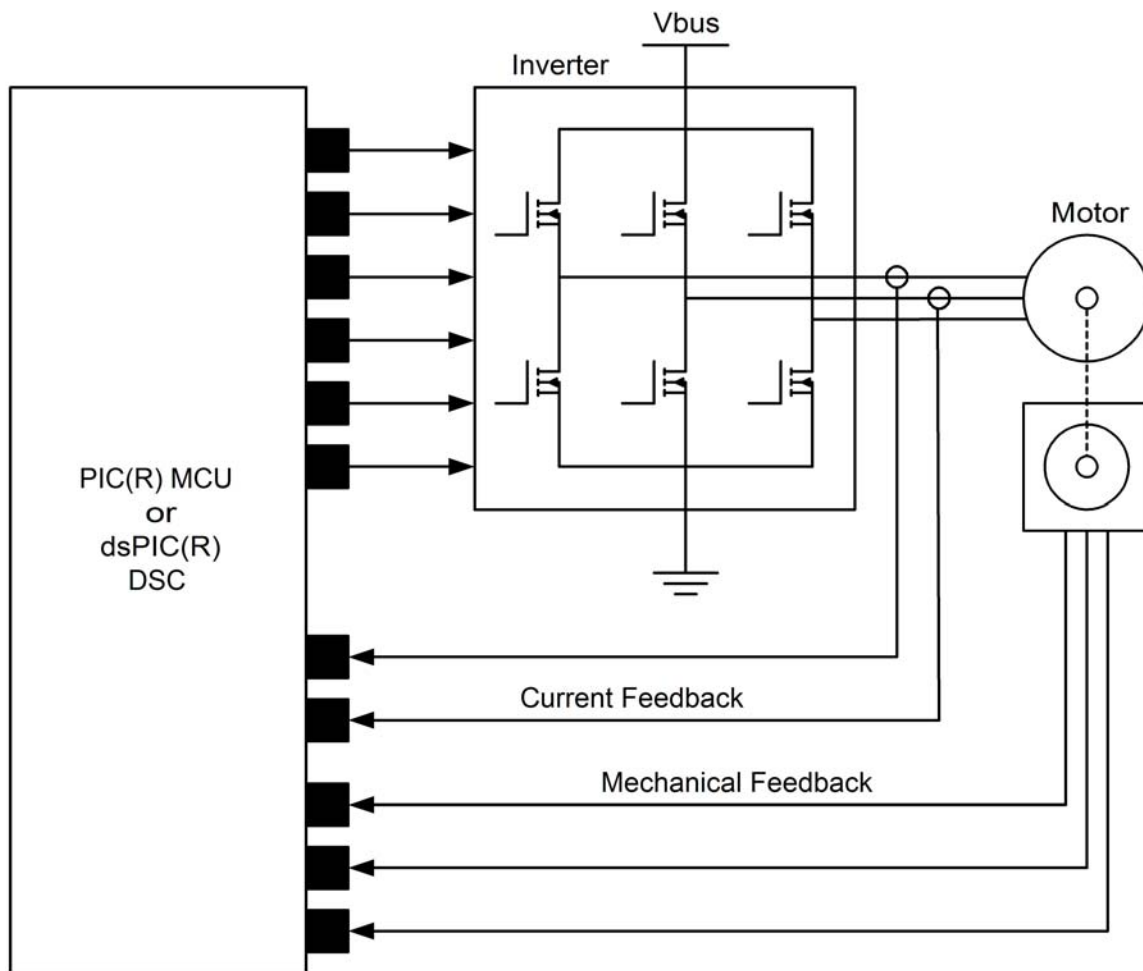
For applications that require fast dynamic response, the V/Hz control method will give sluggish response. Furthermore, the motor currents will be very high during load or speed changes. The sluggish response occurs because the components of stator current that control motor torque and the rotor field cannot be separated. A change in drive voltage or frequency will cause a change in both torque and rotor currents.

Ideally, we would like to use an algorithm that lets us control motor torque independently of other motor variables. The FOC algorithm lets us accomplish this goal. FOC controls the voltage, frequency and instantaneous phase of the motor voltage to produce the desired stator currents. (The V/Hz control method does not control the phase.) FOC will obtain the best motor efficiency and dynamic response for a given application.

FOC - A Matter of Perspective
If the motor is observed electrically from the perspective of the input terminals, all signals inside the motor will appear sinusoidal. Sinusoidal signals can be difficult to process in software, especially if we want to use PID controllers to regulate motor currents. If we change the point of reference used in our calculations, then the signals inside the AC motor can be made to look mathematically like DC values under steady state conditions.

Specifically, FOC measures the AC motor currents. In a stationary reference plane, the 3-phase stator currents can be combined to form a single rotating current vector in time. Instead of using a stationary reference, we can also use a rotating reference plane that turns synchronously with the motor. With the rotating reference plane, steady-state AC quantities look stationary!

Here is a helpful analogy: Imagine that you are standing on the side of a circular car-race track. From your stationary perspective, all of the cars seem to be moving around the track at a very high speed. What we really want to know is which car is winning the race (the relative position of the cars), but it is hard to tell with the pack of cars going by so quickly!

Instead of watching the cars from the side of the track, let's hop into the pace car and drive next to the lead car. From this perspective, the pack of cars becomes more or less stationary from our point of view. The only thing that will be changing over time is the relative position of all the other cars to the lead position, which is our moving reference point. The actual speed of the cars moving around the track becomes irrelevant, assuming you are not afraid of high speeds!

Now, let's take this analogy and apply it to the phase currents of an AC motor. Using this analogy, the speed of the cars moving around the track is comparable to the motor drive frequency. The relative position of the cars is comparable to the phase of the stator current vector.

FOC Coordinate System Transformations
FOC uses a pair of conversions called the Clarke and Park Transforms to get from the stationary reference plane to the rotating reference plane. First, two of the three phase currents are measured. Note that you do not even need to know (or measure) the value of the third phase current. This is because the sum of the 3-phase currents should sum to 0. The measured currents represent the vector components of the current in a 3-axis coordinate system with each axis separated by 120 degrees.
It is easier to represent the rotating current vector in a 2-axis orthogonal coordinate system, so the Clarke Transform just converts the measured currents so that the current vector is represented with two vector components instead of three. The two vector components calculated using the Clarke Transform still vary with time.

Clarke Transform Equations
Iα = Ia
Iβ = 0.577(Ia +2Ib)

Park Transform Equations
Id = Iα*cosθ + Iβ*sinθ
Iq = -Iα*cosθ + Iβ*sinθ

Next, the Park Transform is used to rotate the 2-axis coordinate system so that is aligned with the rotating motor. The rotation angle is represented by θ. Now, you may wonder where the value of θ comes from. When using FOC for a synchronous 3-phase motor, the rotating reference plane would always be aligned with the rotor and θ could be obtained directly from the rotor position using a sensor. However, an ACIM is an asynchronous machine that requires slip to operate.

One method that can be used to calculate θ is to use equations that model the rotor currents. The rotor-current model calculates the required slip frequency from the measured stator currents. The rotor current model also requires knowledge of the rotor resistance and inductance. These values form a time constant that adjusts the motor slip to the correct value during transient current events. After a slip frequency has been calculated, a value of θ can be calculated using the rotor velocity, which will align the reference plane ahead of the rotor to provide the slip. So, the rotating reference plane is aligned with the applied stator current vector, which spins faster than the rotor.

DC Current?
The key to FOC is that the Clarke and Park transformations provide DC representations of the stator phase currents under steady state conditions. But, we know that the motor current is really an AC signal represented as a rotating current vector. It is only because the coordinate system is synchronously rotating with the current vector that the transformed current components appear as DC values. If the value of either current component changes over time, this means that the amplitude and phase of the motor current vector has changed.

Most importantly, one component of the transformed stator current vector determines the amount of motor torque. The other component determines the rotor field. With FOC, the component of current responsible for motor torque can be isolated and controlled separately. This is why FOC lets an AC motor be controlled like a DC motor. Figure 3 shows a time history of the transformed torque current component, taken from an actual FOC application during a 2x speed increase. This is the signal that the FOC algorithm 'sees', instead of the AC current signal that was measured at the motor terminals. This signal represents the current required to accelerate the motor to the new speed.

Figure 3: Time History of the Transformed Stator Current Component Representing Motor Torque During a 2X Motor Speed Change
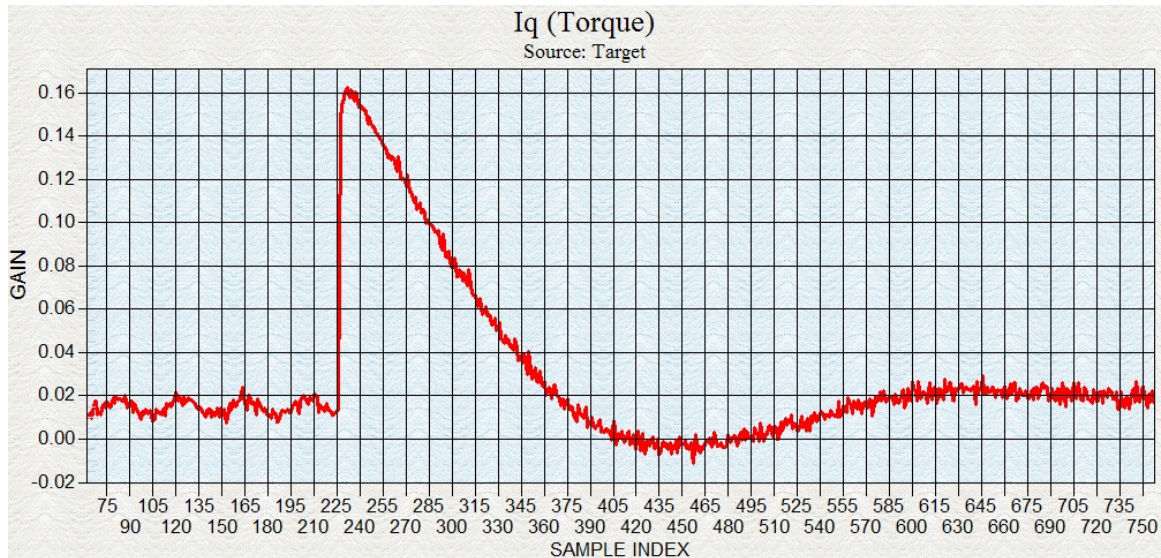
The FOC Control Loops

In practice, the two transformed current components are separately regulated using PID controllers in software. The outputs of the two PID controllers provide two voltage vector components that determine how the motor phases need to be energized to produce the desired stator currents. The reference input for one PID controller is set to a constant value so that the rotor will generate a constant field. The reference input to the other PID controller determines the amount of motor torque. The reference torque level is usually supplied from a third PID control loop that regulates the motor speed.

Back to the Rotating World

The last step in the FOC process is to 'un-wind' the voltage vector components that were generated in the rotating reference plane. The value of θ that was calculated in the rotor current model equations is used, along with inverse Clarke and Park Transforms. The equations are not shown here, but are very similar to the forward transforms.

FOC Summary

FOC controls the amplitude, frequency and phase of the voltage vector to produce the desired amplitude, frequency and phase of the motor currents. The FOC algorithm offers the best efficiency and dynamic response from an ACIM.

The equations for FOC are not complex, but they must be executed relatively frequently to get good performance. One reason is that the old value of θ from the prior iteration of the FOC equations must be used to transform the measured current values. Then, a new value is calculated using the rotor current model equations. The FOC equations are typically executed every 50 µsec to minimize the amount of angular error between iterations. The frequent calculation of the FOC equations demands that a fast 16-bit MCU or DSC be used. A system block diagram like the one shown in Figure 2 can be used for FOC.

Author's Note:
The FOC algorithm can be efficiently executed on Microchip Technology's dsPIC30F and dsPIC33F DSC families. These families offer 30 MIPS and 40 MIPS performance, respectively. An implementation of the FOC algorithm is described in AN908, which is available from the Microchip Web site at www.microchip.com. (This implementation of the algorithm uses less than 1/3 of the available CPU processing power.)

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