New Developments in Commutation and Motor Control Techniques

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Introduction

The field of motion control is not generally known for its headline-grabbing breakthroughs or fast-paced developments. Motor designs tend to evolve slowly, and engineers are understandably cautious when it comes to changing time-honored approaches. Lately though, there has been a beehive of activity around the use of advanced current control techniques, particularly field oriented control (FOC). This math-intensive technique for controlling brushless DC and AC induction motors has become a major focus of the motion control industry due to its potential for improved performance and lower energy consumption.

Field oriented control is a significant improvement over the standard approach for brushless DC motors of trapezoidal Hall-based commutation, and it has a speed range advantage over the more sophisticated technique of sinusoidal commutation. For AC induction motors, FOC is a significant improvement over standard variable speed drive techniques, and is a cousin of flux vector control, which is a somewhat similar technique for controlling inexpensive 3-phase AC induction motors to get them to perform as if they were more expensive brushless DC motors. In fact, many vendors use these two terms interchangeably.

Compared to other servo motor types such as DC brush, which are still used in a number of important applications, brushless DC and AC induction motors provide greater power density, much greater reliability, and in the case of the AC induction motor, lower cost. To gain full access to these capabilities, motion designers are utilizing fast algorithm platforms in the form of DSP (digital signal processors) and specialized microprocessors to improve performance, and increase efficiency.

In brushless DC motor applications, higher performance means smoother motion and greater operating speed. The potential for AC induction motors is even more exciting. Compared to simple “all on/off” control, FOC means that motors can be run more efficiently, sized more optimally, and operated with less heat generation. It also allows features such as direction reversal, and may allow elimination of external hardware such as brakes or clutches. Considering that 60–65% of all energy in the US is used to drive electric motors, it is no wonder that the marketplace is increasingly demanding more efficient motors.

Magnetic attraction

From the standpoint of torque generation, a good working model for most motors is the simple bar magnet. The bar magnet spins around its center (modeling the motor’s rotor) and interacts with magnet fields generated in the stator by fixed, non-moving coils. For brushless DC motors the rotor magnetic field is generated by magnets mounted directly on the rotor. For AC induction motors the rotor magnetic field is generated by induction (therefore the name of the motor) from the magnetic fields in the stator. The direction of this magnetic field, unlike for the brushless DC motor, changes based on several factors including the stator excitation frequency and current, the rotor speed, and the torque experienced by the motor.

The stator windings for brushless DC motors generally come in a 3-phase configuration, as do the windings for AC induction motors used with FOC techniques. Particularly for AC induction motors it is worth noting that other winding configurations are also used, notably the single phase AC induction motor. This motor is the workhorse found in most family A/C units, refrigerators, washers, and dryers, but it does not lend itself to the most advanced vector control techniques because the stator windings can not be individually controlled.

In any case, the three stator phases are arranged to be 120 electrical degrees apart from each other. It is the sum of the force generated by these three phases that will ultimately generate useable motor rotation. Depending on how the individual magnetic coils are phased, they can interact to create force that does not generate rotational torque, or they can create force which does drive rotation. These two different kinds of force are known as quadrature (Q) and direct (D), with the useful *quadrature* forces (not to be confused with quadrature encoding scheme for position feedback devices) running perpendicular to the pole axis of the rotor, and the non-torque generating *direct* forces running parallel to the rotor’s pole axis. Figure 1 shows this.

The trick to generating rotation is to maximize Q (quadrature) while minimizing D (direct) torque generation. In the case of a brushless DC motor, this is, at least in concept, easy, because brushless DC motors have magnets mounted directly on the rotor. Thus if the rotor angle is measured using a Hall sensor or position encoder, the direction of the magnetic field from the rotor is known. Things get more interesting for velocity and torque control applications where sensorless control is attempted. Since

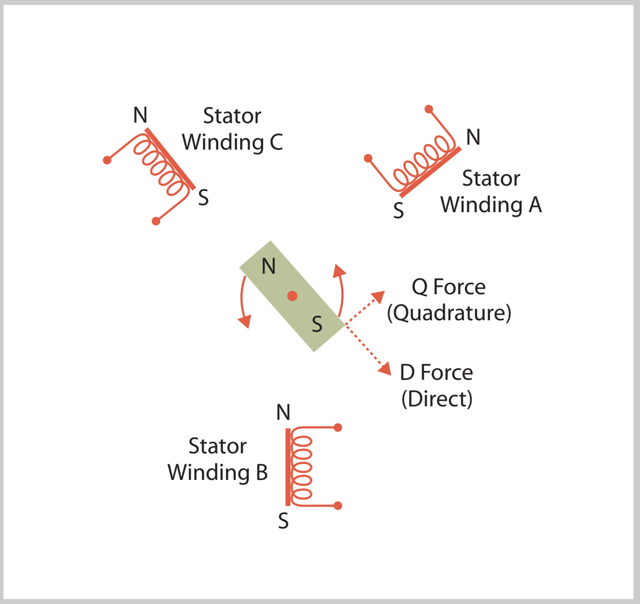

Figure 1. 3-phase brushless DC motor D (direct) and Q (quadrature) forces on the rotor

there are no direct mechanical measurements available for the rotor position, the angle must be inferred from the back-EMF voltage profile at the three windings. Although not trivial, back-EMF control is fairly common these days. Remember though that back-EMF requires that the motor be spinning, so it is not appropriate for positioning applications that must hold at a steady position.

In the case of an AC induction motor, a similar approach is used, however because of an additional requirement to maintain some amount of inductive flux, the D force is not driven to zero, but instead to a small constant value characteristic of the motor. Also, measuring the location of the rotor using Hall sensors or an encoder is not sufficient to determine the rotor's magnetic angle, because it does not tell us the effective magnetic field angle generated by the rotor. Recall that this magnetic field is induced, and thus changes continuously.

This difference between the rotor location and the rotor magnetic angle is called the slip angle. The greater the actual torque on the motor, the greater the amount of slip, and thus the greater the compensating torque drive by the motor. This equilibrium is not unlike the way a hydrostatic transmission works. The greater the difference in speed between the engine and the wheels, the greater the torque generated by the transmission. This means that the motor's rotation speed will be less than the driven frequency at the stator.

For the kinds of applications that AC induction is commonly used in, such as A/C units, washers, dryers, etc., a slip-reduced motor speed is not a problem. But for positioning applications, or to run the motor at its highest level of efficiency, this slip must be explicitly controlled. There are a few ways to do this, but they all require a measurement, or an estimate, of the rotor's induced electric field. Once again, a common way to achieve this is by using back-EMF techniques. Another popular approach is known as flux vector control, which measures the mechanical rotor angle, and attempts to derive the rotor magnetic angle algorithmically using estimations for various characteristics of the motor.

Field of oriented control dreams

Field oriented control has become an important drive/commutation approach for brushless DC motors, and is becoming that as well for AC induction motors, because it delivers a wide range of usable motor speeds. It is instructive to compare FOC to the previously most common method for brushless DC motors, sinusoidal commutation.

Figure 2 shows control schemes for both sinusoidal commutation and field oriented control. In the sinusoidal control approach, the torque command is "vectorized" through a sinusoidal lookup table, thereby developing a separate command for each winding of the motor. As the rotor advances, the lookup angle advances in kind. Once the vectorized phase command is generated, it is passed on to a current loop, one for each winding, which attempts to keep the actual winding current at the desired current value.

An important feature of this approach is that as the frequency of motor rotation increases, so does the difficulty of maintaining the desired current. This is because the current loop directly "sees" the rotation frequency, and any lag in the current loop, a certain amount of which is inevitable, results in an error between the desired stator torque, and the actual. This lag, insignificant at low rotation speeds, generates increasing amounts of D (unwanted) torque at higher rotation speeds, resulting in a reduction of available torque.

The control scheme for a field oriented control approach differs in that the current loop occurs *de-referenced* from the motor's rotation. That is, independent of the motor's rotation. In the FOC approach there are two actual current loops, one for the Q torque, and one for the D torque. The Q torque loop is driven with the user's desired torque from the servo controller. The D loop is driven with an input command of zero, so as to minimize the unwanted direct torque component.

The trick to making all of this work are math-intensive transform operations known as Park and Clarke transforms that convert the vectorized phase angle into the de-referenced D and Q reference frame. This is done twice, once to convert the output of the D and Q control loops into the 3-phase motor command, and once to convert the measurement of the rotor's angle back into the D and Q frame. While these transforms have been known about for years, their practical implementation in brushless DC and AC induction drives has awaited the availability of cheap, high performance DSPs and microprocessors.

Now that these are available, AC induction motors which utilize an FOC approach can develop motor efficiencies of

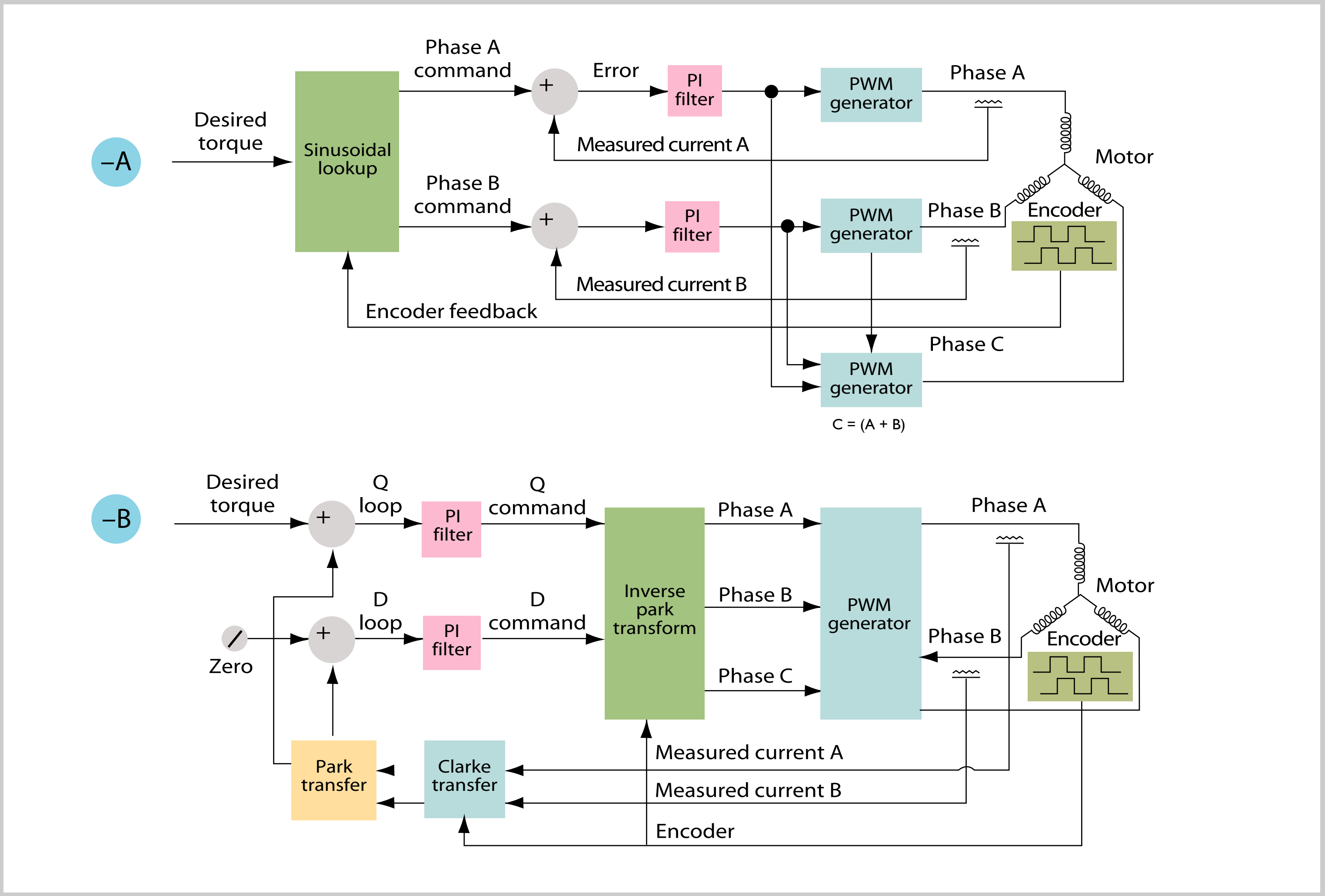

Figure 2. Overviews of sinusoidal commutation (2A) and field oriented control schemes (2B)

85+%, compared to around 60% for non field-oriented approaches. brushless motors which adopt an FOC approach, by comparison, can achieve even higher efficiencies of up to 95%. Sinusoidal commutation for brushless DC motors also works very efficiently, but is not as efficient as FOC at the very highest speed range of the motor.

Where the magnetic field hits the road

Practically speaking, your selection of motor and amplifier will often dictate the control technique that you will use.

If you are using a brushless DC motor for positioning, then sensorless control is not an option. You will need an encoder and most likely a Hall sensor as well. If you want to gain the maximum performance from your motor you will gravitate toward field oriented control. However unless you are prepared to build your own amplifier (a daunting task for most) you will purchase a packaged drive with this feature built in.

In this configuration the drive generally includes high-level motion control functions such as profile generation, position servo loop, and PLC-style inputs and outputs. There are a number of compact, single axis drives that offer Hall-based, sinusoidal, or field oriented control. These drives are typically located on a RS/485, CANbus, Ethernet, or other serial bus. All you need to do is hook up the motor and power, and send commands.

If you are using a card-based approach, either one that you have purchased, or one that you have designed yourself, your ability to adopt field oriented control is limited. This is because most off-the-shelf amplifiers input an analog +/- 10Volt control signal and do not provide field oriented control. The ones that do are generally expensive, because they include a lot of features that you will not be using by having a separate motion card. There is good news however, which is that there are a number of vendors which offer sinusoidal commutation control. This can be done in the motion card by outputting two analog +/- 10V signals representing the A and B phase desired current. For many applications sinusoidal commutation provides a huge improvement over 6-step Hall based commutation, and is still an excellent choice for a wide range of motion applications.

If you are using brushless DC motors for velocity control applications, such as in centrifuges, tape drives, or other non-positioning applications, you have a number of design options. Sensorless control is certainly a possibility, although drives that offer sensorless field oriented control are still rare. More common are sensorless drives that provide a sinusoid-like commutation function. These can be purchased at the IC level, or at the drive level.

If you are working with AC induction motors, you are probably designing for a velocity or torque control applications rather than positioning applications. Much discussed in technical journals, practical examples of AC induction motors being used as positioning are rare except for some specialized domains such as very high power drives.

In any case, you have many choices, but they generally break down into a "design it yourself" approach, or a "buy the drive" approach. If you decide to buy a drive, you have a range of performance levels to choose from beginning at simple speed control inverters, to very sophisticated field oriented and flux vector drives.

If you decide to build your own controller card or amplifier, simple variable speed control is not that difficult to achieve if you are familiar with basic inverter design and MOSFET or IGBT switching techniques. For more advanced designs you can look to available off-the-shelf ICs to perform field oriented control for AC induction motors.

Summary

Developments in control techniques, a growing demand for energy efficiency, and newly available low cost DSPs and microprocessors, have combined to significantly raise the bar for brushless DC and AC induction motor performance. Whether you build your own controller or buy off-the-shelf, knowing how to implement these new approaches is important for maximizing cost effectiveness, and minimizing project design times.

OEMs steer toward intelligent drives

Off-the-shelf programmable drives emerged more than thirty years ago and were used for applications such as machine tools and factory-floor automation. While robust, they were expensive and awkward to program. OEMs designing lower power and more cost sensitive machines have typically steered clear of these "big iron" solutions in preference to IC or card-based solutions. But now they are taking a closer look at the latest generation of intelligent drives.

Compact and powerful, these products combine low cost, network connectivity, and sophisticated motion capability. The ION digital drive from PMD is an example of such a product. Measuring just 4" x 3" x 1.5" (slightly larger than a deck of paying cards) this product offers serial or CANbus connectivity and can control DC brush, brushless DC, or step motors. It has features typically found in much larger drives including field oriented control, S-curve profiling, PID position loop with bi-quad filtering, and ultra efficient MOSFET drivers.

The most eye opening aspect of these products is their price. At $200–$500 per axis, they compare favorably to the alternative approach of motion cards with purchased amplifiers, and are more scalable. Adding an axis is a simple matter of installing another drive. In card-based systems, adding an axis can mean the purchase of a larger card and unused axis capacity.

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About Performance Motion Devices

Performance Motion Devices (PMD) is the recognized world leader in motion control ICs, cards, and modules. Dedicated to providing cost-effective, high performance motion systems to OEM customers, PMD utilizes extensive in-house expertise to minimize time-to-market and maximize customer satisfaction.