TMS320F28069M, TMS320F28068M InstaSPIN™-MOTION Software

Technical Reference Manual

Literature Number: SPRUHJ0

April 2013

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1. TMS320F2806xM InstaSPIN-MOTION Enabled MCUs

TMS320F2806xM are the first devices (69M and 68M - 80 or 100 pin packages) from Texas Instruments that includes InstaSPIN-MOTION. InstaSPIN-MOTION is a comprehensive motor-, motion- and speed-control software solution that delivers robust system performance at the highest efficiency for motor applications that operate in various motion state transitions. InstaSPIN-MOTION builds on and includes TI's InstaSPIN-FOC solution, combined with SpinTAC™ Motion Control Suite from LineStream Technologies (Figure 1).

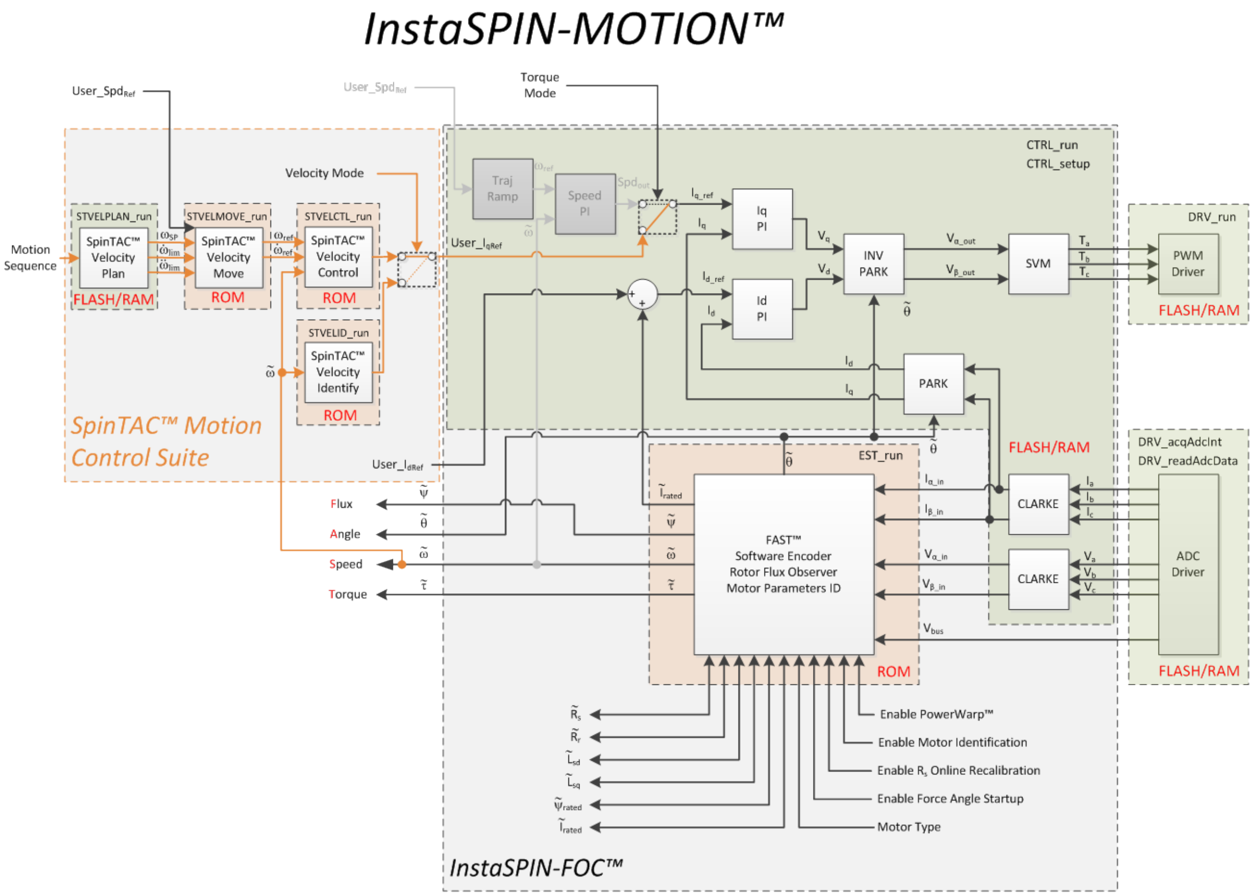


Figure 1. InstaSPIN-MOTION = InstaSPIN-FOC + SpinTAC Motion Control Suite

InstaSPIN-FOC takes advantage of the FAST™ premium software sensor for rotor flux measurement. This is used for motor identification, automatic current control tuning and sensorless feedback in an FOC torque controller and speeds deployment of efficient, sensorless, variable speed and load three-phase motor solutions. The InstaSPIN-FOC feature overview is provided in the InstaSPIN-FOC Technical Reference Manual.

The SpinTAC™ Motion Control Suite adds maximum control with minimal effort. The SpinTAC™disturbance-rejecting speed controller proactively estimates and compensates for system disturbances in real-time, improving overall product performance. The SpinTAC™ speed controller is tuned using a single parameter that is typically effective over the ENTIRE operating range. The compensation tuning eliminates the need for new tuning sets at different speeds or loads, eliminates gain staging, significantly slashes setup time shortens design cycles.

The SpinTAC™motion engine calculates the ideal reference signal (with feed forward) based on user-defined parameters. SpinTAC™ supports standard industry curves, and LineStream's proprietary "smooth trajectory" curve. The SpinTAC™ motion sequence planner operates user-defined state transition maps, making it easy to design complex motion sequences.

InstaSPIN-MOTION enables more expertise on chip. The core algorithms embedded in the read-only-memory (ROM) on TI's 32-bit C2000™ Piccolo™ microcontrollers (MCUs).

InstaSPIN-MOTION is ideal for applications that require accurate speed control, minimal disturbance, and for applications that undergo multiple state transitions or experience dynamic changes. Table 1 provides examples of applications that will most benefit from InstaSPIN-MOTION.

Table 1. InstaSPIN-MOTION Application Examples

Application Characteristics	**Examples**
Accurate speed control	Industrial fans Conveyor systems Elevators/escalators Automotive body parts (electric windows, sunroofs, etc.) Optical disc drives/hard drives Medical mixing
Minimal disturbance	Dental tools Power tools
Undergoes multiple state transitions/dynamic changes	HVAC pumps, fans and blowers Generators Air conditioning compressors Washing machines Exercise equipment Medical pumps

This document will focus on the additive features provided in InstaSPIN-MOTION. This document is a supplement to all standard TMS320F2806x documentation, including the standard device datasheet (TMS320F28069 Device Datasheet), technical reference manual, and user's guides. In addition, the InstaSPIN-MOTION Documentation Package includes the InstaSPIN-FOC and InstaSPIN-MOTION User's Guide, which covers the scope and functionality of:

F2806xM devices
F2806xM ROM contents
InstaSPIN-MOTION system solutions

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-MOTION Solution Features and Benefits

InstaSPIN-FOC is a sensorless FOC solution that can identify, tune, and control your motor in minutes. InstaSPIN-FOC is at the core of InstaSPIN-MOTION, providing the following features:

- The FAST unified software observer, which exploits the similarities between all motors that use magnetic flux for energy transduction. The FAST estimator measures rotor flux (magnitude and angle) in a sensorless FOC system.
- Automatic torque (current) loop tuning with option for user adjustments
- Automatic or manual field weakening and field boosting
- Bus voltage compensation

InstaSPIN-MOTION adds the SpinTAC™ Motion Control Suite (see Figure 2) from LineStream Technologies to InstaSPIN-FOC:

- IDENTIFY: Automatically estimates system inertia, which is used by the SpinTAC™ speed controller to provide the most accurate control.
- CONTROL: A disturbance-rejecting speed controller, which proactively estimates and compensates for system errors. The controller offers single-parameter tuning that typically works over the entire operating range.
- MOVE: A motion engine, which insures that your motor transitions from one speed to another as smoothly as possible.
- PLAN: Allows users to quickly build complex motion sequences with logic-based state transitions.

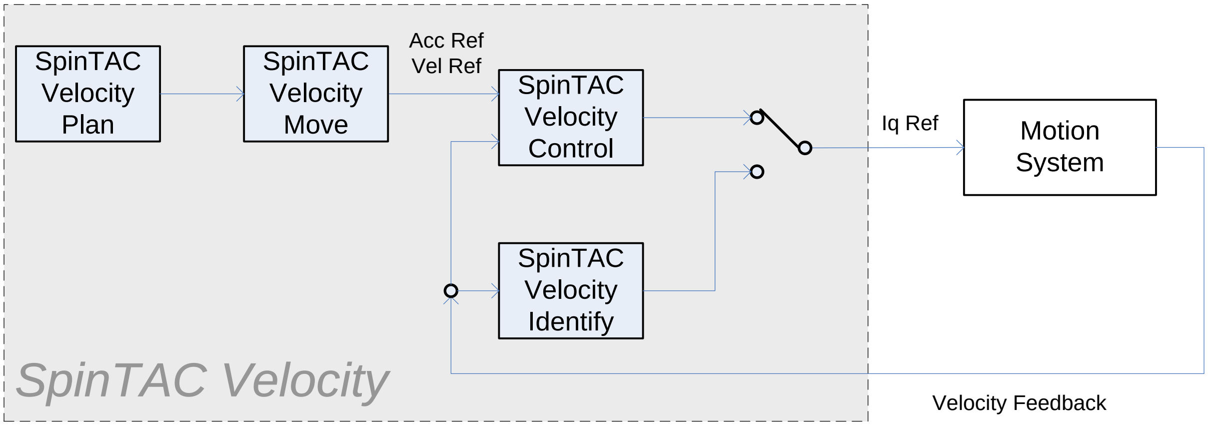


Figure 2. SpinTAC™ Motion Control Suite Components

IDENTIFY

SpinTAC™ Velocity Identify estimates Inertia (the resistance of an object to rotational acceleration around an axis). The greater the system inertia, the greater the torque needed to accelerate or decelerate the motor. The SpinTAC™ speed controller uses the system's inertia value to provide the most accurate system control. SpinTAC™ Velocity Identify automatically measures system inertia by spinning the motor in the application and measuring the speed feedback.

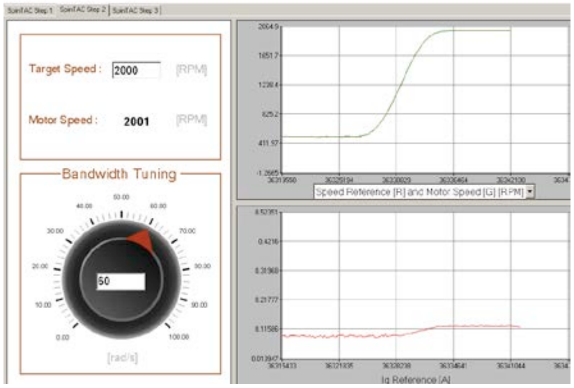
CONTROL

SpinTAC™ Velocity Control is an advanced speed controller featuring Active Disturbance Rejection Control (ADRC), which proactively estimates and compensates for system disturbance, in real-time. SpinTAC™ automatically compensates for undesired system behavior caused by:

- Uncertainties (e.g. - resonant mode)
- Nonlinear friction
- Changing loads
- Environmental changes

SpinTAC™ Velocity Control presents better disturbance rejection and trajectory tracking performance than a PI controller, and can tolerate a wide range of inertia change. This means that SpinTAC™ improves accuracy and system performance, and minimizes mechanical system duress.

With single coefficient tuning, the SpinTAC™ controller allows users to quickly test and tune their velocity control from soft to stiff response. This single gain (bandwidth) typically works across the entire variable speed and load range of an application, reducing complexity and system tuning time typical in multi-variable PI-based systems. These systems often require a dozen or more velocity & load tuned coefficient sets to handle all possible dynamic conditions.



Target Speed : 2000 [RPM]

Motor Speed : 2001 [RPM]

60

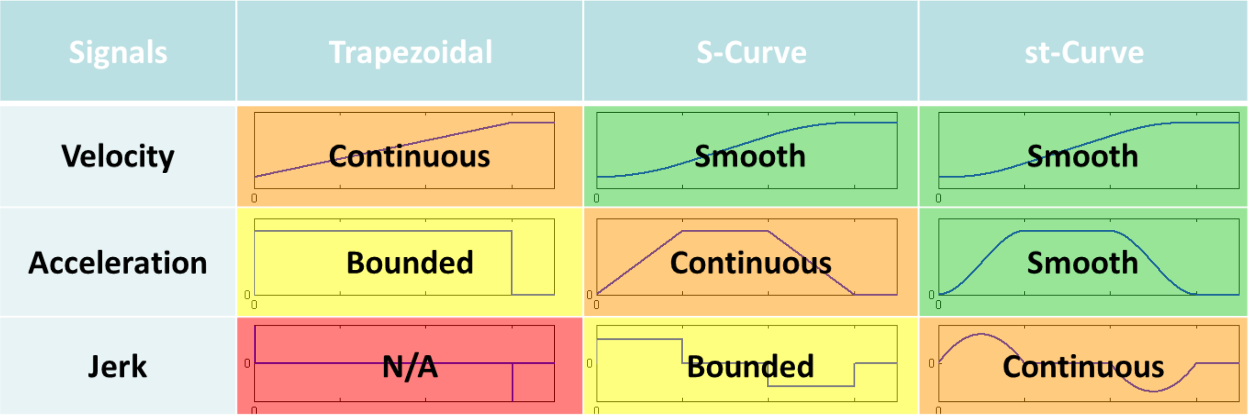
Figure 3. Simple Tuning Interface

The InstaSPIN-MOTION (F2806xM) GUI (see Figure 3), in conjunction with the InstaSPIN-MOTION Quick Start Guide, allow users to quickly evaluate InstaSPIN™-MOTION using TI's evaluation kits and the TI provided motors, or their own motor. The GUI is designed to quickly guide you through the InstaSPIN-MOTION evaluation process. You can obtain the GUI, free of charge, from http://www.ti.com/tool/motorkitscncd69miso. Once you determine that InstaSPIN-MOTION is right for your application, use the MotorWare-based projects, in conjunction with the InstaSPIN-FOC and InstaSPIN-MOTION User's Guide to design your project and conduct performance testing.

MOVE

SpinTAC™ Velocity Move provides an easy way to smoothly transition from one speed to another by computing the fastest path between Speed A and Speed B. SpinTAC™ Velocity Move generates a profile based on start velocity, desired velocity, and configured system limitations for acceleration and jerk. Jerk represents the rate of change of acceleration. A larger jerk will increase the acceleration at a faster rate. Steps, or sharp movement between two speeds, can cause systems to oscillate. The bigger the step, the greater this tendency. Control over jerk can round the velocity corners, reducing oscillation. As a result, acceleration can be set higher. Controlling the jerk in your system will lead to less mechanical stress on your system components and can lead to better reliability and less failing parts.

As opposed to pre-defined lookup tables, SpinTAC™ Velocity Move runs on the processor, consuming less memory than traditional solutions. Besides the industry standard trapezoidal curve and s-Curve, SpinTAC also provides a proprietary curve: st-Curve, which is even smoother than s-Curve and allow users to limit the jerk of the motion.



Signals	Trapezoidal	S-Curve	st-Curve
Velocity	Continuous	Smooth	Smooth
Acceleration	Bounded	Continuous	Smooth
Jerk	N/A	Bounded	Continuous

Figure 4. Chart describing curves available in SpinTAC™ Move

Figure 4 describes the curves that are available for use in SpinTAC™ Move. The LineStream proprietary st-Curve provides the smoothest motion by smoothing out the acceleration of the profile. For most applications the st-Curve represents the best motion profile.

PLAN

SpinTAC™ Velocity Plan provides easy design and execution of complex motion sequences. The trajectory planning feature allows users to quickly build various states of motion (speed A to speed B) and tie them together with state based logic. Figure 5 displays the motion sequence for a washing machine. This complex motion sequence was easily designed using the SpinTAC™ Velocity Plan. The trajectories are directly embedded into the C code on the microcontroller.

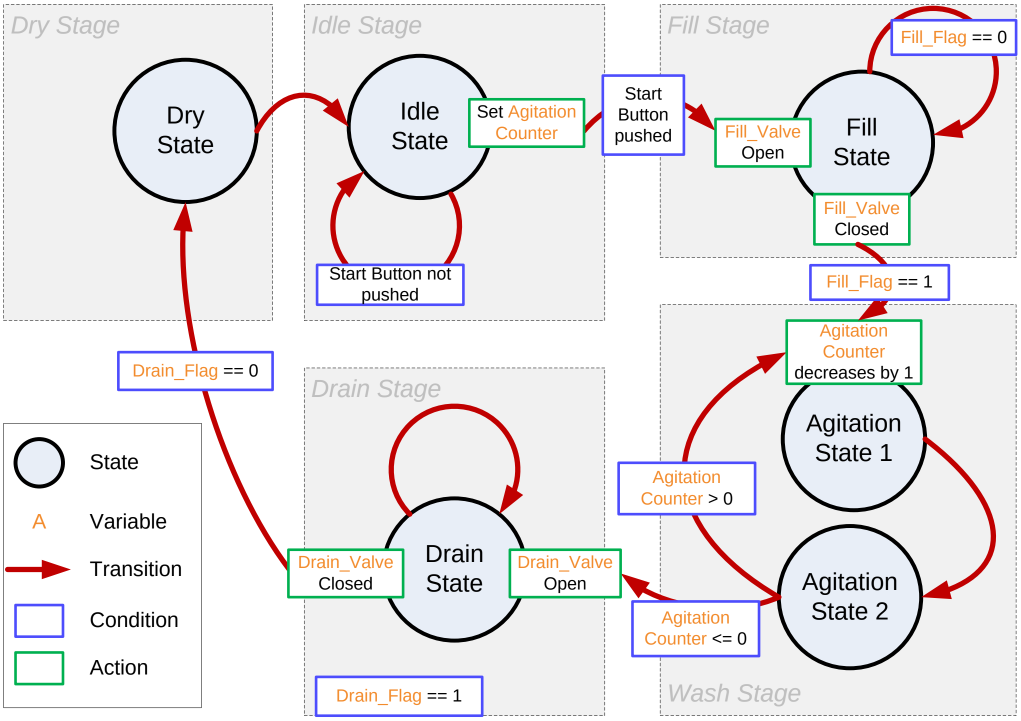


Figure 5. State Transition Map for a Washing Machine

SpinTAC™ Velocity Plan can be used to implement a motion sequence for nearly any application. Figure 6 describes the state transition map for a garage door system that can be easily implemented in SpinTAC™ Velocity Plan.

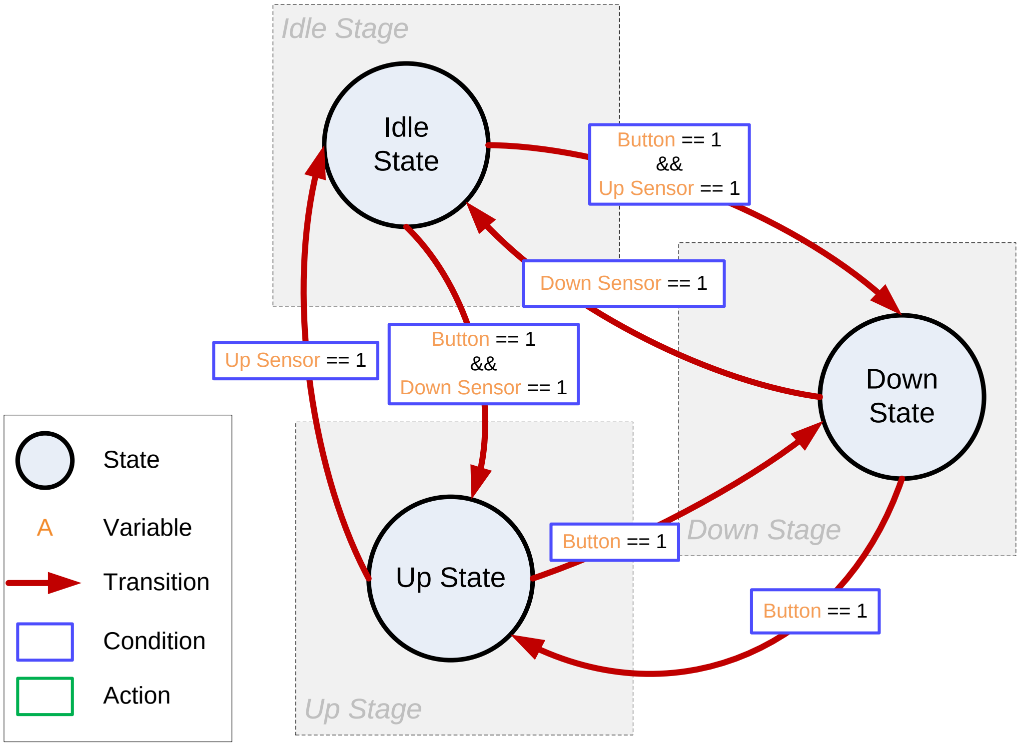


Figure 6. State Transition Map for a Garage Door System

InstaSPIN-MOTION eliminates motion control challenges found in traditional motor systems:

- Achieving desired motor performance across varying conditions required multiple sets of multi-parameter, proportional-integral (PI) controllers needing time-intensive tuning.
- Defining the motor’s desired motion in traditional systems required simplistic, inflexible trajectories, resulting in mechanical stress.
- Hand-coded, calculation-heavy trajectories consume valuable memory.

InstaSPIN-MOTION replaces inefficient, older design techniques with a solution that maximizes system performance and minimizes design effort. The motor expertise is embedded on the chip, allowing users to focus on optimizing their application rather than struggling with motion control.

Additional information about InstaSPIN-FOC features is provided in the InstaSPIN-FOC Technical Reference Manual.

5. InstaSPIN-MOTION Block Diagrams

InstaSPIN-MOTION is designed in a modular structure. Customers can determine which functions will be included in Flash memory when their system is deployed. InstaSPIN-FOC is available in ROM or in user memory (with the exception of the FAST Observer, which always resides in ROM). SpinTAC Control, Identify, and Move components are available in ROM SpinTAC Plan and Public Library are available in RAM.

InstaSPIN-MOTION supports a wide array of system designs. InstaSPIN-MOTION uses the FAST™ software encoder for sensorless FOC systems (see TMS320F2806xF InstaSPIN-FOC TRM for additional information). InstaSPIN-MOTION also supports solutions that leverage mechanical sensors (e.g., encoders, resolvers). These scenarios are described below.

Scenario 1: SpinTAC™ Speed Control with InstaSPIN-FOC Sensorless Solution

In this scenario (see Figure 7 and Figure 8), SpinTAC™ Velocity Control receives the speed estimate from the FAST™ estimator, generates the torque reference signal, and sends it to InstaSPIN-FOC via IqRef. This works with InstaSPIN-FOC in user FLASH/RAM (see Figure 7) or in ROM (see Figure 8). The SpinTAC™ Motion Control Suite provides the motion sequence state machine, generates the reference trajectory and controls the system speed.

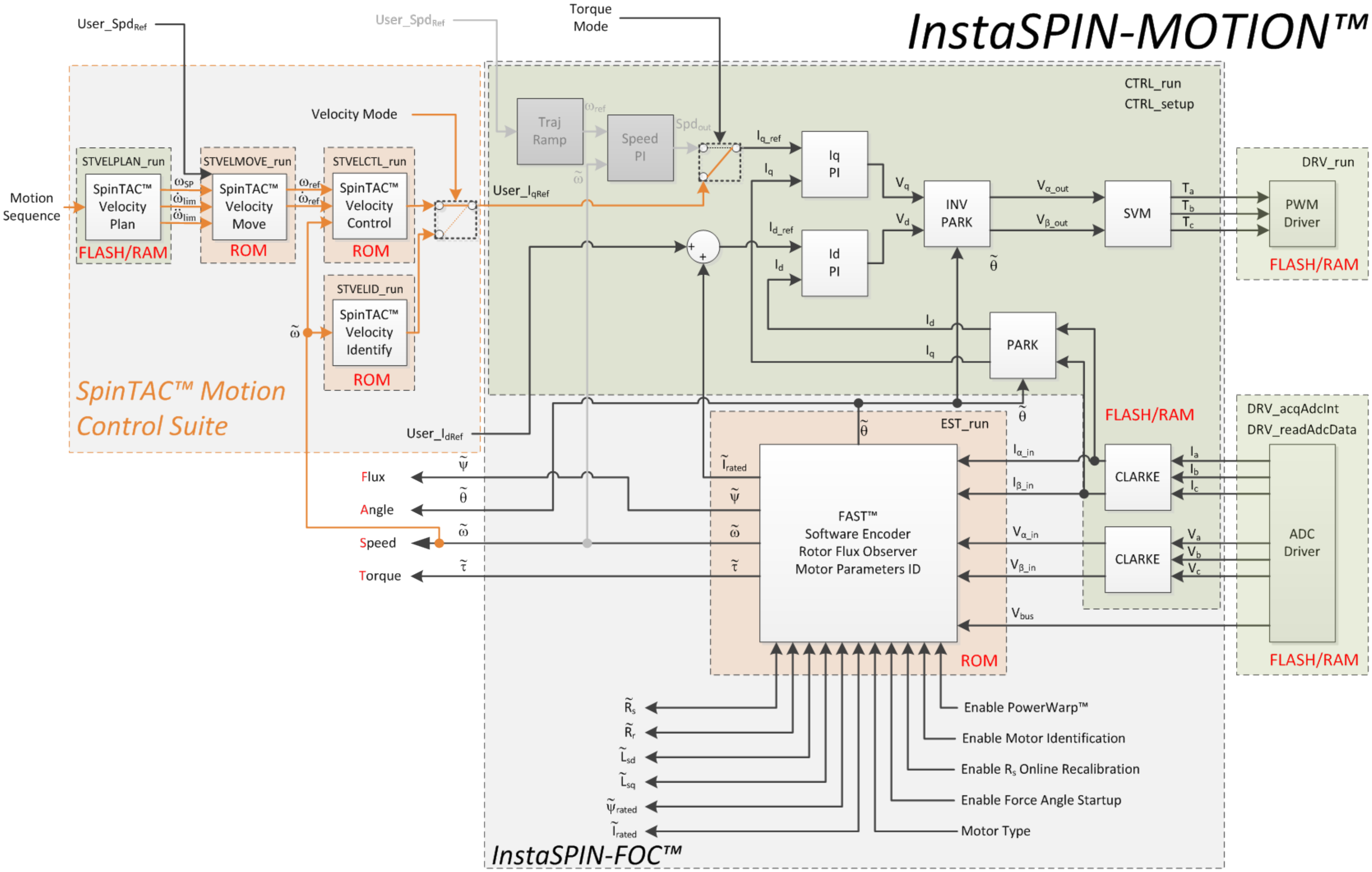


Figure 7. InstaSPIN-MOTION with InstaSPIN-FOC in user memory, with exception of FAST and SpinTAC in ROM

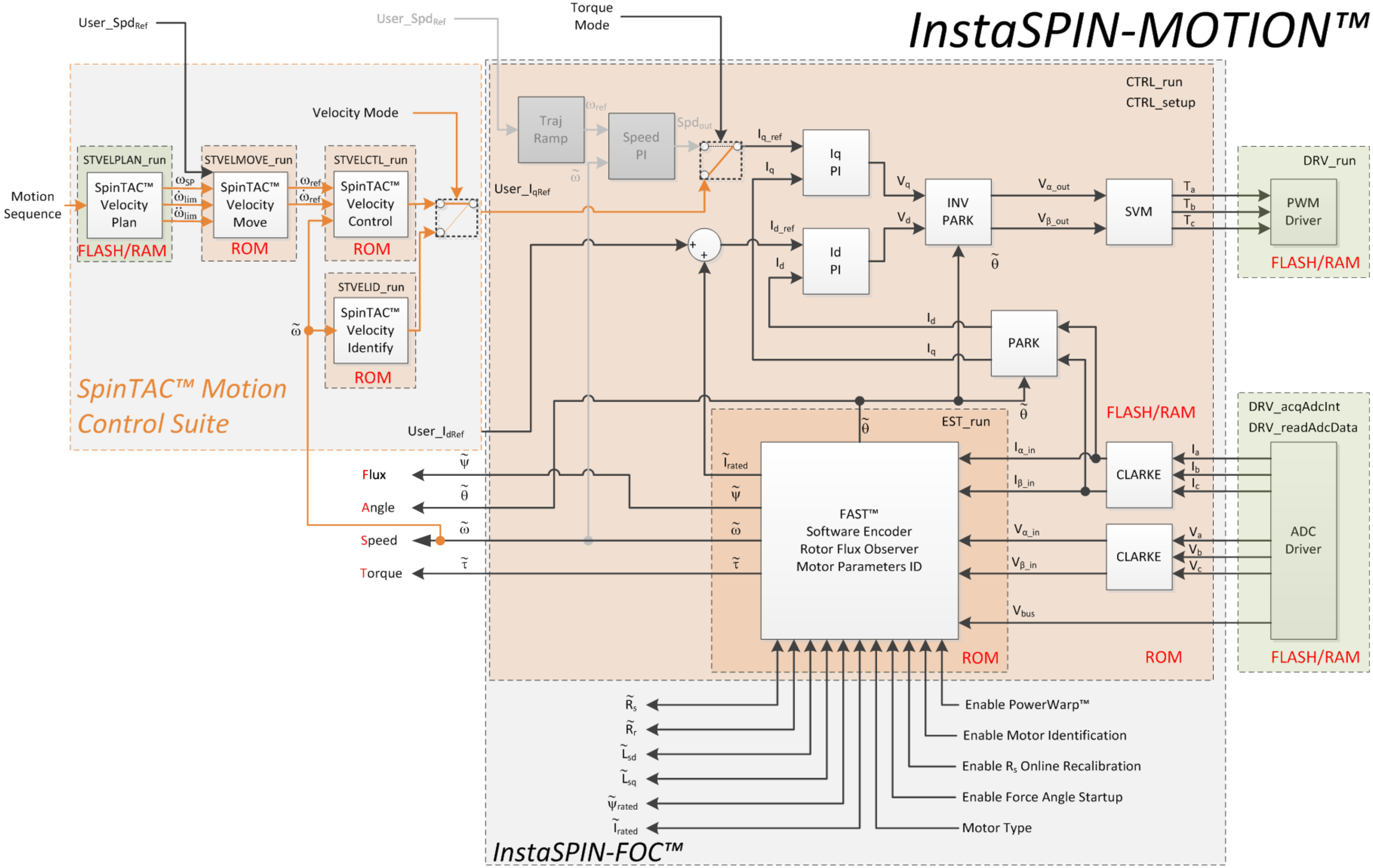


Figure 8. InstaSPIN-MOTION in ROM

Scenario 2: InstaSPIN-MOTION in a sensored FOC solution

While sensorless solutions are appealing and cost effective for many applications, there are some applications that require the rigor and accuracy of a sensor. For these applications (see Figure 9), the quadrature encoder provides position information, which is then converted to a speed estimate. SpinTAC™ Velocity Control receives the speed estimate, generates the torque reference signal and sends it to InstaSPIN-FOC via IqRef. The SpinTAC™ Motion Control Suite provides the motion sequence state machine, generates the reference trajectory and controls the system speed.

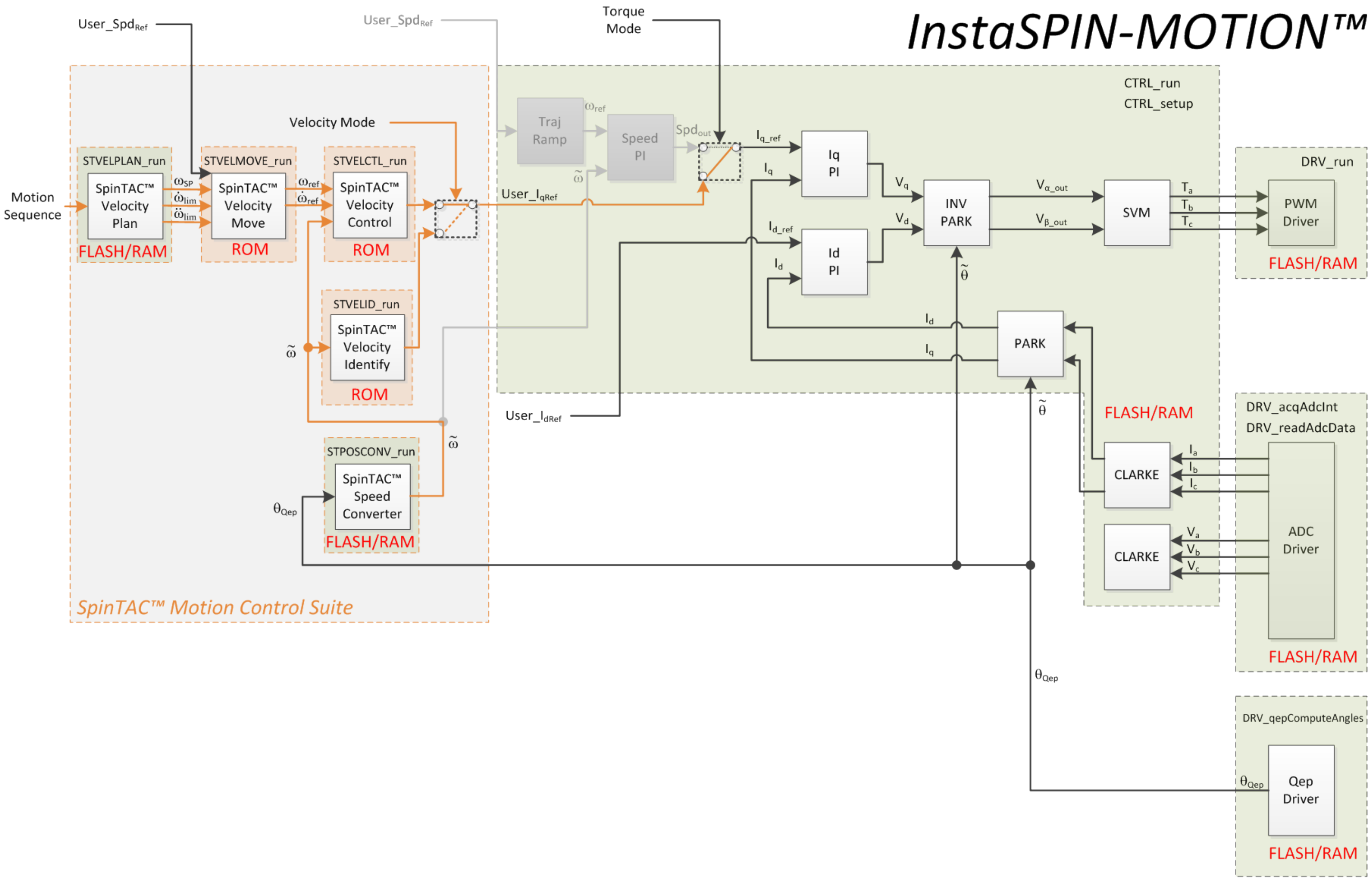


Figure 9. InstaSPIN-MOTION in a Sensored FOC Solution

The variables in Figure 7, Figure 8 and Figure 9 are defined as follows:

θ_{Qep}: position angle signal from encoder

θ_{M}: formatted sawtooth position signal to be used in SpinTAC Position Controller

θ_{SP}: Sawtooth position reference signal generated by SpinTAC Position Move

$\omega_{\lim}$: Speed Limit (used in position profile generation) $\dot{\omega}_{\lim}$: Acceleration Limit

$\ddot{\omega}_{\lim}$: Jerk Limit

ω_{Ref} : Speed Reference

$\dot{\omega}_{Ref}$: Acceleration Reference

$\tilde{T}_r$: Motor time constant

6. The SpinTAC™ Motion Control Suite Improves System Performance

Cycle transitions, changing loads, and environmental disturbances cause significant wear and tear on motors. Automatic, real-time reduction of disturbances can extend the life and performance of motors. In systems that remain unaffected by outside influences, the SpinTAC™ controller demonstrates its performance benefits by significantly reducing overshoot and undershoot during transitions. In systems that are affected by outside disturbances, the SpinTAC™ controller provides advanced disturbance rejection, holding set points more closely than is achievable with standard PI control. This functionality improves the performance of applications that require accurate speed control, applications that require precision and minimal disturbance during operation, and applications that undergo multiple state transitions.

The functionality of the SpinTAC™ controller is combined with SpinTAC™ Move, which controls jerk, rounding the velocity corners and reducing oscillation. As a result, acceleration can be set higher. Controlling the jerk in your system will lead to less mechanical stress on your system components and can lead to better reliability and less failing parts.

SpinTAC™ Plan trajectory planning feature allows users to quickly build various states of motion (speed A to speed B) and tie them together with state based logic. SpinTAC™ Velocity Plan can be used to implement a motion sequence for nearly any application. Consider washing machines, for example. Figure 10 displays the motion profile for three stages of a standard washing machine. The first stage represents the agitation cycle, rotating between 250 RPM and -250RPM repeatedly. The second and third stages represent two different spin cycles. The second stage spins at 500 RPM and the third stage spins at 2000 RPM. This profile was easily created using SpinTAC™ Plan (the labs provided in the InstaSPIN-FOC and InstaSPIN-MOTION User Guide will demonstrate how this profile was created).

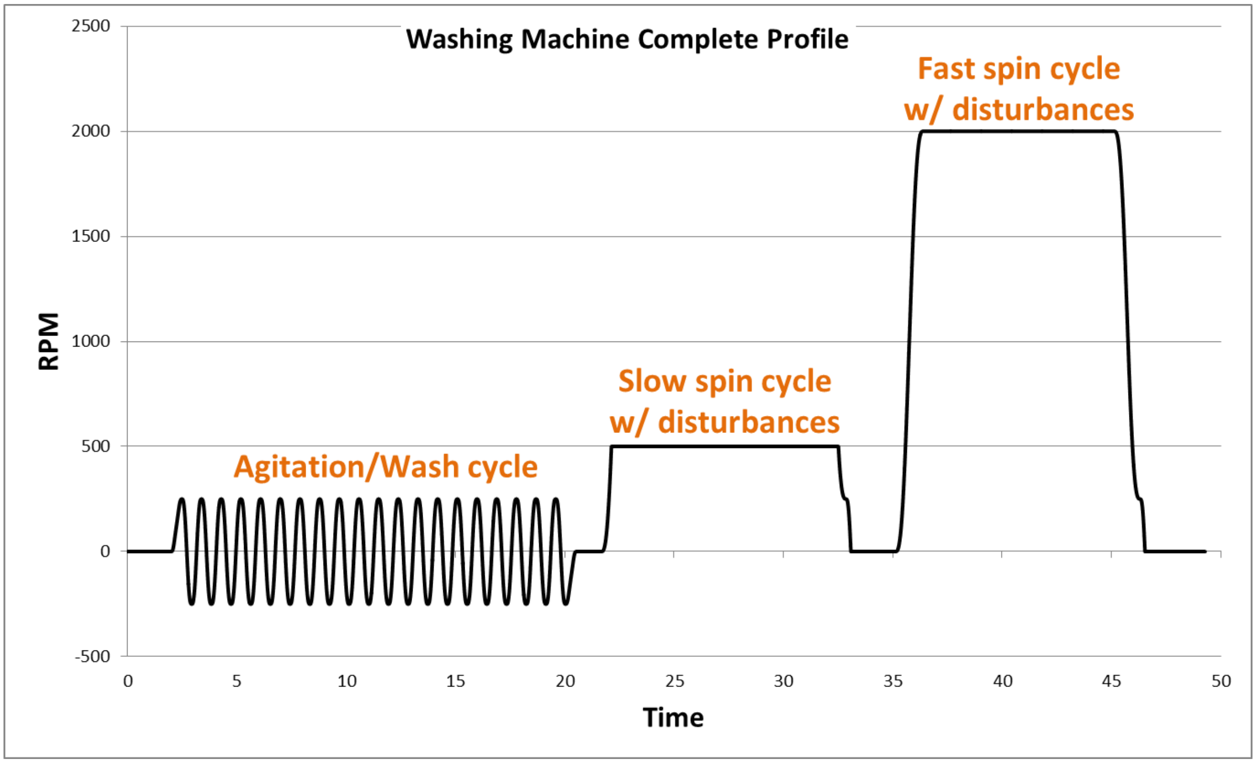


Figure 10. Washing Machine Profile

The washing machine profile was used to demonstrate the performance characteristics of the SpinTAC™ Motion Control Suite. During the agitation cycle, the motor repeatedly rotates between positive and negative RPMs. These machines typically have multiple spin cycles, with disturbances caused by the shifting weight of the clothing in the drum.

The washing machine profile was run twice – once using a standard PI controller and once using LineStream's SpinTAC™ controller with the motion profile generator. The data was then plotted against the reference curve for comparison. During the spin cycles, pulse and ramp disturbances were injected by a dynamometer to demonstrate the disturbance recovery of each controller.

Agitation Cycle

During agitation, the motor switches between the 250 RPM and -250 RPM set points 20 times. The results, shown in Figure 11, demonstrate that SpinTAC™ more closely matched the reference profile. Additionally, the maximum error for PI was 91 RPM (341-250 = 91 RPM) whereas the maximum error for SpinTAC™ was 30 RPM (280 – 250 = 30 RPM).

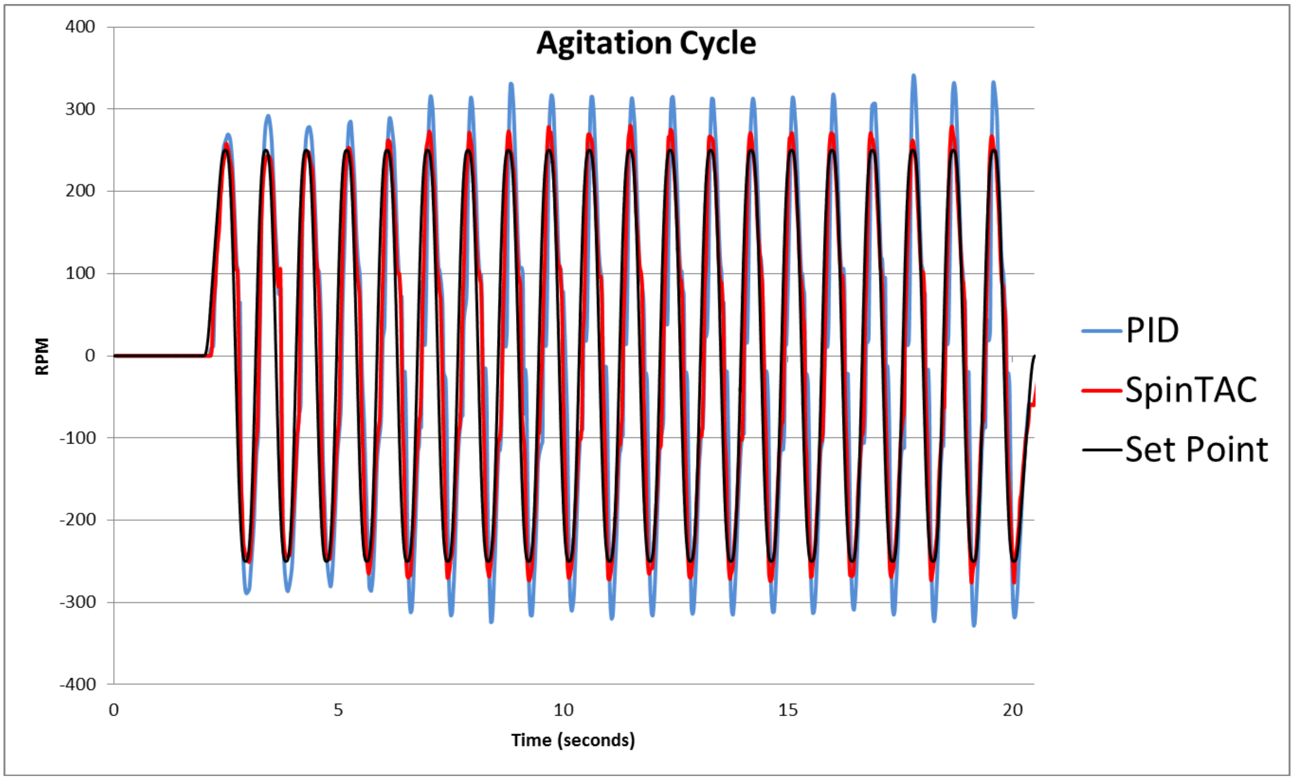


Figure 11. SpinTAC™ Minimizes Error

Spin Cycles

The first spin cycle attempts to maintain 500 RPM, even when disturbances are introduced. Figure 12 shows that the SpinTAC™ controller recovered from disturbances more quickly and with less oscillation than the PI controller. Additionally, SpinTAC™ does not suffer from the overshoot and undershoot shown by the PI controller when it tries to reach the initial 500 RPM set point.

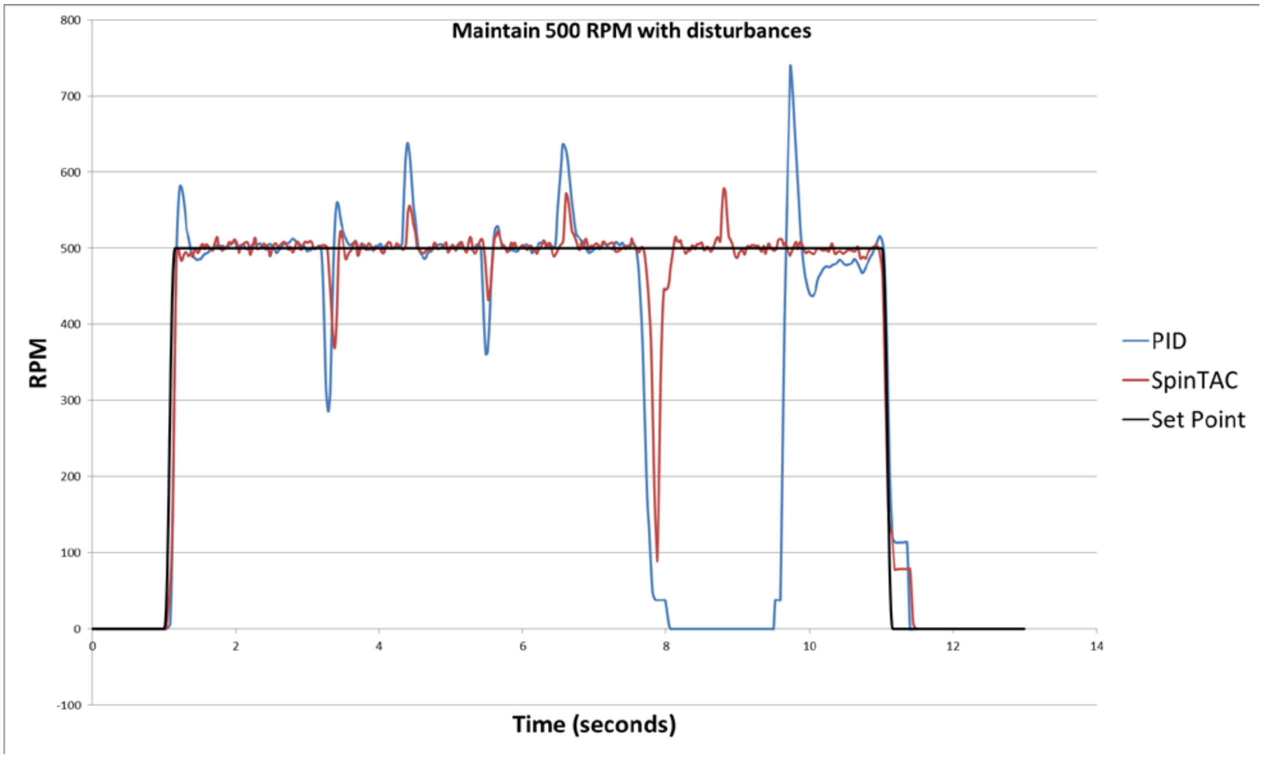


Figure 12. First Spin Cycle - 500 RPM

During the second spin cycle, shown in Figure 13, the SpinTAC™ controller consistently recovered from disturbances at 2000 RPM more quickly and with less oscillation than the PI controller. Note that SpinTAC™ does not suffer from the overshoot and undershoot shown by the PI controller when it tries to reach the initial 2000 RPM set point.

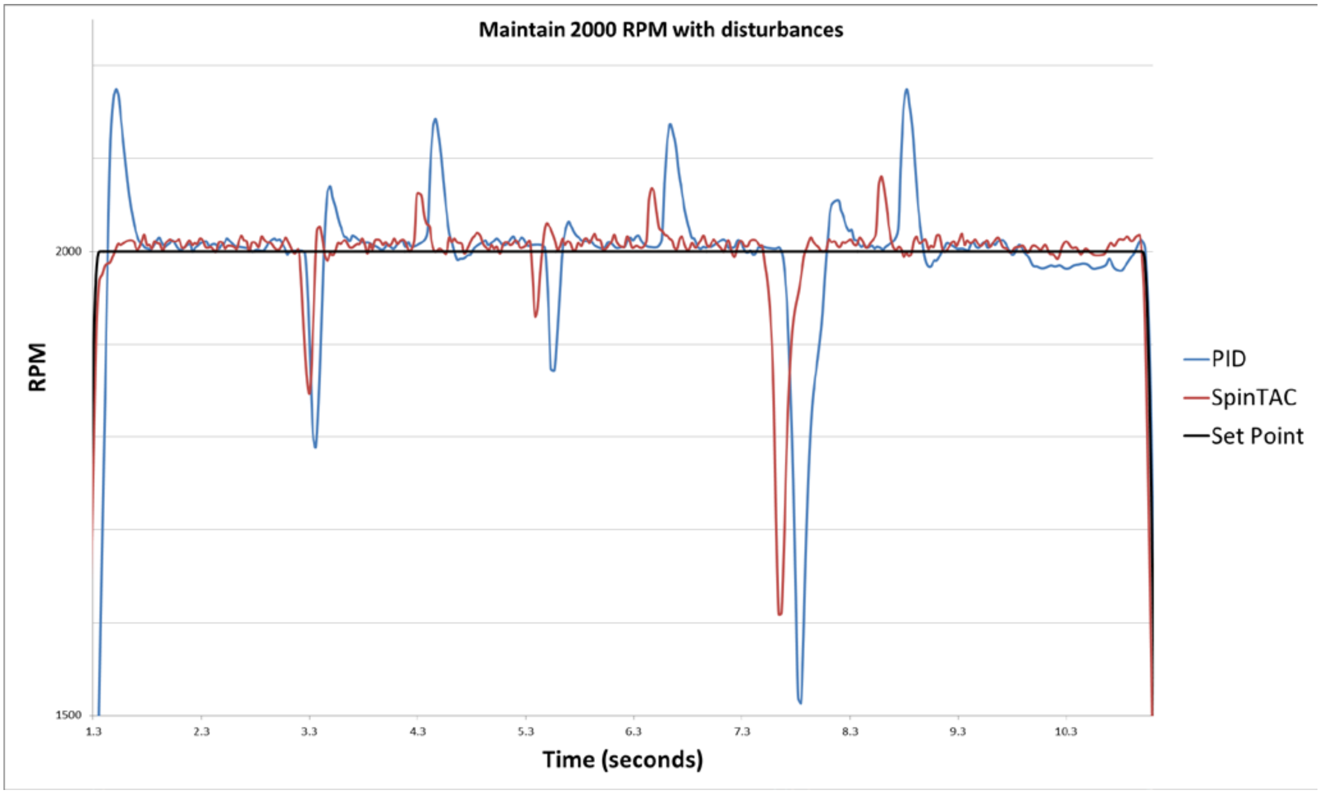


Figure 13. Second Spin Cycle - 2000 RPM

Additionally, the PI controller could not recover from the ramp disturbance at the 9.75 second mark. Instead, it shows a steady-state error of roughly 20 RPM.

SpinTAC™ Works Over the Entire Operating Range

Both the SpinTAC™ controller and the PI controller were tuned once, before executing the washing machine profile. From the example, it is evident that the SpinTAC controller tuning works over the entire operating range, while the PI controller does not work ideally over the entire operating range. Whether the motor switches between the 250 RPM and -250 RPM, or maintains 500RPM or 2000RPM spin cycles, there is no need for new tuning sets.

The SpinTAC Motion Suite can benefit a wide range of applications, some of which are shown in Figure 14.

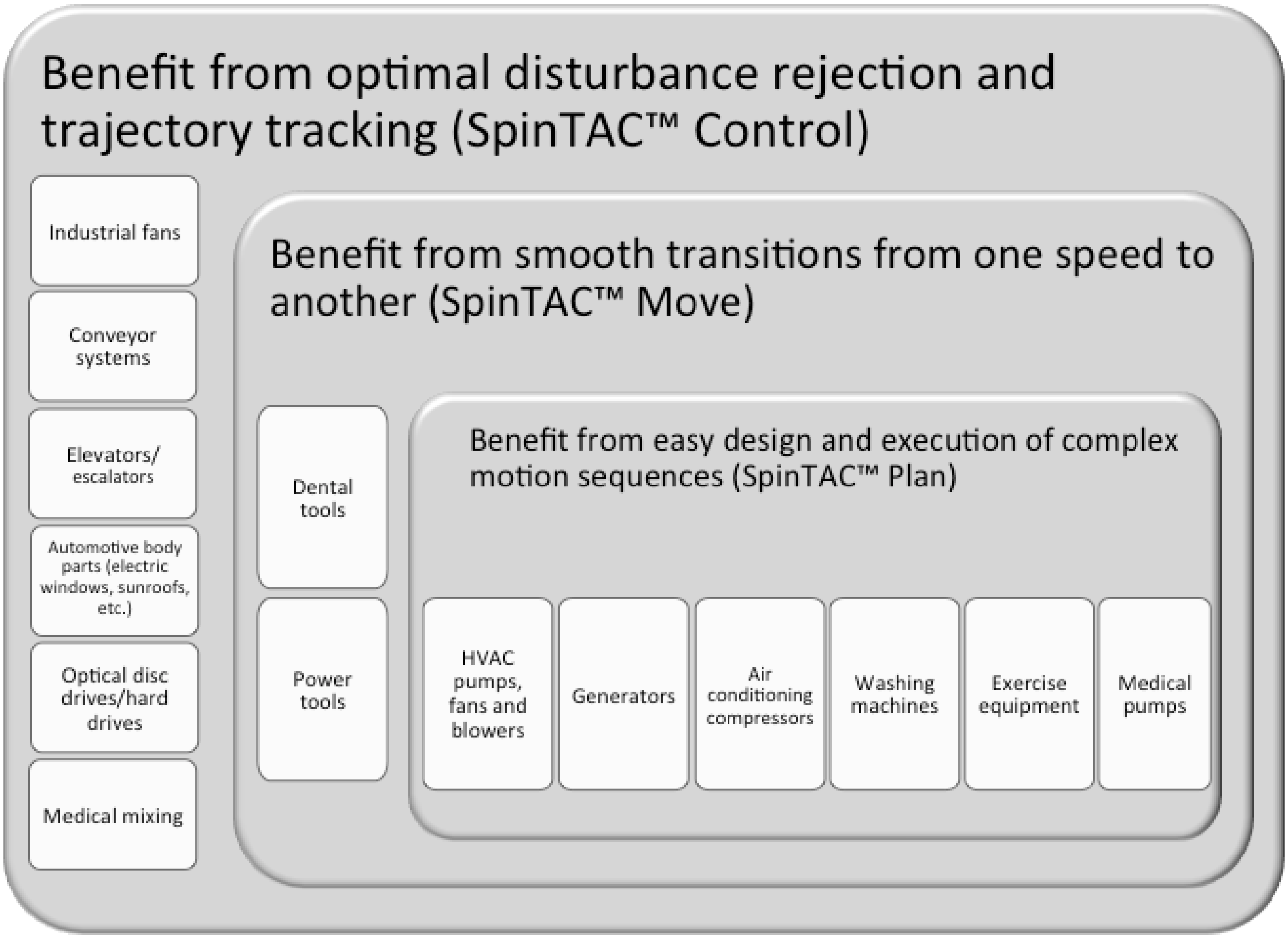


Figure 14. Examples of Applications that can benefit from the SpinTAC Motion Suite

7. SpinTAC™ Replaces Hard-to-Tune PID Controllers

Large OEMs may work with external design houses to optimize their tuning parameters. However, many small and medium size OEMs are challenged by tuning their own PI controls. With InstaSPIN-MOTION, OEMs can save weeks of tuning time.

While PI controls are versatile and applicable to numerous control systems, the tuning process can be complex and time-intensive. Similarly, performance of PI loops can be unpredictable over a wide operating range and as system dynamics change over time. While the use of advanced control techniques, such as model-based compensation, can address these challenges, they require significant time for implementation and testing. They also add complexity to the system, and can result in performance degradation when the system dynamics vary.

SpinTAC™ addresses these challenges by replacing traditional PI controls. The advantages are highlighted in Table 2 - PI vs. SpinTAC™. SpinTAC**™** incorporates advanced control features, such as feed-forward and an observer, and can be tuned in a fraction of the time required to tuned PI control. Instead of having to tune multiple control parameters, the SpinTAC™ controller can be tuned by adjusting a single parameter. Once tuned, it will perform across a wide-operating range.

SpinTAC™ is designed to perform in all kinds of systems. In systems that remain unaffected by outside influences, the SpinTAC™ controller demonstrates its performance benefits by eliminating overshoot and undershoot during transitions.

In systems that are affected by outside disturbances, the SpinTAC™ controller provides advanced disturbance rejection, holding set points more closely than is achievable with standard PI control, as shown in Figure 15.

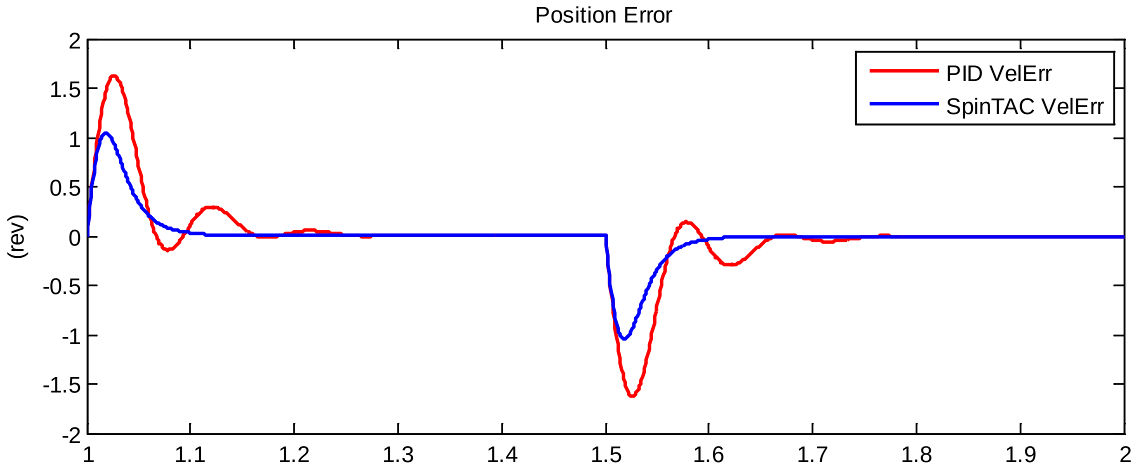


Figure 15. Disturbance Recovery: SpinTAC™ vs. PID

Table 2. PI vs. SpinTAC™

Topic	PI Controllers	SpinTAC™
Performance	Unpredictable	Compensating
Tuning Parameters	Multiple	Single
Tuning Process	Complex	Simple – the identification process takes a few minutes
Start-up	Difficult – requires control expertise	Simple – accomplished in 3 steps
Disturbance Recovery	Overshoot and undershoot when disturbances are introduced and during transitions	Advanced disturbance rejection holds set points more closely
Ongoing Maintenance	Requires retuning	None

8. Evaluating InstaSPIN-MOTION Performance

Getting the best possible performance out of your motion system is important. A poorly tuned regulator can result in wasted energy, wasted material, or an unstable system. It is important that speed controller performance be evaluated at many different speed and load operating points in order to determine how well it works in your application.

Speed controllers can be compared on a number of different factors. However, two metrics - disturbance rejection and profile tracking - can be used to test performance and determine how well your controller is tuned for your application.

Test-Bed Description

Tests were conducted using the following equipment:

1. TMS320F28069M Control Card with InstaSPIN-MOTION Version 1.6
2. Texas Instruments Code Composer Studio Version 5.3
3. Texas Instruments Inverters:
    a. DRV8301-69M-KIT
    b. TMDSHVMTRPFCKit Version 1.1
4. Motors:
    a. Teknic M2310P
    b. Estun EMJ-04APB22
5. Dynamometer:
    a. Magtrol HD-715 Dynamometer
    b. Magtrol DSP7001 Controller
    c. Magtrol 6510e Power Analyser
    d. DC Power Supply

Each controller was tuned using the same method. For the Estun motor these controllers were tuned experimentally by injecting 25% rated torque (45 oz-in) disturbances while running the motor at 100% rated speed (3000 rpm). This resulted in the following gains:

PI Speed Controller

- Kp = 20
- Ki = 0.098

SpinTAC Speed Controller

- Bandwidth = 35 radians/s

The inertia used by the SpinTAC speed controller was estimted with the dyne coupled with the motor. The value was found to be 0.483 A / (krpm/s).

For the Teknic motor these controllers were tuned experimentally by injecting 50% rated torque (19.4 oz-in) disturbances while running the motor at 50% rated speed (2000 rpm). This resulted in the following gains:

PI Speed Controller

- Kp = 9
- Ki = 0.03

SpinTAC Speed Controller

- Bandwidth = 16 radians/s

The inertia used by the SpinTAC speed controller was estimted with the dyne coupled with the motor. The value was found to be 4.23 A / (krpm/s).

These determined gains were held constant throughout all of the tests. This was done purposfully in order to highlight the wide operating range of the SpinTAC speed controller.

8.1. Control Loop Performance SpinTAC vs PI

8.1.1. Disturbance Rejection

Disturbance rejection tests the controller's ability to compensate for external disturbances, which will impact the motor speed. In the disturbance rejection test, a load torque is applied to the system, held on for a short period of time and then removed from the system. Figure 16 is an example of a disturbance rejection test. The response of the controller is measured using the maximum speed error and settling time. The maximum speed error shows the deviation from the goal speed, and is an indication of how aggressively your controller is tuned. Aggressive tuning will produce a low maximum error. In Figure 16 the PI controller presents a greater maximum speed error than the SpinTAC controller, indicating that the SpinTAC controller is more responsive in compensating for system error.

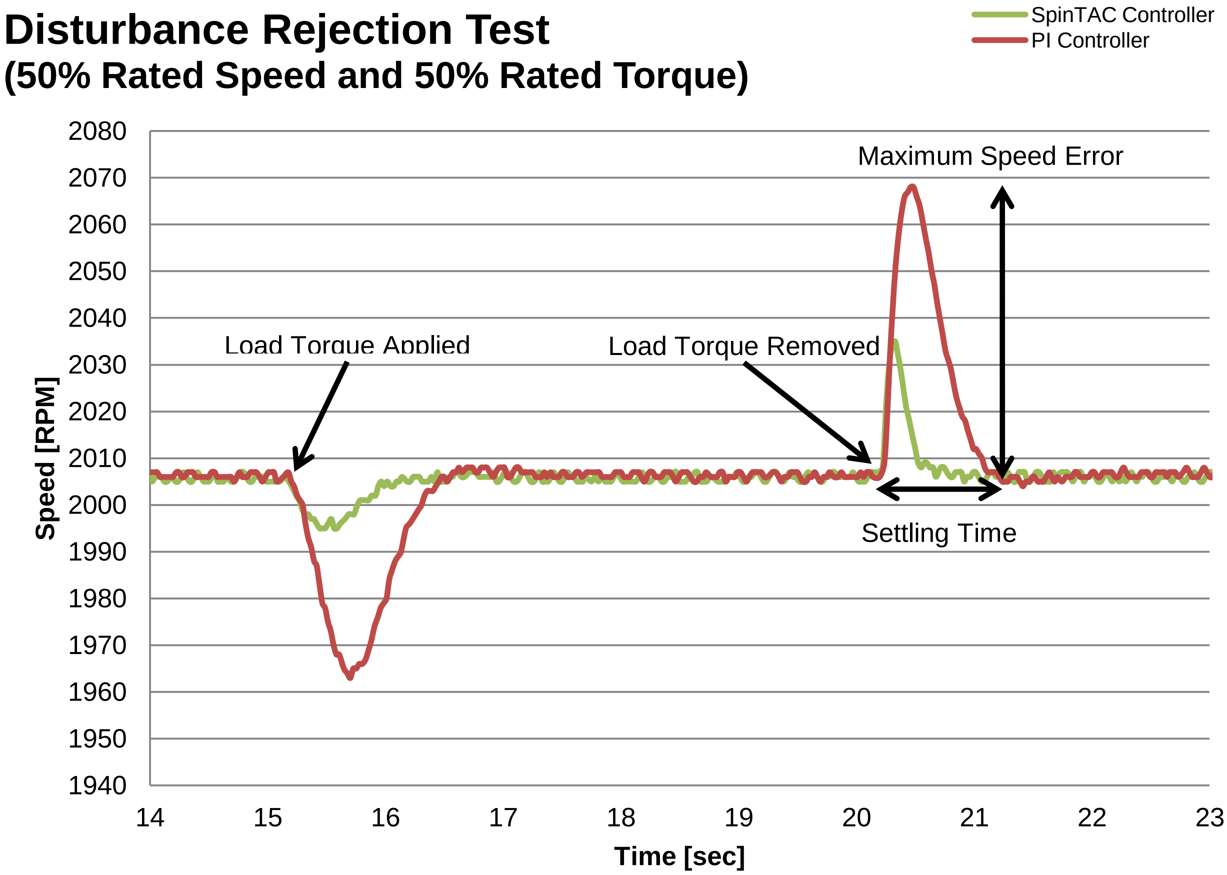


Figure 16. Disturbance Rejection Test of Maximum Speed Error and Settling Time

Settling time refers to the amount of time from the point when the disturbance happens until the speed returns to a fixed band around the goal speed. This is also an indication of how aggressively your control loop is tuned. If the controller is tuned too aggressively it will have a long settling time because it will oscillate around the goal speed before settling. In Figure 16, the PI controller has a longer setting time that the SpinTAC controller. Note that there is very little oscillation in either controller as they settle back to the goal speed.

There may be a difference in settling time when loads are applied to the system, and when loads are removed from the system. When a load is applied to a motor, the controller may reach saturation, at which point the controller's output is limited. However, when the load is removed, the motor transitions from a loaded state to zero load. The settling time and overshoot is entirely dependent upon the controller. Figure 17 shows an example of this case where the controller was placed into saturation.

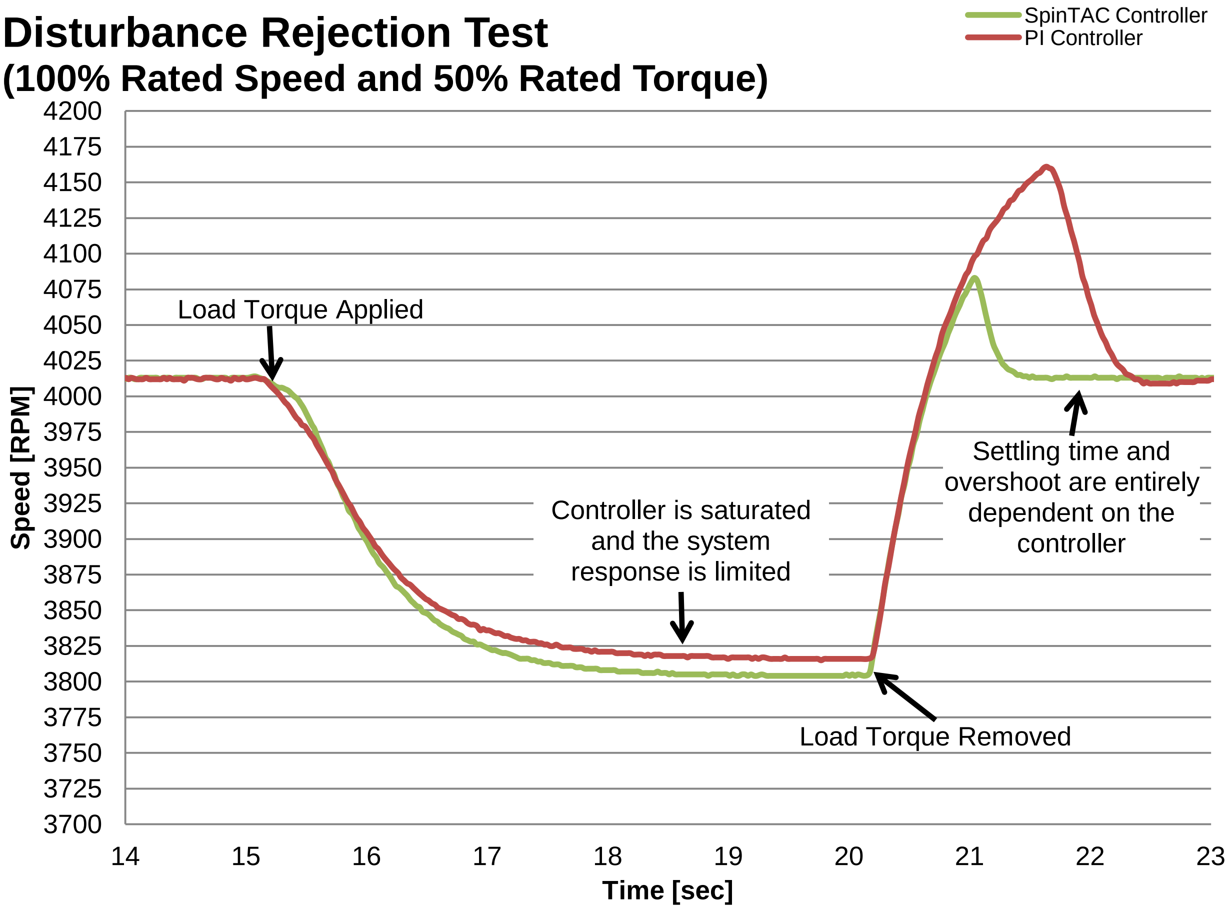


Figure 17 - Disturbance Rejection Test with Controller Saturation

When doing disturbance rejection testing it is important to test at multiple speed and load combinations. Speed controllers have different performance characteristics when placed into different situations. In order to properly evaluate the effectiveness of your speed controller, tests should be done across the entire application range. The test results will indicate whether the controller will meet the application specifications, or whether the controller needs to be tuned multiple times for different operating points. As part of these tests we have tested at nine different speed and load combinations in order to test a wide range of operation.

It is also important to be able to create repeatable disturbances. This can be accomplished using a dynamometer or a disturbance motor. Creating repeatable disturbance is an important factor when evaluating multiple controllers. If test conditions cannot be replicated, it is difficult to adequately compare the responses of two controllers.

For the following test results, a disturbance load profile was created that applied 25%, 50%, and 100% of rated torque to the motor. The test compared the performance of the SpinTAC speed controller to a standard PI controller, and the following parameters were measured for each:

- Average Recovery Time (from the point of disturbance until within 2% of the target speed) - The average recovery time was measured when the load was applied, and when the load was removed from the system.
- Absolute Average Speed Error – positive or negative deviation from the goal speed when a system disturbance is introduced
- Maximum Speed Error – maximum deviation from the goal speed when a disturbance is introduced

Table 3. SpinTAC vs. PI Disturbance Rejection Test Results (Teknic Motor)

	1000 RPM			2000 RPM			4000 RPM		
	SpinTAC	PI	SpinTAC Advantage (percentage improvement over PI)	SpinTAC	PI	SpinTAC Advantage (percentage improvement over PI)	SpinTAC	PI	SpinTAC Advantage (percentage improvement over PI)
25% rated torque									
Avg Recovery Time (s) – load applied	1.34	1.84	27.34	1.20	1.67	28.27	0.85	1.79	52.46
Avg Recovery Time (s) – load removed	0.43	0.93	53.29	0.41	0.89	53.55	0.54	1.02	46.82
Abs Avg Error (RPM)	3.06	4.16	26.44	5.98	6.63	9.74	12.23	12.42	1.53
Avg Max Error (RPM)	17	29	41.38	16	27	40.74	18	26	30.77
50% rated torque									
Avg Recovery Time (s) – load applied	1.01	1.33	23.81	1.01	1.45	30.34	4.98	5.04	1.19
Avg Recovery Time (s) – load removed	0.51	1.04	51.30	0.56	1.06	46.52	1.33	2.54	47.20
Abs Avg Error (RPM)	3.7	7.9	53.16	6.21	10.2	39.12	81.92	87.66	6.55
Avg Max Error (RPM)	36	71	49.30	35	69	49.28	197	185	-6.49
100% rated torque									
Avg Recovery Time (s) – load applied	0.76	1.20	36.67	0.78	1.16	32.73	4.98	5.08	1.95
Avg Recovery Time (s) – load removed	0.40	1.00	59.84	0.52	1.02	48.89	1.90	3.12	39.09
Abs Avg Error (RPM)	5.4	15.39	64.91	7.99	17.54	54.45	345.42	360.74	4.25
Avg Max Error (RPM)	87	158	44.94	80	151	47.02	829	837	0.96

Table 4. SpinTAC vs. PI Disturbance Rejection Test Results (Estun Motor)

	750 RPM			1500 RPM			3000 RPM		
	SpinTAC	PI	SpinTAC Advantage (percentage improvement over PI)	SpinTAC	PI	SpinTAC Advantage (percentage improvement over PI)	SpinTAC	PI	SpinTAC Advantage (percentage improvement over PI)
25% rated torque									
Avg Recovery Time (s) – load applied	0.69	1.52	54.34	0.60	1.36	57.96	0.60	1.35	52.87
Avg Recovery Time (s) – load removed	0.42	1.12	61.75	0.40	1.03	61.58	0.41	1.01	59.01
Abs Avg Error (RPM)	1.97	3.81	48.13	3.05	5.25	41.90	6.16	9.08	32.12
Avg Max Error (RPM)	37	47	21.28	36	47	23.40	38	49	22.45
50% rated torque									
Avg Recovery Time (s) – load applied	0.35	1.31	72.97	0.33	1.33	76.23	0.36	1.13	67.07
Avg Recovery Time (s) – load removed	0.44	1.36	67.32	0.40	1.25	68.02	0.364	1.14	67.33
Abs Avg Error (RPM)	2.67	5.91	54.87	3.86	7.13	45.89	6.89	11.14	38.19
Avg Max Error (RPM)	76	96	20.83	74	95	22.11	76	97	21.65
100% rated torque									
Avg Recovery Time (s) – load applied	0.56	2.26	75.09	0.5	2.14	76.68	4.98	5.06	1.58
Avg Recovery Time (s) – load removed	0.38	1.16	66.78	0.4	0.92	55.93	0.44	0.74	40.60
Abs Avg Error (RPM)	8.64	57.98	85.09	9.54	59.95	84.09	94.25	103.74	9.15
Avg Max Error (RPM)	440	697	36.87	440	665	33.83	585	646	9.44

8.1.2. Reference Tracking

Reference tracking tests how well the controller follows a changing target speed. The two metrics to evaluate in this testing is the maximum error and the absolute average error. The maximum speed error shows how much the controller overshoots while changing speeds. This is an indication of how aggressively your controller is tuned. If you controller is not tuned aggressively enough, the speed will overshoot the target, and will take a long time to recover. If the controller is tuned too aggressively it will overshoot, and then oscillate as it settles on the goal speed. If the controller is correctly tuned, it will minimally overshoot and then smoothly return to the goal speed.

Absolute average error is an average of the absolute value of the instantaneous speed error over the entire profile. This measure shows the amount of deviation throughout the entire profile. It takes into account all of the little errors as the motor is running. If the controller is tuned too aggressively it will result in larger absolute average error because the controller will be oscillating throughout the profile. If the controller is not tuned aggressively enough, it will result in a larger absolute average error because it is continuously falling behind what the profile is commanding the motor to do.

A tracking profile was created to exercise the motor in a repeatable a pattern. The profile was used to compare the performance of SpinTAC and PI controllers. The profile included quick transitions as well as gentle sweeping transitions. Figure 18 is a plot of the speed profile used during the reference tracking tests. The blocked off areas are areas where additional plots will be shown detailing the differences between the SpinTAC and PI controllers.

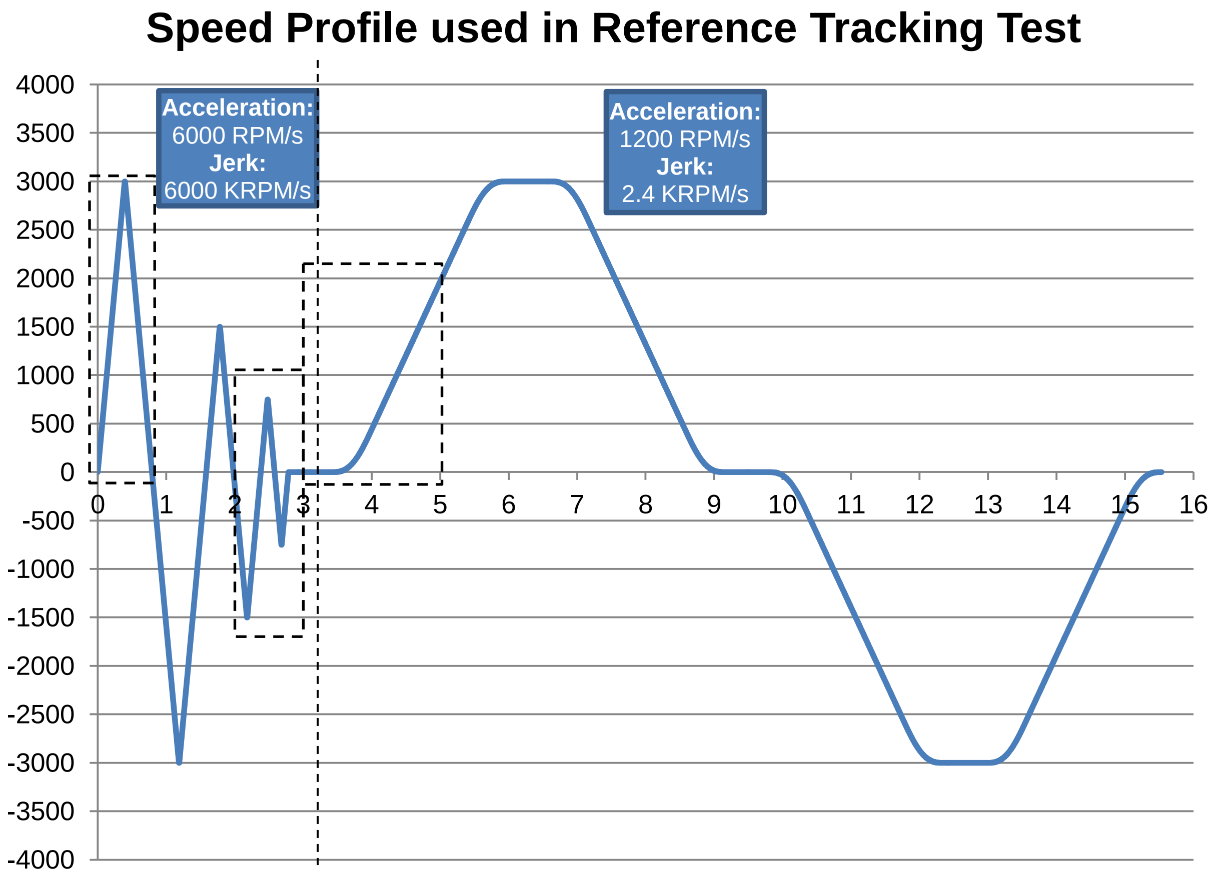


Figure 18. Speed Profile used During Reference Tracking Test

There are some differences between the SpinTAC and PI controller that should be called out and evaluated in addition to the absolute average error and maximum error of the profile tracking. Figure 19 shows how the PI controller greatly overshoots the speed reference when it makes a very drastic change. It then takes quite a bit of time to recover from that initial error, while the SpinTAC controller has no problems with the drastic reference change.

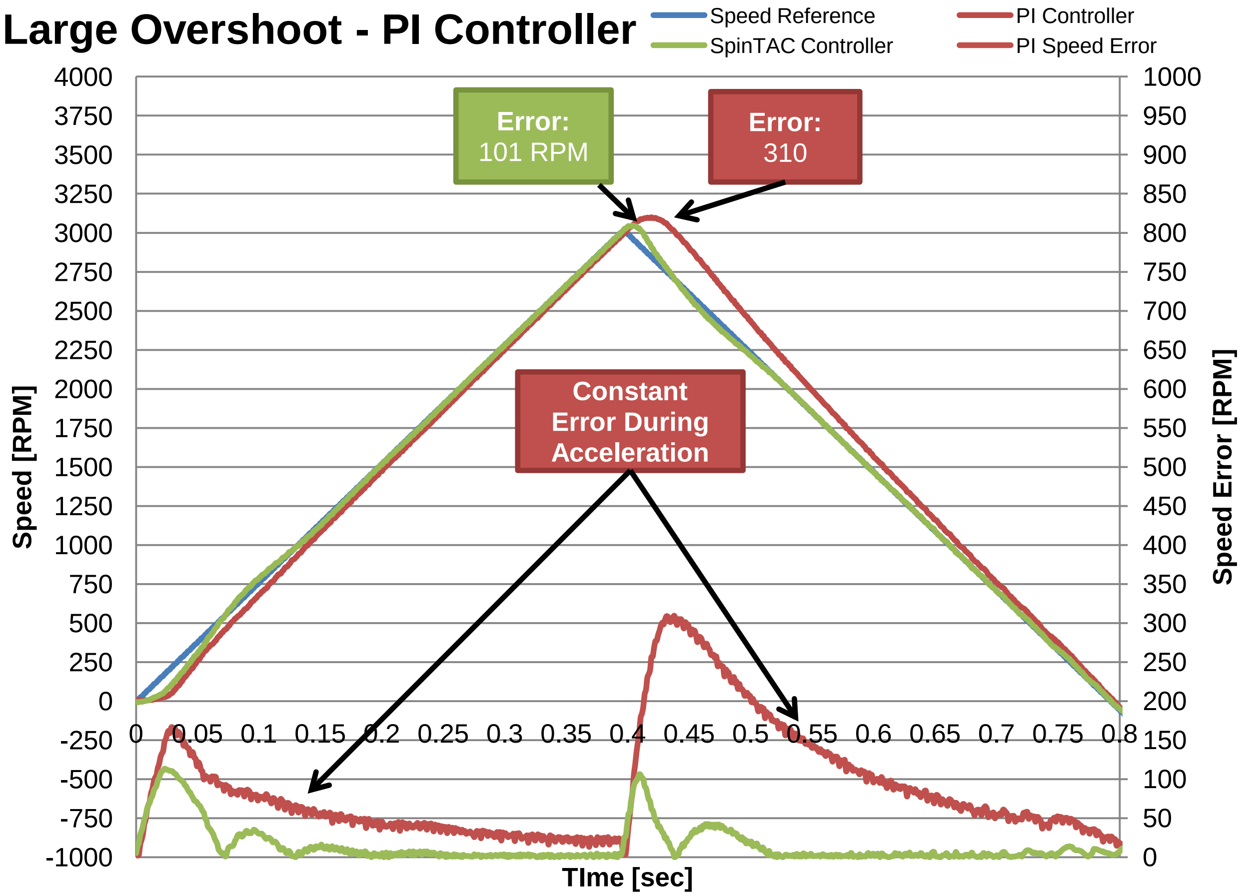


Figure 19. Large Overshoot for PI Controller during Reference Tracking

Figure 20 shows how the PI controller falls behind the reference as the drastic changes in the reference continue. The PI controller cannot keep up, while the SpinTAC controller has no difficultly in accurately tracking the speed reference.

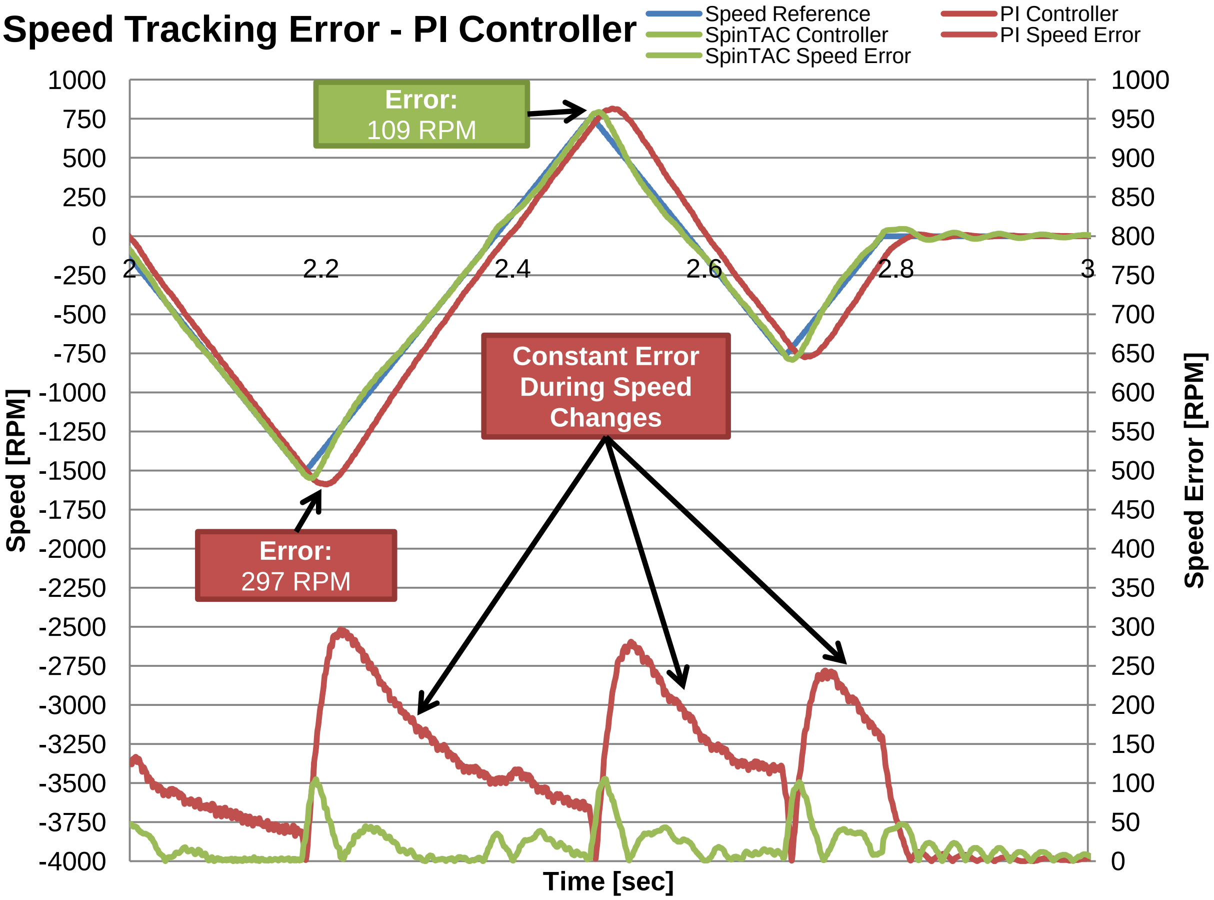


Figure 20. Speed Tracking Error for PI Controller during Reference Tracking

When starting from zero speed with a slow trajectory change, the PI controller has more difficulty than the SpinTAC controller. This is due to the SpinTAC controller's superior ability to track a changing reference signal. Figure 21 shows an example of this from the reference tracking test.

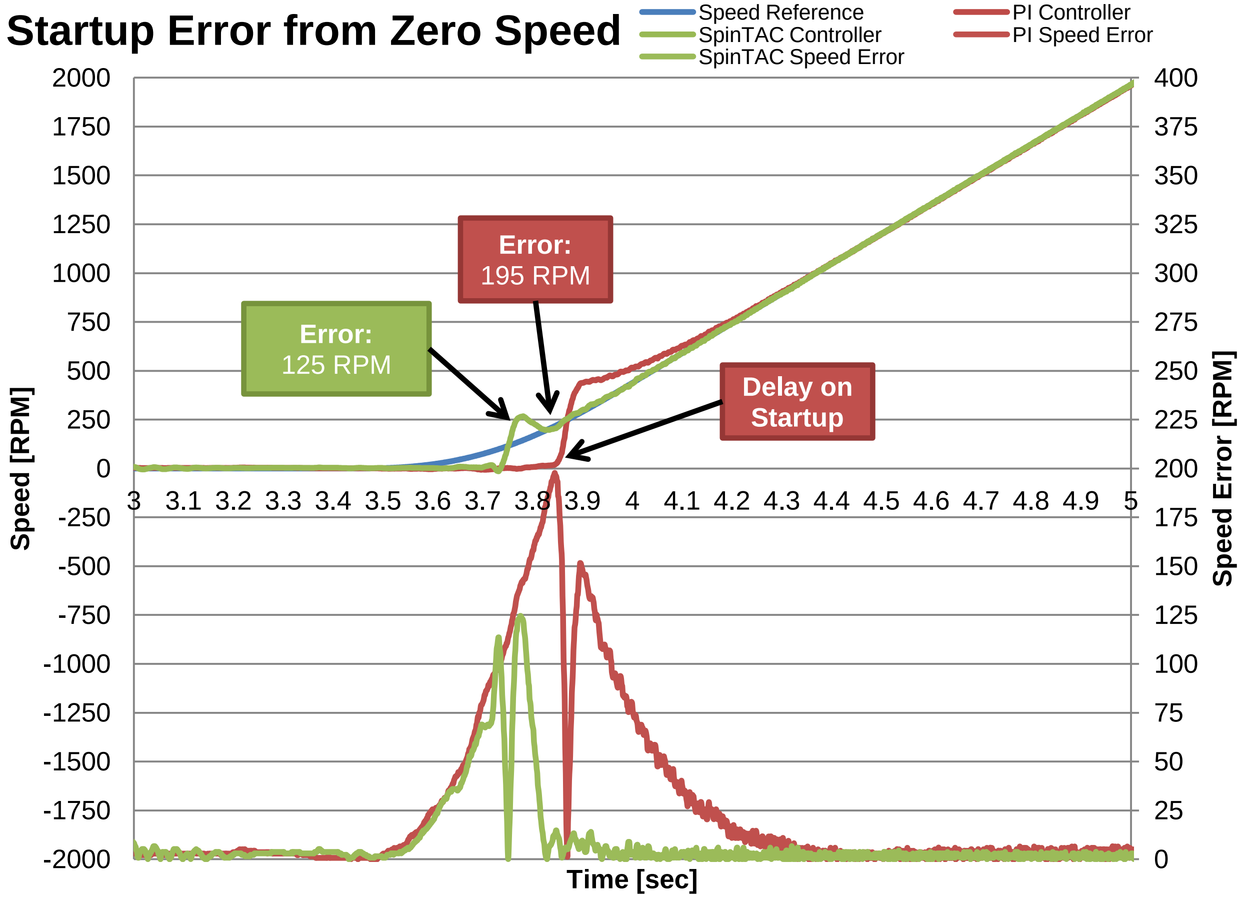


Figure 21. Startup Error from Zero Start for PI Controller

It is important to test multiple speeds and accelerations in your profile as well as multiple different loads. Speed controllers have different performance characteristics when placed into different situations. In order to properly evaluate the effectiveness of your speed controller, tests should be conducted across the entire application range. This includes when you design the profile for testing. Care needs to be taken to ensure that the application speeds and accelerations are built into the profile. The results of these tests will inform you if your controller will meet the application specifications or if your controller needs to be tuned multiple times for different operating points. You should notice in Figure 18 that there is a wide range of speeds and accelerations that are tested.

It is also important to be able to create repeatable profiles. Creating a repeatable profile can be done using SpinTAC™ Move and SpinTAC™ Plan (the InstaSPIN-FOC and InstaSPIN-MOTION User Guide provides detailed information on SpinTAC Move and SpinTAC Plan, as well as lab projects). Repeatable profiles are required so that all controllers will be tested using the same reference in the same order and for the same length of time. This ensures that test conditions are as identical as possible. The profile for this test was made using SpinTAC Move and SpinTAC Plan to ensure that an identical profile was presented to both the SpinTAC and PI controllers.

The following parameters were measured:

- Absolute Average Speed Error – positive or negative deviation from the goal speed over the entire speed profile
- Maximum Speed Error – maximum deviation from the goal speed during the speed profile

Table 5. SpinTAC vs. PI Profile Tracking Test Results

	Trapezoidal Curve			st-Curve		
	SpinTAC	PI	SpinTAC Advantage (percent improvement over PI)	SpinTAC	PI	SpinTAC Advantage (percent improvement over PI)
Teknic Motor						
Abs Avg Error (RPM)	6.01	19.94	69.86	5.98	19.51	69.35
Max Error (RPM)	266.06	430.00	38.13	263.00	334.71	21.42
Estun Motor						
Abs Avg Error (RPM)	5.39	16.11	66.54	5.73	16.124	64.46
Max Error (RPM)	248.29	312.74	20.61	181.64	307.61	40.95

8.1.3. Step Response

Step response tests how quickly a controller can respond to a sudden input change. The two metrics to evaluate during this testing are settling time and maximum overshoot. This test is also a measure of stability of your controller. If the controller oscillates upon reaching the goal speed than it is not very stable.

A step profile was applied to each controller. This step input bypassed the profile generator. The following parameters were measured:

- Settling Time (from the step input until within 2% of the target speed) – the settling time reflects how long it takes the controller to reach the goal speed and bring the speed of the motor within a narrow band around the goal speed.
- Maximum Overshoot - maximum speed the motor reaches after the step input

Figure 22 compares the step responses of the SpinTAC and PI controllers. It also gives a visual representation of how these metrics were calculated. The SpinTAC controller was able to reach the goal speed with zero overshoot and the minimal amount of settling time. It achieved the minimal amount of settling time because the controller did not allow the motor speed to exceed the goal speed.

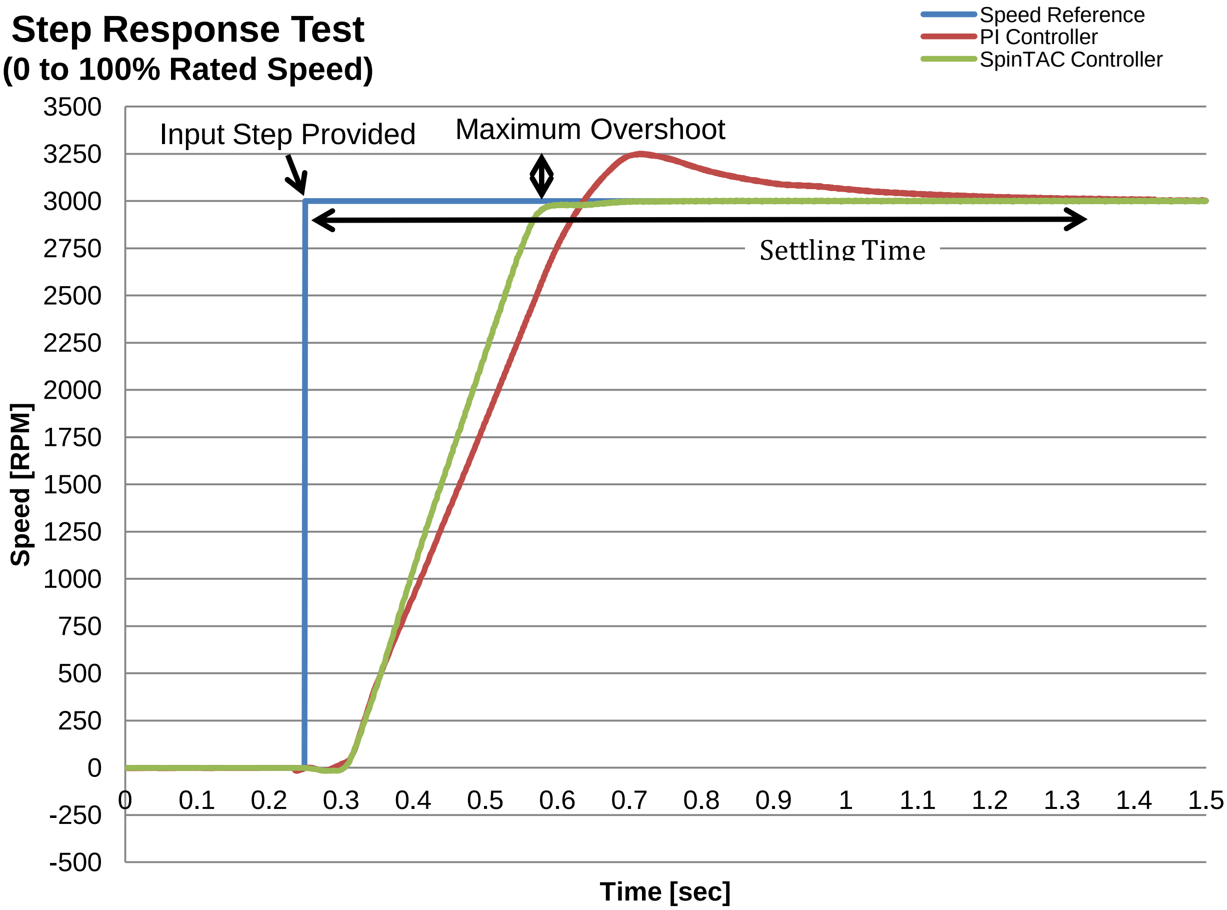


Figure 22. Step Response Test of Maximum Overshoot and Settling Time

Table 6. SpinTAC vs. PI Step Response Test Results (Teknic Motor)

	Settling Time (s)			Overshoot (RPM)		
	SpinTAC	PI	SpinTAC Advantage (percent improvement over PI)	SpinTAC	PI	SpinTAC Advantage (percent improvement over PI)
0-4000 RPM						
	2.67	3.45	22.66	73.00	140.40	48.01
	2.48	3.39	26.84	71.50	139.60	48.78
	2.52	3.51	28.21	70.10	138.20	49.28
	2.54	3.59	29.25	71.50	138.20	48.26
	2.64	3.39	22.12	70.10	139.60	49.79
0-2000 RPM						
	0.84	1.51	44.37	317.00	319.60	0.81
	0.90	1.42	36.62	325.00	320.30	-1.47
	0.86	1.42	39.44	332.00	320.30	-3.65
	0.93	1.45	35.86	390.00	320.30	-21.76
	0.92	1.42	35.21	325.00	319.60	-1.69
0-1000 RPM						
	0.65	1.28	49.38	239.00	316.20	24.41
	0.79	1.10	28.18	269.00	317.60	15.30
	0.57	1.27	55.12	195.00	319.10	38.89
	0.59	1.38	57.25	203.00	318.40	36.24
	0.59	1.18	50.00	24.16	318.40	38.76

Table 7. SpinTac vs. PI Step Response Test Results (Estun Motor)

	Settling Time (s)			Overshoot (RPM)		
	SpinTAC	PI	SpinTAC Advantage (percent improvement over PI)	SpinTAC	PI	SpinTAC Advantage (percent improvement over PI)
0-3000 RPM						
	0.44	1.16	61.81	2.90	250.50	98.84
	0.54	1.10	50.91	2.90	251.20	98.85
	0.38	1.32	71.21	2.90	252.70	98.85
	0.40	1.21	66.94	2.90	252.00	98.85
	0.42	1.41	70.21	2.90	252.70	98.85
0-1500 RPM						
	0.25	1.12	78.00	3.70	261.50	98.59
	0.37	1.30	71.54	19.00	262.20	92.75
	0.47	1.12	58.04	3.70	263.70	98.60
	0.42	1.10	61.82	3.70	263.70	98.60
	0.44	1.13	61.06	3.70	262.90	98.59
0-750 RPM						
	0.41	0.81	49.63	63.72	286.40	77.75
	0.32	0.61	47.54	76.17	179.44	57.55
	0.43	0.71	39.44	71.04	279.80	74.61
	0.32	0.62	48.39	13.91	292.20	95.24
	0.32	0.73	56.16	24.16	177.97	86.42

8.1.4. Inertia Estimation Repeatability

The system inertia is an important input into the SpinTAC speed controller. The inertia value is estimated using SpinTAC Velocity Identify. SpinTAC Velocity Identify is produces a very accurate inertia estimation. In order to test the repeatability of SpinTAC Velocity Identify, the inertia estimation process was ran 100 times for each motor. The results are collected in Figure 23 and Figure 24.

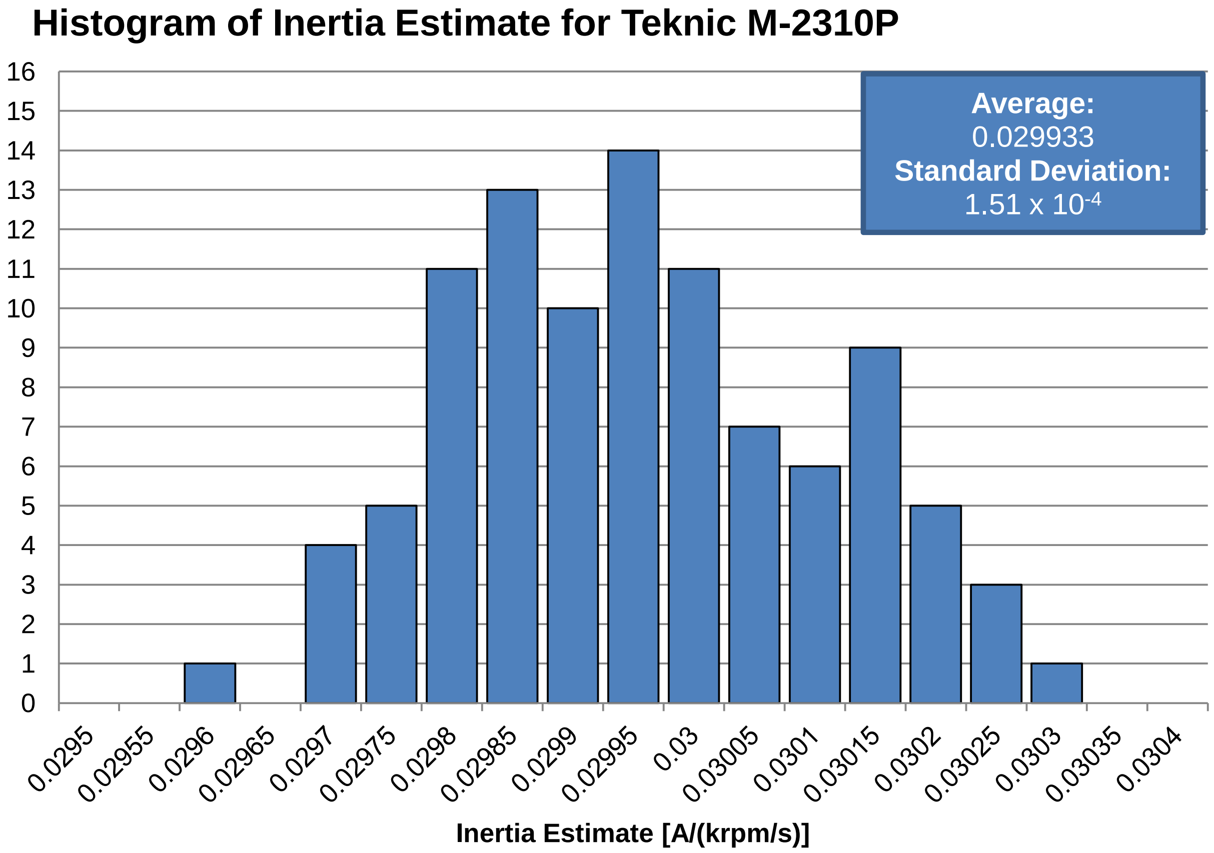


Figure 23. Inertia Estimation Results for Teknic M-2310P

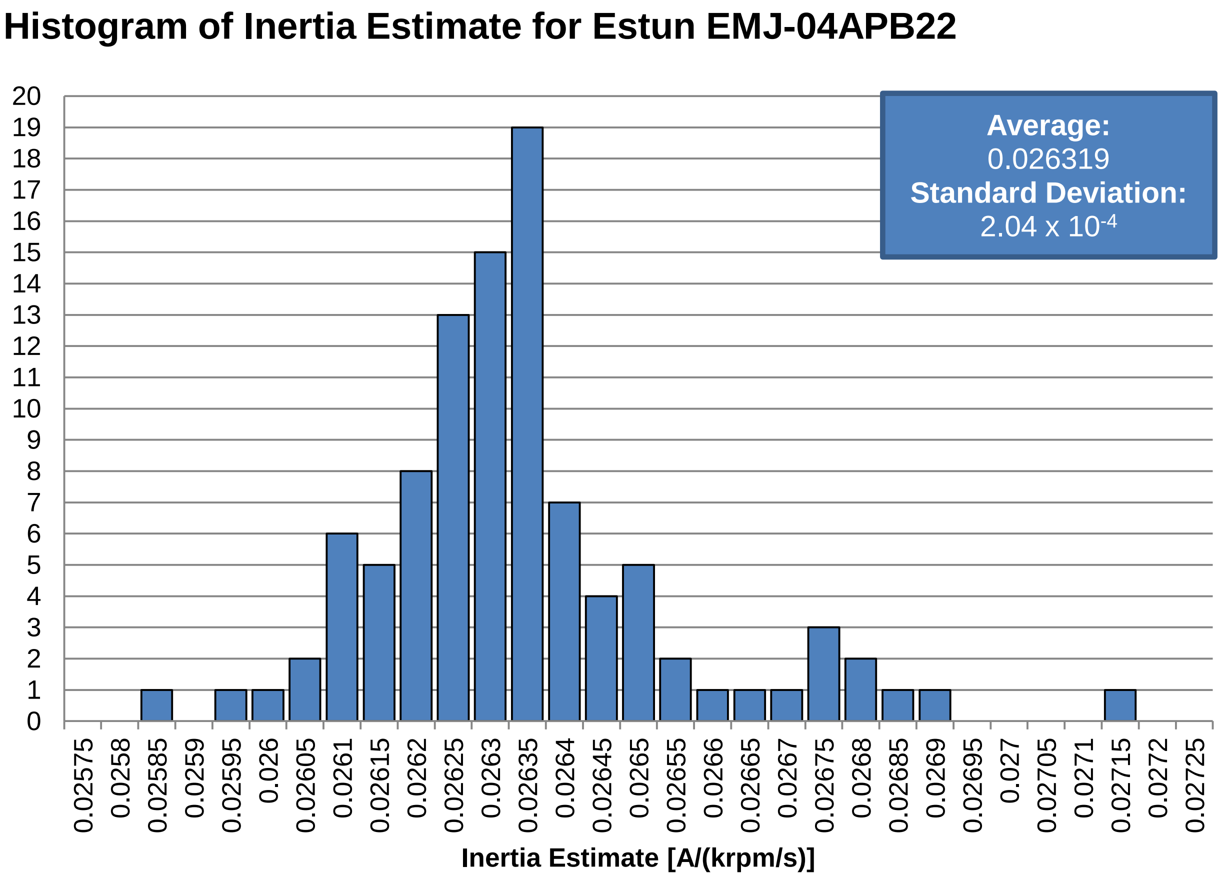


Figure 24. Inertia Estimation Results for Estun EMJ-04APB22

From the above results it is clear that SpinTAC Velocity Identify has a very high degree of repeatability. It is not required that the inertia estimation that is provided to the SpinTAC controller be the perfect inertia value. As a robustness feature, the SpinTAC speed controller can accept a wide range of inertia changes. However, the SpinTAC speed controller will always produce the best performance if the inertia value provided to it is accurate.

9. Microcontroller Resources

The TMS320F2806xM microcontroller resources required by the InstaSPIN libraries are discussed in detail in the InstaSPIN-FOC/MOTION User's Guide~~.~~

The following resources were measured to determine their consumption by the InstaSPIN-MOTION library:

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

9.1. CPU Utilization

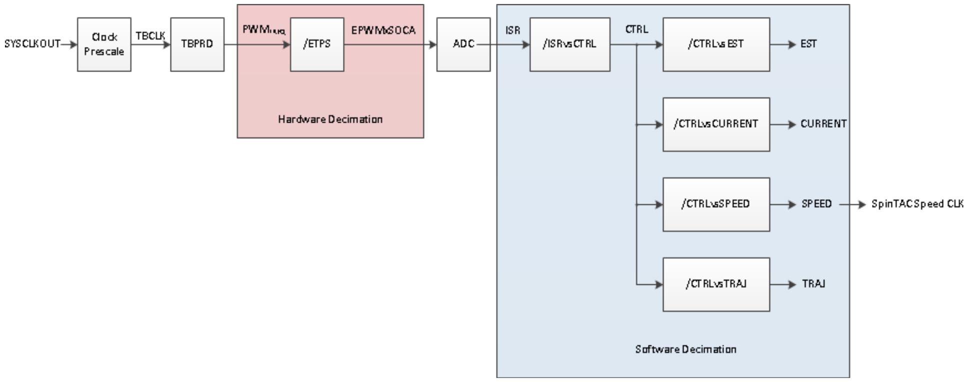


Table 8 indicates CPU cycle utilization of SpinTAC™ components running out of ROM on the 28069M and 28068M devices. Note that this data is for the SpinTAC components only, and does include InstaSPIN-FOC. Refer to the InstaSPIN-FOC Technical Reference Manual for InstaSPIN-FOC CPU utilization and memory footprint for.

The Speed Count is used to calculate the SpinTAC™ sample time. SpinTAC is called from main ISR but can be decimated using the same decimation rate used to run the Speed controller. The correct decimation rate can be calculated by multiplying the USER_NUM_ISR_TICKS_PER_CTRL_TICK by the USER_NUM_CTRL_TICKS_PER_SPEED_TICK.

Notes:

- Microcontrollers were run at 90MHz with the PWM at 20 kHz.
- In Table 8 and Table 9, RES=1 indicates that the component is in Reset
- In Table 8 and Table 9, ENB=1 indicates that the component is enabled
- In Table 8 and Table 9, the typical state appears in **bold**

Table 8. SpinTAC CPU Cycle Utilization with Library Executing in RAM

Function Name		CPU Cycles			Executed From		
		Min	Avg	Max	ROM	RAM	FLASH
STVELCTL_run (Velocity Control)					☐	☐	☐
	RES = 1, ENB =0	162	162	162			
	RES = 0, ENB = 1	**577**	**577**	**577**			
	First call after ENB = 1	1013	1013	1013			
		783	783	783			
	Change Inertia parameter	791	791	791			
	RES = 1, ENB = 1	166	166	166			
STVELMOVE_run (Velocity Move)					☐	☐	☐
	RES = 1, ENB = 0	206	206	206			
stcurve	**RES = 0, ENB = 1**	**709**	**733**	**753**			
	First call after ENB = 1	1321	1384	1446			
scurve	**RES = 0, ENB = 1**	**680**	**709**	**728**			
	First call after ENB = 1	1355	1387	1419			
trap	**RES = 0, ENB = 1**	551	597	606			
	First call after ENB = 1	1015	1047	1079			
	RES = 1, ENB = 1	195	195	195			
STVELPLAN_run (Velocity Plan)					☐	☐	☐
	RES = 1, ENB = 0	163	163	163			
	RES = 0, ENB = 1	**187**	**187**	**187**			
	First call after ENB = 1	324	324	324			
	STAY FSM State	187	187	187			
	Transition FSM State	360 (average) + Variable part based on configuration.					
	Condition FSM State	313 (average) + Variable part based on configuration.					
STVELPLAN_runTick (ISR function)		63	74	84			
STVELID_run (Velocity Identify)					☐	☐	☐
	RES = 1, ENB = 0	143	143	143			
	RES = 0, ENB = 1	**212**	**235**	**665**			
	First call after ENB = 1	931	931	931			
	RES = 1, ENB = 1	143	143	143			

Table 9. SpinTAC CPU Cycle Utilization with Library Executing in Flash

Function Name		CPU Cycles			Executed From		
		Min	Avg	Max	ROM	RAM	FLASH
STVELCTL_run (Velocity Control)					☐	☐	☐
	RES = 1, ENB =0	199	199	199			
	RES = 0, ENB = 1	**624**	**624**	**624**			
	First call after ENB = 1	1101	1101	1101			
	Change Bandwidth	853	853	853			
	Change Inertia parameter	862	862	862			
	RES = 1, ENB = 1	200	200	200			
STVELMOVE_run (Velocity Move)					☐	☐	☐
	RES = 1, ENB = 0	244	244	244			
stcurve	**RES = 0, ENB = 1**	**773**	**785**	**791**			
	First call after ENB = 1	1443	1515	1587			
scurve	**RES = 0, ENB = 1**	**736**	**764**	**784**			
	First call after ENB = 1	1468	1515	1562			
trap	**RES = 0, ENB = 1**	**608**	**656**	**665**			
	First call after ENB = 1	1139	1170	1201			
	RES = 1, ENB = 1	229	229	229			
STVELPLAN_run (Velocity Plan)					☐	☐	☐
	RES = 1, ENB = 0	196	196	196			
	RES = 0, ENB = 1	**228**	**228**	**228**			
	First call after ENB = 1	373	379	384			
	STAY FSM State	229	229	229			
	Transition FSM State	430 (average) + Variable part based on configuration.					
	Condition FSM State	361 (average) + Variable part based on configuration.					
STVELPLAN_runTick (ISR function)		110	119	127			
STVELID_run (Velocity Identify)					☐	☐	☐
	RES = 1, ENB = 0	175	175	175			
	RES = 0, ENB = 1	**255**	**280**	**734**			
	First call after ENB = 1	1068	1068	1068			
	RES = 1, ENB = 1	175	175	175			

9.2. Memory Utilization

Table 10 indicates memory utilization of the different parts of the SpinTAC™ implementation.

Table 10. Total Memory Usage of SpinTAC™ Components

Code Configurations		Memory Sizes (16bit Words)		
ROM Code	User Code	RAM	Flash	Total
ROM	RAM	0x145B	0x0000	**0x145B**
ROM	FLASH	0x01D9	0x1282	**0x145B**

Table 11 breaks down the code size and RAM usage of each of the SpinTAC™ components.

Table 11. Code Size and RAM Usage for SpinTAC™ Components

Component	Code (.text) (16 bit words)	RAM (.ebss) (16 bit words)
Velocity Control	0x2EF	0x74
Velocity Move	0x44E	0x84
Velocity Plan	0x7CD	0x4E
Velocity ID	0x348	0x5B

Table 12 breaks down the maximum stack utilization of SpinTAC™ components when run individually. The stack consumption of InstaSPIN-FOC™ is included. To calculate the stack usage, the entire memory section where the stack is placed is filled with known values. The corresponding code was then run for a couple minutes. The memory area where the stack was allocated was analyzed and the amount of used memory was calculated.

Table 12. Stack Utilization of SpinTAC™ Components + InstaSPIN-FOC™

Configuration (InstaSPIN-FOC is running in all cases)	Maximum Stack Used (16bit Words)
Velocity Control	0x120
Velocity Move	0x120
Velocity Plan + Move + Control	0x120
Velocity ID	0x120

For the 2806xF and 2806xM devices, InstaSPIN-FOC v1.6 and SpinTAC v2.2.1 is stored in address range of 0x3F8000 to 0x3FBFF and the last part of L8-RAM is reserved for InstaSPIN variables, address range 0x013800 to 0x013FFF. Figure 25 shows the memory locations that have been assigned for InstaSPIN-FOC and SpinTAC.

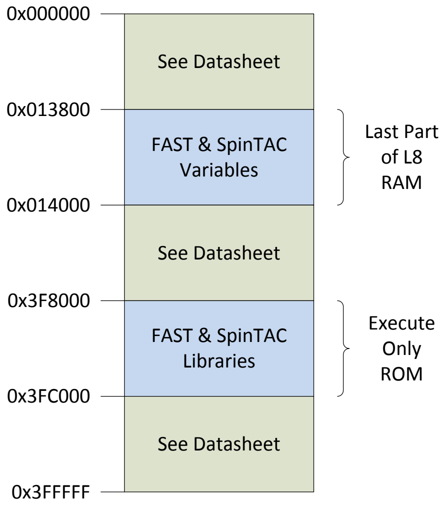


Figure 25. 2806xF & 2806xM Allocated Memory for InstaSPIN-FOC & SpinTAC Library

Appendix A Definition of Terms and Acronyms

- SpinTAC™ Motion Control Suite:
  - Includes and advanced speed controller, a motion engine, and a motion sequence planner. The SpinTAC™disturbance-rejecting speed controller proactively estimates and compensates for system disturbances in real-time, improving overall product performance. The SpinTAC™motion engine calculates the ideal reference signal (with feed forward) based on user-defined parameters. SpinTAC™ supports standard industry curves, and LineStream's proprietary "smooth trajectory" curve. The SpinTAC™motion sequence planner operates user-defined state transition maps, making it easy to design complex motion sequences.

- LineStream Technologies:
  - Pioneers in the world of embedded controls software. Boasting a team of motor control experts from six different countries cumulatively speaking fifteen languages and possessing over eighty years of industry experience, LineStream is fast becoming the world's preeminent stronghold of embedded motor control knowledge.

- Active Disturbance Rejection Control (ADRC):
  - Estimates and compensates for system disturbance, in real-time.

- InstaSPIN™-MOTION:
  - A comprehensive motor-, motion- and speed-control software solution that delivers robust system performance at the highest efficiency for motor applications that operate in various motion state transitions. InstaSPIN-MOTION builds on and includes InstaSPIN-FOC, combined with SpinTAC™ Motion Control Suite from LineStream Technologies

- 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.

- 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 **F**lux signal for stable flux monitoring and field weakening
    - Superior rotor flux **A**ngle estimation accuracy over wider speed range compared to traditional observer techniques independent of all rotor parameters for ACIM
    - Real-time low-noise motor shaft **S**peed signal
    - Accurate high bandwidth **T**orque signal for load monitoring and imbalance detection
- FOC: Field-Oriented Control
- SVM: Space-vector Modulation
- PowerWarp™
  - Mode of operation used for AC Induction Motors (ACIM) that allows minimum current consumption.
- Forced-Angle
  - Used for 100% torque at start-up until the FAST™ rotor flux angle tracker converges within 1st electrical cycle
- 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
- PI: Proportional-Integral regulator
- 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.
- ACIM: Alternating Current Induction Motor
- PMSM: Permanent Magnet Synchronous Motor
- IPM: Interior Permanent Magnet motor
- CCS: Code Composer Studio

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