

TI Designs: TIDA-01250

Smart Solenoid Driver With Predictive Maintenance Reference Design



Description

This reference design is a solenoid driver that implements additional monitoring control as well as diagnostic features. These features enable for example lose spring detection, valve aging recognition and dynamic control of solenoid current. This predictive maintenance feature-set helps to decrease or even eliminate factory downtime. Moreover the control of the solenoid current supports energy saving and increased valve lifetime. The integrated IO-Link interface provides the possibility of communication between the programmable logic controller (PLC) and actuator to leverage the predictive maintenance feature-set. The switching of the solenoid is realized using the PWM output of the microcontroller (MCU) to drive the current of a FET, which then supplies the solenoid switching current. The current signature is sampled with the on-chip 12-bit ADC and stored in the on-chip FRAM. This reference design implements a moving average calculation and a calculation of extreme values of the current signature curve.

Features

- Solenoid Driver:
 - Based on MSP430™ PWM Output
 - Configurable PWM Output for Different Drive Currents
- Current Signature Captured by Integrated 12-Bit ADC:
 - Current Signature Can be Stored in MSP430 FRAM
 - Single Processing Functions Implemented in Firmware:
 - Moving Average
 - Detection of Local Extreme Values
- Configuration Through UART or IO-Link

Applications

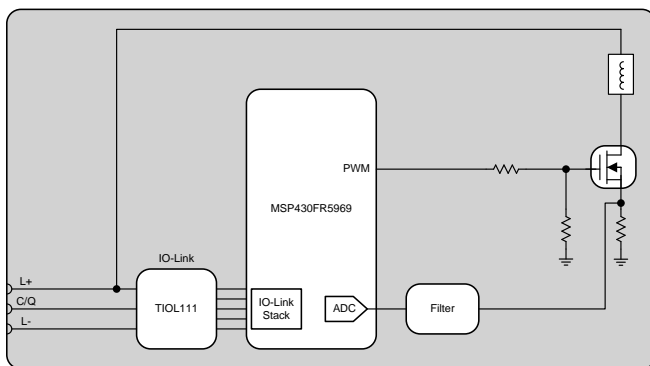
- [Factory Automation](#) and Control
- Solenoid Valve for Actuators

Resources

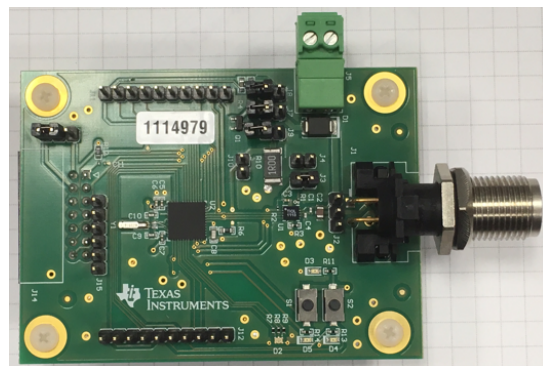
TIDA-01250	Design Folder
MSP430FR5969	Product Folder
TIOL111	Product Folder



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1 System Description

Within the factory automation and control segment of the industrial sector, solenoid drivers can be used for actuators in pneumatic as well as hydraulic valves. This reference design shows an exemplary implementation of a solenoid driver using an MCU to control an external FET that supplies the current for the solenoid. The MCU adds functionalities for predictive maintenance of the solenoid valve and its configuration.

By monitoring the proper functionality of solenoid valves and detecting changes in both the driving current and the switching speed, one can indicate upcoming failures and prevent breakdowns by scheduling the exchange of the affected parts. Predictive maintenance can offer certain advantages due to decreased down times.

The TIDA-01250 TI Design shows an exemplary implementation of a solenoid driver with predictive maintenance and covers three distinct features:

- Solenoid driver circuit
- Current signature caption
- Flexible configurability using IO-Link (or serial communication)

This TI Design enables the user to connect a solenoid valve and capture the according current signature. The firmware provides both raw and averaged data points as well as an exemplary implementation delivering characteristic current signature parameters. The data can be stored in the MCU's ferroelectric RAM (FRAM) or be sent to a host where more extensive and specific data processing can take place.

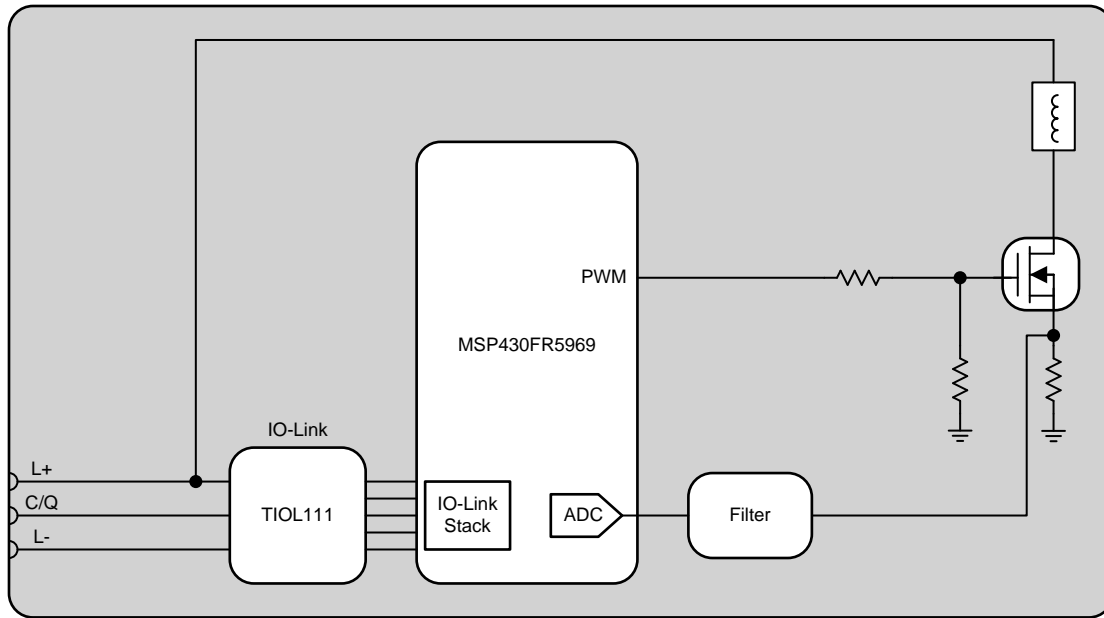
1.1 Key System Specifications

Table 1. Key System Specifications

PARAMETER	DESCRIPTION
POWER SUPPLY AND PROTECTION	
Operating supply voltage (L+ to L-)	7- to 36-V DC
LDO output voltage	3.3 V
LDO output current	20 mA
Reverse polarity protection	±55 V
Integrated protection	±8-kV IEC 61000-4-2 (ESD) Contact Discharge
	±2-kV IEC 61000-4-4 (EFT) Criterion A (5/50 ns)
	±1-kV/500-Ω IEC 61000-4-5 (Surge) (1.2/50 μs)
Fault indicator	Temperature
	Power
	Current
USER INTERFACE	
RGB LED	User definable LEDs through MSP430
Power LED (green)	Power indicator (3.3 V)
2x LED (green)	User definable LEDs through MSP430
2x buttons	User definable buttons through MSP430
CONNECTORS	
FET connector	Connectors J7, J8, and J9 to use external FET
LaunchPad™ connectors	Possibility to extend feature set through LaunchPad and BoosterPack™ ecosystem
Programming connector	JTAG programming connector for MSP430
UART connector	UART to USB connection
SYSTEM FEATURES (FIRMWARE IMPLEMENTATION)	
Baud rate	9600 baud; user definable through MSP430
Signal conditioning	User definable through MSP430
Sampling frequency	7.8125 kHz; user definable through MSP430

2 System Overview

2.1 Block Diagram



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Figure 1. TIDA-01250 Block Diagram

2.2 Highlighted Products

The following subsections detail each circuit block in the TIDA-01250 block diagram in further detail. The TIOL111 has been chosen as the newest Texas Instruments transceiver device enabling IO-Link communication. The MSP430FR5969 on the other hand has been chosen for both its integrated 12-bit ADC and the FRAM memory, enabling fast write-read cycles and data logging. Furthermore it can host the required IO-Link stack. For more information on each of these devices, see their respective product folders at www.TI.com.

NOTE: Depending on the application needs, a different MSP430 device can be used to run the application. There is a variety of smaller memory or higher integration/ performance level MSP430 devices fitting the application needs.

2.2.1 TIOL111

The robust TIOL111 family of transceivers implements the IO-Link interface for industrial point-to-point communication. When a device is connected to an IO-Link master through a three-wire interface, the master can initiate communication and exchange data with the remote node while the TIOL111 acts as a complete physical layer for the communication.

These devices are capable of withstanding up to 1 kV (500 Ω) of IEC61000-4-5 surge and feature integrated reverse polarity protection.

A simple pin-programmable interface allows easy interfacing to the controller circuits. The output current limit can be configured using an external resistor.

Fault reporting and internal protection functions are provided for undervoltage, short-circuit current, and overtemperature.

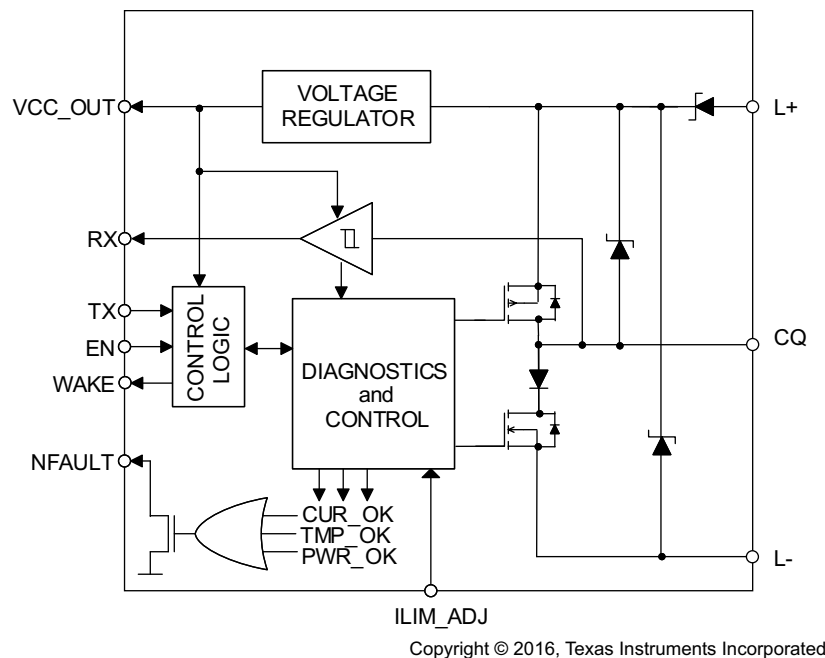
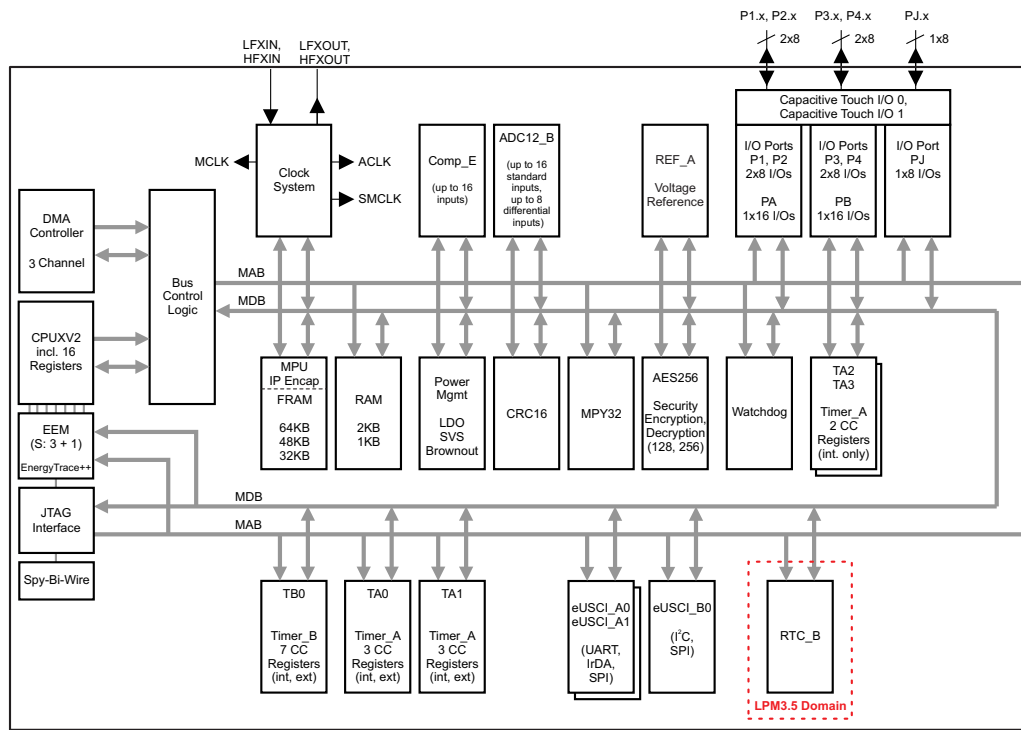


Figure 2. TIOL111 Block Diagram

2.2.2 MSP430FR5969

The Texas Instruments MSP430 family of ultra-low-power MCUs consists of several devices that feature different combinations of peripherals targeted for various applications. Combined with extensive low-power modes, the architecture is optimized to achieve extended battery life in portable measurement applications. The MSP430 MCU features a powerful 16-bit RISC CPU, 16-bit registers, and constant generators that contribute to maximum code efficiency. The digitally controlled oscillator (DCO) allows the MCU to wake up from low-power modes to active mode typically in less than 10 μ s.



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Figure 3. MSP430FR5969 Block Diagram

Key features of this device include:

- Embedded microcontroller:
 - 16-bit RISC architecture up to 16-MHz clock
 - Wide supply voltage range (1.8 to 3.6 V)
- Optimized ultra-low-power modes:
 - Active mode: Approximately 100 μ A/MHz
 - Standby (LPM3 With VLO): 0.4 μ A (typical)
 - Real-time clock (RTC; LPM3.5): 0.25 μ A (typical)
 - Shutdown (LPM4.5): 0.02 μ A (typical)
- Ultra-low-power FRAM:
 - Up to 64KB of nonvolatile memory
 - Ultra-low-power writes
 - Fast Write at 125 ns per word (64KB in 4 ms)
 - Unified memory = Program + Data + Storage in one single space
 - 1015 write cycle endurance
 - Radiation resistant and nonmagnetic

- Intelligent digital peripherals:
 - 32-bit hardware multiplier (MPY)
 - Three-channel internal DMA
 - RTC with calendar and alarm functions
 - Five 16-bit timers with up to seven capture/compare registers each
 - 16-bit cyclic redundancy checker (CRC)
- High-performance analog:
 - 16-channel analog comparator
 - 12-bit analog-to-digital converter (ADC) with internal reference and sample-and-hold and up to 16 external input channels
- Multifunction input/output ports:
 - All pins support capacitive touch capability with no need for external components
 - Accessible bit-, byte-, and word-wise (in pairs)
 - Edge-selectable wake from LPM on all ports
 - Programmable pullup and pulldown on all ports
- Code security and encryption:
 - 128-bit or 256-bit AES security encryption and decryption coprocessor
 - Random number seed for random number generation algorithms
- Enhanced serial communication:
 - eUSCI_A0 and eUSCI_A1 support:
 - UART with automatic baud-rate detection
 - IrDA encode and decode
 - SPI at rates up to 10 Mbps
 - eUSCI_B0 supports:
 - I²C with multiple slave addressing
 - SPI at rates up to 8 Mbps
 - Hardware UART and I²C Bootstrap Loader (BSL)
- Flexible clock system:
 - Fixed-frequency DCO with 10 selectable factory-trimmed frequencies
 - Low-power low-frequency internal clock source (VLO)
 - 32-kHz crystals (LFXT)
 - High-frequency crystals (HFXT)

For complete module descriptions, see the [MSP430FR59xx family user's guide](#) (SLAU367).

2.3 System Design Theory

Valves, relays, and contactors all use electromechanical solenoids for their operation. Solenoid coils are rated to operate from 12-V to 24-V DC and 110-V to 230-V AC systems with a different power consumption ratings. Solenoid coils need more current only during actuation; in steady state, the coils need approximately 30% of their nominal current. Solenoid coils operating with nominal current consistently raise the temperature in the coil due to higher power dissipation. This reference design provides a solution to control the solenoid current as well as monitor the proper operation of the plunger in valves using pulse width modulation-based (PWM) controllers along with a Back-EMF recognition.

2.3.1 Characteristics of Solenoid Coils

Electromechanical solenoids consist of an electromagnetically inductive coil wound around a movable steel or iron slug called the armature (or plunger). The coil is shaped such that the armature can be moved in and out of its center, altering the inductances of the coil as well as becoming an electromagnet. The armature provides a mechanical force to activate the control mechanism, for example opening and closing a valve.

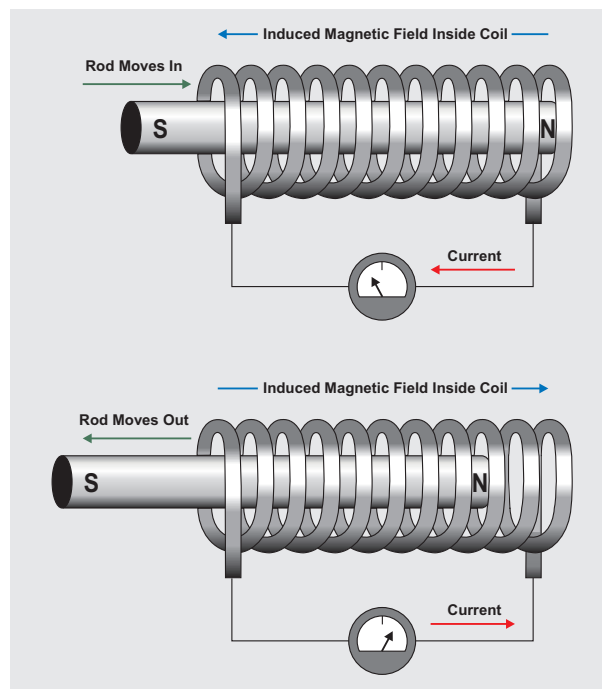


Figure 4. Working of a Solenoid

A main electrical characteristic of a solenoid is that of an inductor that opposes any change in current. This characteristic is why current does not immediately reach a maximum level when a solenoid is energized. Instead, the current rises at a steady rate until it is limited by the DC resistance of the solenoid. An inductor (in this case, a solenoid) stores energy in the form of a concentrated magnetic field. Whenever current is present in a wire or conductor, a magnetic field, however small, is created around the wire. With the wire wound into a coil, such as in a solenoid, the magnetic field becomes very concentrated. This electromagnet can control a mechanical valve through an electrical signal. As soon as the solenoid is energized, the current increases, causing the magnetic field to expand until it becomes strong enough to move the armature. The armature movement increases the concentration of the magnetic field as the armature's own magnetic mass moves farther into the magnetic field. Note that a magnetic field changing in the same direction of the current creating it induces an opposing voltage into the windings. Because the magnetic field quickly expands when the armature strokes, the field causes a brief reduction in the current through the solenoid windings. After the armature strokes, the current continues on its normal upward path to its maximum level.

A typical current waveform is shown in [Figure 5](#). Notice the prominent dip in the rising portion of the current waveform. There is more information that can be derived from the current signature. This signature requires detailed information of the solenoid itself, such as the current delta and the time delta between the first peak and the following dip. Because the armature of a solenoid is pushed back by a spring, information like a broken or aged spring can be derived.

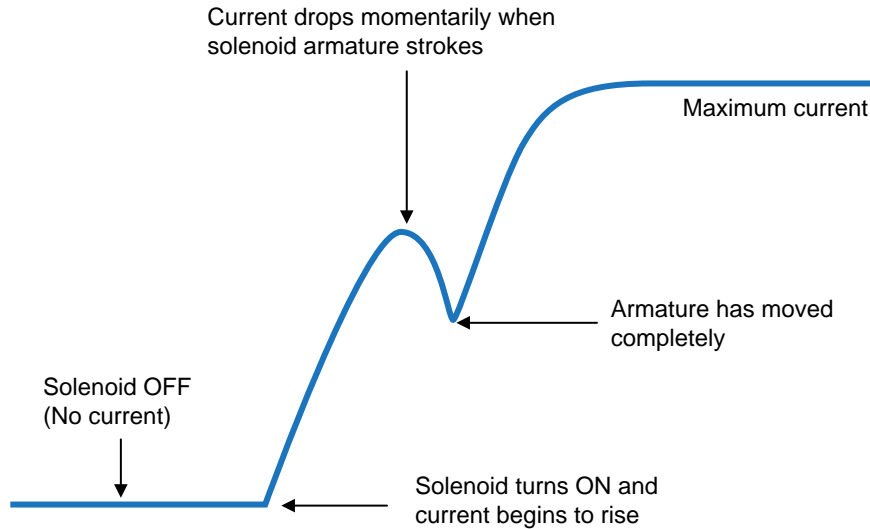


Figure 5. Typical Solenoid Current During Switch-on Phase

This TI Design captures with an ADC the voltage across a sense resistor to distinguish the current signature of the solenoid. The firmware is able to detect the first peak, indicating the stroke of the armature as well as the dip, which provides the information of a fully moved plunger. This information as well as the delta in time and current can be sent together with the entire captured ADC data set to the PLC system. Therefore, a bidirectional interface like IO-Link has been used in this TI Design.

2.3.2 Hardware Description

2.3.2.1 Overview Building Blocks

[Figure 6](#) shows the different building blocks of the TI Design. All components are located on the top layer of the PCB for easy evaluation.

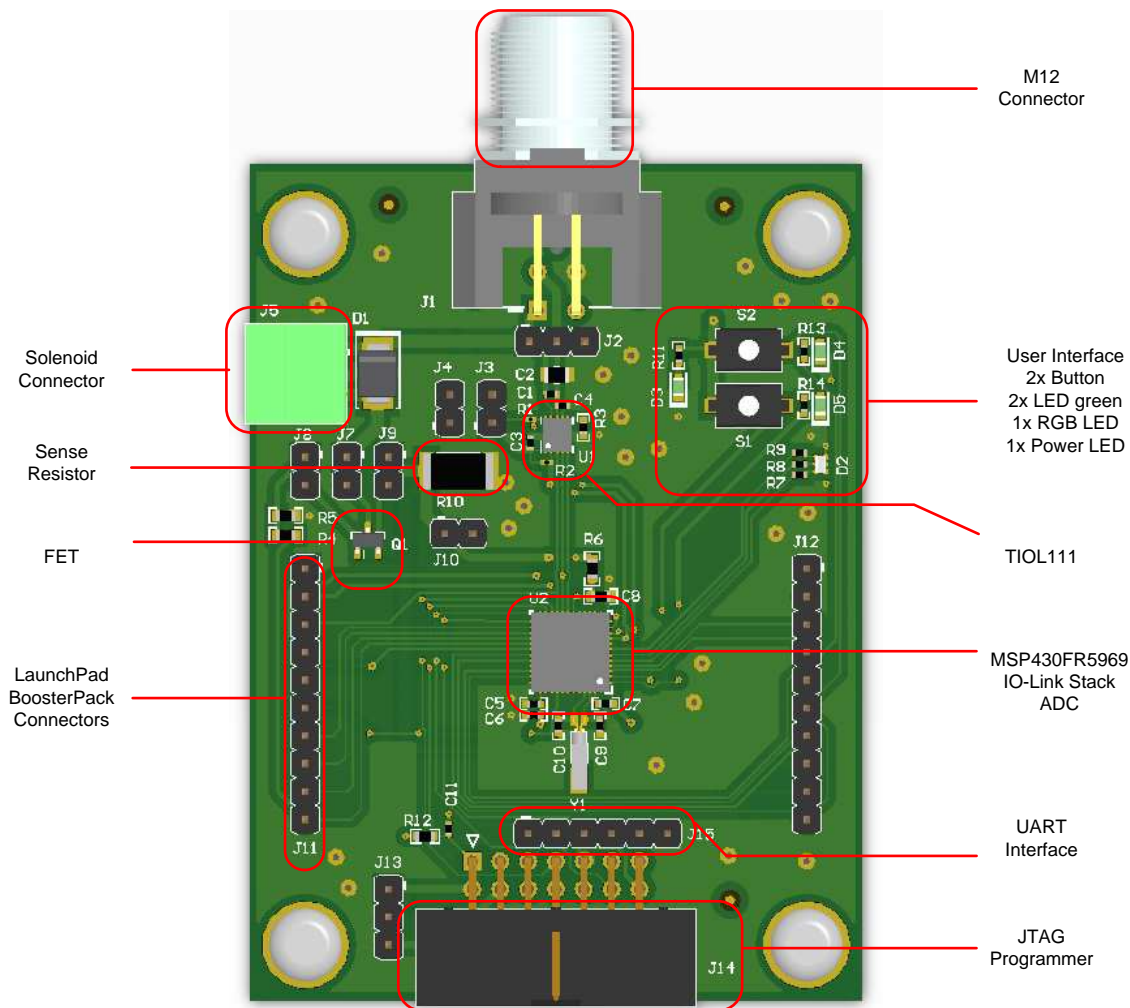


Figure 6. TIDA-01250 Board Description

- M12 connector: The board uses an industry standard M12 connector. L+, L-, and C/Q signals are available at this M12 connector J1 (see [Figure 7](#)).
- User interface: The board indicates with a green LED the availability of the 3.3 V of the integrated LDO of the TIOL111. In addition, the user has the flexibility to use two push-buttons, two green LEDs, and one RGB LED. All can be controlled by the MSP430 MCU (see [Figure 10](#)).
- TIOL111: This device is the IO-Link PHY with an integrated LDO, reverse polarity protection, and IEC 61000-4-x protection. The device also contains a fault indicator, which monitors the devices temperature, current, and power (see [Figure 7](#)).
- MSP430FR5969: The MCU controls with a PWM signal the FET, which results in a certain current for the solenoid. The MSP430 also includes the ADC that captures the voltage across the sense resistor (see [Figure 11](#)).
- UART interface: The system has the possibility to be controlled through the UART interface (J15) from a PC. The captured ADC data plus the calculation are provided through the UART interface (see [Figure 10](#)).
- JTAG programmer: This is the connector (J14) for the MSP-FET430UIF programmer.
- LaunchPad and BoosterPack connectors: These connectors (J11 and J12) enable the user to extend the TI Design with features provided by the BoosterPack ecosystem. For more information, see the [LaunchPad page](#).
- FET: The FET switches on and off the solenoid and is controlled by the MSP430 MCU. For higher power solenoids, an external FET can be connected as well (see [Figure 8](#)).

- Sense resistor: The ADC of the MSP430 measures the voltage across the sense resistor R10. By changing the value of R10 (default: R10 = 1 Ω), the ADC input full-scale can be adjusted. The resistor has to withstand the solenoid current and the resulting power consumption (see Figure 8).
- Solenoid connector: Connector J5 is used to connect an external solenoid. Verify the solenoid maximum current consumption with the capabilities of the FET and sense resistor (see Figure 8).

2.3.2.2 Power Supply

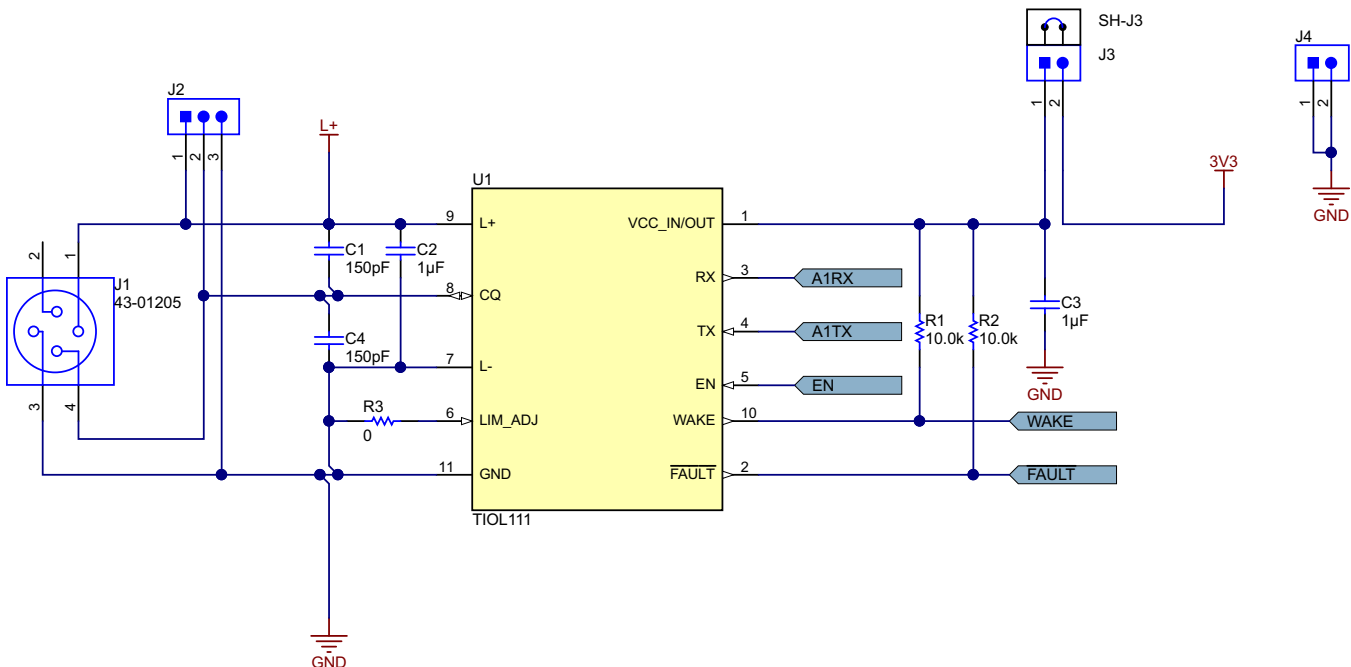
The entire system is powered with nominal 24-V DC through J1 or J2. The minimum input voltage is either given by the minimum input voltage of TIOL111 (7 V) or the specification of the connected solenoid. The maximum input voltage is 36 V (TIOL111). The integrated LDO inside the TIOL111 generates 3.3 V for the remaining system with a capable output current of 20 mA. Also available is a TIOL111 with a 5-V LDO available.[3]. It is also possible to directly provide an external 3.3 V to the system. In this case, remove SH-J3 from J3 and provide 3.3V to J3-PIN2 and GND to J4 (see Figure 7).

Without having a solenoid connected, the reference design has the power consumption shown in Table 2. The LED D3 indicating the availability of the 3.3-V is always active. In Table 2, the consumption is calculated based on Equation 1:

$$I_{LED, D3} = \frac{V_{CC} - V_f}{R_{11}} = \frac{3.3\text{ V} - 2\text{ V}}{68.1\ \Omega} = 19.09\text{ mA} \tag{1}$$

Table 2. Current and Power Consumption

VOLTAGE SUPPLY (3.3 V)	CURRENT CONSUMPTION (mA)	CURRENT CONSUMPTION WITHOUT D3 (mA)	POWER CONSUMPTION (mW)	POWER CONSUMPTION WITHOUT D3 (mW)
TIOL111 + MSP430 (+D3)	23	3.91	75.9	12.9
MSP430 (+D3)	20	0.91	66.0	3.0



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Figure 7. Input Circuitry—M12 Connector and IO-Link PHY

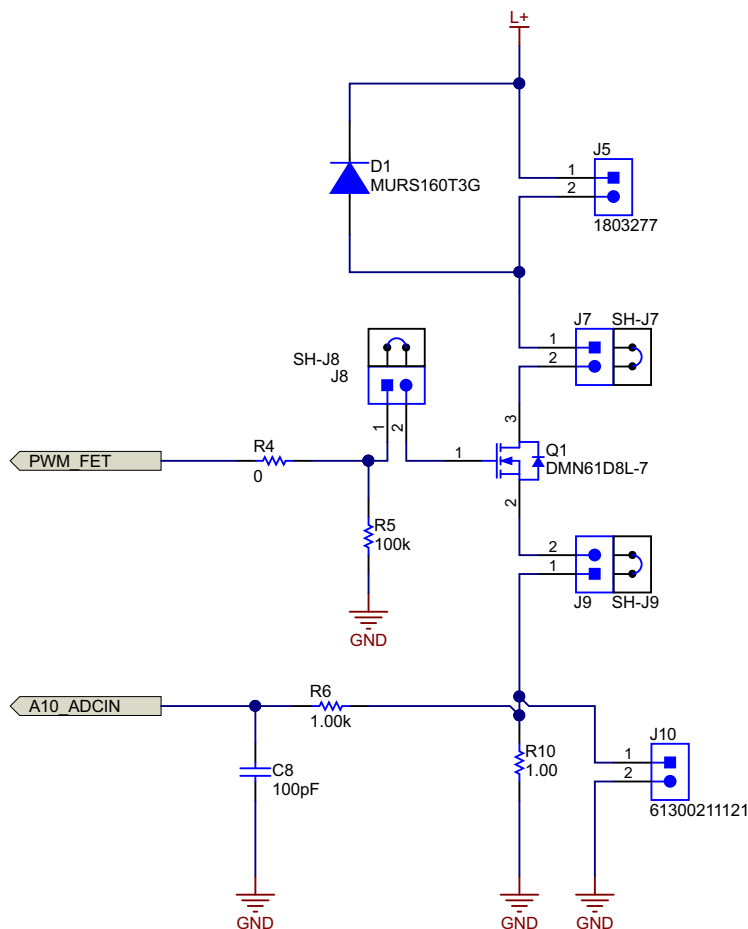
2.3.2.3 Interface

The system communicates through the IO-Link interface. All protection, like reverse polarity, ESD, and surge, is integrated in the TIOL111 IO-Link PHY. With this interface, the user can send the command to switch on or off the solenoid. In addition, solenoid specific parameters can be sent from the host (IO-Link master) to the system. The measured solenoid current signature and calculated parameter can also be sent back to the host system. This information can be used for diagnostic purposes and enables the user to exchange certain building blocks of the actuator or the entire system before it fails and prevents a costly system shutdown.

Another possibility to communicate with this TI Design is the UART interface, which is beneficial for evaluating and debugging the solenoid control mechanism.

2.3.2.4 Solenoid and FET

The solenoid can be connected to the TI Design at connector J5 (see Figure 8). The FET switches on and off the solenoid. See the datasheet for the maximum current capabilities of the FET. At room temperature, the FET is able to handle a continuous drain current in the SOT-23 package of 470 mA. To drive a higher power solenoid, bypass the onboard FET by removing jumpers SH-J7, SH-J8 and SH-J9 and connect an external FET to J7-Pin1 (DRAIN), J8-Pin1 (GATE) and J9-PIN1 (SOURCE). Therefore, remove the jumpers SH-J7, SH-J8 and SH-J9. An external FET can be connected to J7-Pin1 (DRAIN), J8-Pin1 (GATE) and J9-PIN1 (SOURCE). Note the gate voltage provided by the MSP430 is limited to the supply voltage of the MSP430. In this TI Design, this supply voltage is 3.3 V.



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Figure 8. Front-End Circuitry—FET, Sense Resistor, Solenoid Connector

2.3.2.5 Programming

With the connector J14, the MSP-FET430UIF can be connected to program the MSP430 MCU (see Figure 9).

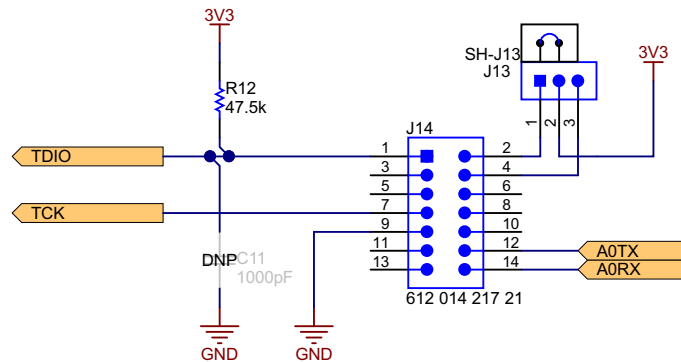
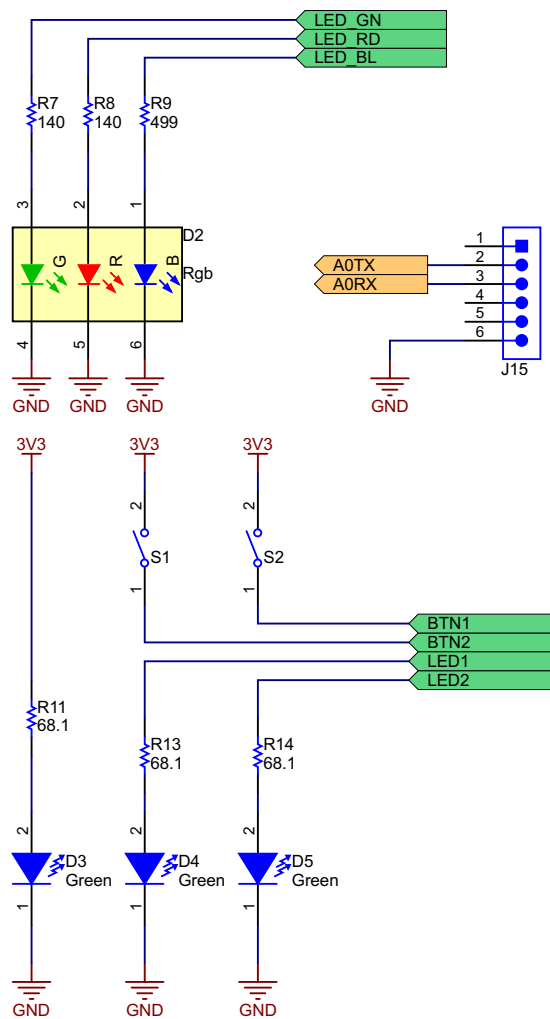
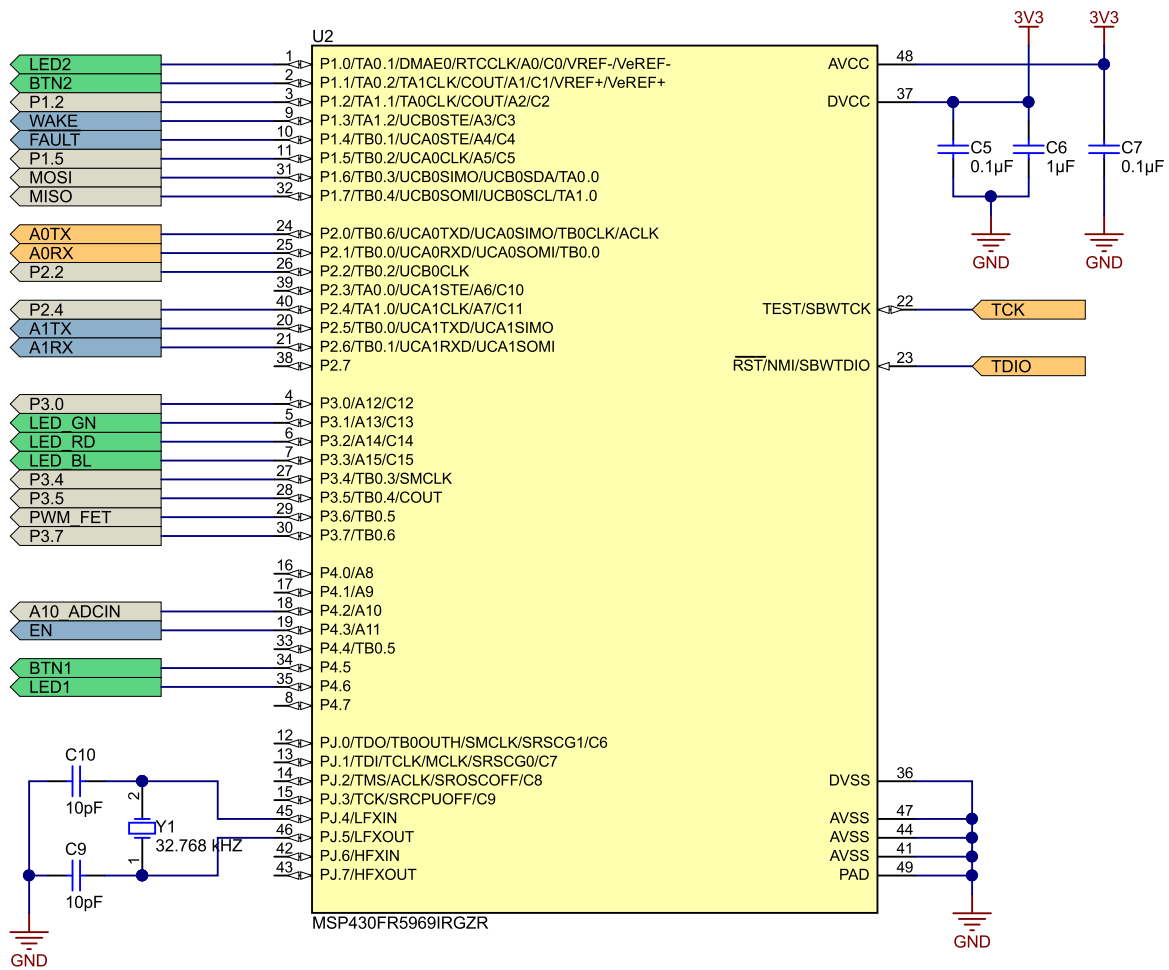


Figure 9. Interface for MSP-FET430UIF Programmer



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Figure 10. User Interface—Indicator LEDs and Push-Buttons



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Figure 11. Digital Processing—MSP430 Including ADC Measuring Solenoid Current

Table 3. Overview Connectors and Jumpers

CONNECTOR	DESCRIPTION
J1: M12 CONNECTOR	
J1-PIN1	24-V DC; L+
J1-PIN2	NC
J1-PIN3	GND; L-
J1-PIN4	C/Q
J2: HEADER	
J2-PIN1	24-V DC; L+
J2-PIN2	C/Q
J2-PIN3	GND; L-
J4: HEADER	
J4-PIN1	GND
J4-PIN2	GND
J5: HEADER	
J5-PIN1	Solenoid: L+ (24-V DC)
J5-PIN2	Solenoid L- (GND)
J10: HEADER	
J10-PIN1	External sense resistor
J10-PIN2	External sense resistor (GND)
J11 and J12: HEADER	
J11	LaunchPad connector (details in schematic)
J12	LaunchPad connector (details in schematic)
J14: PROGRAMMING CONNECTOR	
J14	Connector for MSP-FET430UIF
J15: HEADER	
J15-PIN2	UART: TX
J15-PIN3	UART: RX
J15-PIN6	GND
JUMPER	
J3	Current measurement for 3.3 V Provide external 3.3 V
J7	External FET: DRAIN
J8	External FET: GATE
J9	External FET: SOURCE
J13	INT/EXT supply from programmer

2.3.3 Firmware Implementation

The TIDA-01250 TI Design includes firmware running on the MSP430FR5969. The firmware implements the solenoid driver control and data acquisition using the on-chip 12-bit ADC as well as serial communication through UART. Note that software for an IO-Link stack has been developed by TE Concept, which can be obtained following the link in [Section 5](#).

The firmware used in this design guide does not use the IO-Link Stack; the user can still adapt the firmware to support IO-Link communication and use the IO-Link PHY onboard after obtaining the stack from TE Concept.

[Figure 12](#) shows the used MCU blocks as a general overview of the firmware implementation.

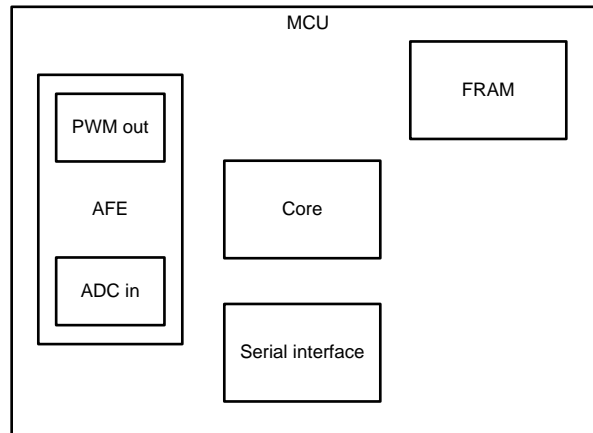


Figure 12. Block Diagram of Used MCU Blocks

The firmware implements three main functionalities:

- PWM generation for the hold current of the solenoid
- Data acquisition through the 12-bit ADC and data pre-processing
- Configuration and data transfer through UART (IO-Link ready with adaptations)

The software example is kept simple and can be adapted to the specific application by the user. During start-up, the hardware modules like the clock system, the 12-bit ADC, and the serial communication module are initialized. The timers are configured to generate the PWM and to control the required sampling frequency. After this, the CPU enters low power mode 0 (LPM0) until an interrupt is generated by button S2. This interrupt will wake up the CPU, which then initiates the output of the peak current to switch on the solenoid and starts the analog-to-digital (A/D) conversion. After a short period of time during which the solenoid switched, the PWM output is started to provide the hold current. A second button press of the same button S2 then triggers the PWM output to stop and end further data sampling. After that, the CPU calculates a moving average over 8 samples and sends the averaged data to the host. Then, the CPU returns to LPM0.

UART communication is currently configured to a speed of 9600 baud, 8 data bits, 1 stop bit, and no parity. When receiving the acquired data, note that due to a 12-bit A/D conversion result, 2 bytes are needed for the current representation so that 2 bytes are sent per A/D conversion. After every conversion result, the representation of carriage return and line feed are sent for better visualization at the host processor.

The overall firmware flow is shown in [Figure 13](#).

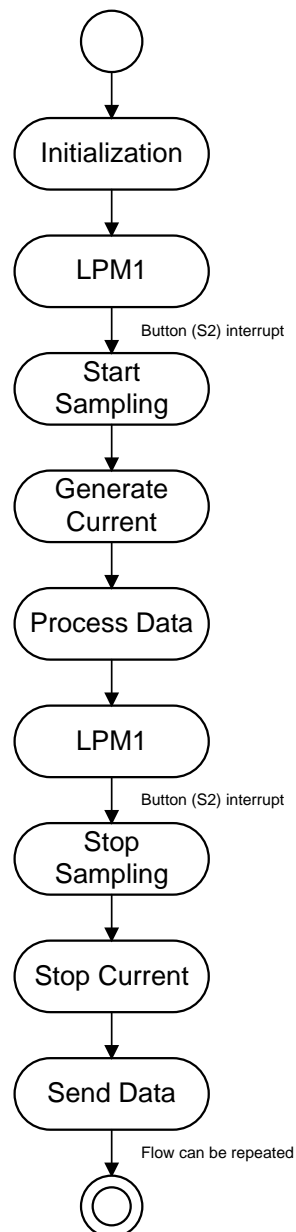


Figure 13. Simplified Firmware Flow Diagram

The default setting of the hold current PWM is 100%, equaling the peak current. With each new solenoid switching after pushing the button S2 for "ON", the duty cycle is decreased by 10%. When reaching a 10% duty cycle, the next "ON" time PWM output will automatically be set to 100% duty cycle again. Button S1 can be pressed to reset the duty cycle to 100%. This implementation allows the user to test how low the hold current can be set to still hold the solenoid in the switched position while saving maximum energy.

The user has the option to control the current amplitude and the number of samples taken by using UART commands. In order to simplify the firmware a number of commands has been established. The commands are shown in [Table 4](#) and [Table 5](#):

Table 4. "On" Commands

BYTE 1 = ON	BYTE 2 = PWM DUTY CYCLE	BYTE 3 = NUMBER OF A/D CONVERSIONS
0x11	0x10 (10%)	0x10 (100 samples)
	0x20 (20%)	0x25 (250 samples)
	0x30 (30%)	0x50 (500 samples)
	0x40 (40%)	—
	0x50 (50%)	—
	0x60 (60%)	—
	0x70 (70%)	—
	0x80 (80%)	—
	0x90 (90%)	—
	0x01 (100%)	—

Table 5. "Off" Commands

BYTE 1 = OFF	BYTE 2 = DATA	BYTE 3 = DON'T CARE
0x22	0x11 (raw data)	—
	0x22 (averaged data)	—
	0x33 (min. / max. data)	—
	0x44 (all data)	—

The first byte of the protocol distinguishes between the on and off commands. The following 2 bytes then represent the action to be executed by the MCU.

For further energy saving, the user can choose a lower power mode. This mode affects the clocks that remain active and might require further firmware changes. Moreover, any adaptations needed can be included into the firmware by the user. The current firmware implementation is designed as proof of concept and not as a factory-ready solution.

To download the software files for this reference design, see [Section 5](#).

3 Hardware, Firmware, Testing Requirements, and Test Results

3.1 Required Hardware and Firmware

3.1.1 Hardware

For a basic test setup, see [Section 3.2.1](#).

3.1.2 Firmware

The firmware packaged with this TI Design is intended to showcase a smart solenoid driver application. The firmware is not optimized for every kind of solenoid and is not adequate for production. However, the user can adapt the firmware to fit the desired application.

This firmware was developed and tested in Code Composer Studio™ (CCS). CCS is an integrated development environment (IDE) for Texas Instruments' (TI) embedded processor families. CCS comprises a suite of tools used to develop and debug embedded applications. It includes compilers for each of TI's device families, source code editor, project build environment, debugger, profiler, simulator, real-time operating system, and many other features. The intuitive IDE provides a single user interface that goes through each step of the application development flow.

The firmware can easily be adapted, debugged, and programmed to the MSP430FR5969 using the CCS IDE. Following the hardware design guidelines of the TIDA-01250 design, no additional devices are required to get started with the firmware.

3.2 Testing and Results

3.2.1 Test Setup

To test the TIDA-01250 design, use the setup shown in [Figure 14](#), which requires the following equipment:

- Power supply: 24-V DC
- PC with CCS and a terminal program
- Oscilloscope with two channels
- Solenoid
 - SMC: 24-V DC, 3 W (VDW22LA)
 - ASCO: 24-V DC, 6.9 W (SCG256B004VMS)
- TIDA-01250 board

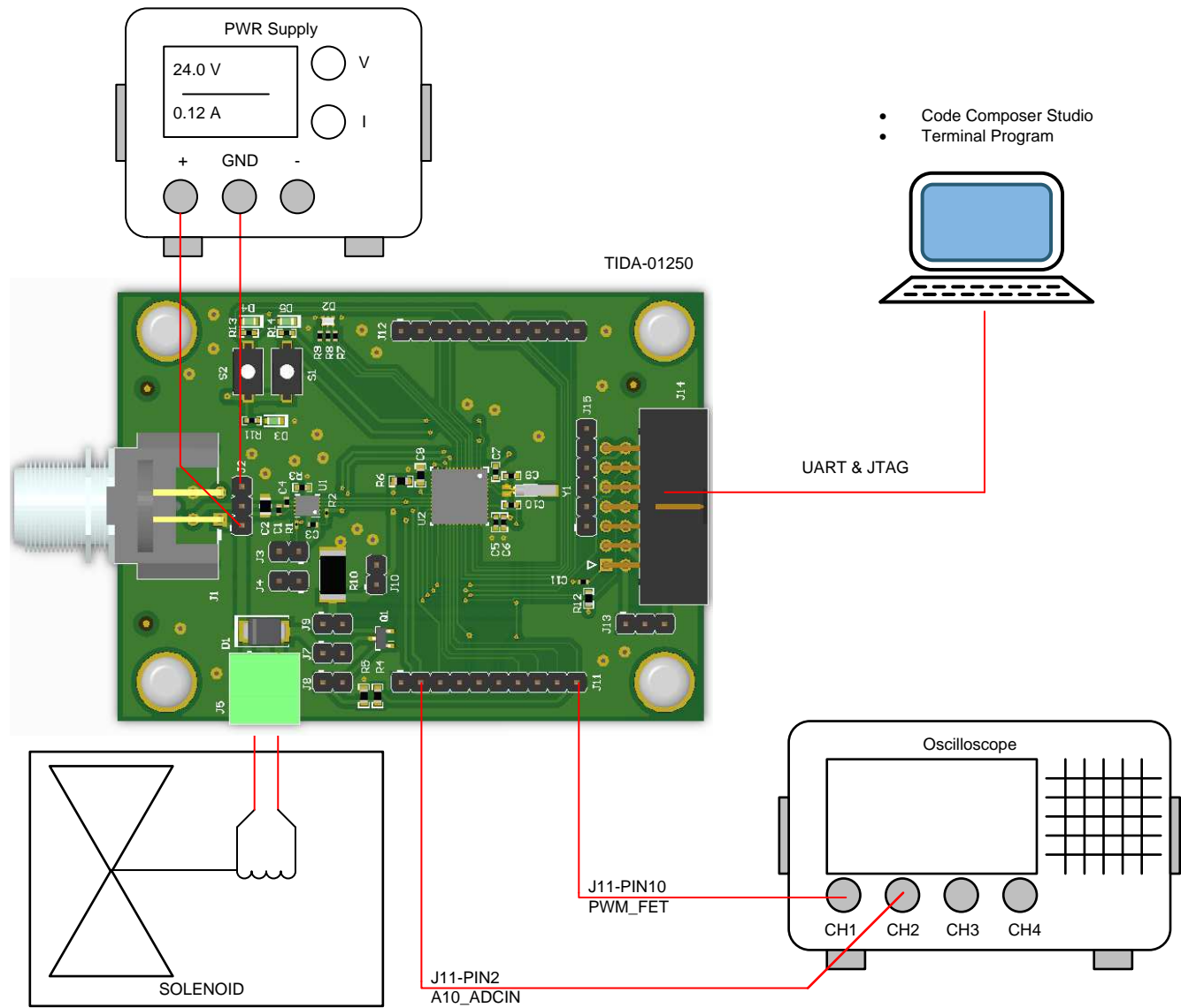


Figure 14. TIDA-01250 Test Setup

Table 6. Connections for Test Setup

CONNECTOR	DESCRIPTION	CONNECTED TO
J2-PIN1	L+ (24 V)	Power supply 24 V
J2-PIN3	L- (GND)	Power supply GND
J14	UART and JTAG	PC through MSP-FET tool
J11-PIN2	ADC input	Scope CH2
J11-PIN10	PWM output	Scope CH1
J5	Load	Solenoid

To prepare for the tests, the firmware is programmed to the MSP430FR5969 and then started. Afterwards, the board is connected to a terminal program running on the PC to receive the acquired data. By pressing the buttons S1 and S2, the firmware is controlled to switch the solenoid and to acquire and send the A/D conversion results. See [Section 3.2.2](#) for the obtained test results.

3.2.2 Test Results

The following sections [Section 3.2.2.1](#) and [Section 3.2.2.2](#) show test results of two different solenoids:

1. SMC
 - Model: VDW22LA
 - Supply voltage: 24-V DC
 - Power consumption: 3 W
 - Results in a solenoid current: 125 mA
2. ASCO
 - Model: SCG256B004VMS
 - Supply voltage: 24-V DC
 - Power consumption: 6.9 W
 - Results in a solenoid current: 287.5 mA

When the system is set up according to [Section 3.2.1](#), pressing push-button S2 switches on the solenoid. At the same time, the ADC within the MSP430 captures 400 data points. The oscilloscope triggers and does a single shot of the switch-on phase of the solenoid and the PWM signal from the MSP430 that controls the FET.

During the switch-on phase, the duty cycle is set to 100%, and after 30 ms, the firmware starts with the preset duty cycle. The following plots show the results for three different settings of the duty cycle: 100%, 60%, and 30%.

By having the duty cycle set to 100%, there is obviously no savings in power consumption.

3.2.2.1 Solenoid 1—SMC

Table 7. Current and Power Consumption for Different Duty Cycle

DUTY CYCLE	CURRENT CONSUMPTION (mA)	POWER CONSUMPTION at 24-V DC (W)
100%	124	2.98
90%	122	2.93
80%	107	2.57
70%	88	2.11
60%	73	1.75
50%	58	1.39
40%	44	1.06
30%	30	0.72

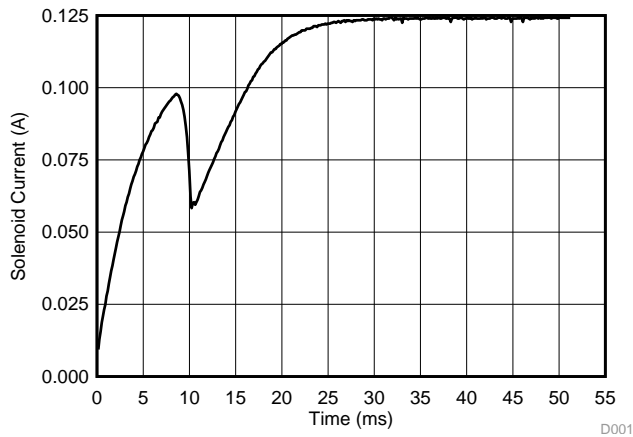


Figure 15. ADC Capture; Duty Cycle: 100%

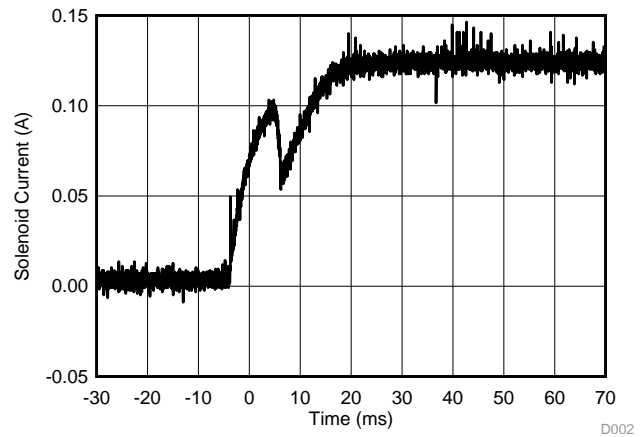


Figure 16. Scope Plot; Duty Cycle: 100%

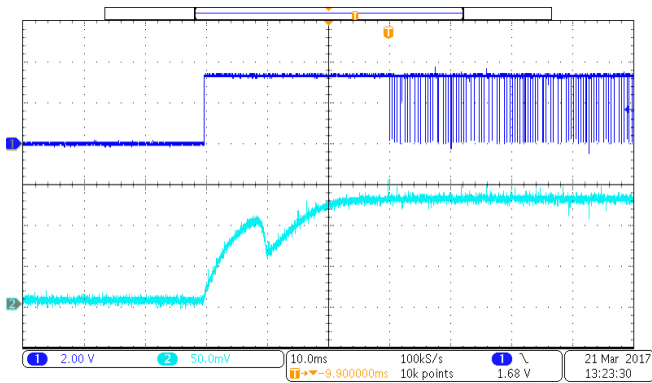


Figure 17. Scope Plot of Solenoid Current and PWM Signal; Duty Cycle: 100%

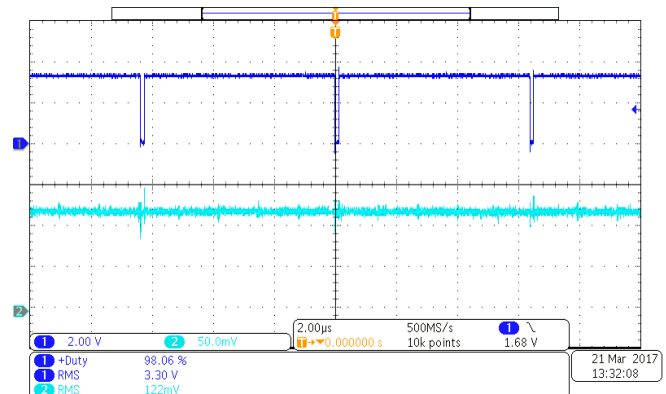


Figure 18. Zoomed-in Scope Plot of Solenoid Current and PWM Signal; Duty Cycle: 100%

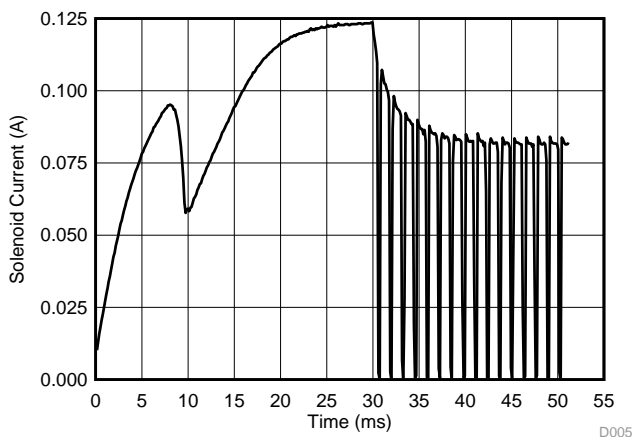


Figure 19. ADC Capture; Duty Cycle: 60%

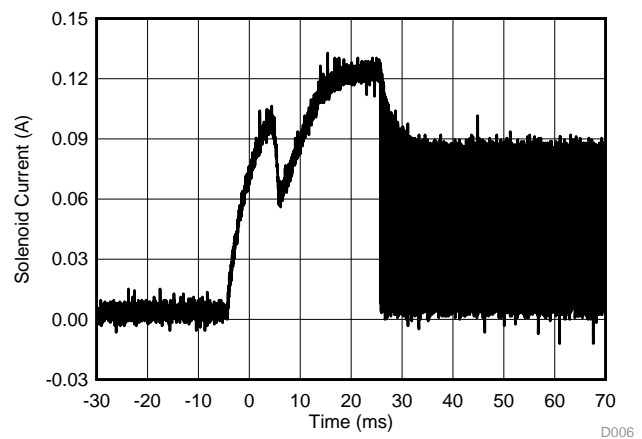


Figure 20. Scope Plot; Duty Cycle: 60%

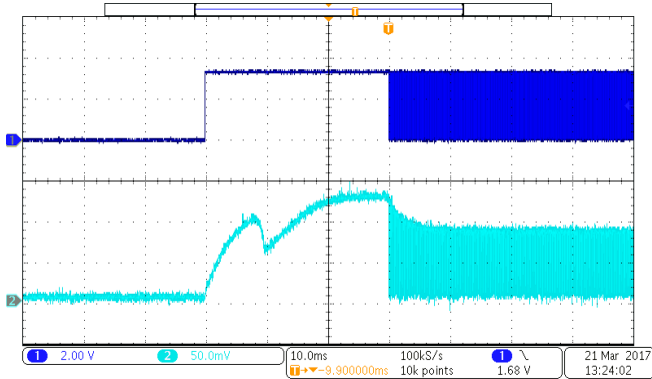


Figure 21. Scope Plot of Solenoid Current and PWM Signal; Duty Cycle: 60%

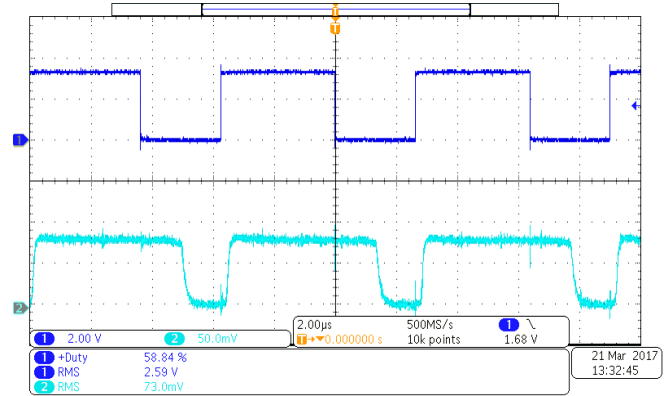


Figure 22. Zoomed-in Scope Plot of Solenoid Current and PWM Signal; Duty Cycle: 60%

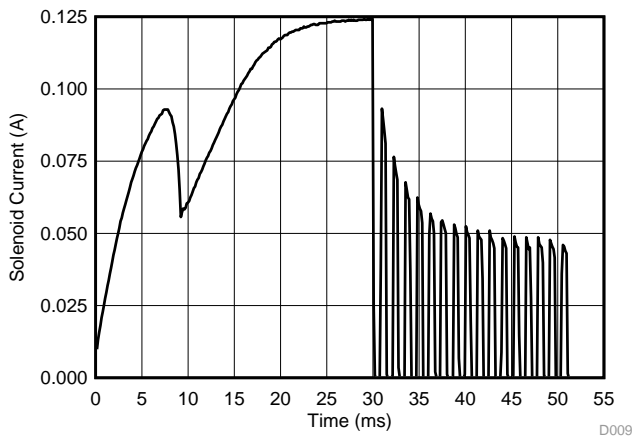


Figure 23. ADC Capture; Duty Cycle: 30%

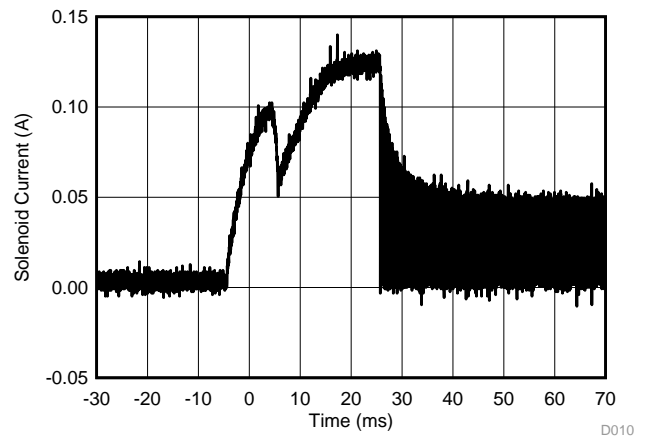


Figure 24. Scope Plot; Duty Cycle: 30%

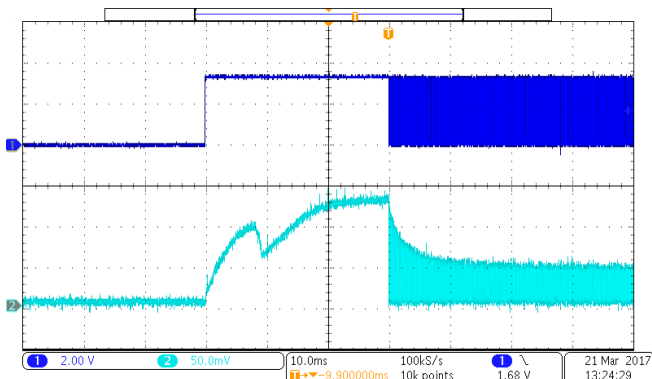


Figure 25. Scope Plot of Solenoid Current and PWM Signal; Duty Cycle: 30%

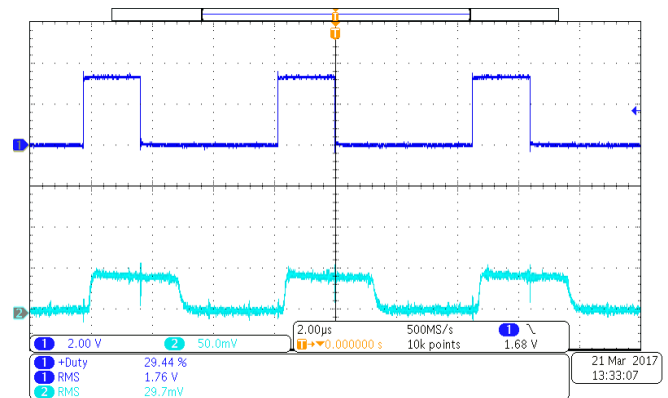


Figure 26. Zoomed-in Scope Plot of Solenoid Current and PWM Signal; Duty Cycle: 30%

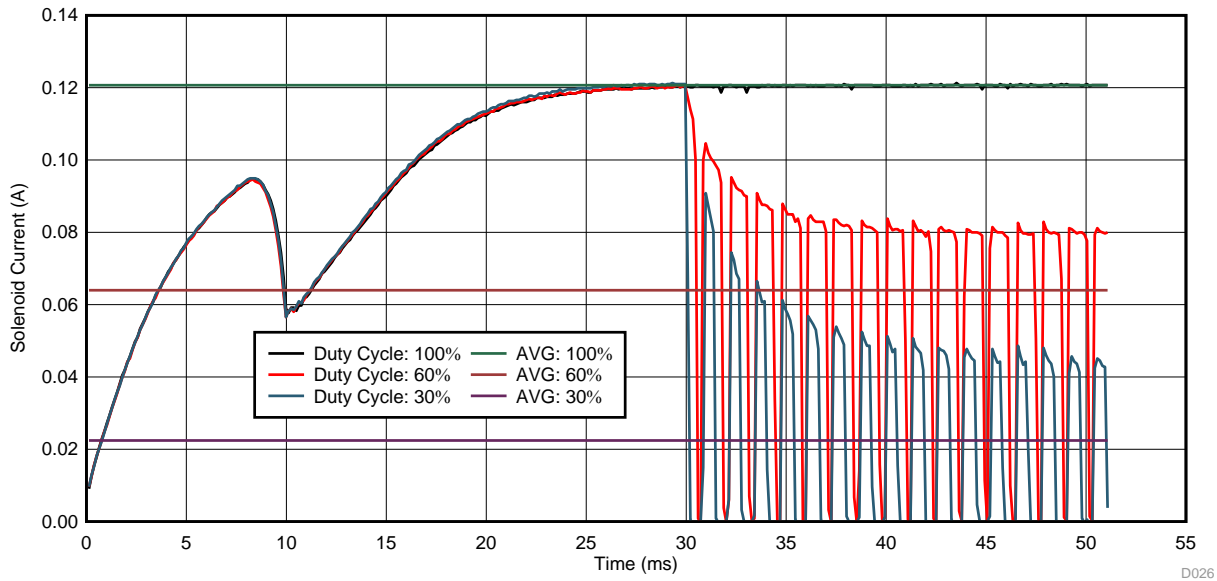


Figure 27. ADC Capture—Comparison of Duty Cycle: 100%, 60%, 30% With Average Current

3.2.2.2 Solenoid 2—ASCO

Table 8. Current and Power Consumption for Different Duty Cycle

DUTY CYCLE	CURRENT CONSUMPTION (mA)	POWER CONSUMPTION at 24-V DC (W)
100%	270	6.48
90%	261	6.26
80%	215	5.16
70%	177	4.25
60%	146	3.50
50%	115	2.76
40%	86	2.06
30%	57	1.37

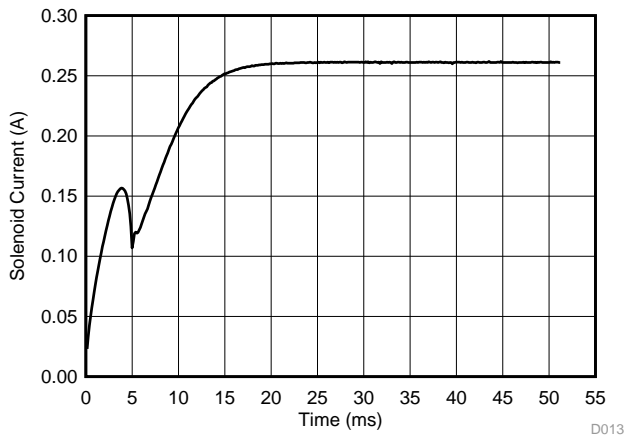


Figure 28. ADC Capture; Duty Cycle: 100%

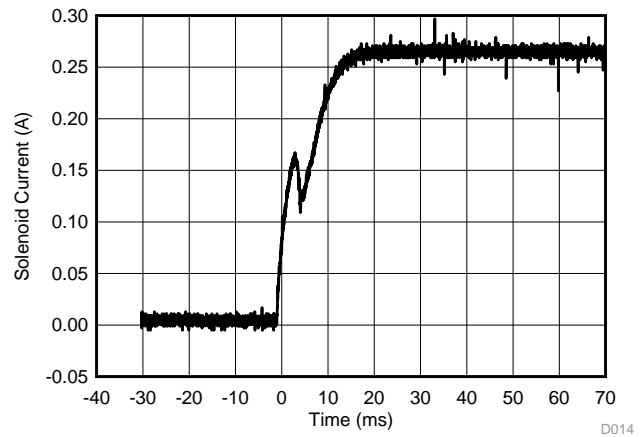


Figure 29. Scope Plot; Duty Cycle: 100%

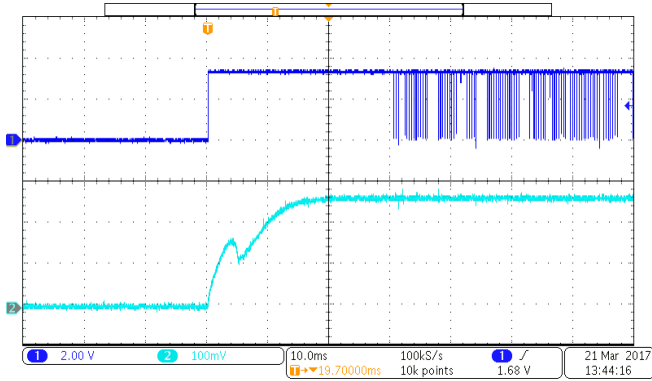


Figure 30. Scope Plot of Solenoid Current and PWM Signal; Duty Cycle: 100%

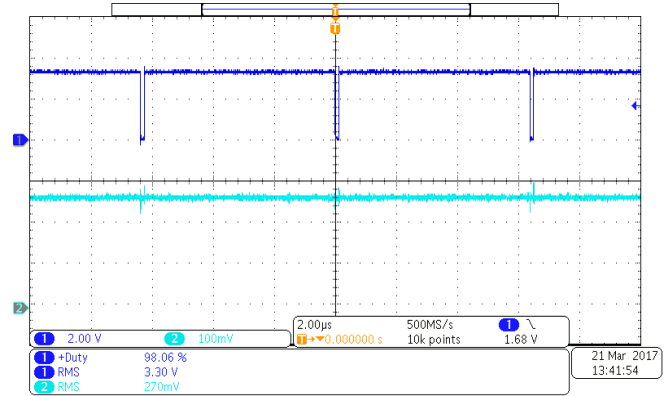


Figure 31. Zoomed-in Scope Plot of Solenoid Current and PWM Signal; Duty Cycle: 100%

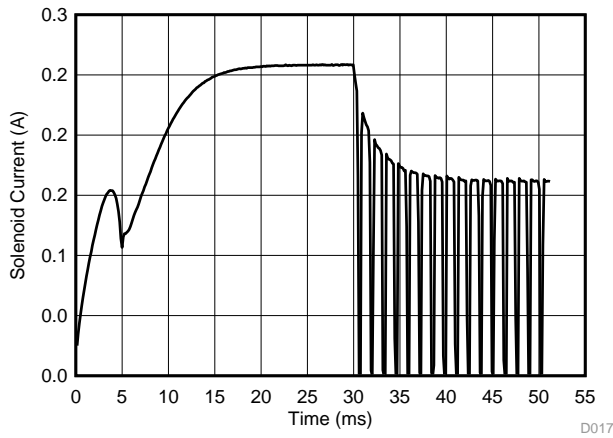


Figure 32. ADC Capture; Duty Cycle: 60%

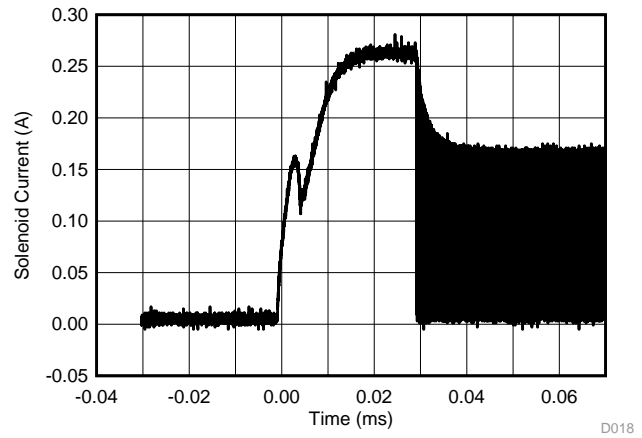


Figure 33. Scope Plot; Duty Cycle: 60%

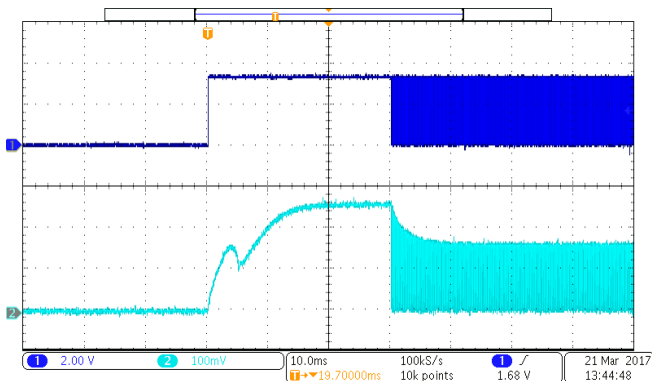


Figure 34. Scope Plot of Solenoid Current and PWM Signal; Duty Cycle: 60%

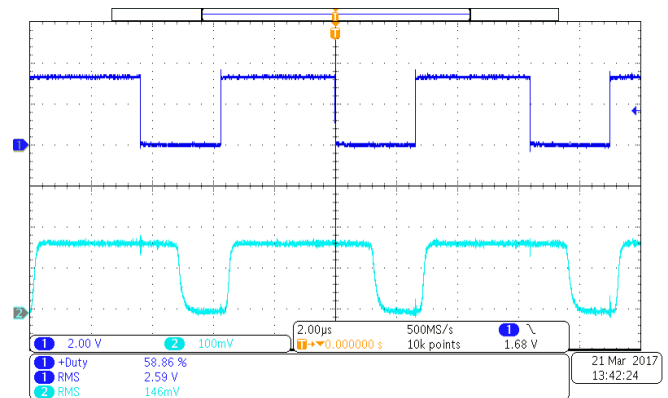


Figure 35. Zoomed-in Scope Plot of Solenoid Current and PWM Signal; Duty Cycle: 60%

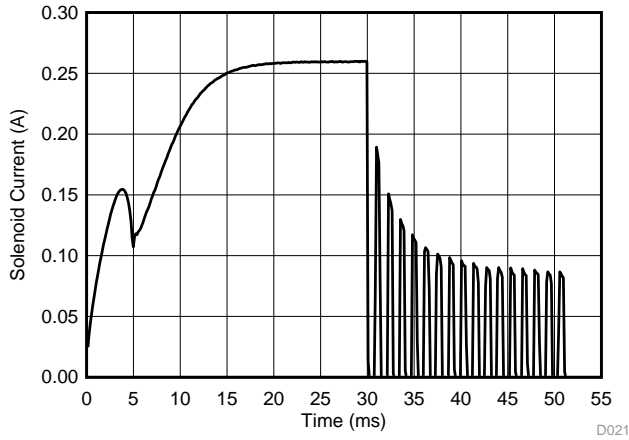


Figure 36. ADC Capture; Duty Cycle: 30%

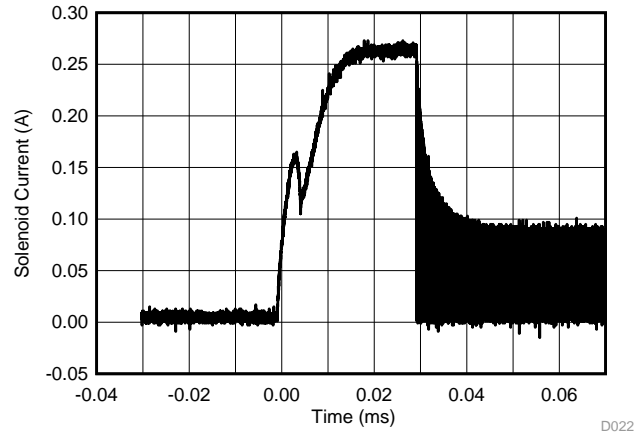


Figure 37. Scope Plot; Duty Cycle: 30%

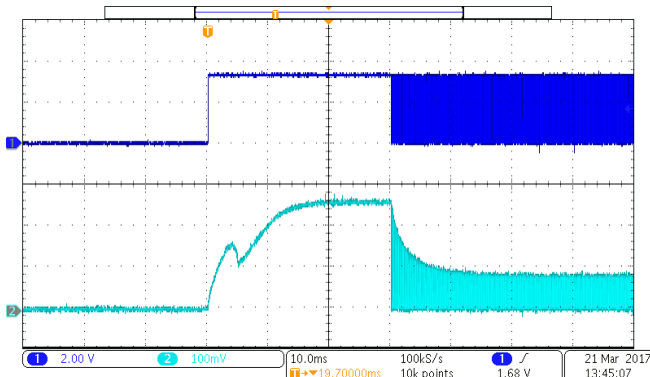


Figure 38. Scope Plot of Solenoid Current and PWM Signal; Duty Cycle: 30%

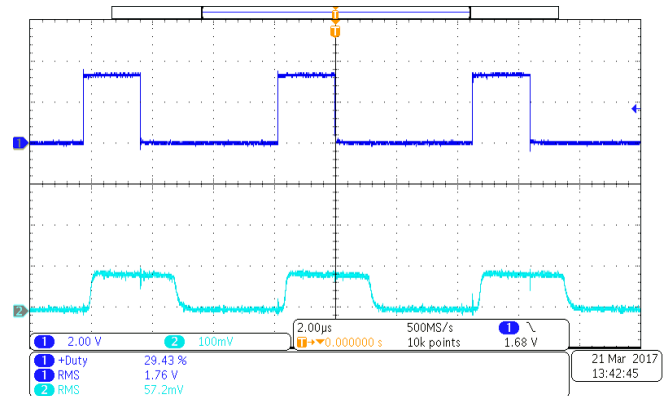


Figure 39. Zoomed-in Scope Plot of Solenoid Current and PWM Signal; Duty Cycle: 30%

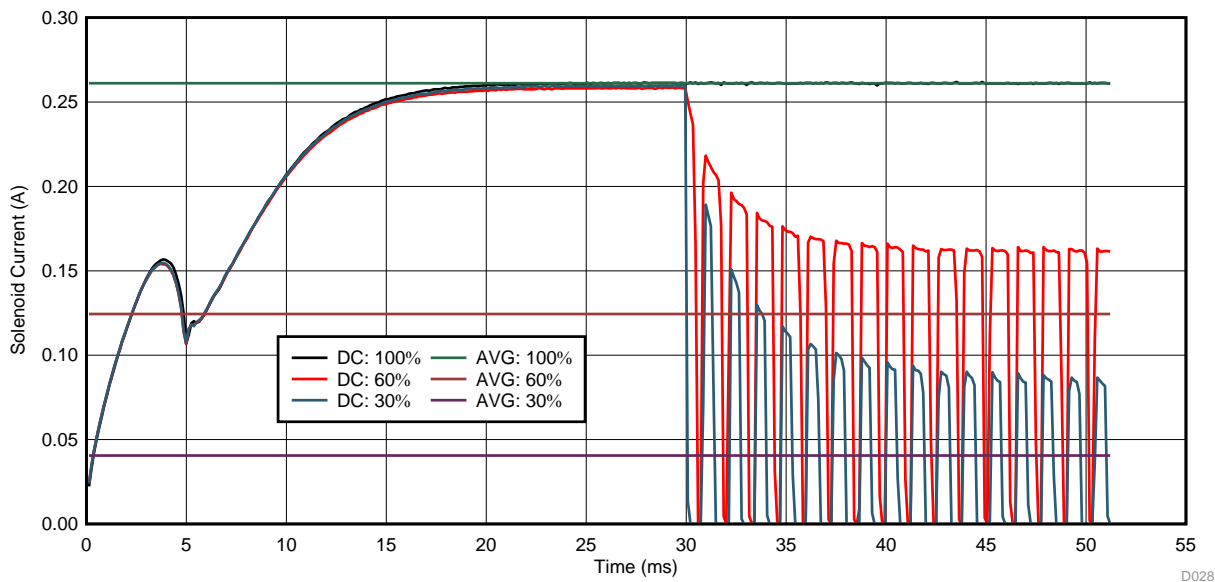


Figure 40. ADC Capture—Comparison of Duty Cycle: 100%, 60%, 30% With Average Current

4 Design Files

4.1 Schematics

To download the schematics, see the design files at [TIDA-01250](#).

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at [TIDA-01250](#).

4.3 PCB Layout Recommendations

4.3.1 Layout Prints

To download the layer plots, see the design files at [TIDA-01250](#).

4.4 Altium Project

To download the Altium project files, see the design files at [TIDA-01250](#).

4.5 Gerber Files

To download the Gerber files, see the design files at [TIDA-01250](#).

4.6 Assembly Drawings

To download the assembly drawings, see the design files at [TIDA-01250](#).

5 Software Files

To download the software files, see the design files at [TIDA-01250](#).

6 Related Documentation

1. Texas Instruments, [MSP430FR59xx Mixed-Signed Microcontrollers](#), MSP430FR5969 Datasheet (SLAS704)
2. Texas Instruments, [MSP430FR59xx User's Guide](#), MSP430FR5969 User's Guide (SLAU367)
3. Texas Instruments, [TIOL111 IO-Link Device Transceivers with Integrated Surge Protection](#), TIOL111 Datasheet (SLLSEV5)
4. Texas Instruments, [Combined Voltage and Current Output Terminal for Analog Outputs \(AO\) in Industrial Applications](#), TIPD119 Reference Guide (SLAU519)

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7 About the Authors

ALEXANDER WEILER is a systems engineer at Texas Instruments, where he is responsible for developing reference design solutions for the industrial segment. Alexander brings to this role his extensive experience in high-speed digital, low-noise analog, and RF system-level design expertise. Alexander earned his diploma in electrical engineering (Dipl.-Ing.(FH)) from the University of Applied Science in Karlsruhe, Germany.

BRITTA RUELANDER is a systems engineer for MSP430 at Texas Instruments Germany where she is responsible for new product development for the MSP430 product line and supports reference design solutions for the industrial segment.

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