Shaft sensors are VERY expensive.

Many applications cannot afford the cost of a shaft sensor.
Assuming no saliency, stationary frame equations are:

\[
\begin{bmatrix}
  v_\alpha \\
  v_\beta
\end{bmatrix} = R_s \begin{bmatrix}
  i_\alpha \\
  i_\beta
\end{bmatrix} + p L_s \begin{bmatrix}
  i_\alpha \\
  i_\beta
\end{bmatrix} + k_E \omega_{syn} \begin{bmatrix}
  -\sin(\theta_e) \\
  \cos(\theta_e)
\end{bmatrix}
\]

Diagram:
- Rotor with surface-mount magnets
- Non-salient design (magnetically round)
- Back EMF component
Stationary Frame Back EMF Observer

\[ i(t) = \left( \frac{V_{in}(t) - \text{emf}(t)}{R_s} \right) \left( 1 - e^{-\frac{t}{\tau}} \right) \]

Back EMF Observer

Low Pass Filter

\[ \sum \]

\[ \Phi I \rightarrow -1 \]

\[ V_{in} \]

\[ \text{emf} \]

\[ i \]

\[ \text{emf} \]

\[ \text{emf} \]
Back-EMF Observer Performance

One of three phases of Baldor PMSM motor

Observer simulation
Observer sampling frequency = 10 KHz

Back-EMF
Estimated Back-EMF
Evolution of Sensorless Drive Technology

- Sensorless Commutation
- Linear Observers
- Sliding Mode Observers
- Direct Torque Control
- Saliency Tracking
- InstaSPIN-FOC

Year:
- 1970
- 1980
- 1990
- 2000
- 2010

Date: March, 2013
InstaSPIN-FOC Solution

DRV8301  DRV8312 Kits
High Voltage Motor Control + PFC Kit

InstaSPIN-FOC

BLDC FOC – March 2013
PMSM FOC – March 2013
ACIM FOC – March 2014
IPM FOC – March 2013
Stepper FOC – Under Study
SR – Under Study
## Solving The Problems

<table>
<thead>
<tr>
<th>Typical observers and FOC solutions</th>
<th>TI’s FAST software encoder and InstaSPIN™-FOC solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor model based observers have a heavy dependence on motor parameters and the changing of those parameters during operation</td>
<td><strong>no Datasheet required!</strong> Relies on fewer motor parameters plus Off-line parameter identification of YOUR motor On-line parameter monitoring and re-estimation of YOUR motor</td>
</tr>
<tr>
<td>Complex observer tuning, done multiple times for speed/loads, for each motor</td>
<td>No tuning of the observer required. Once motor parameters identified it works the same way every time, across speed/torque dynamics, no “knobs to turn”</td>
</tr>
<tr>
<td>Angle tracking performance is typically only good enough at over 5-10Hz and may have challenges with highest speeds and compensation for field weakening;</td>
<td><strong>FAST™</strong> provides reliable angle tracking within one electrical cycle of rotation, and with quality sense inputs can track at under 1 Hz frequency.</td>
</tr>
<tr>
<td>Dynamic performance is typically heavily influenced by user’s hand tuning of the observer; Over load stall events typically crash the observer.</td>
<td>Angle tracking is completely robust under dynamics and <strong>FAST™</strong> recovers and re-locks after an over load stall event.</td>
</tr>
<tr>
<td>How to start from zero speed</td>
<td><strong>InstaSPIN™-FOC</strong> includes Zero Speed start forced angle, able to provide 100%+ torque at start-up with <strong>FAST™</strong> taking over in less than one electrical cycle; and in conjunction with other initial rotor position detection algorithms as an input, can start with full closed loop control</td>
</tr>
<tr>
<td>Observer feedback near 0 speed is not stable so the control system immediately has poor angle and speed feedback.</td>
<td><strong>FAST™</strong> is completely stable near zero speed, providing accurate speed and angle estimation.</td>
</tr>
<tr>
<td>Tuning FOC current control is challenging – especially for novices</td>
<td>Automatically tunes current controllers based on the parameters identified. User may update gains or use own controllers if desired</td>
</tr>
<tr>
<td></td>
<td>Fully tuned observer and efficient and stable torque controller in less than 2 minutes</td>
</tr>
</tbody>
</table>
### Typical observers and FOC solutions

<table>
<thead>
<tr>
<th>Systems have a high reliance on quality of feedback</th>
<th>FAST™ includes automatic hardware/software calibration and offset compensation; complements Piccolo ADC and oscillator compensation capability. FAST™ requires 2 currents (3 for 100%+ modulation) and 3 phase voltages to support full dynamic performance.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple techniques for multiple motors: standard back-EMF, Sliding Mode, Saliency tracking, induction flux, or “mixed mode” observers</td>
<td>FAST™ works across all three phase motor types, synchronous and asynchronous, across all dynamics. It even supports salient IPM motors by allowing enhanced estimation for motors with different Ls-d and Ls-q and always works in Necessary Torque Per Minimum Amp mode; Includes PowerWarp™ technology for induction motors, delivering MASSIVE energy savings.</td>
</tr>
<tr>
<td>Field weakening region can be challenging for some observers and most hand tuned FOC systems as the Back-EMF signals grow too large and effect tracking and stability</td>
<td>Flux sensing allow for very easy field weakening/boosting applications with stable angle and current control</td>
</tr>
<tr>
<td>Angle tracking degrades with rotor temperature changes</td>
<td>Angle estimation is independent of rotor resistance and inductance</td>
</tr>
<tr>
<td>Speed estimator is problematic and often noisy.</td>
<td>Mechanical and electrical speed estimations do not require differentiation (which introduces noise)</td>
</tr>
<tr>
<td>Torque and vibration sensors still required for many systems</td>
<td>Instantaneous, accurate shaft torque estimate!</td>
</tr>
<tr>
<td>Stable operation in all power quadrants: Some sensorless FOC techniques are unstable in generating quadrants.</td>
<td>FAST™ is stable in ALL operating modes.</td>
</tr>
</tbody>
</table>
TI Spins Motors…Smarter, Safer, Greener.
InstaSPIN™-FOC with FAST
simplify design of a sensorless torque controller

“simple”
Motion

“starting”
Speed Control

Torque Control

Inverter Switching

User Code or ROM

Speed Control

Iq Control

Id Control

3-phase Space Vector Generation

Field Weaken
Field Boost

Torque

Angle

Flux

Speed

PWM

ADC

3PHI

P

W

M

OFF Line
Motor ID

On-line Motor ID
& Compensation

ACI PowerWarp™

FAST™
SW Encoder

Speed PI Controller

–
User to tune

Flexible software architecture: Full sensorless FOC from
ROM or just FAST from ROM

Full load start-up features, 100% duty cycle, stable at and
through 0 speed, four quadrant

F lux changes monitored in real time
A ngle accuracy best available, over widest range!
S peed signal independent of Angle - no phase lag!
T orque signal accurate to multiple decimals!

Dave Wilson
TI Spins Motors…Smarter, Safer, Greener.
InstaSPIN™-FOC

- Uses FAST™ as a superior sensor for Field Oriented Control
- Motor parameter identification and on-line motor parameter compensation
- Automatic FOC Torque Loop Tuning (Id and Iq, Kp and Ki)
- Generic speed loop (provides generic compensation, adequate for most applications)
- Flexibility to use FOC loop from ROM, same code in Flash/RAM, or create your own
- Max Torque Per Amp for all three phase motors, including salient IPM and Induction
- Automatic or manual field weakening with stable current control
- ACI PowerWarp™ Technology: 28% energy savings vs. leading AC Drive
Motor Identification
No datasheet required!

- For permanent magnet machines, FOC operation requires only the current rating from the user. Motor ID takes care of the rest.†
- For ACIM FOC operation, the user provides only the rated current, rated voltage, and rated frequency. Motor ID takes care of the rest. †
- For ACIM FOC operation, rotor parameters are not required. †*
- Automatic offset correction for all voltage and current measurements.
- Automatic current loop tuning
- Dynamic Rs observer running in real time.

† For speed control applications, additional information is required about motor pole-pairs and load inertia.
* For speed control applications, rotor resistance is automatically calculated for use in determining motor slip.
Observer / Estimator

Commanded $i_d$ (flux) + PI Controller $I_d$ + PI Controller $V_d$

Commanded $i_q$ (torque) + PI Controller $I_q$ + PI Controller $V_q$

Reverse Park Transform

SVM

Inverter $V_u$, $V_v$, $V_w$

Motor ID values

ADC

Sampled $V_u$, Sampled $V_v$, Sampled $V_w$, Sampled $I_u$, Sampled $I_v$

$1/RC$

Mechanical Speed

Electrical Speed

Torque

Angle

Flux

Motor Type

I_d

I_q

I_w (optional)

Dave Wilson

TI Spins Motors...Smarter, Safer, Greener.
Angle Estimation Error:
750 RPM with Dynamic Load

Fig. 29: Estimated Angle Error with Staircase Load
Angle Estimation Error: 150 RPM (10 Hz), Full Load
On-line Simulation: Evaluate FAST from your desk!

Motor Parameters
- Default values
- Select from library of motors
- Flexible to support highly customized motor parameters

Profile
- Default values
- Customize
- Application Specific profiles will be added

Supports 4 main 3ph motor types
Simulation Settings
- Default values
- Customization
- Customize control tuning
- VisSim from

Simulation Results
- Static graphs
- WebScope®
- Zoom +/-
- Overlay
ACIM Energy Savings Mode

Old Way (Triac Drive)

Dave Wilson
TI Spins Motors…Smarter, Safer, Greener.
PowerWARP™ Lab Testing

- PowerWARP™ is a capability of InstaSPIN™-FOC designed to improve induction motor efficiency at partially applied loads.
- Motor efficiency with PowerWARP™ is dramatically improved from 5% to 20% at 1 lb.in. load.
- The efficiency improvement decreases with increasing torque as expected.
- At rated torque, the efficiency curves for PowerWARP™ on and off are identical.
- Note that output power is maintained with PowerWARP™ mode enabled.

Motor efficiency is boosted dramatically at lower loads, with a trade-off in dynamic torque and speed response, though the control system remains stable.
Algorithm is based on reducing motor copper losses in the stator **AND** the rotor!

Angle observer will accurately track flux angle under load transient conditions (smooth stall recovery even when motor has been defluxed).
What about advanced applications?

InstaSPIN-FOC turns your motor into a highly responsive & efficient torque machine, like this high performance Tesla…*but* with a novice driver. And in some applications that’s good enough…

InstaSPIN-MOTION is the expert driver that controls

- Speed
- Response/speed correction
  - [under-damped < Ideal Gain < over-damped]
    - slow to react
    - too aggressive
- Movements between speeds
- and everything along the way from origin to destination

**Simplify velocity control & motion design**
InstaSPIN-FOC to InstaSPIN-MOTION

InstaSPIN-MOTION SpinTAC™ suite
- Builds upon InstaSPIN-FOC (or use with sensors)
- IDENTIFY: system inertia identification for enhanced feedback into controller
- CONTROL: single variable controller replaces PI and typically works across system conditions
- MOVE: generation of Speed A to Speed B with various trajectories (trap, S-curve, ST-curve)
- PLAN: logic-based execution of different MOVEs

InstaSPIN-FOC Speed Control
- Initial PI gains are just a first starting point
- Does not incorporate real inertia of system
- Control requires
  - Tuning of 2-variable PI controller
  - “gain staging”, different sets of tuning at various operating points
- Movements / Trajectories
  - Only offers constant fixed acceleration

Speed PI tuning
Complex
Inconsistent across use

Building Motions
Even more complex
Only as good as control

Dave Wilson
TI Spins Motors…Smarter, Safer, Greener.
SpinTAC™ Components

Account for mechanical inertia - Robust speed control - Simplified tuning

Identify: Measure Inertia

- Inertia is important for accurate control
- Short acceleration test to identify system inertia

Control: Maximum control, minimum effort

- Disturbance-rejecting controller
- Single variable to tune response
- Typically effective across full variable speed and load range

1. Press button to measure inertia
2. Adjust knob to tune
**SpinTAC™ Components**

**Move:**
**Build Trajectories**
- Select Motion Type for Speed A to B
- Define constraints (accel, jerk)
- SpinTAC™ generates the ideal curve

**Plan:**
**Design Motion Sequence**
- Define operating states and transitions
- Connect logic-based moves
- Execute the motion sequence

Example:

If \(<\text{Agitation Counter} = 0>\)
move to Slow Spin Cycle

The ideal curve is automatically generated.
The TI InstaSPIN-FOC Advantage

🌟 Unified control topology. Exploits similarities between PMSM, ACIM, and IPMM.

🌟 Angle estimator accurate over wide steady state speed range (Typically 1 Hz to 1 kHz)

🌟 Angle lock within one electrical cycle.

🌟 Angle lock more robust than traditional SMO under transient conditions.

🌟 Full torque starting. Field testing completed on combustion engine starter motor, bus traction control, ebike traction control, and multiple washers.

🌟 Angle estimate for ACIM is independent of rotor parameters

🌟 Creates high quality speed signal without differentiation noise

🌟 Creates high quality motor flux signal for flux monitoring and field weakening applications

🌟 Creates accurate motor torque signal for load monitoring

🌟 Robust commissioning algorithm. Can learn most motors in under 2 minutes!

🌟 Energy savings mode for ACIMs.
  (In field tests with HVAC load, 28% more energy savings obtained vs. popular optimal fan drive from a leading drives manufacturer.)
The InstaSPIN™-MOTION Advantage

Simplify design

- Easily design and execute complex motion sequences
- Single coefficient tuning minimizes effort and reduces complexity

Reduce time

- Automatic motor commissioning and speed control parameterization
- Develop and evaluate quickly using the new MotorWare library

Improve performance

- Disturbance-rejecting controller provides tighter control across the entire operating range
- Profile generator enables ideal transitions from one speed to another
Future Work

🌟 Initial Position Detection for smoother starting.

🌟 Dynamic Maximum Torque Per Amp (MTPA) with IPM machines.

🌟 Current regulator decoupling in synchronous frame.

🌟 Utilize integrated PGAs on C2000 family devices for dynamic scaling of feedback signals (improve low speed performance even further).
InstaSPIN-FOC Training
Libraries in Execute Only ROM

F2806xF, F

0x000000
See Datasheet

0x013800
FAST + SPIN Variables

0x014000
See Datasheet

0x3F8000
FAST + SPIN Libraries

0x3FC000
See Datasheet

0x3FFFFF
Last Part of L8 RAM

Execute Only ROM

F2805xF, F

0x000000
See Datasheet

0x008000
FAST + SPIN Variables

0x008800
See Datasheet

0x3F8808
FAST + SPIN Libraries

0x3FC52F
See Datasheet

0x3FFFFF
Execute Only ROM

L0 RAM

F2802xF

0x000000
See Datasheet

0x000600
FAST Variables

0x000800
See Datasheet

0x3FC000
FAST Libraries

0x3FE000
See Datasheet

0x3FFFFF
Execute Only ROM

Last Part of M1 RAM

Execute Only ROM
Example Use Case
All FOC in ROM

Dave Wilson

TI Spins Motors…Smarter, Safer, Greener.
Estimator Only in ROM
All in ROM, and Estimator-only Projects

Dave Wilson

TI Spins Motors…Smarter, Safer, Greener.
MotorWare™ is a directory structure.
• MotorWare™ contains several example projects for each solution
  – Lab 1 – CPU and inverter setup
  – Lab 2 – Using InstaSPIN™-FOC for the first time
  – Lab 3 – Using board and motor parameters from user.h
  – Lab 4 – Running in torque mode
  – Lab 5 – Tuning current and speed control loops
  – Lab 6 – Running SpinTAC move and plan
  – Lab 7 – Looking at the details of Rs online recalibration
  – Lab 9 – Field weakening
  – Lab 10 – Overmodulation
  – Lab 12 – SpinTAC sensored speed control
  – Lab 13 – SpinTAC position control
MotorWare™ contains code that produces html documentation using Doxygen

```c
/// \brief Gets the angle value from the estimator in per unit (pu), IQ24.
/// \details This function returns a per units value of the rotor flux angle. This value wraps around
/// at 1.0, so the return value is between 0x00000000 or _IQ(0.0) to 0x00FFFFFF or _IQ(1.0).
/// An example of using this angle is shown:
/// \code
/// _iq Rotor_Flux_Angle_pu = EST_getAngle_pu(handle);
/// \endcode
/// \param[in] handle The estimator (EST) handle
/// \return The angle value, pu, in IQ24.

_iq EST_getAngle_pu ( EST_Handle handle )

Gets the angle value from the estimator.
This function returns a per units value of the rotor flux angle. This value wraps around at 1.0, so the return value is between 0x00000000 or _IQ(0.0) to 0x00FFFFFF or _IQ(1.0). An example of using this angle is shown:

_iq Rotor_Flux_Angle_pu = EST_getAngle_pu(obj->estHandle);

Parameters:
[in] handle The estimator (EST) handle

Returns:
The angle value, pu, in IQ24.
```
MotorWare™ contains a software architecture ready to be used with an RTOS, with minimum performance hit.

MotorWare™

- USER INTERFACE
  - EST
  - DLOG
  - CLARKE
  - IPARK
  - CTRL
  - PARK
  - PID
  - SVGEN
  - TRAJ
- HAL
  - ADC
  - COMP
  - FLASH
  - CAN/CAP
  - CPU
  - GPIO
  - CLK/OSC
  - CLA
  - EMU
  - I2C/LIN
  - PIE
  - PLL
  - PWM
  - QEP
  - PWMDAC
  - SCI
  - SPI
  - TIMER
  - WDOG
- QUEUE Manager
- Platform
- HW
- Motor

Dave Wilson
TI Spins Motors…Smarter, Safer, Greener.
• MotorWare™ uses inlined functions.
• Inline Function Performance using Objects with module API structure

<table>
<thead>
<tr>
<th>Function</th>
<th>Macro</th>
<th>Inline C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clarke</td>
<td>18</td>
<td>16</td>
</tr>
<tr>
<td>PID</td>
<td>39</td>
<td>30</td>
</tr>
<tr>
<td>SVGGEN</td>
<td>118</td>
<td>101</td>
</tr>
</tbody>
</table>

• Advantages of Inlined Structure:
  – Inline C vs Macro
    • Better API definition (inputs and outputs are allocated to registers)
    • More efficient C functions
    • With inlined functions we can step through the code
      – Macros are a single line of code, not possible to step through it
MotorWare™ Explorer

Resource Explorer

Dave Wilson  TI Spins Motors…Smarter, Safer, Greener.
InstaSPIN Review Quiz

Q: What are the three sub-modules of InstaSPIN-FOC?
   Motor ID, FAST, PowerWARP™

Q: List at least three types of motors that InstaSPIN-FOC can control.
   BLDC, PMSM, IPM, ACIM, (soon Stepper)

Q: What component of InstaSPIN-FOC results in energy savings with an ACIM?
   PowerWARP™

Q: List at least five system ADC measurements that are required by FAST.
   Vu, Vv, Vw, Iu, Iv, Iw
InstaSPIN Review Quiz

Q: List the four outputs of the FAST observer.
   Flux, Angle, Speed, Torque

Q: How are FAST enabled processors distinguished from non-FAST devices?
   F suffix

Q: TRUE or FALSE: MotorWARE™ uses macros instead of inline code to enable easier debugging.  FALSE.  It’s the other way around.

Q: List at least two development boards for use with InstaSPIN software.
   DRV8312, DRV8301, High Voltage Kit

Q: Which semiconductor company provides the most innovative and exciting solutions for motor control?