TMS320F28054F, TMS320F28052F InstaSPIN-FOC™ Software

Technical Reference Manual

Literature Number: SPRUHW0
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1 TMS320F2805xF InstaSPIN-FOC™ Enabled MCUs

TMS320F2805xF are the third family of devices (54F and 52F — 80-pin package) from Texas Instruments that include the FAST™ (Figure 1) estimator and additional motor control functions needed for cascaded speed and torque loops for efficient three-phase field-oriented motor control (FOC).

Together — with F2805xF peripheral drivers in user code — they enable a sensorless (also known as self-sensing) InstaSPIN-FOC solution which can identify, tune the torque controller and efficiently control your motor in minutes, without the use of any mechanical rotor sensors. This entire package is called InstaSPIN-FOC, which is made available in ROM. The user also has the option of executing all FOC functions in user memory (FLASH or RAM), which makes calls to the proprietary FAST estimator firmware in ROM. InstaSPIN-FOC was designed for flexibility to accommodate a range of system software architectures and customization. The range of this flexibility is shown in and Figure 3.

This document is a supplement to all standard TMS320F2805x documentation, including the standard device data sheet [*TMS320F2805x Piccolo Microcontrollers* (SPRS797)], technical reference manual, and user's guides. An additional document included with the InstaSPIN-FOC documentation package is the *InstaSPIN-FOC™ and InstaSPIN-MOTION™ User's Guide* (literature number SPRUHJ1), which covers the scope and functionality of:

- F2805xF devices
- F2805xF ROM contents
- FAST flux estimator
- InstaSPIN-FOC system solutions.

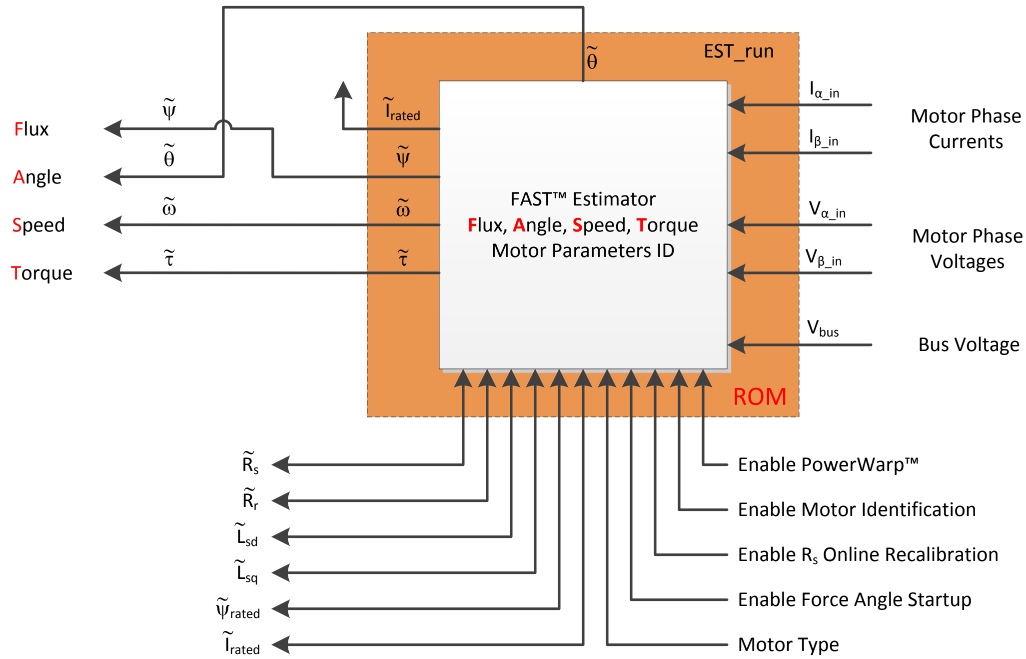

Figure 1. FAST - Estimating Flux, Angle, Speed, Torque - Automatic Motor Identification

2 FAST Estimator Features

- Unified observer structure which exploits the similarities between all motors that use magnetic flux for energy transduction
  - Both synchronous (BLDC, SPM, IPM), and asynchronous (ACIM) control are possible
  - Salient compensation for Interior Permanent Magnet motors: observer tracks rotor flux and angle correctly when Ls-d and Ls-q are provided
- Unique, high quality motor feedback signals for use in control systems
  - High-quality Flux signal for stable flux monitoring and field weakening
  - Superior rotor flux Angle estimation accuracy over wider speed range compared to traditional observer techniques independent of all rotor parameters for ACIM
  - Real-time low-noise motor shaft Speed signal
  - Accurate high bandwidth Torque signal for load monitoring and imbalance detection
- Angle estimator converges within first cycle of the applied waveform, regardless of speed
- Stable operation in all power quadrants, including generator quadrants
- Accurate angle estimation at steady state speeds below 1 Hz (typ) with full torque
- Angle integrity maintained even during slow speed reversals through zero speed
- Angle integrity maintained during stall conditions, enabling smooth stall recovery
- Motor Identification measures required electrical motor parameters of unloaded motor in under 2 minutes (typ)
- "On-the-fly" stator resistance recalibration (online Rs) tracks stator resistance changes in real time, resulting in robust operation over temperature. This feature can also be used as a temperature sensor of the motor's windings (basepoint calibration required)
- Superior transient response of rotor flux angle tracking compared to traditional observers
- PowerWarp™ adaptively reduces current consumption to minimize the combined (rotor and stator) copper losses to the lowest, without compromising ACIM output power levels

3 InstaSPIN-FOC Solution Features

- Includes the Flux Angle Speed Torque (FAST) estimator, used to measure rotor flux (both magnitude and angle) in a sensorless field-oriented control (FOC) system
- Automatic torque (current) loop tuning, with option for user adjustments
- Automatic speed loop tuning provides stable operation for most applications. (Better transient response can be obtained by optimizing parameters for a particular application)
- Automatic or manual field weakening and field boosting
- Bus Voltage compensation
- Automatic offset calibration insures quality samples of feedback signals

4 InstaSPIN-FOC Block Diagrams

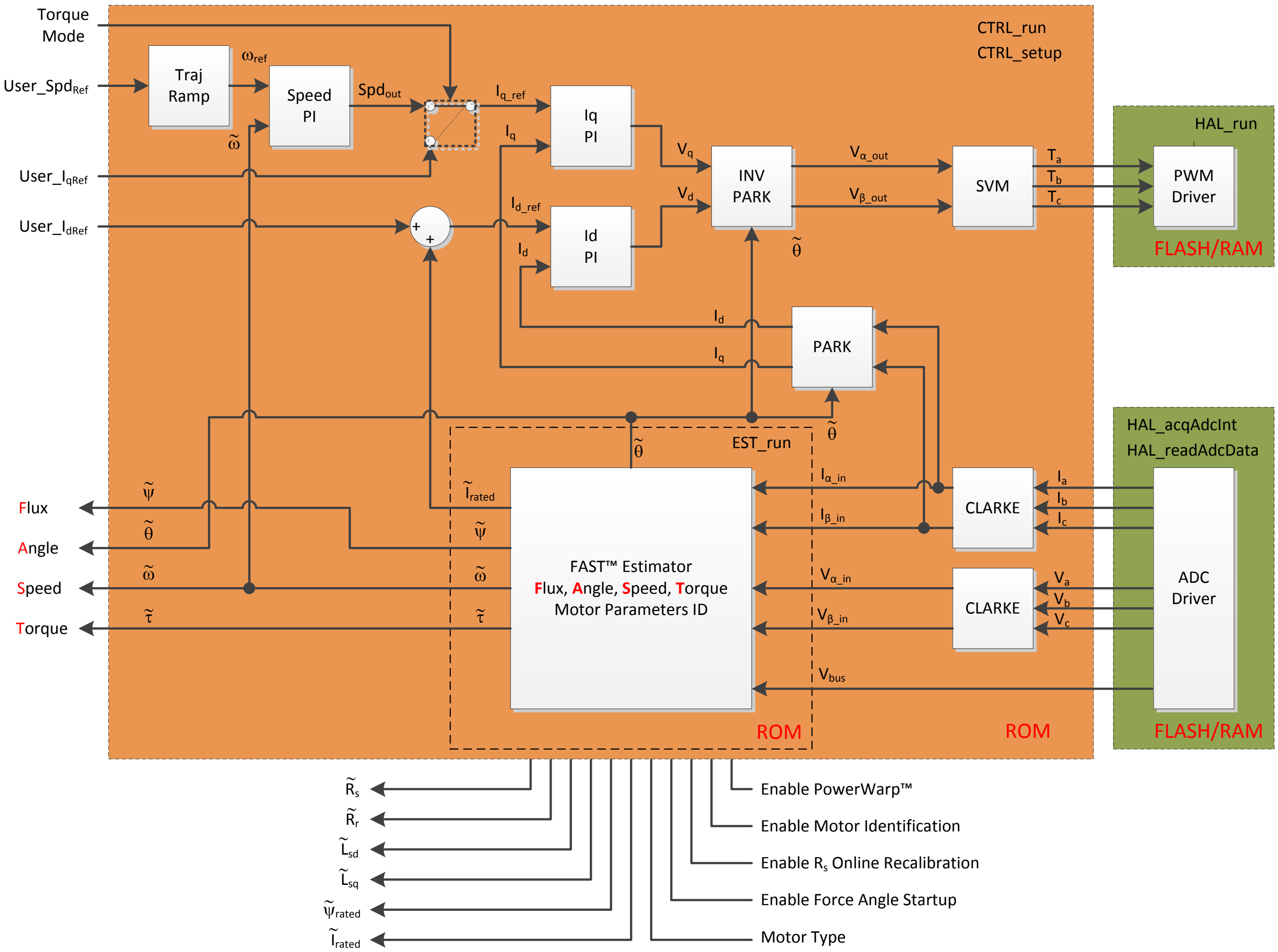

Figure 2. Block Diagram of Entire InstaSPIN-FOC Package in ROM

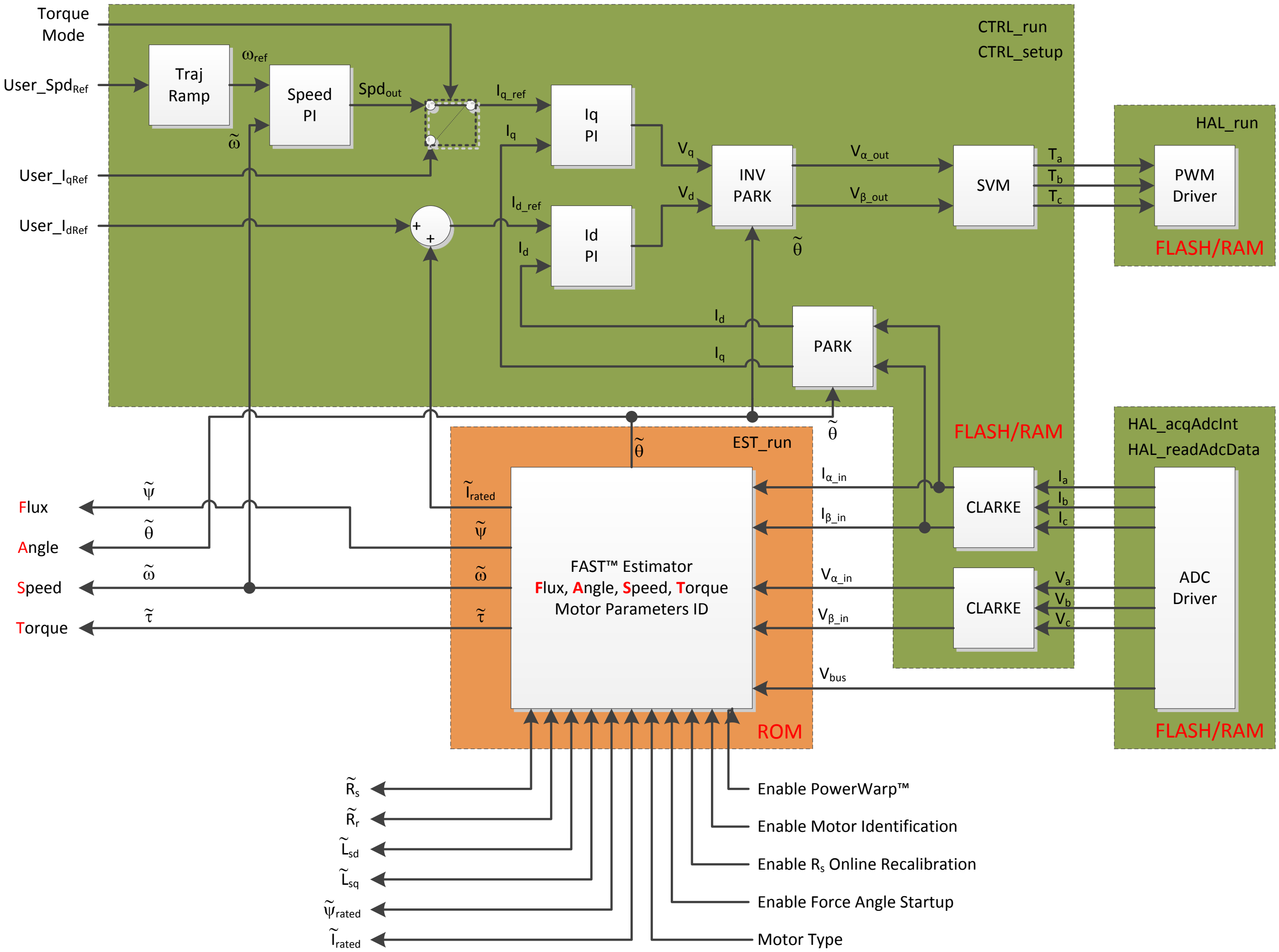

Figure 3. Block Diagram of InstaSPIN-FOC in User Memory, with Exception of FAST in ROM

5 Comparing FAST Estimator to Typical Solutions

Table 1 shows a comparison of the FAST estimator and InstaSPIN-FOC solution to typical software sensors and FOC solutions.

Table 1. FAST Estimator Compared to Typical Solutions

Topic	Typical Software Sensors and FOC Solutions	Fast Estimator and InstaSPIN-FOC Solution
Electrical Motor Parameters	Motor-model based observers heavily dependent on motor parameters.	Relies on fewer motor parameters. Off-line parameter identification of motor – no data sheet required. On-line parameter monitoring and re-estimation of stator resistance.
Estimator Tuning	Complex observer tuning, done multiple times for speed/loads, for each motor.	No estimator tuning required. Once motor parameters are identified, it works the same way every time, across speed/torque dynamics.
Estimator Accuracy	Angle-tracking performance is typically only good at over 5-10Hz with challenges at higher speeds and compensation for field weakening. Dynamic performance influenced by hand tuning of observer; Motor stalls typically crash observer.	FAST provides reliable angle tracking which converges within one electrical cycle of the applied waveform, and can track at less than 1 Hz frequency (dependent on quality and resolution of analog sensing). Angle tracking exhibits excellent transient response (even with sudden load transients which can stall the motor, thus enabling a controlled restart with full torque).
Start-up	Difficult or impossible to start from zero speed. Observer feedback at zero speed is not stable, resulting in poor rotor angle accuracy and speed feedback.	InstaSPIN-FOC includes: • Zero Speed start with forced-angle • 100% torque at start-up • FAST rotor flux angle tracking converges within one electrical cycle. FAST is completely stable through zero speed, providing accurate speed and angle estimation.
Current Loop	Tuning FOC current control is challenging – especially for novices.	Automatically sets the initial tuning of current controllers based on the parameters identified. User may update gains or use own controllers, if desired. The algorithm to fully tune the observer and torque controller takes less than 2 minutes.
Feedback Signals	System offsets and drifts are not managed.	FAST includes automatic hardware/software calibration and offset compensation. FAST requires 2-phase currents (3 for 100% and over-modulation), 3-phase voltages to support full dynamic performance, DCbus voltage for ripple compensation in current controllers. FAST includes an on-line stator resistance tracking algorithm.
Motor Types	Multiple techniques for multiple motors: standard back-EMF, Sliding Mode, Saliency tracking, induction flux estimators, or "mixed mode" observers.	FAST works with all 3-phase motor types, synchronous and asynchronous, regardless of load dynamics. Supports salient IPM motors with different Ls-d and Ls-q. Includes PowerWarp™ for induction motors = energy savings.
Field-Weakening	Field-weakening region challenging for observers - as the Back-EMF signals grow too large, tracking and stability effected.	FAST estimator allows easy field weakening or field boosting applications due to the stability of the flux estimation in a wide range, including field weakening region.
Motor Temperature	Angle tracking degrades with stator temperature changes.	Angle estimation accuracy is improved from online stator resistance recalibration.
Speed Estimation	Poor speed estimation causes efficiency losses in the FOC system and less stable dynamic operation.	High quality low noise Speed estimator, includes slip calculation for induction motors.
Torque Estimation	Torque and vibration sensors typically required.	High bandwidth motor Torque estimator.

6 FAST Provides Sensorless FOC Performance

6.1 FAST Estimator Replaces Mechanical Sensor

Field-oriented control (FOC) of an electric motor results in superior torque control, lower torque ripple, and in many cases, improved efficiency compared to traditional AC control techniques. For best dynamic response, rotor flux referenced control algorithms are preferred to stator flux referenced techniques. To function correctly, these systems need to know the spacial angle of the rotor flux with respect to a fixed point on the stator frame (typically the magnetic axis of the phase A stator coil). This has traditionally been accomplished by a mechanical sensor (for example, encoder or resolver) mounted to the shaft of the motor. These sensors provide excellent angle feedback, but inflict a heavy toll on the system design. There are six major system impacts resulting from sensored angle feedback, as discussed below and illustrated in Figure 4:

1. The sensor itself is very expensive (often over $2500 for a good resolver and several dollars for high volume integrated encoders).
2. The installation of the sensor requires skilled assembly, which increases labor costs.
3. The sensor often requires separate power supplies, which increases system costs and reduces reliability.
4. The sensor is the most delicate component of the system, which impacts system reliability, especially in harsh real-world applications.
5. The sensor feedback signals are brought back to the controller board via connectors, which also increases system costs and can significantly reduce reliability, depending on the type of connector.
6. The cabling required to bring the sensor signals back to the controller creates multiple challenges for the system designer:
   - Additional costs for the cable, especially if there is a substantial distance between the motor and controller.
   - Susceptibility to sources of noise, which requires adding expense to the cable with special shielding or twisted pairs.
   - The sensor and associated cabling must be earth grounded for safety reasons. This often adds additional cost to isolate these signals, especially if the processor which processes the sensor signals is not earth grounded.

In some applications where the motor is enclosed (for example, compressors), a sensored solution is impractical due to the cost of getting the feedback wires through the casing. For these reasons, designers of FOC systems are highly motivated to eliminate the sensor altogether, and obtain the rotor flux angle information by processing signals which are already available on the controller circuit board. For synchronous machines, most techniques involve executing software models of the motor being controlled to estimate the back-EMF waveforms (rotor flux), and then processing these sensed waveforms to extract an estimation of the rotor shaft angle, and a derivation of its speed. For asynchronous machines the process is a bit more complicated, as this software model (observer) must also account for the slip which exists between the rotor and rotor flux.

However, in both cases, performance suffers at lower speeds due to the amplitude of the back-EMF waveforms being directly proportional to the speed of the motor (assuming no flux weakening). As the back-EMF amplitude sinks into the noise floor, or if the ADC resolution cannot faithfully reproduce the small back-EMF signal, the angle estimation falls apart, and the motor drive performance suffers.

To solve the low-speed challenge, techniques have been created that rely on high frequency injection to measure the magnetic irregularities as a function of angle (that is, magnetic saliency) to allow accurate angle reconstruction down to zero speed. However, this introduces another set of control problems. First, the saliency signal is non-existent for asynchronous motors and very small for most synchronous machines (especially those with surface mount rotor magnets). For the motors that do exhibit a strong saliency signal (for example, IPM motors), the signal often shifts with respect to the rotor angle as a function of loading, which must be compensated. Finally, this angle measurement technique only works at lower speeds where the fundamental motor frequency does not interfere with the interrogation frequency. The control system has to create a mixed-control strategy, using high-frequency injection tracking at low speed, then move into Back-EMF based observers at nominal and high speeds.

With any technique, the process of producing a stable software sensor is also extremely challenging, as this motor model (observer) is essentially its own control system that needs to be tuned per motor across the range of use. This tuning must be done with a stable forward control loop. Needed is a stable torque (and usually speed) loop to tune the observer, but how do you pre-tune your forward control without a functioning observer? One option is to use a mechanical sensor for feedback to create stable current and speed loops, and then tune your software sensor in parallel to the mechanical sensor. However, the use of a mechanical sensor is often not practical. This problem has delayed market use of software sensors for sensorless FOC control.

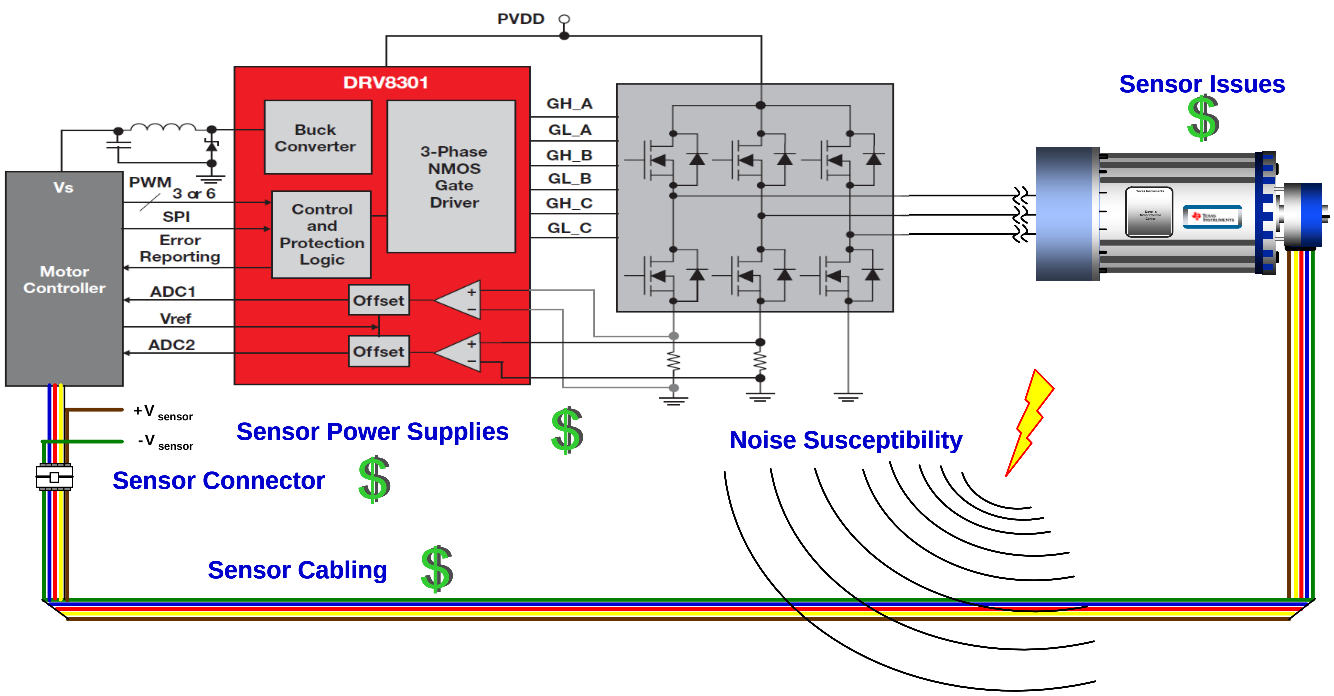

Figure 4. Sensored FOC System

In summary, these existing solutions all suffer from various maladies including:

- Poor low-speed performance (back-EMF and SMO)
- Poor high-speed performance (saliency observers)
- Poor dynamic response
- Calculation intensive (multi-modal observers)
- Parameter sensitivity
- Requirement for observer tuning.

The most recent innovation in the evolution of sensorless control is InstaSPIN-FOC. Available as a C-callable library embedded in on-chip ROM on several TI processors, InstaSPIN-FOC was created to solve all of these challenges, and more. It reduces system cost and development time, while improving performance of three-phase variable speed motor systems. This is achieved primarily through the replacement of mechanical sensors with the proprietary FAST estimator. FAST is an estimator that:

- Works efficiently with all three phase motors, taking into account the differences between synchronous/asynchronous, salient/non-salient, and permanent/non-permanent/induced magnets.
- Dramatically improves performance and stability across the entire operating frequency and load range for a variety of applications.
- Removes the manual tuning challenge of traditional FOC systems:
  - Observers and estimators, completely removes required tuning.
  - Current loop regulators, dramatically reduces required tuning.

- Eliminates or reduces motor parameter variation effects.
- Automatically designs a stable and functional control system for most motors in under two minutes.

6.2 Rotor Angle Accuracy Critical for Performance

Why has the need for a precise estimation of the rotor flux angle driven many to use mechanical sensors?

For efficient control of three-phase motors, the objective is to create a rotating flux vector on the stator aligned to an ideal orientation with respect to the rotor in such a way that the rotor field follows the stator field while creating necessary torque and using the minimum amount of current.

- **Stator**: stationary portion of the motor connected to the microprocessor-controlled inverter.
- **Ideal Orientation**: 90 degrees for non-salient synchronous; slightly more for salient machines, and slightly less in asynchronous machines since part of the current vector is also used to produce rotor flux.
- **Rotor**: rotating portion of the motor, produces torque on the shaft to do work.

To achieve this, you need to extract the following information from the motor:

- Current being consumed by each phase.
- Precise relative angle of the rotor flux magnetic field (usually within ± 3 electrical degrees), so you can orient your stator field correctly.
- For speed loops, you also need to know rotor speed.

6.3 Phase Currents Key to Estimator Accuracy

Resistor shunt current measurement is a very reasonable technique for measuring phase current in a motor control inverter. There are three widely used examples, the 1-, 2-, and 3-shunt resistor measurements. While at first the 1- and 2-shunt techniques seem to reduce cost, they require much faster and more expensive amplifier circuits. These 1- and 2-shunt current measurements also limit the capability of the current feedback which will limit the ability of the drive to use the full voltage that is provided to the inverter. The 3-shunt technique is superior and not much different in cost due to the advantage of using cheap slow current amplifier circuits. For best performance and cost with the FAST and InstaSPIN-FOC, the 3-shunt technique is recommended.

For more details, see the *InstaSPIN-FOC™ and InstaSPIN-MOTION™ User's Guide* (literature number SPRUHJ1).

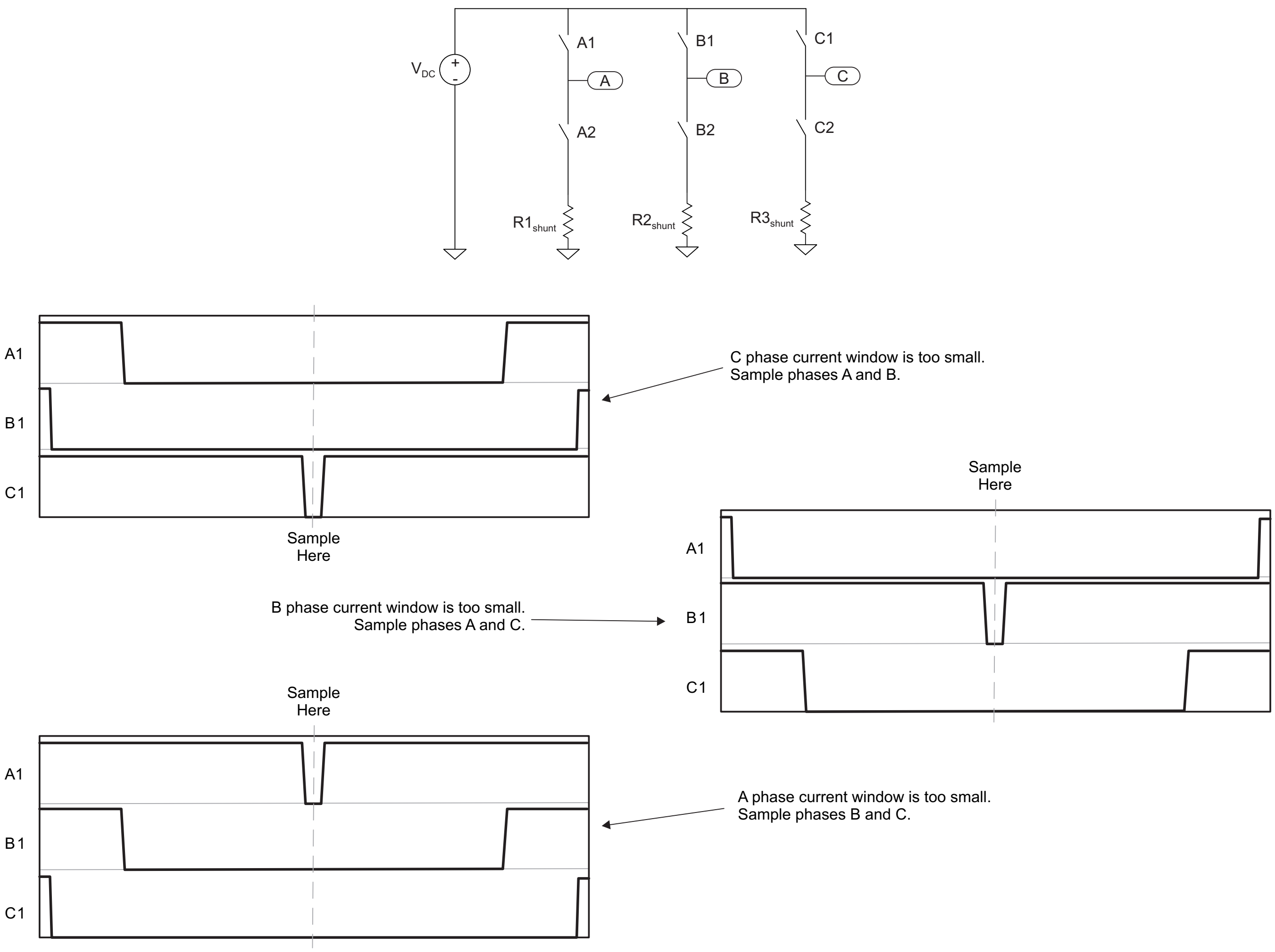

Figure 5. Inverter Using the 3-Shunt Current Sampling Technique

7 Evaluating FAST and InstaSPIN-FOC Performance

FAST and InstaSPIN-FOC performance data is being collected and will be provided in a future revision of this document.

8 Microcontroller Resources

The F2805xF microcontroller resources required by the InstaSPIN libraries are discussed in detail in the *InstaSPIN-FOC™ and InstaSPIN-MOTION™ User's Guide* (literature number SPRUHJ1).

Specifically for the library implementation and where the code is loaded and executed from, the following resources categories are discussed in this document:

- CPU Utilization
- Memory Allocation
- Stack Utilization
- Digital and Analog Pins Utilization

8.1 CPU Utilization

InstaSPIN-FOC provides flexibility throughout its design, including its software execution clock tree. Figure 6 illustrates the options available to the designer to manage the real-time scheduling of each of the major software functions. Balancing motor performance with CPU loading is not difficult, shortening system integration time.

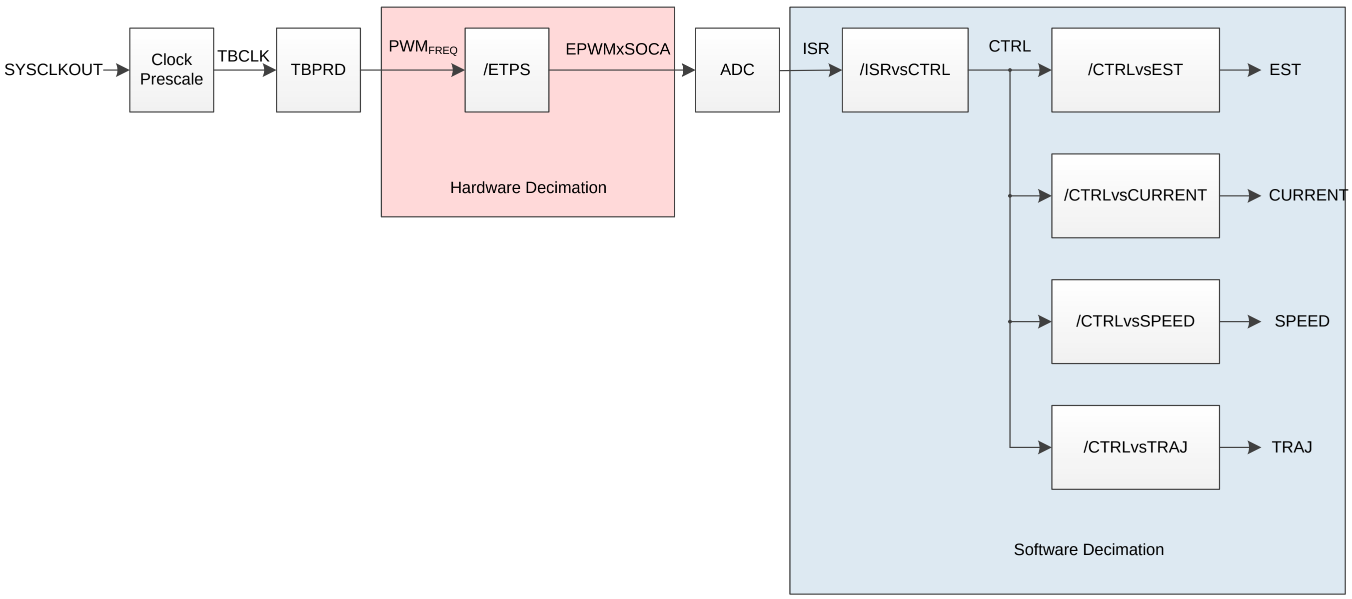

Figure 6. Software Execution Clock Tree Provides Flexibility with Real-Time Scheduling

Executing from a combination of single-cycle memory (RAM and ROM) and also from FLASH, total execution time for the minimum full implementation of InstaSPIN-FOC depends on the software execution clock tree. Table 2 shows the CPU cycles used when a minimum full implementation of InstaSPIN is done, as well as users' code is loaded to FLASH. Note the impact of the software execution tree to total execution time. Table 3 shows the CPU loading and available MIPs for other system functions.

Table 2. CPU Cycles for MIN Implementation Executing from ROM, RAM, and FLASH

Function Name	CPU Cycles			Executed From		
	Min	Average	Max	ROM	RAM	FLASH
HAL_acqAdcInt	25	25	25	×	×	✓
HAL_readAdcData	108	108	108	×	×	✓
Ctrl_run				✓	×	×
R_s Online Disabled, ISR vs CTRL = 1, CTRL vs EST = 1	2345	2355	2425			
CTRL vs EST = 2	1154	1760	2425			
CTRL vs EST = 3	1154	1562	2425			
ISR vs CTRL = 2, CTRL vs EST = 1	58	1207	2425			
CTRL vs EST = 2	58	909	2425			
CTRL vs EST = 3	58	810	2425			
ISR vs CTRL = 3, CTRL vs EST = 1	58	824	2425			
CTRL vs EST = 2	58	626	2425			
CTRL vs EST = 3	58	560	2425			
R_s Online Enabled, ISR vs CTRL = 1, CTRL vs EST = 1	2807	2821	2894			
CTRL vs EST = 2	1154	1993	2894			
CTRL vs EST = 3	1154	1717	2894			
ISR vs CTRL = 2, CTRL vs EST = 1	58	1439	2894			
CTRL vs EST = 2	58	1025	2894			
CTRL vs EST = 3	58	887	2894			
ISR vs CTRL = 3, CTRL vs EST = 1	58	979	2894			
CTRL vs EST = 2	58	702	2894			
CTRL vs EST = 3	58	610	2894			
HAL_writePwmData	64	64	64	×	×	✓
CTRL_setup	37	51	178	✓	×	×

Table 3. CPU Loading for Full Implementation Executing from ROM and FLASH

F2805xF CPU = 60 MHz Available MIPs = 60 MIPs PWM = 10 kHz	CPU Utilization [%]	MIPs Used [MIPS]	MIPS Available [MIPS]
R_s Online Disabled, ISR vs CTRL = 1, CTRL vs EST = 1	43.28	25.97	34.03
CTRL vs EST = 2	33.37	20.02	39.98
CTRL vs EST = 3	30.07	18.04	41.96
ISR vs CTRL = 2, CTRL vs EST = 1	24.15	14.49	45.51
CTRL vs EST = 2	19.18	11.51	48.49
CTRL vs EST = 3	17.53	10.52	49.48
ISR vs CTRL = 3, CTRL vs EST = 1	17.77	10.66	49.34
CTRL vs EST = 2	14.47	8.68	51.32
CTRL vs EST = 3	13.37	8.02	51.98
R_s Online Enabled, ISR vs CTRL = 1, CTRL vs EST = 1	51.05	30.63	29.37
CTRL vs EST = 2	37.25	22.35	37.65
CTRL vs EST = 3	32.65	19.59	40.41
ISR vs CTRL = 2, CTRL vs EST = 1	28.02	16.81	43.19
CTRL vs EST = 2	21.12	12.67	47.33
CTRL vs EST = 3	18.82	11.29	48.71
ISR vs CTRL = 3, CTRL vs EST = 1	20.35	12.21	47.79
CTRL vs EST = 2	15.73	9.44	50.56
CTRL vs EST = 3	14.20	8.52	51.48

NOTE: Both the CLA and InstaSPIN-FOC are configured for Zone 1 security, therefore the CLA is not accessible to the user on F2805xF devices.

8.2 Memory Utilization

Figure 7, Figure 8, and Table 4 show the memory map of the F28054, the location in ROM where the InstaSPIN-FOC library is located, and the required allocation of L8 RAM for the library to use. For a general memory map of these devices, see the device-specific data sheet.

Address	Data Space	Prog Space
0x00 0000	*M0 Vector RAM (Enabled if VMAP = 0)*	
0x00 0040	M0 SARAM (1K x 16, 0-Wait)	
0x00 0400	M1 SARAM (1K x 16, 0-Wait)	
0x00 0800	Peripheral Frame 0	Reserved
0x00 0D00	PIE Vector - RAM (256 x 16) (Enabled if VMAP = 1, ENPIE = 1)	
0x00 0E00	Peripheral Frame 0	
0x00 1400	CLA Registers	
0x00 1480	CLA-to-CPU Message RAM	
0x00 1500	CPU-to-CLA Message RAM	
0x00 1580	Reserved	
0x00 2000	Reserved	
0x00 4000	USB Control Registers(A)	Reserved
0x00 5000	Peripheral Frame 3 (4K x 16, Protected) DMA-Accessible	
0x00 6000	Peripheral Frame 1 (4K x 16, Protected)	
0x00 7000	Peripheral Frame 2 (4K x 16, Protected)	
0x00 8000	L0 DPSARAM (2K x 16) (0-Wait, Secure Zone + ECSL, CLA Data RAM2)	
0x00 8800	L1 DPSARAM (1K x 16) (0-Wait, Secure Zone + ECSL, CLA Data RAM 0)	
0x00 8C00	L2 DPSARAM (1K x 16) (0-Wait, Secure Zone + ECSL, CLA Data RAM 1)	
0x00 9000	L3 DPSARAM (4K x 16) (0-Wait, Secure Zone + ECSL, CLA Program RAM)	
0x00 A000	L4 SARAM (8K x 16) (0-Wait, Secure Zone + ECSL)	
0x00 C000	L5 DPSARAM (8K x 16) (0-Wait, DMA RAM 0)	
0x00 E000	L6 DPSARAM (8K x 16) (0-Wait, DMA RAM 1)	
0x01 0000	L7 DPSARAM (8K x 16) (0-Wait, DMA RAM 2)	
0x01 2000	L8 DPSARAM (8K x 16) (0-Wait, DMA RAM 3)	
0x01 4000	Reserved	
0x3D 7800	User OTP (1K x 16, Secure Zone + ECSL)	
0x3D 7BFA	Reserved	
0x3D 7C80	Calibration Data	
0x3D 7CC0	Get_mode function	
0x3D 7CD0	Reserved	
0x3D 7E80	PARTID	
	Calibration Data	
0x3D 7EB0	Reserved	
0x3D 8000	FLASH (128K x 16, 8 Sectors, Secure Zone + ECSL)	
0x3F 7FF8	128-Bit Password	
0x3F 8000	Boot ROM (32K x 16, 0-Wait)	
0x3F FFC0	*Vector (32 Vectors, Enabled if VMAP = 1)*	

Figure 7. F28054F Memory Map

Table 4. F2805xF Allocated Memory for InstaSPIN-FOC Library

Features	F2806xF	F2806xM	F2805xF	F2805xM	F2802xF
FAST	Yes	Yes	Yes	Yes	Yes
SpinTAC	No	Yes	No	Yes	No
Maximum Number of Motors that can be controlled	2	2	2	2	1
Relocalable Controller Structure	No	No	Yes	Yes	Yes
FAST Version	1.6	1.6	1.7	1.7	1.7
Public Library needs to be added to project	No	No	No	No	Yes
ROM Library Start [address, hex]	3F 8000	3F 8000	3F 8808	3F 8808	3F C000
Library Required RAM [size, hex, words]	800	800	800	800	200
Library Start RAM [address, hex]	01 3800	01 3800	00 8000	00 8000	00 0600

Figure 8 highlights the pieces of ROM EXE-only memory used by the libraries. EXE-only is execute only memory where read access is not possible.

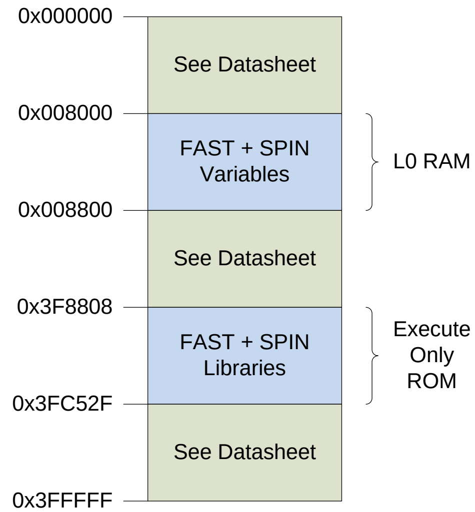

Figure 8. F2805xF Allocated Memory for InstaSPIN-FOC Library

8.3 Security Zones

The F2805xF devices offer different security zones, selectable by the user. Keep in mind that the security zone configuration might affect the operation of the interface to the library. For example, if the memory area where the controller object is placed is secured, then libraries in ROM would not be able to write to this memory; therefore, not updating the controller object properly. For more details, see the security section of the *TMS320F2805x Piccolo Microcontrollers* data manual (SPRS797).

The libraries in ROM, as well as the RAM, that are pre-allocated for the estimator are in the Z1 section. Make sure that the RAM utilized to place the variables used to interface with the library are accessible by the Z1 security zone.

8.4 Linker Command File Settings

In order for the 2805xF devices to use InstaSPIN, the volatile memory area used by the libraries in ROM must be reserved. The following code listing of the RAM area shows that L0 RAM should not be used. To avoid conflicts between user's memory and library used memory, variables declared by the user must not use this memory range.

```
   RAMM0             : origin = 0x000050, length = 0x0003B0
 //RAML0             : origin = 0x008000, length = 0x000800
   RAML1             : origin = 0x008800, length = 0x000800
   RAML2             : origin = 0x009000, length = 0x000800
   RAML3             : origin = 0x009800, length = 0x000800
```

8.5 Interfacing FAST ROM Libraries

In order to interface the ROM libraries, the user needs to include a library in their project. This library contains the symbolic addresses to the software in ROM. The following is the relative MotorWare path to the symbols library for this particular family.

```
sw\modules\fast\lib\32b\f28x\f2805x
```

As can be seen in the project screen capture shown in Figure 9, a symbols-only library was linked in the project.

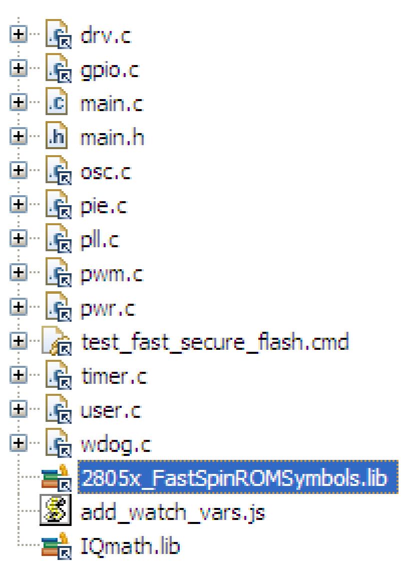

Figure 9. 2805x Project with ROM Symbols Library

The same estimator header files are needed as shown for the 2805x device variant (est.h, est_Flux.h, est_Ls.h, est_Rs.h).

Also, as explained for the F2805x device variant, some of the functions of the controller object (CTRL_Obj) are also included in ROM. The following relative path is an example of a controller header file path for one of the boards TI offers:

```
sw\solutions\instaspin_foc\boards\hvkit_rev1p1\f28x\f2805x\src\ctrl.h
```

8.6 Pin Utilization

Flexibility in the design of InstaSPIN-FOC allows for multiple motors to be supported. Table 5 lists the minimum and maximum pins used per motor. Note that a F2805xF microcontroller provides (14) ePWM outputs with the 80-pin package.

Table 5. Pin Utilization Per Motor

Pin Type	Pin Name	Pins Usage Per Motor	
		Min	Max
Digital	PWM1A	3 (Requires External Fault and External Complementary Mode with Dead Time)	7
	PWM1B (Optional)		
	PWM2A		
	PWM2B (Optional)		
	PWM3A		
	PWM3B (Optional)		
	Trip Zone (Optional)		
Analog	IA	5 (Only two currents and no VBUS ripple compensation)	7
	IB		
	IC (Optional)		
	VA		
	VB		
	VC		
	VBUS (Optional)		

8.7 Consideration of Analog Front-End (AFE) Module

In InstaSPIN applications, motor line current and phase voltage are required by the algorithm. Before these analog signals are sampled by the processor, all signals are processed by an analog circuit. The external analog circuits add component cost and increase board size. The 2805x series of processors addresses this issue by adding internal analog conditioning components for the motor feedback signals, called the analog front end (AFE).

For more detailed information about the 2805x device, see *TMS320x2805x Piccolo Technical Reference Manual* (SPRUHE5).

8.7.1 Routing Current Signals

Before addressing about the implementation and usage of the PGAs and comparators, it is recommended to consider how current feedback signals are routed from the shunt and then to the input of the PGA. When a shunt resistor is used to measure line current, its value must be small to reduce the amount of power dissipated in the shunt. Because the value is small, so is the resulting voltage drop across the shunt. There is a significant amount of current flowing through the shunt resistors. Copper traces that connect the shunts from the bottom of the power device and then to ground become a resistor in series with the shunt. The parasitic resistance that forms on the copper trace must be taken into consideration when measuring motor line currents with a shunt resistor.

The AFE can have up to three different grounds. The 2805x device has multiple groups of amplifier blocks. Each group of amplifiers has a different ground. M1 ground is used for the group of three PGAs that will feedback three-phase motor currents for this document. For systems with power factor correction, there is another single PGA and its ground is PFC ground. The fixed-gain amplifier block uses M2 ground for its reference and is used in this document for three motor voltage feedbacks.

Two options for the feedback of motor shunt current signals to the M1 PGA block of the AFE are discussed. The first option is to use only the internal op-amps for the current feedback as shown in Figure 10. All three op-amps share the same ground for the inverting input and therefore a differential signal of the shunt current cannot be created. With single-ended signals, careful layout must be done when grounding the shunts to reduce the amount of differing trace resistance between shunts. It is advised to have the shunt grounds as close together as possible. A trace must run from the point that the shunts come together to the M1gnd pin of the integrated circuit. Because common mode noise can be added to the amplifier, the M1gnd pin and PGA inputs must be made as short as possible. The three phase current traces must be routed as close to the M1gnd trace as possible to reduce the size of the Faraday loop. The Faraday loop is created around the phase current trace that starts from the top of the shunt to the IC and then back on the M1gnd trace to the bottom of the shunt, through the shunt and back to the top of the shunt.

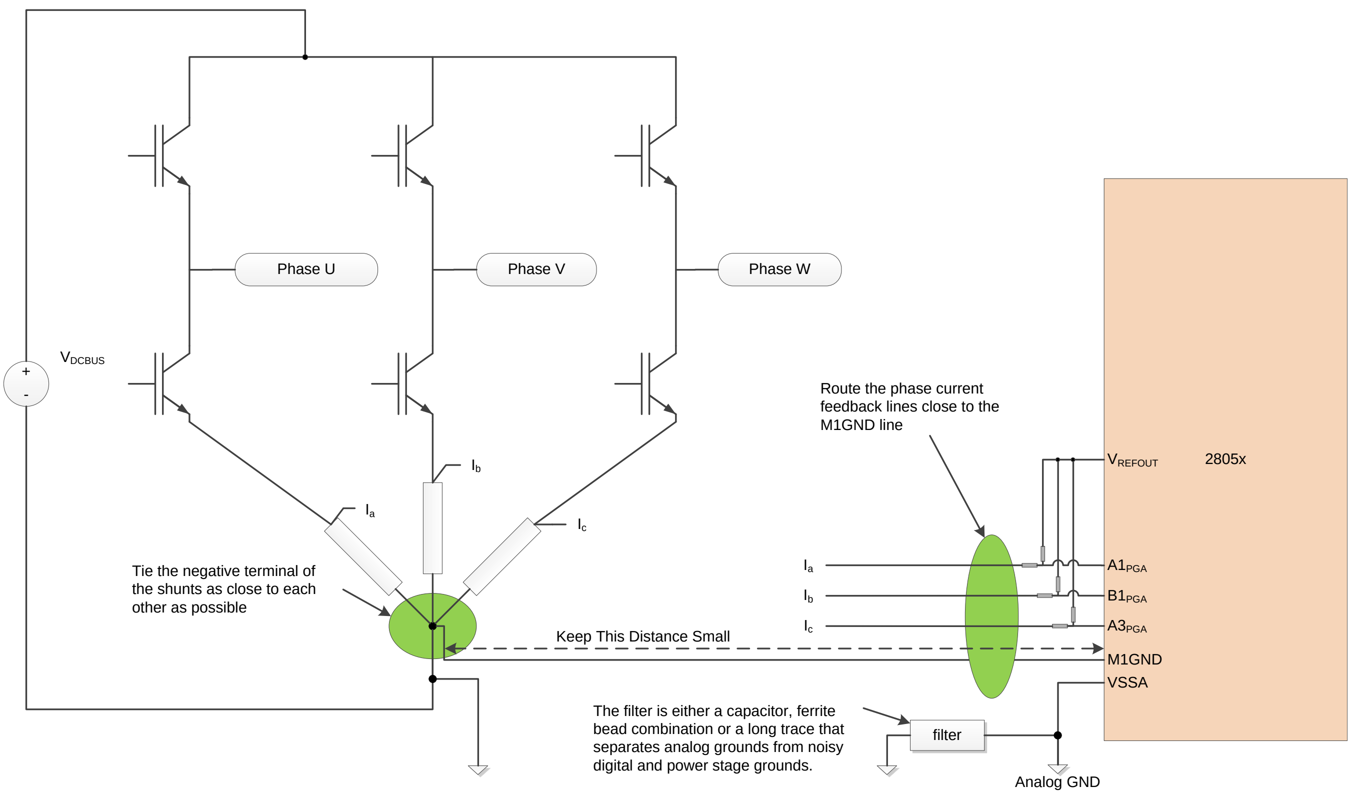

Figure 10. Current Signal Routing Directly to PGAs With Single-Ended Connections

The second, and most noise immune option, is to use external op-amps in a differential amplifier configuration. A true Kelvin connection can feedback directly to the differential amplifier, and then the output of the differential amplifier is sent into the PGA input. Figure 11 shows a typical layout when using external differential op-amps. Since the Kelvin connection has low impedance and is a truly differential signal, it provides excellent noise immunity. The external op-amp circuit converts the differential circuit into a single-ended output. The single-ended output is more susceptible to noise and therefore it is best to place the output of the op-amp as close to the AFE input of the processor.

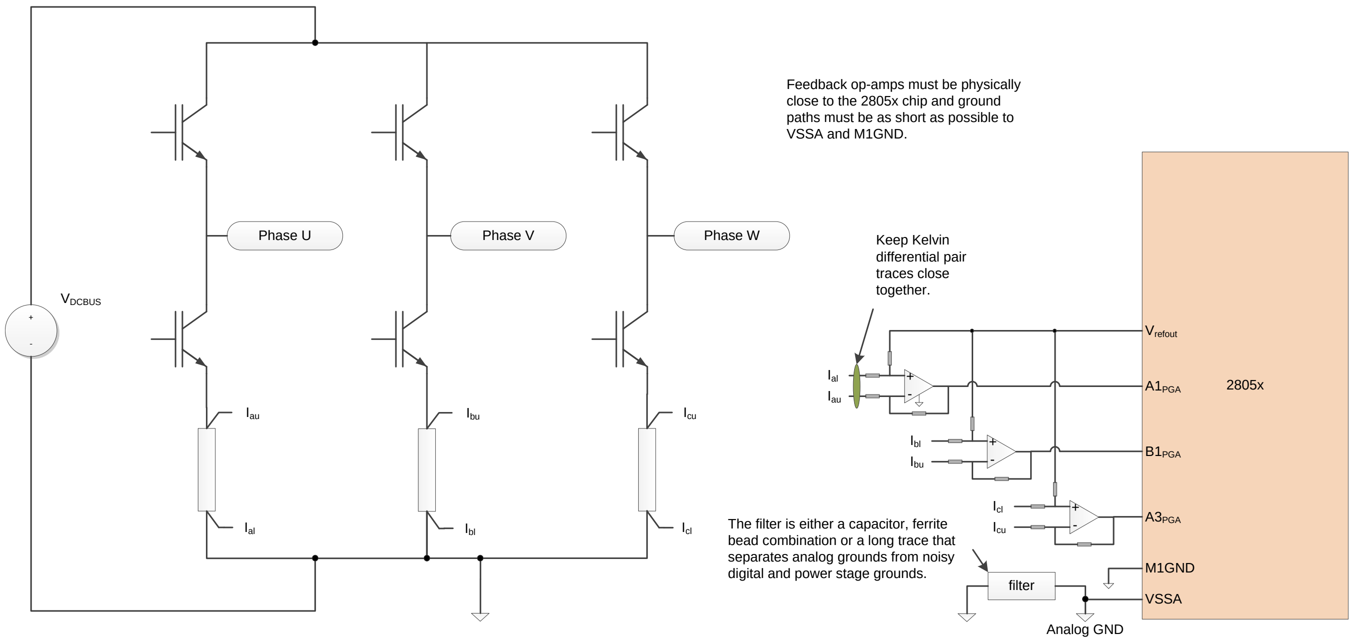

Figure 11. Feedback of Phase Currents Using External Differential Amplifiers

Why use the PGAs when external amplifiers are already being used? One case would be if many different current rated motors are powered with the same inverter. Amplification of the current signal can be adjusted to best suit the motor size that is controlled. The output of the PGA block is the input of the comparator windows. The PGA still needs to be connected to enable the use of the fault detection circuitry.

8.7.2 Voltage Reference Connection

Current can flow through the shunt in both positive and negative directions which will create both a positive and negative voltage that is fed back to the shunt amplifier circuit. Most cost-effective motor inverters do not have both positive and negative power supplies that can handle this bipolar signal. A bipolar current signal is brought into an amplifier that will only be effective from zero to the positive voltage supply. To allow the unipolar op-amp circuit to measure a bipolar signal, a voltage reference is summed into the non-inverting side of the current feedback op-amps. The AFE of the 2805x device contains a 6-bit DAC with a voltage follower for providing an output reference for this reason. A circuit configuration that can use a voltage reference to measure the bipolar current signal is shown in Figure 12.

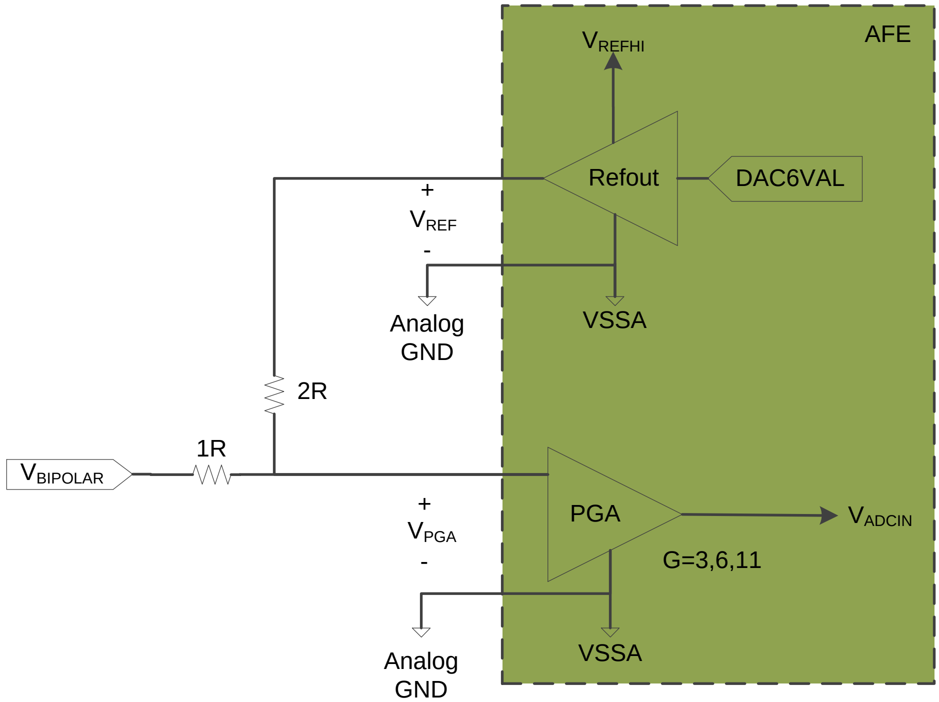

Figure 12. Using the AFE's Built-In Voltage Reference For Measuring a Bipolar Signal

Equation 1 shows how to calculate the voltage at V_{PGA}. As an example, set the PGA gain = 3. V_{ADCIN} will be $2V_{BIPOLAR} + V_{REF}$. Assume the system's V_{REFHI} is 3.3 V. To allow for maximum voltage swing in both directions, V_{REF} is set to 1.65 V. Now the maximum peak $V_{BIPOLAR}$ voltage that can be measure is ±0.825 V.

$$V_{PGA}=\frac{2R\cdot(V_{BIPOLAR}-V_{REF})}{(1R+2R)}+V_{REF}=\frac{2}{3}V_{BIPOLAR}+\frac{1}{3}V_{REF} \quad (1)$$

Suppose the same hardware is used and a higher resolution is required. The PGA gain = 6. V_{ADCIN} is $4V_{BIPOLAR} + 2V_{REF}$. V_{REF} must be adjusted to be 0.825 V. The maximum peak $V_{BIPOLAR}$ voltage that can be measured is ±0.4125 V.

The voltage reference output is adjusted by a 6-bit DAC. The VREFOUTCTL register controls the DAC's voltage output by Equation 2 below.

$$V_{REF}=\frac{V_{REFHI}\cdot(VREFOUTCTL_{DACVAL}+1)}{64} \quad (2)$$

8.7.3 Routing Voltage Signals

In sinusoidal motor control drives, the voltage signals vary slowly when compared to current signals. Therefore, larger hardware filters can be applied to the voltage feedback signal which helps to make it less susceptible to noise. Voltage signals are unipolar, so no special circuit and reference have to be used. Lower voltage motors (under 400 V_{DCBUS}) typically only require resistor dividers with a capacitive low-pass filter. For a brushless DC motor control the voltage needs as little phase shift as possible and, therefore, the low-pass filtering depends on the maximum speed achieved by the motor. The only critical layout of voltage feedback signals is that the low-pass filter capacitor must be located as close to the AFE or A/D input pin as possible.

Appendix A Definition of Terms and Acronyms

ACIM — Alternating current induction motor.

CCStudio — Code Composer Studio.

FAST — Unified observer structure which exploits the similarities between all motors that use magnetic flux for energy transduction, automatically identifying required motor parameters and providing the following motor feedback signals:

- High-quality Flux signal for stable flux monitoring and field weakening.
- Superior rotor flux Angle estimation accuracy over wider speed range compared to traditional observer techniques independent of all rotor parameters for ACIM.
- Real-time low-noise motor shaft Speed signal.
- Accurate high bandwidth Torque signal for load monitoring and imbalance detection.

FOC — Field-oriented control.

Forced-Angle — Used for 100% torque at start-up until the FAST rotor flux angle tracker converges within first electrical cycle.

InstaSPIN-FOC — Complete sensorless FOC solution provided by TI on-chip in ROM on select devices (FAST observer, FOC, speed and current loops), efficiently controlling your motor without the use of any mechanical rotor sensors.

IPM — Interior permanent magnet motor.

Motor Parameters ID or Motor Identification — A feature added to InstaSPIN-FOC, providing a tool to the user so that there is no barrier between running a motor to its highest performance even though the motor parameters are unknown.

PI — Proportional-integral regulator.

PMSM — Permanent magnet synchronous motor.

PowerWarp™ — A mode of operation for AC induction motors (ACIM) that minimizes motor losses under lightly loaded conditions.

Rs-Offline Recalibration — InstaSPIN-FOC feature that is used to recalibrate the stator resistance, Rs, when the motor is not running.

Rs-Online Recalibration — InstaSPIN-FOC feature that is used to recalibrate the stator resistance, Rs, while the motor is running in closed loop.

SVM — Space-vector modulation.

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