High-performance motor control at low speeds

Chris Clearman - May 11, 2015

Sensorless motor control has primarily been applied to applications where the majority of the operating time is at higher electrical frequencies (mechanical speeds). This is due primarily to the fact that most sensorless techniques require a back-EMF (Bemf) signal that is generated by the rotor’s rotation at a minimum frequency. Being able to continuously estimate the rotor flux angle at zero and very low speeds and stably move between low-speed and high-speed estimators can improve the effectiveness of sensorless startup under load.

If you are a frequent reader of the Spin Cycle blog, you may be aware of TI’s FAST software observer used in the InstaSPIN-FOC software. FAST’s minimum frequency of operation is much lower than that of other observers, sometimes below 1 Hz. But it still requires a minimum frequency.

Figure 1: Frequency of operation for FAST software observer

With sensorless techniques such as FAST, the initial rotor flux angle is unknown and, until enough Bemf is measured so that the algorithm can start estimating correctly, the estimates are unpredictable. But this estimated angle – even though incorrect – will be feeding the control system that will be applied to the motor and that may induce rotor movement. With just a small amount of rotor movement, though, enough Bemf voltage is produced so that the algorithm can converge on a reasonable angle estimate, allowing controlled high-torque drive into an area of excellent operation. So if enough torque is generated for rotor movement, this method can be used to start the motor, but it may not be consistent in start-up performance.

Generating enough Torque

As the starting load is increased, the torque you can generate will be based on the current and the alignment of the fields (determined by the accuracy of the angle estimate). To insure you can generate enough current, it is imperative that the speed controller’s maximum (positive and negative) output be larger than the rated current that is required to generate the rated torque. In the example in Figure 2, note the below waveform captured when starting a motor under full load. Producing the torque required to move this rated load requires 4A of current. In this case, the speed controller’s maximum output was set to (6.0), and you can see that this 6A current was reached in the first electrical cycle to move the rotor. In this example, FAST was able to provide a valid angle, which allowed the control system to regulate the current usage immediately to only the required 4A.

Figure 2: Full load (4A continuous / 6A peak) start-up
Even though you are generating a stable feedback angle, that angle is not necessarily aligned properly to generate maximum torque. You are basically just sweeping a stator field and waiting for the rotor field to lock on and synchronize. When the stator field is not properly oriented, you will not produce enough torque or, in the worst case, produce torque in the opposite direction required. Improving this situation requires a better starting angle for the control system. But how do we do this when most sensorless control algorithms, including FAST, can’t provide a valid angle at zero speed?

**Alignment**
One way to do initial alignment in a field-oriented control (FOC) system is to inject a DC current into the Id portion of the control system (none into Iq). This is the D-axis, which is defined as the orientation of the rotor flux.

![Figure 3. Field-oriented control: Orienting Stator Flux (green) to Rotor Flux (red) to maximize torque production for a given stator current](image)

If this current is large enough to move the rotor (and any load), the injection will result in the rotor now being at a known angle (0 radians), meaning that while the forced angle is still emulated, it is at least starting in the proper orientation and in the best position to produce torque. This injection of DC current can be done “manually,” or you can take advantage of the RsRecalibration flag included in our InstaSPIN-FOC solution.

Start-up under load testing was one of the items I covered in a recent Spin Cycle post. While the methods described there can dramatically improve the sensorless start-up capabilities for most applications, there are still some limitations, especially in applications that may have highly dynamic loads up to 100 percent of rated torque output.

**Continuous Angle Tracking**
To truly solve the start-up problem, you need to be able to continuously estimate the rotor flux angle at zero and very low speeds and to transition between the low-speed and high-speed observers in a stable manner.

Two functions are required, which TI is offering in a new set of libraries with our InstaSPIN-FOC technology. The library is in two parts:

- IPD_HFI: Initial Position Detection (IPD) and High-Frequency Injection for Zero- and Low-Speed Operation
- AFSEL: Logic transitions between IPD_HFI and FAST

![Figure 4. Frequency of operation with FAST and IPD_HFI](image)

The operation of these functions is described in more detail on the next page.
**Initial (Zero Speed) Position Detection**
The IPD_HFI module’s IPD portion uses the BH curve of the iron that the stator coil is wrapped around in order to determine the rotor’s north pole and thus the d-axis. The magnetic field strength will bias the stator’s BH curve operating point as shown in the below figure. Supporting and opposing magnetic fields are applied with the stator coil. When both fields support, the BH curve is pushed further into saturation. When the magnetic fields oppose, the BH curve operating point moves further into the linear region. The difference in inductance between these two BH curve operating points allows the IPD algorithm to determine where the rotor north pole is located.

![Figure 5. BH curve and relative location for different rotor orientations](image)

**Low Speed Position Detection**
Once the rotor’s north pole is located, it must be tracked at all times during the motor’s operation to achieve best control system performance, even during the very short time between start-up and when FAST can reliably provide valid angle estimations. The IPD_HFI module employs a high-frequency signal to track the north pole. However, this capability relies on the motor design having a large saliency. Saliency can be introduced by placing the rotor magnets below the rotor’s surface with gaps in the rotor’s iron left in between poles. Contrast this to a non-salient surface mounted design in the figure below.
For the salient type motor, the reluctance difference for flux flowing through the magnet is greater than reluctance of the iron path because the magnetic material has a much less relative permeability than the surrounding iron. As the rotor’s angle advances, the reluctance undergoes a periodic variation. If the inductance is measured on a coil of the stator, it will look something like below:
The HFI part of IPD_HFI uses this information to stay locked onto the rotor's north pole while the rotor is spinning at low speeds. To make certain that the HFI's angle is locked onto the north pole and not a south pole peak, the IPD portion initializes the HFI to the D-axis north pole. Selection of the high-frequency signal used to excite this reluctance signature is selected based on the motor's time constant.

**Transitional Logic**
The HFI algorithm works very well at low speeds but it has a maximum speed limit. Before this maximum speed limit is reached, motor control has to be handed over to a higher speed observer such as FAST. The module that selects between low-speed (HFI) and high-speed (FAST) estimators is the angle frequency select (AFSEL). AFSEL requires angle and frequency inputs from both the low-
and high-speed estimators and a setting for the speed at which the control is passed from one estimator to the other.

![Diagram](image)

**Figure 8. InstaSPIN-FOC with FAST (EST), IPD_HFI, and AFSEL**

**Limitations**
Besides the need for a salient rotor design, one of the approach's key limitations is the effect of the current through the motor on the saliency effect. To start a motor under load, the motor must consume enough current to produce the needed torque. As the currents increase, the reluctance variation diminishes and hence the inductance variation also diminishes. As a result, the module's HFI portion will not estimate the angle location precisely enough to maximize torque production. This effect must be tested and is highly dependent on the motor design and the initial saliency (variation). More variation is always better.

**Example Implementation**
TI has released an example “Torque Control” implementation as “proj_lab21” starting with MotorWare revision 1.01.00.14

Initially the project is just being released on the DRV8301 Rev D EVM inverter with our C2000 Piccolo F28069 microcontroller. In future revisions of MotorWare, support will be extended to different combinations of inverters and controllers as well as further system examples such as “Speed Control.” You can learn more about InstaSPIN and IPD_HFI at [www.ti.com/instaspin](http://www.ti.com/instaspin).

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