Analog Devices: High Efficiency, Low Cost, Sensorless Motor Control.

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Abstract

In this paper we consider the sensorless control of two types of high efficiency electric motors, the brushless direct current (BLDC) motor, and the brushless alternating current (BLAC) motor. In both cases the controller is implemented on a low cost 28 pin ADMCF32x flash based embedded digital signal processor that is optimized for the appliance industry. Not only do these algorithms run on code compatible devices, but they share an underlying statistically founded Kalman filter architecture.

Introduction

In these days of soaring fuel prices everyone is concerned about the efficiency of their appliances. The energy consumed by the electric motor represents a large portion of the total energy used in electric appliances such as refrigerators, air-conditioners, and washing machines. Thus, many manufacturers are now using three phase, permanent magnet, inverter driven, variable speed motors to achieve their efficiency goals.

Two common motors are the brushless direct current (BLDC) motor, and the brushless alternating current (BLAC) which is also known as the permanent magnet synchronous motor (PMSM). These motors are intrinsically more efficient than the induction motor because the magnetic field of the rotor is supplied by the permanent magnets rather than by the electromagnet used in the induction machines. Thus, they are suitable for the new generation of appliances.

Controlling these new motors is not a trivial task. Achieving the peak efficiency requires that the magnetic field that is created by the stator currents be kept in very precise alignment with the permanent magnets on the moving rotor.

In the past, various types of sensors were mounted on the rotor to keep track of the position and velocity. These included Hall effect sensors, resolvers, optical encoders, and tachogenerators. Today the use of such sensors is not acceptable. It adds too much to the system cost and reduces the reliability of the product.

Sensorless controllers rely on software estimators to take the place of these hardware sensors. The task of an estimator is to provide the same high quality rotor position and velocity information that the hardware sensor used to supply. There are many types of estimators in use today ranging from ad-hoc solutions, to simple mathematical observers, to advanced, statistically-optimal algorithms such as the Kalman filter. Precise control of the pulse width modulated (PWM) inverter, and accurate measurement of the motor currents is required for these estimators to work correctly. In all cases, removing the hardware sensors places an additional computational burden on the controller.

The digital signal processor (DSP) is the enabling technology that makes it possible to achieve higher efficiency, higher reliability, improved acoustic noise *and* lower cost. The incredible computational speed of these devices means that much of the burden of controlling a motor that was once carried out by hardware can now be done in software.

The Analog Devices DashDSP (ADMCF32x) family of embedded DSP motor controllers is optimized for the appliance manufacturer. This tiny 28 pin package combines the computational power of a DSP with integrated analog to digital converters and three phase PWM to handle the most demanding sensorless control applications. The integrated flash memory is ideal for development, and pin-compatible ROM versions provide cost reduction for full production runs.

Kalman Filtering

Sensorless control relies on estimating the position and velocity of the rotor based on the available voltage and current measurements. There are lots of ad hoc methods and quite a few observers that are founded in the mathematics of systems theory. The famous Kalman filter is regarded as superior to these other methods since it makes explicit provision for the noisy environment that is encountered in motor control. Furthermore, the Kalman filter provides a general theory for estimation that can be applied to any type of motor.

In trying to make these estimates there are two sources of information that we may use. First, we have a mathematical description, or model, of how this particular type of motor behaves. This embodies all our scientific understanding of the laws of motion and the rules by which electricity and magnetism cause the motor to turn. Secondly, we have some instantaneous measurements of the motor at the current moment in time. These measurements might include some of the voltages and currents, but not the position or velocity of the rotor.

The Kalman filter gives us an optimal method for combining these two pieces of information: the model and the measurement. The algorithm proceeds in two steps, prediction and correction. In the prediction step, we use the model to predict how the state of the motor will change given the input voltage we have applied. We also predict what measurement should be observed given the new state of the motor. In the correction step, we compare the predicted measurement with the actual measurement. The difference is multiplied by a gain and used to correct the estimate of the motor state.

At each time step the Kalman filter produces an estimate of the state of the motor. But additionally, a state covariance is also calculated. This covariance is a measure of the confidence we may place in the state estimate. The gain that is used in the correction step is based on this covariance so that when we are unsure of the estimate the gain is large and the correction takes place rapidly. When we have more confidence in the estimate then the gain in the correction step is small and so noise on the measurement will have little effect on the estimate. This adaptability of the correction gain is the key to the power of the Kalman filter to overcome a noisy environment and produce high accuracy estimates of the rotor position and velocity.

The Brushless DC Motor

A motor is not mechanically different from a generator. If you put mechanical power into a motor by spinning the rotor, electrical power will be generated on the motor terminals. This generated voltage is called the back electro-motive force (EMF). The back EMF that is observed on the terminals is not constant; it changes with both the position and the speed of the rotor. As the position changes the back EMF will describe a trapezoidal shape which is shown in Figure 1 for one of the three phases. The amplitude of this trapezoid increases linearly as the rotor speed increases. This is true even when this device is used as a motor. In order to make the motor spin faster we must apply enough voltage to overcome the back EMF.

Torque in a permanent magnet motor is produced by the product of the current with the back EMF summed over the three phases. The BLDC motor has a trapezoidal back EMF and so the strategy is to apply a three phase square wave current to the stator windings. By keeping the square top of the current aligned with the square top of the back EMF the sum of the phase torque is held constant. The square current waveform for a single phase is shown on the second line of Figure 1 and the resulting torque is shown on the bottom line.

This control technique is called 120 degree conduction since each phase of the motor conducts current for 120 degrees during each half cycle. It is also called trapezoidal modulation. At any given rotor angle, one phase will be conducting a positive current, one phase will conduct a negative current, and one phase will be inactive. The two active phases contribute equally to the total torque while the inactive phase contributes no torque. Thus the sum of the phase torque is theoretically constant. In practice, the back EMF is not perfectly trapezoidal and the currents impressed on the stator are not perfectly square. This results in non-constant torque output when the motor is running in a steady state. The ripple frequency will be six times the fundamental electrical frequency. The amplitude of the ripple will depend on the motor design and the accuracy of the current controller. This torque ripple can excite acoustic vibrations in the machine that are undesirable.

A typical controller will have an inner loop that controls the current in the two active phases by applying the correct voltage to the stator. A resistive shunt is often placed in the DC link to provide the current feedback for this inner loop. An outer loop controls the speed of the motor by applying the correct reference current to the inner loop. The current is switched or commutated onto the correct phases based on the rotor position.

Since there is always an inactive phase, it can be used to measure the back EMF. One way that this measurement has been used is the zero crossing method of sensorless control. Notice that the point at which the back EMF crosses zero volts is exactly halfway between two commutation points. So when a zero crossing takes place, we can add half the time from the previous zero crossing to predict when the next commutation should take place.

The zero crossing method has some inherent weaknesses. It is easy for the moment of the zero crossing to be obscured by noise thus causing a badly timed commutation. At higher speed the duration of the inactive phase becomes shorter making the timing more critical. At high load there will be larger currents in the active phases. Since the stator is mainly inductive, these large currents do not disappear instantaneously when the phase first becomes inactive. Instead the current circulates through the flyback diode of the inverter. Until this flyback current has decayed, the inactive phase cannot be used to measure back EMF at all. The combination of high speed and high load can make it impossible to observe the zero crossing.

A more robust method uses Kalman filter theory. The mathematical model of the motor includes the position and speed of the rotor and also the back EMF that will be produced. In the prediction step, this model is used to predict how the state of the motor will change during one time step. The predicted back EMF is then compared to the measured back EMF. The difference is used to correct the modeled state of the motor.

Using this Kalman technique, we obtain estimates of the position and speed of the motor at every time step, not merely at the zero crossing. This translates directly into more accurate commutation and thus higher efficiency. Furthermore, since all the available samples of the back EMF are used, the effect of noise on any particular sample is greatly minimized.

Figure 2 is an oscilloscope trace of the ADI Trapezoidal Sensorless reference design running a BLDC motor. The upper trace is the PWM voltage applied to one of the phases with a 100 volts per division scaling. The lower trace is the phase current on a 2 amps per division scale. The time scale is 2 milliseconds per division.

The current waveform clearly shows the active positive and negative currents as well as the inactive period. The voltage trace switches between the 280 volt bus and ground when the phase is active. During the inactive period, the back EMF makes a ramp. Note that by coordinating the sampling of the back EMF with the center of the PWM period the switching noise can be avoided entirely. The flyback period can also be observed when the positive current is switched off. Here we see that while the current is decaying to zero the voltage on this newly inactive phase is held at ground. Only after the current has decayed do we observe the back EMF on this unconnected phase.

The Brushless AC Motor

The brushless AC motor (BLAC) is similar to the BLDC motor but the back EMF is sinusoidal rather than trapezoidal. This is achieved by using overlapped windings on the stator and a larger number of stator poles. Usually, this means that a BLAC will be more expensive than a comparably sized BLDC. The advantage of the BLAC is lower acoustic noise and lower torque ripple.

Since the BLAC is a permanent magnet motor, the torque produced is proportional to the product of the back EMF and the current summed over the three phases. To obtain a constant output torque, the stator is driven with a sinusoidal current which is aligned with the back EMF, see Figure 3. The resulting torque for a single phase is then a sine squared, and the sum of the three phases will be a constant output torque 1.5 times the amplitude of the phase torque. This constant output torque is the key to the lower acoustic noise associated with the BLAC.

This method of control is called 180 degree conduction or sinusoidal modulation since each phase is driven for 180 degrees during each half cycle. Since there is no inactive phase in this scheme, we cannot directly measure the back EMF as we did with the BLDC.

The typical field oriented controller for a BLAC uses the angle of the rotor to calculate what part of the stator current is parallel to the magnets and what part is perpendicular to the magnets. The parallel or direct axis current can be used to strengthen or weaken the magnetic field created by the rotor magnets. The perpendicular or quadrature axis current creates torque. When the rotor angle is known, these two components of the stator current can be controlled independently.

A common scheme for the BLAC has two independent current control loops, one for the direct and one for the quadrature currents. The direct axis current is usually controlled to be of zero magnitude, but may be controlled to a small negative value to achieve higher speeds using the field weakening technique. The quadrature axis current is controlled to achieve the desired torque. An outer loop that controls the rotor speed is used to create the torque command.

There are many techniques for sensorless control of the BLAC, but here the Kalman filtering method truly excels. The model that is used in the prediction step includes the stator currents and the rotor speed and position. The current induced in the stator is driven by the difference between the applied voltage and the back EMF. So, although we cannot measure the back EMF directly, its effects are observed in the stator currents. In the correction step of the Kalman algorithm, the predicted currents are compared to the actual measured currents, and the error is used to correct not only the estimated currents but also the estimated position and velocity of the rotor.

Figure 4 is an oscilloscope trace of the ADI Sinusoidal Sensorless reference design running a BLAC. The upper trace is the PWM voltage applied to one of the phases on a 100 volts per division scale. The lower trace is the phase current on a 2 amps per division scale. The time scale is 2 milliseconds per division. This example is running at 80 Hz electrical speed.

Conclusions

Permanent magnet brushless DC and brushless AC motors are the next step in efficiency for appliance manufacturers. Control of these motors requires that the position and speed of the rotor is known. Sensorless controllers extract this information from the voltages and currents on the motor terminals thus improving the reliability and lowering the total system cost. Kalman filtering provides a general theory for designing these sensorless controllers. The key enabling technology is a highly integrated motor control DSP, such as the Analog Devices DashDSP, that combines high computational power with all the necessary input and output functions on a single chip.

Biography

Tom Flint is a Systems Engineer for Algorithm Development with Analog Devices Embedded DSP Group, focusing on optimized motor controllers for the appliance market. He has been a hardware and software designer for embedded instrumentation and control, in a wide variety of applications since 1989. He completed a doctorate in electrical engineering at the University of Rhode Island in 1998.

Contacts

Analog Devices Motor Control website is located at www.analog.com/industry/motor_control and contains complete product and reference design information.

Publisher

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Figure 1

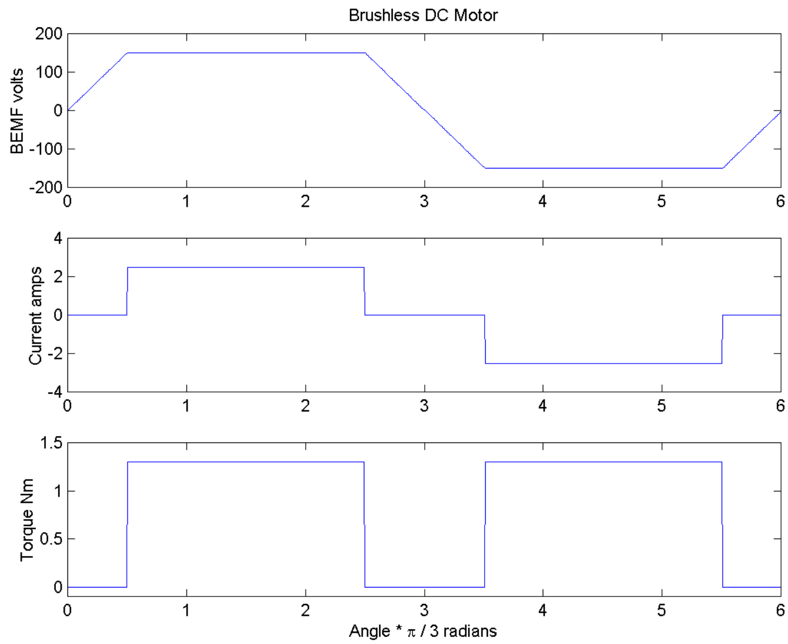

Figure 2

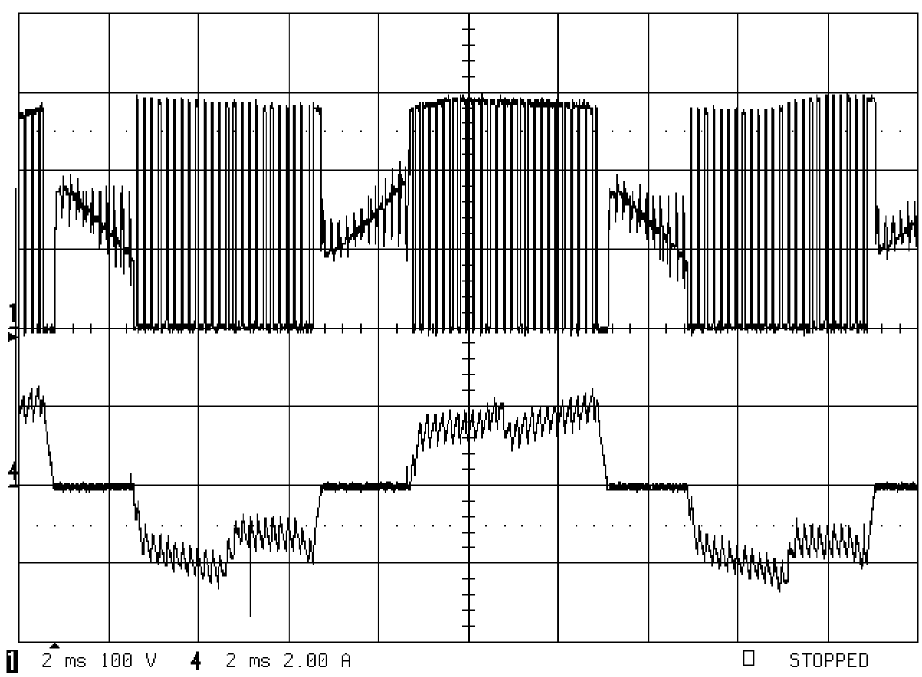

Figure 3

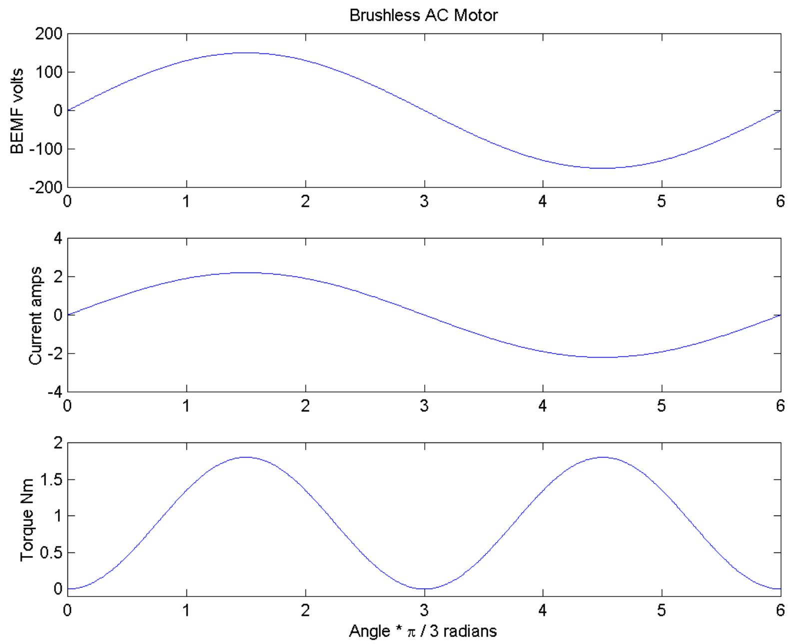

Figure 4