TMS320F28026F, TMS320F28027F
InstaSPIN™-FOC Software

Technical Reference Manual



Literature Number: SPRUHP4
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TMS320F28026F, TMS320F28027F InstaSPIN™-FOC Software

1 TMS320F2802xF InstaSPIN™-FOC Enabled MCUs

TMS320F2802xF are the second family of devices (26F and 27F — 48-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 F2802xF 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. The FAST estimator is called from execute only ROM while the rest of the functions required for InstaSPIN-FOC reside in user memory (FLASH and RAM). InstaSPIN-FOC was designed for flexibility to accommodate a range of system software architectures and customization. The range of this flexibility is shown in Figure 2.

This document is a supplement to all standard TMS320F2802x documentation, including the standard device data sheet [*TMS320F2802x Piccolo Microcontrollers* (literature number SPRS523)], technical reference manual, and user's guides. An additional document included with the InstaSPIN-FOC documentation package is the *TMS320F2806xF, TMS320F2802xF InstaSPIN-FOC/TMS320F2806xM InstaSPIN-MOTION User's Guide* (literature number SPRUHJ1), which covers the scope and functionality of:

- F2802xF devices
- F2802xF ROM contents
- FAST flux estimator
- InstaSPIN-FOC system solutions.

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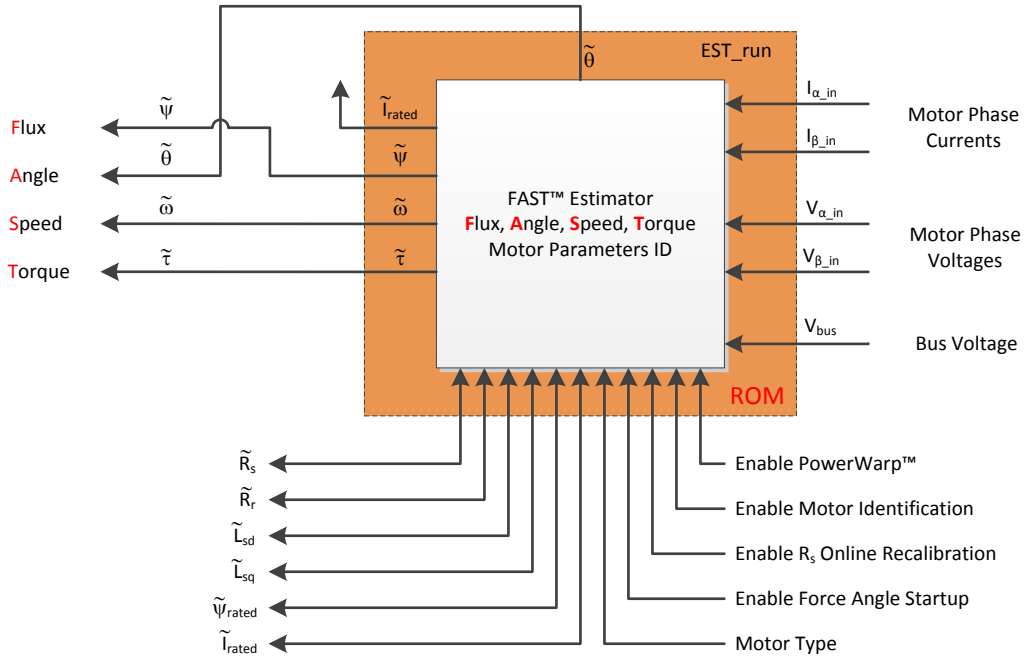


Figure 1. FAST - Estimating Flux, Angle, Speed, Torque - Automatic Motor Identification

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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

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4 InstaSPIN-FOC Block Diagram

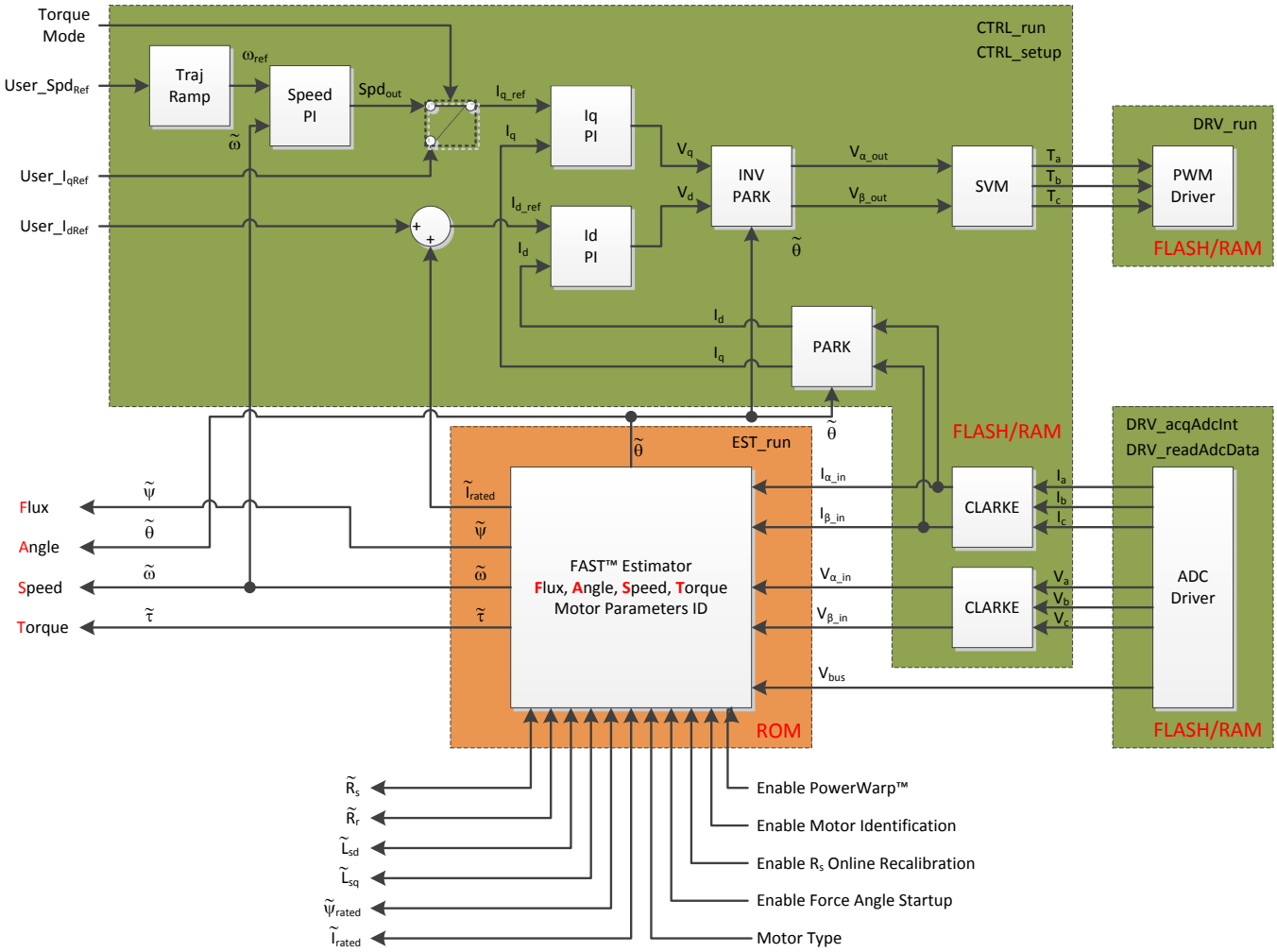


Figure 2. Block Diagram of InstaSPIN-FOC in User Memory, with Exception of FAST in ROM

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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.

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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 3:

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.

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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.

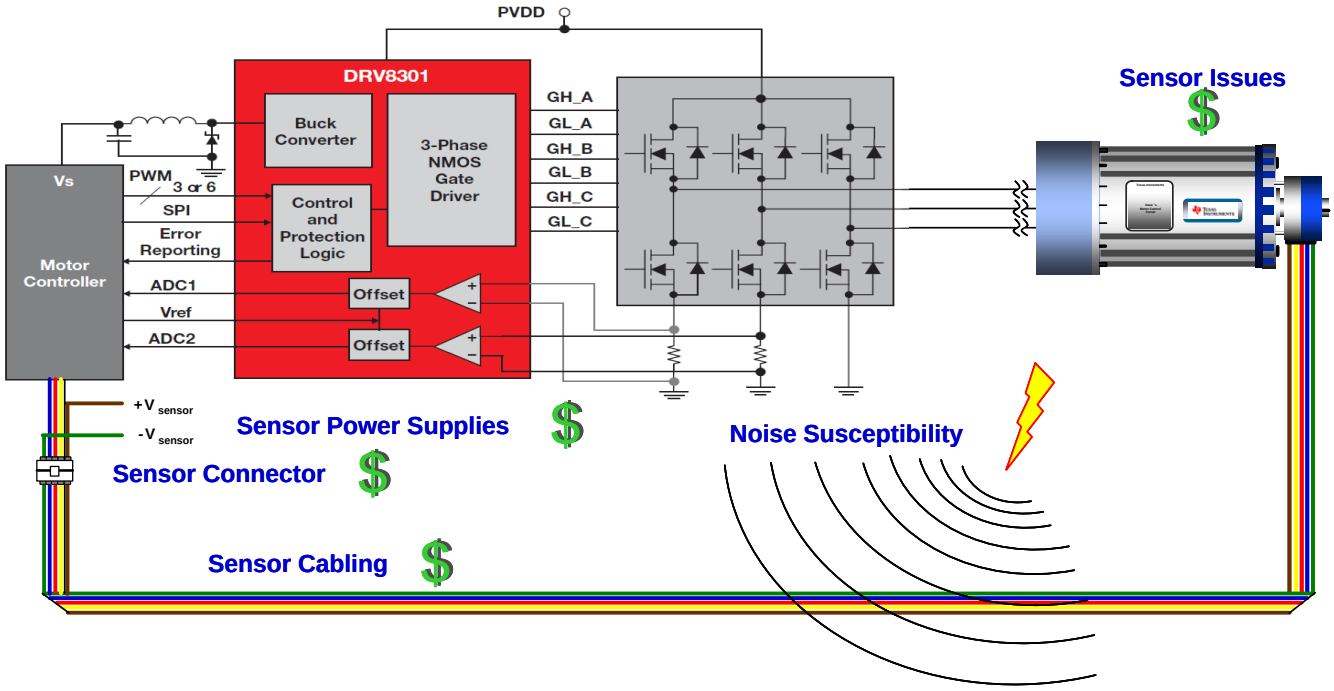


Figure 3. Sensored FOC System

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:
  - Qbservers and estimators, completely removes required tuning.
  - Current loop regulators, dramatically reduces required tuning.

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- 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 *TMS320F2806xF, TMS320F2802xF InstaSPIN-FOC/TMS320F2806xM InstaSPIN-MOTION User's Guide* (literature number SPRUHJ1).

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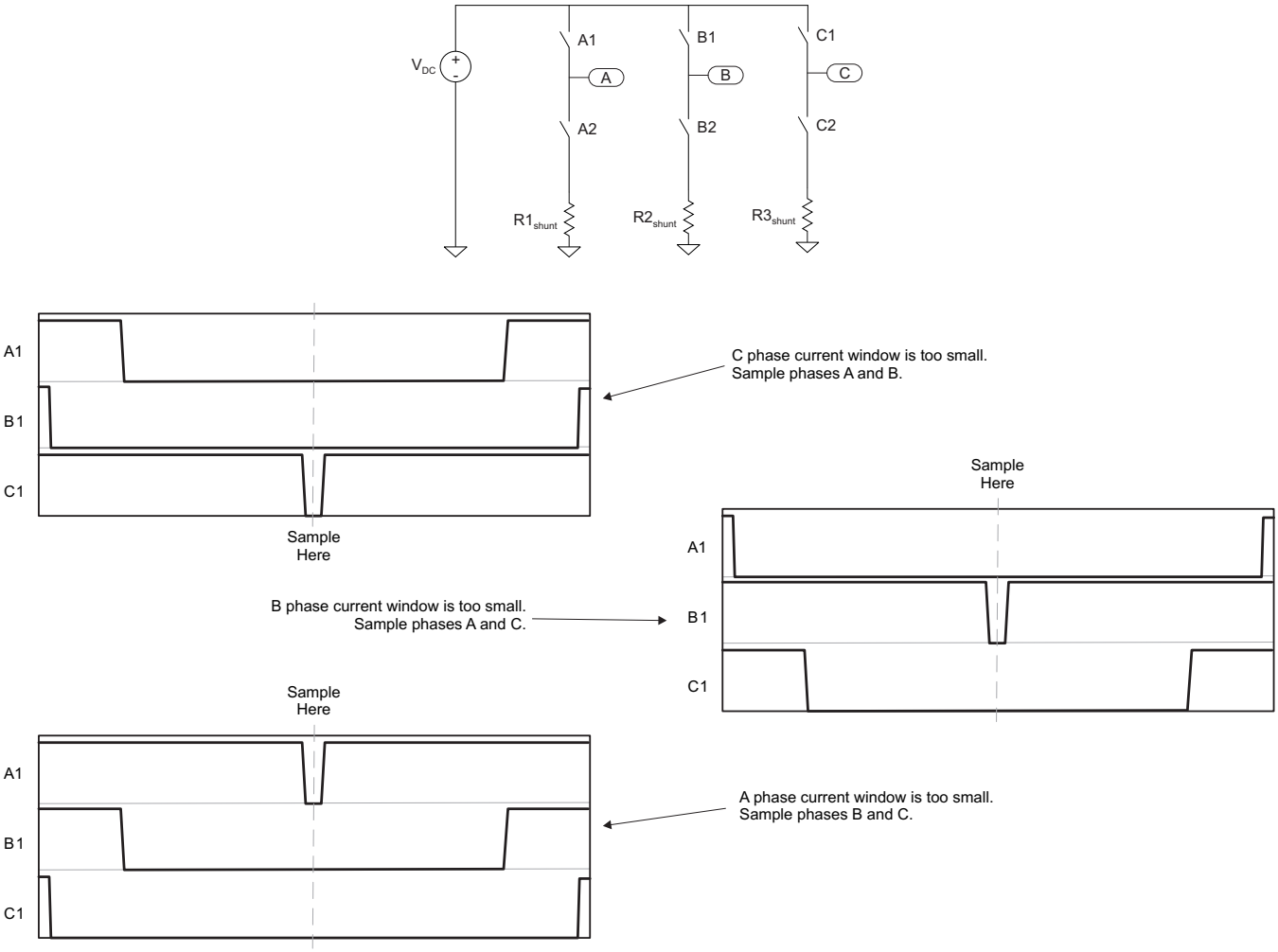


Figure 4. Inverter Using the 3-Shunt Current Sampling Technique

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 F2802xF microcontroller resources required by the InstaSPIN libraries are discussed in detail in the *TMS320F2806xF, TMS320F2802xF InstaSPIN-FOC/TMS320F2806xM 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

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InstaSPIN-FOC provides flexibility throughout its design, including its software execution clock tree. Figure 5 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.

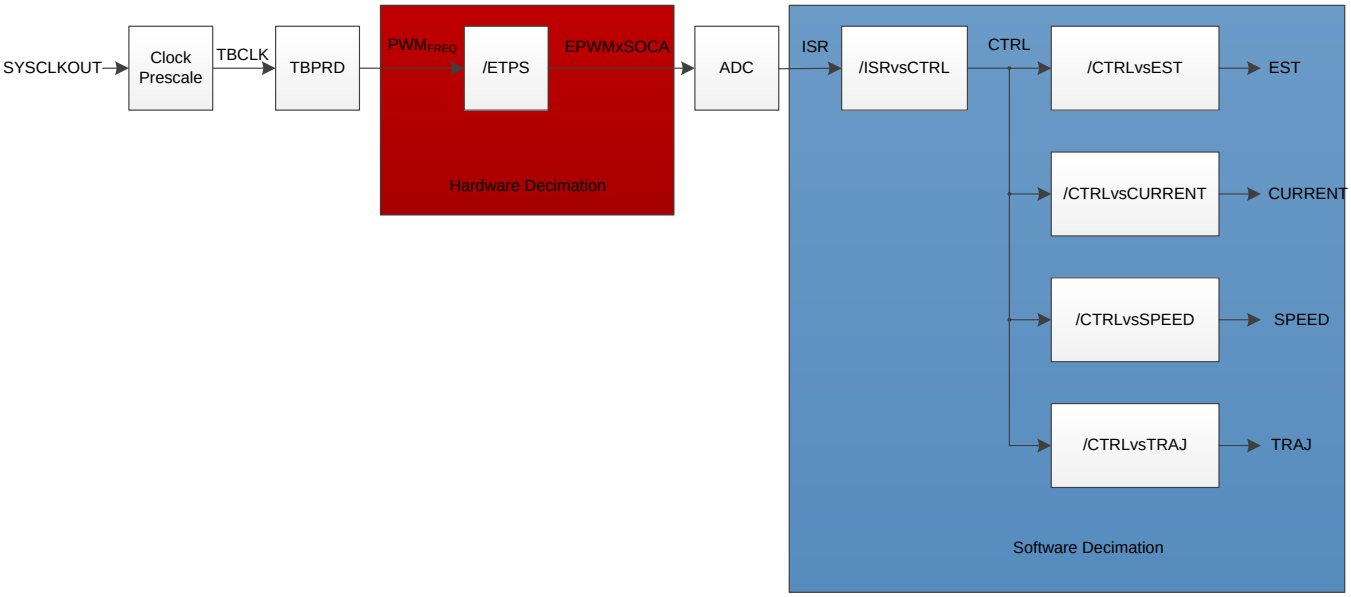


Figure 5. Software Execution Clock Tree Provides Flexibility with Real-Time Scheduling

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

	CPU Cycles			Executed From		
Function Name	**Min**	**Average**	**Max**	**ROM**	**RAM**	**FLASH**
DRV_acqAdcInt	17	17	17	×	✓	×
DRV_readAdcData	94	94	94	×	✓	×

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

Function Name	CPU Cycles			Executed From		
	Min	Average	Max	ROM	RAM	FLASH
Ctrl_run				✓	✓	✓
R_s Online Disabled, ISR vs CTRL = 1, CTRL vs EST = 1	2320	2331	2413			
CTRL vs EST = 2	1131	1735	2413			
CTRL vs EST = 3	1154	1536	2413			
ISR vs CTRL = 2, CTRL vs EST = 1	51	1191	2413			
CTRL vs EST = 2	51	893	2413			
CTRL vs EST = 3	51	793	2413			
ISR vs CTRL = 3, CTRL vs EST = 1	51	811	2413			
CTRL vs EST = 2	51	612	2413			
CTRL vs EST = 3	51	544	2413			
R_s Online Enabled, ISR vs CTRL = 1, CTRL vs EST = 1	2766	2781	2882			
CTRL vs EST = 2	1129	1969	2882			
CTRL vs EST = 3	1129	1692	2882			
ISR vs CTRL = 2, CTRL vs EST = 1	51	1424	2882			
CTRL vs EST = 2	51	1010	2882			
CTRL vs EST = 3	51	871	2882			
ISR vs CTRL = 3, CTRL vs EST = 1	51	966	2882			
CTRL vs EST = 2	51	689	2882			
CTRL vs EST = 3	51	596	2882			
DRV_writePwmData	110	110	110	×	✓	×
CTRL_setup	26	36	188	×	✓	✓

Table 3. Table 3. CPU loading for MIN Implementation Executing from ROM, RAM, and FLASH

2802xF CPU = 60 MHz Available MIPs = 60 MIPs PWM = 15 kHz	CPU Utilization [%]	MIPs Used [MIPS]	MIPS Available [MIPS]
R_s Online Disabled, ISR vs CTRL = 1, CTRL vs EST = 1	64.7	38.82	21.18
CTRL vs EST = 2	49.8	29.88	30.12
CTRL vs EST = 3	44.83	26.9	33.11
ISR vs CTRL = 2, CTRL vs EST = 1	36.2	21.72	38.28
CTRL vs EST = 2	28.75	17.25	42.75
CTRL vs EST = 3	26.25	15.75	44.25
ISR vs CTRL = 3, CTRL vs EST = 1	26.7	16.02	43.98
CTRL vs EST = 2	21.73	13.04	46.97
CTRL vs EST = 3	20.03	12.02	47.99
R_s Online Enabled, ISR vs CTRL = 1, CTRL vs EST = 1	75.95	45.57	14.43
CTRL vs EST = 2	55.65	33.39	26.61
CTRL vs EST = 3	48.73	29.24	30.77
ISR vs CTRL = 2, CTRL vs EST = 1	42.03	25.22	34.79
CTRL vs EST = 2	31.68	19.01	41
CTRL vs EST = 3	28.2	16.92	43.08
ISR vs CTRL = 3, CTRL vs EST = 1	30.58	18.35	41.66
CTRL vs EST = 2	23.65	14.19	45.81
CTRL vs EST = 3	21.33	12.8	47.21

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8.1 Memory Allocation and Utilization

Figure 6, Figure 7, and Table 4 show the memory map of the 28027, the location in ROM where the InstaSPIN-FOC library is located, and the required allocation of M1 RAM for the library to use. For a general memory map of these devices, see the device-specific data sheet.

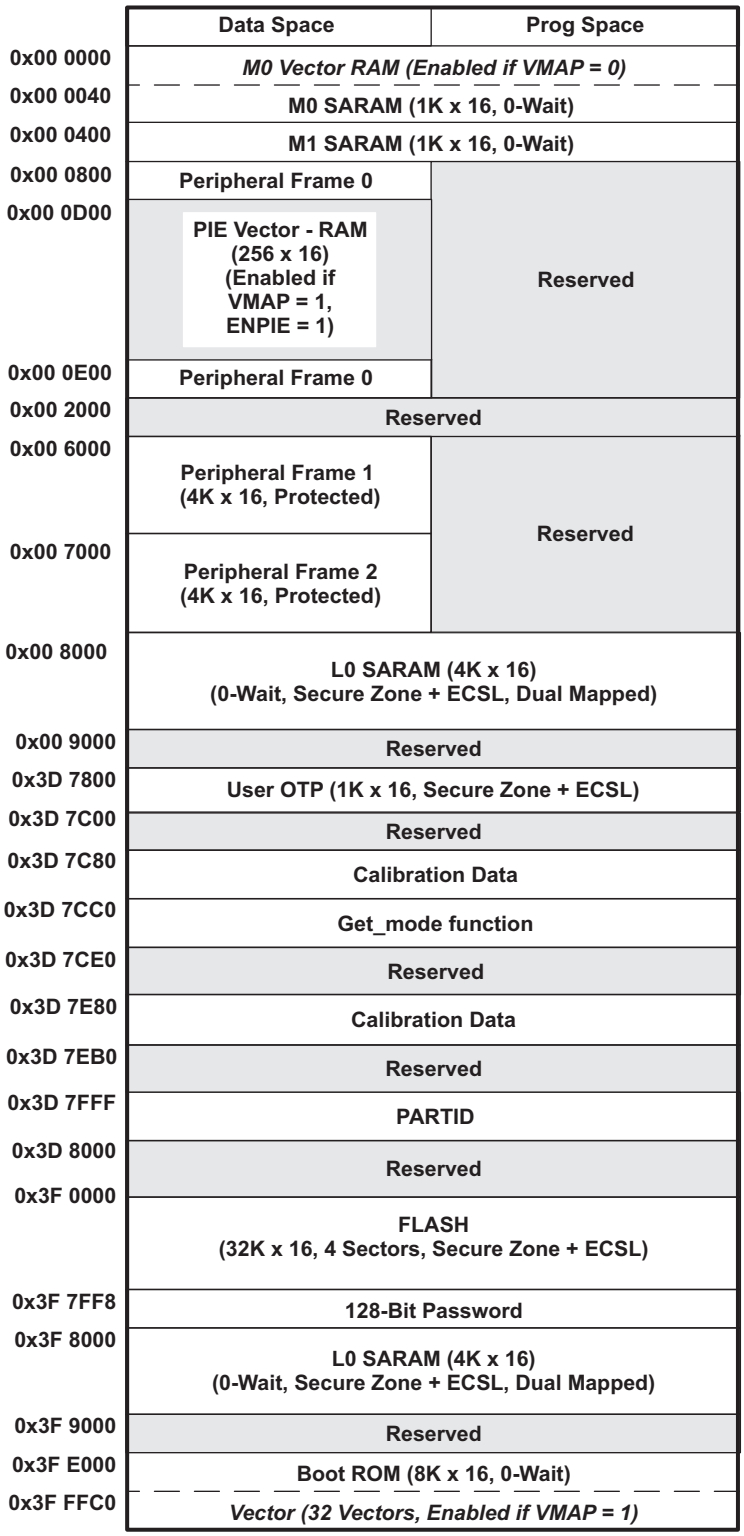


Figure 6. 28027 Memory Map

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Table 4. 2802xF Allocated Memory for InstaSPIN-FOC Library

Features	2802xF
Maximum Number of Motors that can be controlled	1
FAST Version	1.7
ROM Library [size, hex, words]	2000
ROM Library Start [address, hex]	3F C000
Library Required RAM [size, hex, words]	200
Library Start RAM [address, hex]	600

Figure 7 highlights the pieces of ROM EXE-only memory used by the libraries. EXE-only is execute only memory where read access is not possible.

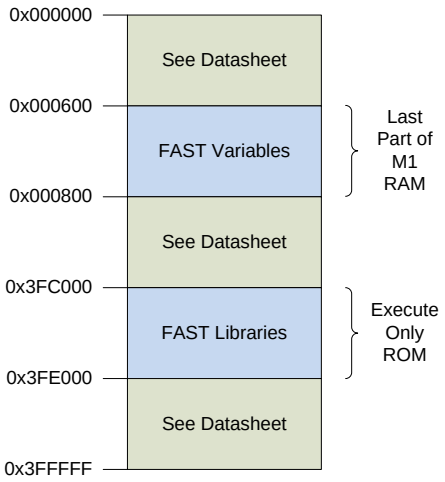


Figure 7. 2802xF Allocated Memory for InstaSPIN-FOC Library

Table 5 summarizes the memory used for the configurations shown in Figure 2 (Min implementation), with user memory in FLASH.

Table 5. User Memory and Stack Sizes

Code Configurations		Memory Sizes (16bit Words)			Maximum Stack Used (16bit Words)
ROM Code	User Code	RAM	Flash	Total	
Min Implementation	FLASH	0x06B2	0x2DD8	**0x348A**	0x0120

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8.2 Pin Utilization

Flexibility in the design of InstaSPIN-FOC allows for multiple motors to be supported. Table 6 lists the minimum and maximum pins used per motor. Note that a F2802xF microcontroller provides (8) ePWM outputs with the 48-pin package.

Table 6. 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)		

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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™ — Mode of operation used for AC induction motors (ACIM) that allows minimum current consumption.

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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