HOW-TO

Electric power steering: one good turn deserves another

By Dave Wilson

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Did you know that the hydraulic steering system in your car siphons off somewhere between one to three miles per gallon from your vehicle's performance and consumes more energy than your car's air conditioner? In fact, it's the third highest energy-loss mechanism in your car, following wind resistance and road friction.

I recently gave a motor-control seminar in San Francisco, where gas prices were the highest in the nation at $2.60 per gallon. On the return flight, I sat behind a gentleman reading *The Arizona Republic* when the front-page headline caught my attention. In bold letters it proclaimed, "Bush: No quick energy fix." After persuading him to part with his paper, I read the chilling details of our country's insatiable addiction to fossil fuels. The president lamented the high cost of gasoline, but said he is powerless to bring the prices down. "I wish I could," he exclaimed, and also indicated that "technology is the ticket."

As developing third-world countries compete for dwindling energy reserves, and oil prices spiral out of control in our energy-hungry world economy, car manufacturers and consumers alike are scrambling for ways to put their automobiles on a diet. As a result, hydraulic power steering may be headed for the same scrap pile as your 33 1/3 vinyl records, as new energy-efficient systems based on electronic motor control take center stage. One forecast suggests that hydraulic power steering will disappear from new cars within five to seven model years. While many gas-miser techniques result in reduced vehicle performance, replacing your three- to five-horsepower steering pump and its associated bulky hydraulics with an electric motor is one enhancement that actually improves performance.

Looking back

But I'm getting ahead of myself. Let's turn the clock back to 1951 when power steering made its first commercial debut. Gas prices were hovering somewhere around 25 per gallon, and nobody really cared much about fuel economy. Large vehicles were the "in" thing, and steering these luxury liners proved to be a real workout. To keep steering-wheel diameters small enough to fit inside a car, a hydraulic solution was devised where torque assist could be applied to the steering rack based on the amount of force applied to the steering wheel. The hydraulic pump was directly connected to the engine, consuming energy even when no steering assist was being requested. But nobody really cared, because gas mileage was not a big deal.

All of this changed in the mid '70s when OPEC began flexing its muscles. The auto industry was brought to its knees in realization of its dependence on the price of foreign oil. I still remember waiting in line during the "energy crisis" to pay $.85 for a gallon of gas (ah, those were the good ol' days). Suddenly, there was plenty of interest in developing rehab programs for these heavy drinking, "gas-o-holic" machines.

Although the energy crisis of the '70s gradually subsided, interest in fuel-efficient technologies continued at a steady pace. Although most activities were geared toward the engine itself, electric hydraulic power steering (EHPS) systems began to appear in the mid '80s from companies such as TRW. The main improvement provided by EHPS was to decouple the hydraulic pump from the engine by driving it directly with an electric motor. However, it still had many of the same drawbacks of traditional hydraulic systems, such as hose leaks and ruptures (the #1 failure mode in hydraulic steering systems), intractable space requirements, complexity, vibration, and environmental problems associated with the hydraulic fluid.

Then it happened. In 1993, Honda introduced the first "all electric" power-steering system on its Acura NSX. Using a brush DC motor installed concentrically around the rack, the system combined torque and velocity information from the steering wheel with vehicle-speed information to calculate the optimum amount of steering assist to provide. The existence of multiple sensors and a processor to digest the data opened up several exciting new possibilities. For example, steering assist could easily be decreased at higher speeds to mitigate "oversteer" instabilities, but boosted at lower speeds where turning assistance is needed most. In addition, by sensing steering-wheel dynamics, the controller aided in providing a smooth "return to center" response following a turn. Finally, a dampening mode was added to reduce road "kickback" when driving over rough surfaces.

Choosing the right motor

By the mid '90s, the race was on for global domination of this revolutionary new market. The Japanese quickly took the lead as Honda migrated its design to the S2000 sports car, and Mitsubishi soon published details of its own electric power steering (EPS) system, also based on a brush DC motor. Since torque assist is the goal of any power steering system, the DC motor is a natural choice for this application since torque can easily be controlled by regulating the motor current. The DC motor is still a popular choice for many Japanese designs, including the EPS system in my 2005 Toyota Prius hybrid vehicle. It's interesting to note that most hybrid vehicles employ EPS not only for the energy savings provided, but also because of the need for continued steering assist even when the engine is off.

But the DC motor also has some unattractive attributes, such as brush arcing and commutator/brush friction. This limits the performance at higher motor speeds and doesn't represent a good solution for larger vehicles. Also, if transistors driving the DC motor get stuck in the on state, "unwanted steer" can result, which is perhaps the most dangerous failure mode in a power steering system. A mechanism is therefore required to mechanically disconnect the motor from the steering system when this condition is detected.

In the mid '90s, another motor type began to steal the limelight, with promising potential for EPS systems. Although the concept of the switched reluctance (SR) motor has been around since the 1830s, economical commutation techniques didn't become available until the early 1970s. SR machines are easy to construct and contain no permanent magnets, resulting in excellent high-temperature performance and superb reliability. In fact, SR machines can survive a single-phase failure and keep on spinning! This level of robustness proved to be irresistible to EPS designers concerned with steering safety. But the rotor generates no magnetic field of its own, which means that only reluctance torque can be produced with its associated high torque ripple. This presented a serious problem for EPS designers, since the most sensitive vibration sensor in the universe is literally right at the tip of your fingers. System engineers had their work cut out for them as they set about developing proprietary current wave-shaping techniques in an effort to mitigate the torque ripple. However, the vibration effect on the steering wheel proved to be too much to overcome economically at the time. Despite this drawback, a compelling argument can still be made that SR-based designs represent a cost-competitive solution compared with other topologies.

Soon, another popular motor started appearing in EPS systems. Targeted primarily at European designs and larger vehicles, brushless permanent magnet (BPM) motors with powerful rare earth magnets promised new levels of efficiency and power densities. Delphi Automotive Systems aggressively established a beachhead with its E-STEER system and shipped over 2.5 million total EPS units between 1999 and 2004. Motorola's Automotive Group also exploits the advantages of BPM motors in their designs. Compared with SR motors, BPM machines exhibit a dramatic reduction in motor vibration, where torque ripple can easily be maintained to less than 2% in sinusoidal back-EMF designs.

Before leaving our discussion on motor types, let's not forget about the ubiquitous AC induction motor (ACIM). Dr. Robert Lorenz, a professor at the University of Wisconsin and co-director of the Wisconsin Electric Machines and Power Electronics Consortium, has much to say about the ACIM based on his many years of experience with it and permanent magnet synchronous motor (PMSM) designs. His research from the late '90s on sensorless automotive EPS systems was based on a modified induction motor. According to Dr. Lorenz, ACIM designs can achieve lower levels of torque ripple than even BPM motors. But the induction machine has one significant advantage: the magnetic field can easily be reduced by simply decreasing the d-axis component of the stator current. As Dr. Lorenz points out, ". . . many designers make the mistake of setting the flux level in an induction machine to a constant operating point, and then just leaving it until they move to high speeds requiring field weakening. By reducing the field at any speeds when little torque is required, operating efficiency can be significantly improved." Dr. Lorenz used this technique to help the University of Wisconsin team take first place in the Future Car Competition using an ACIM as the traction motor. By contrast, field weakening in a BPM machine requires increasing the d-axis stator current. This can negatively affect performance, and magnetic losses in BPM machines can not be easily reduced.

Since the ACIM is devoid of any permanent magnets, it offers another advantage in EPS designs that can be exploited during a system failure. Like the SR motor, the field in an ACIM can be extinguished by simply disabling the inverter transistors. In a fault condition, this effectively turns the rotor into an inert piece of rotating metal in a fraction of a second. Even though no power assist is available, the motor offers no resistance to manual steering.

By contrast, the magnetic field in a permanent magnet motor is, well, permanent. This means that even though the drive transistors are turned off, the motor can still generate magnetic drag as a result of the rotor flux.

First things first

Safety must be *the* most important consideration facing any EPS designer. You can design the most cost-effective, highest-performance power-steering system on the market, but nobody will want it if it has a reputation for occasionally driving you off the road.

A common topology used to ensure reliability in safety-critical automotive systems is referred to as the *asymmetrical architecture approach*. With this technique, a control problem is solved using two different algorithms, running on two different architectures. If the results disagree, a fault condition is generated that places the system in a failsafe condition.

Another innovative technique to enhance EPS reliability has been developed by the Motorola Automotive Group, which produces about 750,000 EPS systems per year. Dr. Tony O'Gorman, a distinguished member of the technical staff at Motorola feels that safety must be integrated into a steering system throughout the design process, not just slapped on as an afterthought. Motorola has developed a patented technique on its MG3 EPS systems referred to as the *Seed Vector Test*, where control vectors are fed serially to a Freescale 8300 digital signal controller. In essence, the controller is given a set of mathematical and logical problems to solve in real-time; these problems are designed to test the hardware and software integrity of the device. If the seed vector results are incorrect, a fault is generated that disables all the transistors driving the motor. As a result, the motor can safely be brought off-line in less than 20ms. As an additional safety measure, the voltage vectors generated by the three-phase inverter are also checked to ensure that proper signals are being supplied to the motor at all times. During a fault condition, unwanted steer cannot result even if one or more of the inverter transistors is shorted, since the motor requires AC waveforms to operate. Under worst-case conditions, the motor may impede motion on the steering wheel, but this is not nearly as hazardous as the wheel suddenly veering off in an unwanted direction.

The most yield from a field

To produce torque, most motors rely on the interaction between their stator and rotor fields. Therefore, it should come as no surprise that the amount of torque produced is a function of the alignment between these two fields. This process is often referred to as *vector control*. When you commutate a brushless DC motor, you're doing vector control. Even brush DC motors do vector control, but instead of being done electronically, the vector control is performed mechanically with brushes and a commutator.

But what alignment works best? It depends on what effect you're looking for. For maximum torque per amp (which is the most common desired outcome), the optimum alignment occurs when the rotor and stator fields are oriented 90º (electrically) with respect to each other. At 0º you have north poles aligned with south poles, and the motor is at equilibrium. While this is a happy condition for the motor, it unfortunately isn't producing any torque for us. At the other extreme is 180º alignment, where you have opposition between the rotor and stator magnets.

Again, the motor isn't producing any torque. But in this case, the motor is not at equilibrium, and the rotor will quickly move away from this position with the slightest provocation. Between these two extremes is 90º, where the motor is working hard to get to its "happy place." Although there is not complete agreement on the terminology, maintaining 90º alignment is a special case of vector control often referred to as *field oriented control (FOC)*.

Recall that in any EPS system, the responsibility of the electric motor is to provide torque assist. A lot of data is processed to determine when and how much torque should be applied, but the bottom line is torque. As already mentioned, this is easily accomplished on brush DC motors by controlling the amplitude of the current into the armature. Regulating this current involves four straightforward steps:

1. Measure the current already flowing in the motor.
2. Compare the current to a desired value and generate an error signal.
3. Amplify the error signal with a controller stage to generate a correction voltage.
4. Apply the correction voltage to the motor via a power stage.

Remember, while the motor is spinning, the commutator is keeping the net rotor flux created by your current properly oriented with respect to the stator field to produce torque. If you think about this procedure being done discretely one step at a time, you essentially have a process that can be done on a digital controller, where the steps I've just listed are repeated over and over, perhaps thousands of times every second.

How's your trig?

But how is torque assist generated in an EPS system that uses a BPM motor? You'll be surprised to find out how similar the process is to that of a DC motor; with two notable exceptions. First, instead of trying to regulate rotor current, we're trying to regulate stator currents, since the positions of the permanent magnets and electromagnets are flipped. Second, since we don't have a commutator to keep the rotor flux and stator field automatically aligned for us, we must assume that responsibility in our control algorithm. This involves a few vector calculations and reference frame transformations, but nothing beyond the cerebral capabilities of the typical reader of this magazine.

Since permanent magnet AC (PMAC) motors are becoming more popular in EPS systems, it's worth spending some time to see how torque control is accomplished with this motor. So, let's go through the procedure one step at a time, where we'll correlate each step to the procedure I previously listed for a DC motor. To aid in understanding the process, we'll assume we have a three-phase AC machine containing a two-pole permanent magnet rotor. The procedure is also valid for machines with more rotor poles; it just means that the angle values calculated must be scaled by the number of rotor-pole pairs that exist. So fasten your seatbelts and let's begin.

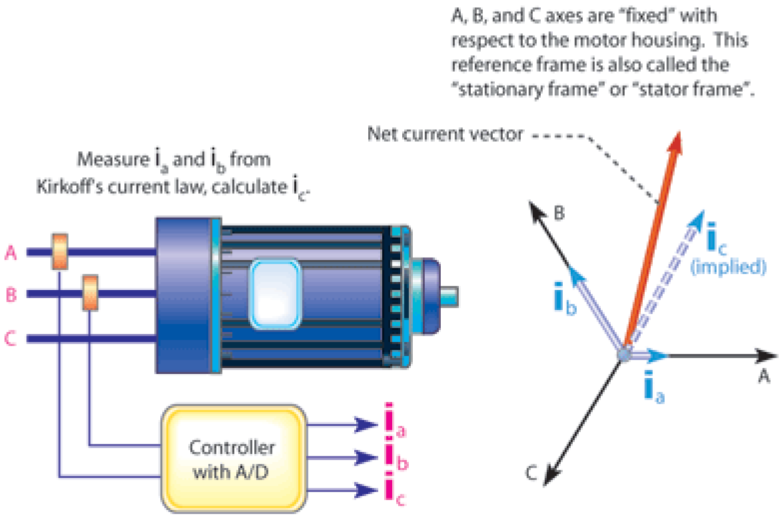


Figure 1: Step 1: Measure the currents already flowing in the motor

STEP 1: Measure the currents already flowing in the motor windings. As seen in Figure 1, it's only necessary to measure two of the three motor phase currents, since the algebraic sum of the currents flowing in two windings must equal the current flowing out of the third winding (unless of course there's another path for current flow, such as a winding short to the motor frame). The current flowing through each stator winding creates a magnetic field oriented along an axis at a specific angle. In a three-phase machine, the windings are spatially configured around the circumference of the machine so that the magnetic axes for each phase are spatially separated from each other by 120º. These magnetic fields add together vectorally as shown in Figure 1 to create a net stator magnetic vector of a specific magnitude and angle, which is a function of the current in each coil.

In high-power industrial systems, these current measurements are typically obtained by looking at the motor phase currents directly (for example, a LEM sensor on each phase). However, this approach is way too costly for EPS systems; a more economical technique must be used. One method gaining in popularity is to measure the DC bus current at specific intervals during the PWM cycle to reconstruct the phase current waveforms. This is one reason why every digital signal controller from Freescale incorporates a hardware trigger mechanism from the PWM module to the ADC, so that the conversions can be acquired at precise moments during the PWM cycle.

STEP 2: Compare the currents to desired values and generate error signals. At this point, let's digress for a moment. On a DC motor, there's a direct correlation between motor current and torque because the commutator keeps the rotor flux and stator field properly aligned at all times. But we don't have a commutator on an AC motor. Instead, we must control the alignment ourselves. As indicated in Step 1, we control the net stator field angle by controlling the currents in each phase. To control motor torque, therefore, all we have to do is determine what component of the stator currents is producing a magnetic field that's orthogonal to the rotor flux at this instant in time and regulate that current component just like we would in a DC motor.

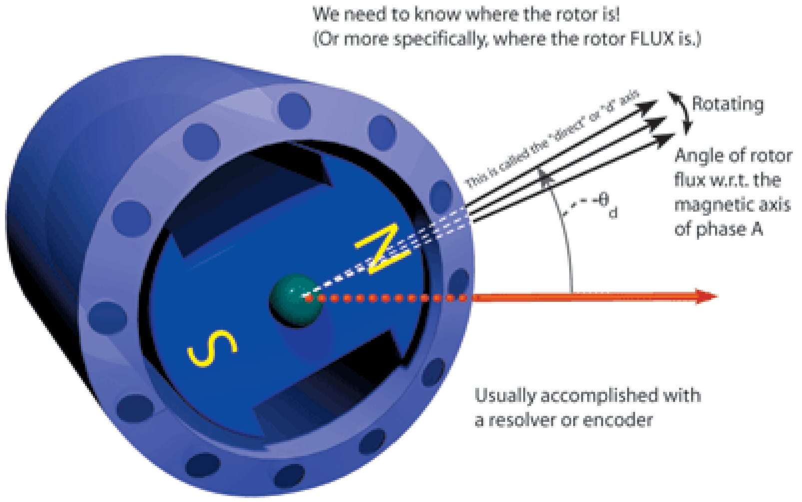


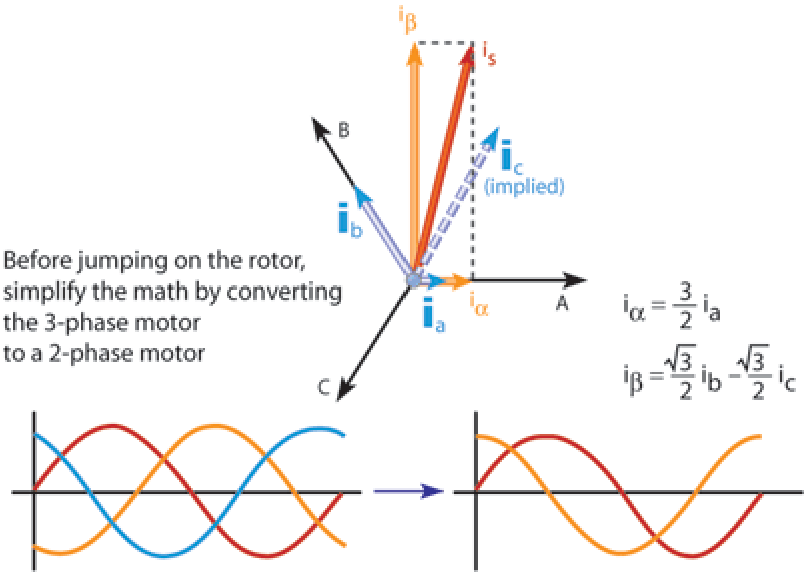
Figure 2: Step 2a: Measure the angle of the rotor position, and the angle of the rotor flux, θ_d

To accomplish this, we need to do two things. First, if we're going to properly align the net stator field to the rotor flux, we need to know where the rotor flux is, as illustrated in Figure 2. There are several ways to do this, but most involve mounting a high-resolution angle sensor on the shaft of the motor, such as an encoder or a resolver. For a BPM motor, if we know the angle of the rotor shaft, we know the angle of the rotor flux. In most cases, this angle is measured as the value between the rotor flux axis and the magnetic axis of the phase A stator winding. The rotating rotor flux axis is often referred to as the *direct axis*, or simply, the *d-axis*.

Second, we need to transfer the motor phase currents we measured in Step 1 to equivalent values on the rotating reference frame established by this d-axis. In so doing, we can dramatically simplify the equations involved with regulating the current. To illustrate why this is, imagine that you're trying to take a close-up video of your child on a merry-go-round. To keep your child in the center of the picture, you not only have to anticipate the up and down motion of the horse, but you also have to factor in the sinusoidal components of the merry-go-round rotation. In other words, trying to servo on a rotating target from a stationary reference point requires many calculations per second and is a challenging problem to say the least.

But what if you jump up on the merry-go-round with your child and try again? By doing so, you don't have to worry about the mathematical artifacts associated with the merry-go-round rotation since they drop out of the equation altogether!

The process of jumping up on the wheel in field-oriented terminology is called the *stationary to rotating frame transformation* or the *Forward Park transform*.

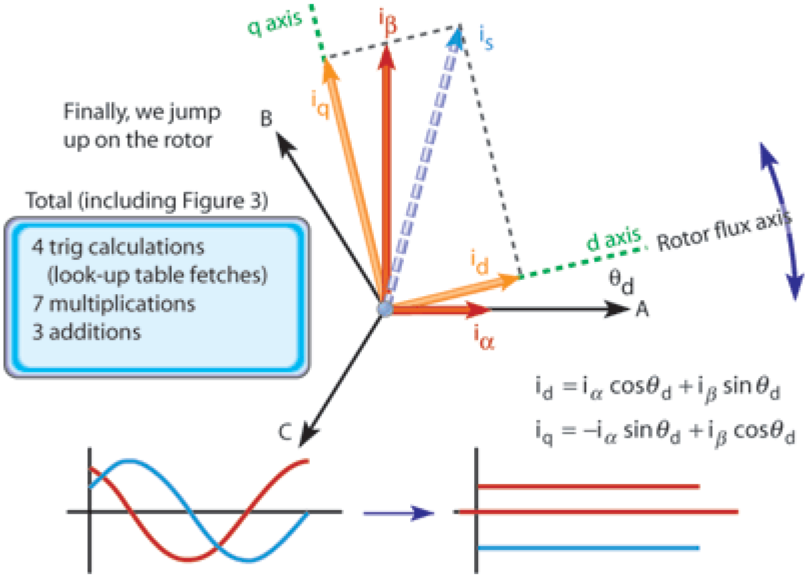


Before jumping on the rotor, simplify the math by converting the 3-phase motor to a 2-phase motor

$$i_\alpha = \frac{3}{2} i_a$$

$$i_\beta = \frac{\sqrt{3}}{2} i_b - \frac{\sqrt{3}}{2} i_c$$

Figure 3: Step 2b: Perform a 3-phase to 2-phase transform on current measurements



Finally, we jump up on the rotor

Total (including Figure 3)

4 trig calculations (look-up table fetches)
7 multiplications
3 additions

$$i_d = i_\alpha \cos\theta_d + i_\beta \sin\theta_d$$

$$i_q = -i_\alpha \sin\theta_d + i_\beta \cos\theta_d$$

Figure 4: Step 2c: Perform a stationary to rotating frame transformation on the measured currents

Before we jump up on the rotating reference frame, it simplifies the equations slightly if we first transform the three-phase motor into a two-phase motor. We accomplish this by converting the three currents into two orthogonal currents that yield the same net stator current vector, as shown in Figure 3. This process is called (surprise, surprise!) *the three-phase to two-phase transformation* or the *Forward Clark transform*. But remember, after this step, we're still in the stationary reference frame. We then jump up on the rotor with the Forward Park transform as illustrated in Figure 4, using the angle information we obtained from Figure 2.

Once on the rotating reference frame, we have two stator current components; one that's directly aligned with the rotor flux on the d-axis (i_d), and one that's at 90 electrical degrees to the rotor flux on a quadrature axis called the *q-axis* (i_q). Here's where it all comes together. The beauty of the transformations I've shown you is that they yield i_d and i_q current components that are DC quantities! All of the sinusoidal artifacts associated with the rotating rotor drop out of the equations altogether. We can now compare each of these DC values with the desired values we want for each axis and generate error signals as shown on the left side of Figure 5. In most cases with BPM motors, we set the commanded value for i_d to zero, since we already have all the flux we need from the rotor's permanent magnets. However, i_q is where all the action is, and this commanded value is responsible for setting the torque in the machine. So when you want more torque assist in an EPS application, i_q is the variable you want to adjust.

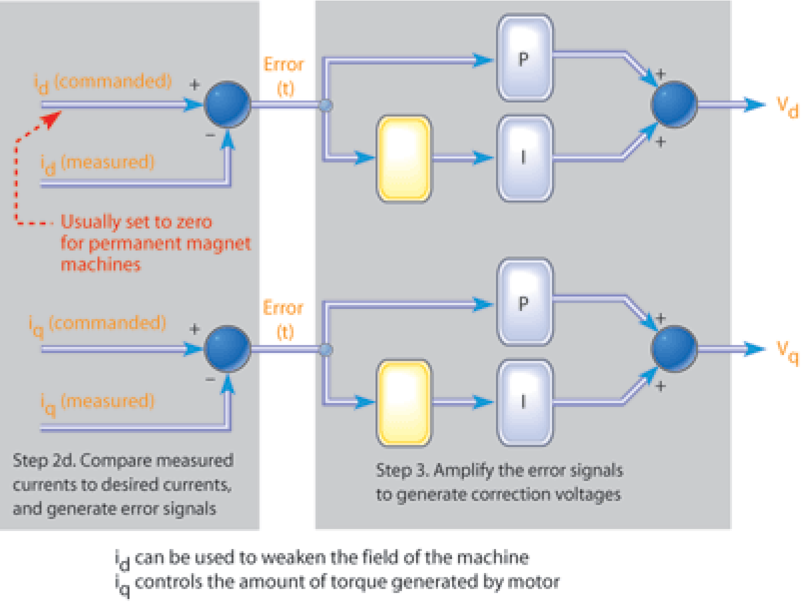


Figure 5: Generate error signals

STEP 3: Amplify the error signals to generate correction voltages. As discussed in the previous step, we now have two measured DC currents (i_d and i_q) that need to be regulated. This is shown in Figure 5, where a separate regulator is employed for each axis. The PI regulator is a popular choice for current mode control. The regulators for i_d and i_q work independently from each other in the rotating reference frame and can be thought of as rotating synchronously with the rotor flux. The outputs of both of these regulators generate voltages that serve to correct for the differences between the measured and commanded values for each axis.

STEP 4: Apply the correction voltages to the motor via a power stage. We now have two voltages (v_d and v_q) that have to be applied to the motor windings to drive the phase currents toward the values that we want. But remember, these values exist on the rotating reference frame. To apply them to the stator windings, we must jump off of the rotor now, and transform v_d and v_q into three stator voltages that when added vectorally, yield the same voltage vector that results when we vectorally add v_d and v_q. To do this, we use the same procedure we used to get up on the rotor, but run it in reverse.

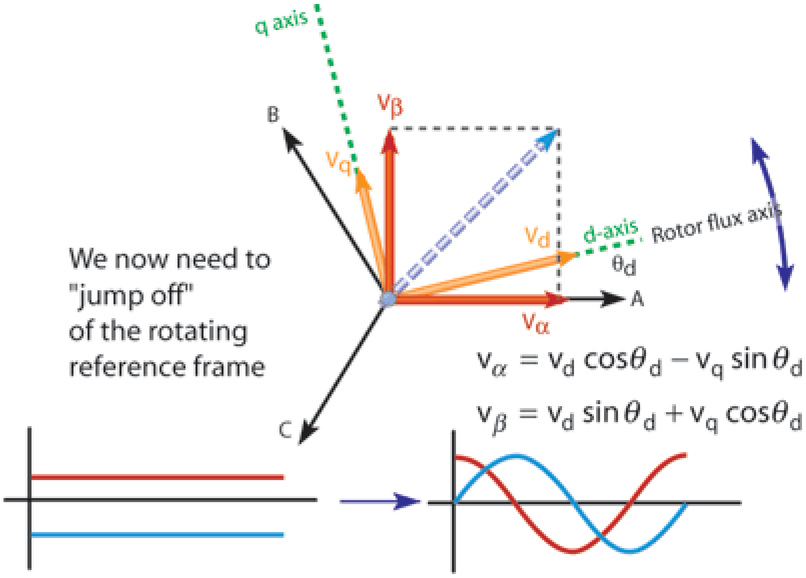


Figure 6: Step 4a: Perform a rotating to stationary frame transformation on the correction voltages

Figure 6 shows the first part of this process. We do what's called a *rotating frame to stationary frame transformation* or the *Reverse Park transform*. This yields two orthogonal voltage vectors (v_α and v_β) in the stationary reference frame whose combination result in the same net vector as the addition of v_d and v_q. Of course, in order to accomplish this, we once again require knowledge of the angle of the rotor flux.

If we use *Space Vector Modulation* (*SVM*, not to be confused with Vector Control), we already have all the information we need to generate the motor phase voltages directly from v_α and v_β. If we use other modulation techniques such as standard PWM, we need to perform one final step: transform v_α and v_β into three equivalent stationary vectors using the two-phase to three-phase transformation known as the *Reverse Clark transform*. This process and its associated equations are shown in Figure 7. These voltages are then applied to the stator windings by a power amplifier that usually takes the form of a six-transistor inverter.

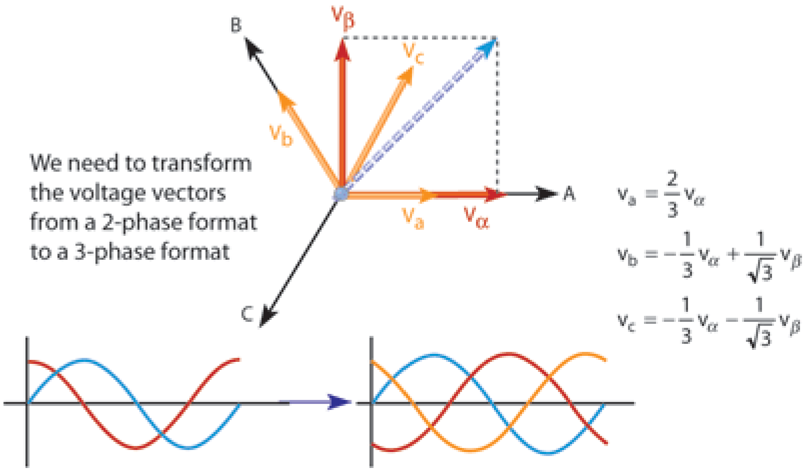


Figure 7: Step 4b: Perform a 2-phase to 3-phase transformation

If you review the steps involved, it should be apparent by now that in order to control torque on an AC motor, we essentially do it the same way as we do on a DC motor. The process of FOC essentially allows us to treat an AC motor like a DC motor. Figure 8 shows a summary of the transformations that make this possible.

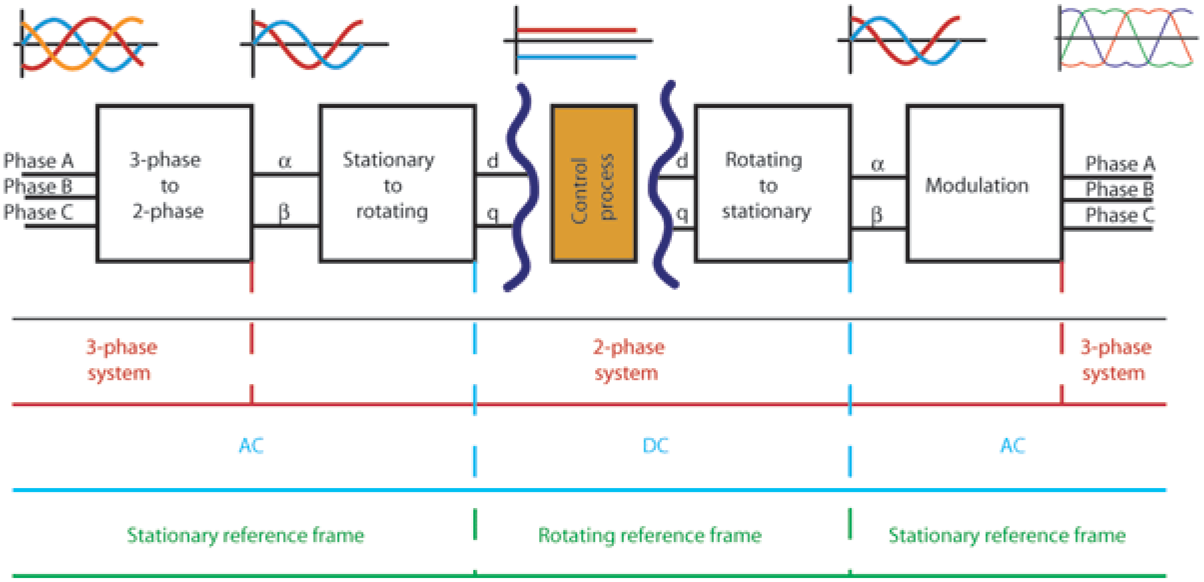


Figure 8: Summary of FOC Transformations

One question I often get asked in my motor control seminars is, "While you are doing all these calculations, the rotor is still moving. Doesn't that introduce an error in all the equations involving the rotor angle?" The answer is, "absolutely." That's why it's so important to perform the calculations as quickly as possible once the stator currents and rotor angle have been sampled. But even *more* important is to perform these calculations as *often* as possible, which translates to a high sampling frequency. Remember, the PWM module acts like a sample-and-hold unit, where the same pulse width values will be used until the next set of calculations is performed. If the sampling frequency is too low, the PWM values become stale and result in poor field-oriented performance. But today's digital signal controllers can perform all of the calculations listed above in about 20µs, allowing sampling frequencies to easily push into the 10 to 20kHz range. This results in excellent FOC for PMAC motors in EPS applications. Figure 9 shows an EPS demo system based on a 56F8300 controller.

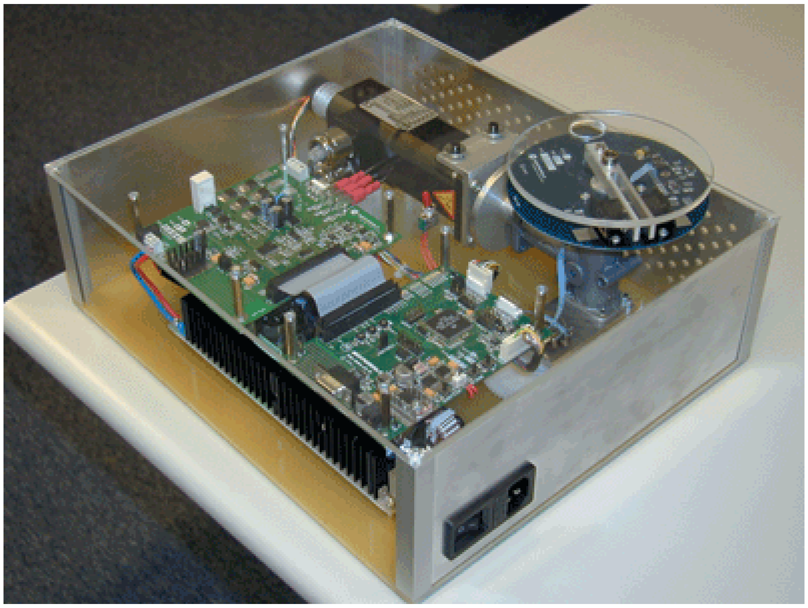


Figure 9: EPS demonstration system from Freescale based on 56F8300 controller

What's next?

Although we're at the end of the article, the story is just beginning. When will electric motors completely take over the steering market, and what is the next hot technology on the horizon for vehicle steering? With regard to the first question, it's anybody's guess, but most experts agree that within a decade, EPS will be the dominant technology. However, as more and more automotive systems incorporate electric motors, the vehicle's "electron accelerator" (the alternator) is quickly becoming overtaxed. Migrating from 12V to 42V systems promises to mitigate the power-utilization problem. Unfortunately, few cohesive standards are emerging in this area, and progress is slower than hoped.

As to the second question, there is much discussion about the potential for "steer-by-wire." This is both exciting and somewhat scary, since it would completely remove any mechanical linkage between the steering wheel and steering rack. With current EPS designs, a system fault results in the motor being disabled, but manual steering is still possible. With steer-by-wire, no mechanical linkage exists, which means that new failsafe strategies need to be developed. As Dr. O'Gorman stated, "system cost must decrease significantly before steer-by-wire will take off." And even when this happens, many speculate that it will take years before the general public is ready to accept this technology.

O'Gorman believes that the benefits of migrating to steer-by-wire systems are not as apparent as the reasons that currently exist for switching to EPS.

Finally, I'm reminded of the futuristic scenes from the recent Hollywood production of *I, Robot*. The personal transport vehicles in the movie had the option of manual *or* automatic steering control, where the "driver" could read a newspaper, watch the news, or even take a nap. But how far over the horizon is this technology? Is it still just the stuff of sci-fi movies? Not according to Dr. Lorenz, who points out that we already have radar proximity technology that can be integrated into cruise control systems to regulate the following distance between vehicles. Also, my 2005 Prius (as well as many other newer vehicles appearing on the market today) has an incredibly accurate navigational system, just waiting to be integrated into other systems in the vehicle. But before "autosteer" systems can migrate from science-fiction to science-fact, a reliable technology is needed to sense vehicle position with respect to the road. In Japan, Toyota already offers an option on the Prius that allows it to parallel-park itself! But most current technologies in this area are based on optical sensing techniques, which have not demonstrated the necessary reliability to be given *carte blanche* control of the steering problem. Dr. Lorenz believes that other road position sensing techniques need to be developed, perhaps based on field sensing technologies like those currently used at intersections to detect the presence of a vehicle.

While these changes would represent a tremendous investment in our transportation infrastructure, the payback in terms of driving comfort and reduction in highway fatalities makes the allure of such a system very appealing indeed. The potential for reduced gridlock suggests that congested urban areas may be the first to adapt such technology. However, Dr. O'Gorman believes that this technology will be born out of military programs or perhaps areas where traffic flow already needs to be tightly regulated, such as airports. In fact, several unconfirmed reports suggest that the U.S. military is already conducting experiments on autosteer technology for transport vehicles (with limited success, I might add). But one thing is for sure: the next few decades will bring about many exciting and revolutionary changes in this rapidly developing area of automotive technology.

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Resources:

"Bush: No quick energy fix," Associated Press article, *The Arizona Republic, Thursday*, April 28, 2005, pp 1, A9.

Torrey, David A. and James M. Kokernak. "Power Steering: Brushless DC or http://powerelectronics.com/mag/power_power_steering_brushless/

"Delphi Electric Power Steering," Delphi Product Brochure, June 2004. www.delphi.com/pdf/s/str_esteer.pdf

Fitzgerald, A. E., Charles Kingsley Jr., and Stephen D. Umans. *Electric Machinery*. New York, NY: McGraw-Hill, 1990.

Novotny, Don and Tom Lipo. *Vector Control and Dynamics of AC Drives*. New York, NY: Oxford University Press, 2000.