

# TI Designs: TIDA-01506

## 汽车类比例电磁阀电流传感器参考设计



### 说明

为了实现自动变速器、电子燃油喷射器和多种汽车执行器应用中的精确控制，对汽车比例电磁阀进行精确控制是必须的。应用。在比例电磁阀中，流过线圈的电流与产生的磁场成正比。设计人员可以通过了解流经电磁阀的电流来估算电枢位置。通过使用高精度电流传感器形成闭环电磁控制，设计人员能够实现对比例电磁阀的精确控制。这种控制顺序意味着高精度电流传感器对于实现电磁阀的精确控制是至关重要的。选择电流传感器时需要考虑的一些主要因素为较小的偏移量、较小的漂移以及较高的脉宽调制 (PWM) 抑制比。通过结合上述三项特性，此参考设计展示了一种使用 TI 电流分流监测产品系列来精确测量流过电磁阀的电流的方法。

### 资源

<a href="#">TIDA-1506</a>	设计文件夹
<a href="#">INA240-Q1</a>	产品文件夹
<a href="#">TPS1H100-Q1</a>	产品文件夹
<a href="#">TPS709-Q1</a>	产品文件夹

### 特性

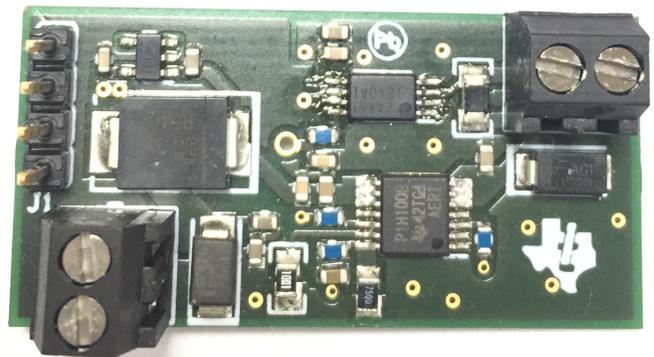
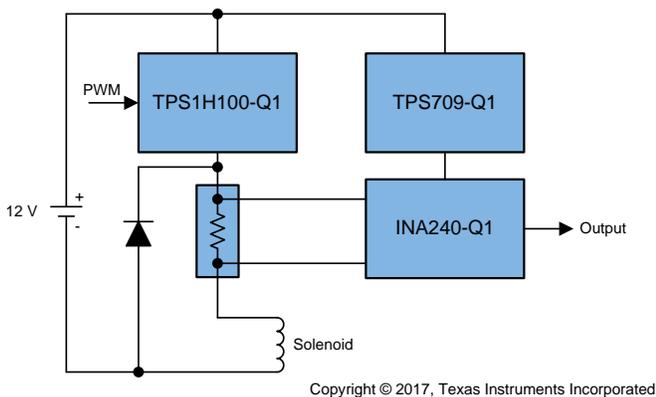
- 未校准精度：在温度范围内（-40°C 至 125°C）电流超过 10mA 时小于 1%
- 适用于各种电磁阀电流范围
- 低漂移、高精度
- 高侧驱动、高侧电磁阀监视器
- 增强型 PWM 抑制有利于实现均匀的电流分布
- 缩短消隐时间，并以较低的占空比实现精确测量

### 应用

- [变速箱控制](#)
  - [变速器](#)
  - [离合器](#)
- [汽车传动器](#)
- [液压悬架](#)
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## 1 System Description

At the time of this writing, proportional solenoids in automotive applications (along with ON/OFF solenoids) are in increased demand to satisfy the new requirements in transmission and hydraulic systems applications. In general, solenoids are current controlled, although voltage-controlled solenoids are available and applicable to some cases. This reference design forces the average current to flow through the solenoid in a closed-loop control with the use of a varying PWM duty cycle. In a closed-loop-control proportional solenoid, the duty cycle varies with respect to solenoid drifts, which means that the duty cycle requires adjustment based on the current sensor information. To have precise control over the duty cycle, the current sensor information is critical, along with the requirement for high-accuracy current sensors. This reference design describes the high-accuracy current sensor with TI's current shunt sensors portfolio and high-side switch.

Current sensors in solenoid applications follow a shunt-based principle. In this principle, PWM signals are made to flow on the 100 mΩ that travels through the high-side switch. The drop across the 100-mΩ shunt is captured using a current shunt amplifier. The current sensor is sensitive to temperature and other noise drifts; therefore, selecting a current sensor with low drift, low noise, and an enhanced PWM rejection ration is vital. The INA240-Q1 from TI's current shunt sensor portfolio perfectly suits these kind of applications. In this design, a freewheeling path has been created from the solenoid back to the shunt to account for the solenoid recirculation currents. A shunt is also inserted between the high-side switch and solenoid to capture the recirculation events (see [图 1](#)).

### 1.1 Key System Specifications

表 1. Key System Specifications

PARAMETER	SPECIFICATIONS
Measurement parameter	Solenoid currents
Sensor type	Shunt (resistive)
Shunt value	100 mΩ
Maximum current through shunt	Depends on selected solenoid (< 1 A in present case)
Sensor power supply	5 V (LDO output)
Sensor current	3 mA
Amplifier gain	x 20
Reverse polarity protection	Yes
Transient protection	Yes
Output voltage	0 V to 2 V
Operating temperature	-40°C to 125°C
Form factor	20 mm x 40 mm

## 2 System Overview

### 2.1 Block Diagram

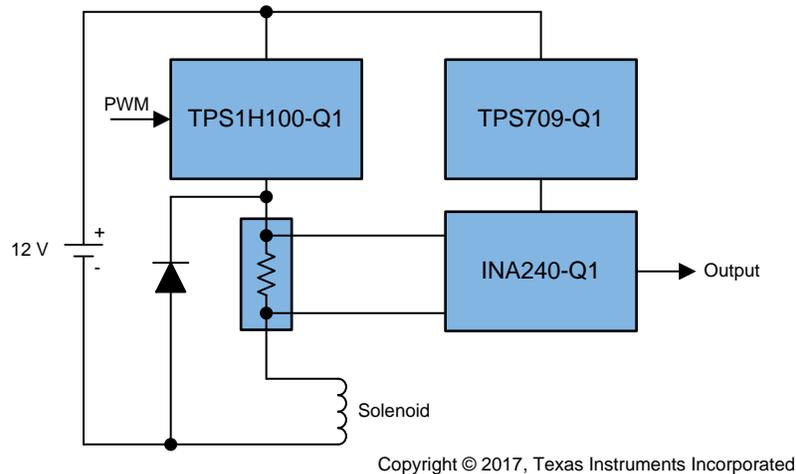


图 1. TIDA-01506 Block Diagram

The primary component of this design is the INA240-Q1 current sense amplifier with PWM operation by the high-side switch. A 100-m $\Omega$  resistor is inserted between the high-side switch and solenoid to account for the recirculation currents. By implementing the INA240-Q1 amplifier, the designer can measure the drops across the shunt at high-accuracy rates over the grade 1 temperature range and provide an analog output for further signal processing.

## 2.2 Highlighted Products

### 2.2.1 INA240-Q1

The INA240-Q1 is a voltage-output, current-sense amplifier. The unique features of enhanced PWM rejection, rejection with high common-mode input voltage, and a high-accuracy chopper-stabilized front end make this amplifier perfectly suited for solenoid current-sensing applications. The device is able to sense drops across shunt resistors over a wide common-mode voltage range from  $-4$  V to 80 V, independent of the supply voltage. The negative common-mode voltage allows the device to operate below ground, which implies that the device is also suitable for low-side sensing. This device operates from a single 2.7-V to 5.5-V power supply, which draws a maximum of 2.4 mA of supply current. The INA240-Q1 amplifier is capable of sensing even smaller voltages as it only has a 5- $\mu$ V typical offset error. Features such as excellent common-mode rejection ratio (CMRR), compatibility with low sides and high sides, and enhanced PWM rejection make the INA240-Q1 a perfect device for this application. The device is available in a TSSOP package.

The main features of this device are as follows:

- Excellent CMRR:
  - 132-dB DC CMRR
  - 93-dB AC CMRR at 50 kHz
- Wide common-mode range:  $-4$  V to 80 V
- Accuracy:
  - Gain drift: 2.5 ppm/ $^{\circ}$ C (max)

- Gain error: 0.20% (max)
- Offset voltage:  $\pm 25 \mu\text{V}$  (max)
- Offset drift: 250 nV/°C (max)
- Quiescent current: 2.4 mA (max)
- Bidirectional sensing using reference pin configuration
- Available gains: 20, 50, 100, and 200
- AECQ100 qualified
- Device temperature grade 1:  $-40^\circ\text{C}$  to  $125^\circ\text{C}$  ambient operating temperature

### 2.2.2 TPS1H100-Q1

The TPS1H100-Q1 is a fully-protected, high-side power switch with an integrated, NMOS power field-effect transistor (FET) and charge pump. Intelligent control of inductive loads, such as a solenoid with programmable current limit features, makes this device a good choice for the present application.

The main features of this device are as follows:

- Qualified for automotive applications (AEC-Q100 qualified)
- Wide operating voltage 3.5 V to 40 V
- Very-low standby current,  $< 0.5 \mu\text{A}$
- Operating junction temperature,  $-40^\circ\text{C}$  to  $150^\circ\text{C}$
- Input control, 3.3-V and 5-V logic compatible
- Programmable current limit with external resistor,  $\pm 20\%$  at 0.5 A
- Electrical transient disturbance immunity certification of ISO7637-2 and ISO16750-2
- Protection:
  - Overload and short-circuit protection
  - Inductive load negative voltage clamp
  - Undervoltage lockout (UVLO) protection
  - Thermal shutdown/swing with self recovery

### 2.2.3 TPS709-Q1

The TPS709-Q1 series of linear regulators are ultra-low quiescent current devices designed for power-sensitive applications. A precision band-gap and error amplifier provides 2% accuracy over temperature. A quiescent current of only  $1 \mu\text{A}$  makes these devices ideal solutions for battery-powered, always-on systems that require very little idle-state power dissipation. These devices have thermal-shutdown, current-limit, and reverse-current protections for added safety. These regulators can be put into shutdown mode by pulling the EN pin low. The shutdown current in this mode goes down to 150 nA, typical. The TPS709-Q1 series is available in WSON-6 and SOT-23-5 packages.

The main features of this device are as follows:

- Qualified for automotive applications
- Grade 1
- Input voltage range: 2.7 V to 30 V
- Ultra-low  $I_Q$ :  $1 \mu\text{A}$

- Reverse current protection
- Low  $I_{\text{SHUTDOWN}}$ : 150 nA
- Supports 200-mA peak output
- 2% accuracy over temperature
- Available in fixed-output voltages: 1.2 V to 6.5 V
- Thermal shutdown and overcurrent protection

## 2.3 System Design Theory

Solenoids convert electrical current into mechanical motion—from a fundamental perspective, a solenoid is simply a linear motor with a fixed range of travel. Solenoids are available in two basic types: on/off solenoids and linear/ proportional solenoids. Solenoids of the on/off type convert electrical information into mechanical information through the closing or opening of valves. Proportional solenoids convert electrical signals into proportional mechanical force, which allows variance in armature position and force relative to the current level. In applications such as transmission and fuel injection, proportional solenoids serve to operate pistons and valves to accurately control fuel pressure or flow. Transmission applications require accurate and smooth control of pressure to change gears seamlessly. The primary focus of this reference design is on proportional solenoids and current monitoring.

### 2.3.1 Characteristics of Solenoid Coils

Electromechanical solenoids consist of an electromagnetically-inductive coil wound around a movable steel or iron slug, which is known as the armature or plunger (see [图 2](#)). The coil is shaped such that the armature can be moved in and out of its center, altering the inductance of the coil as well as effectively making it an electromagnet. The armature provides a mechanical force to activate the control mechanism, for example, opening and closing of a valve or linear movement of the solenoid.

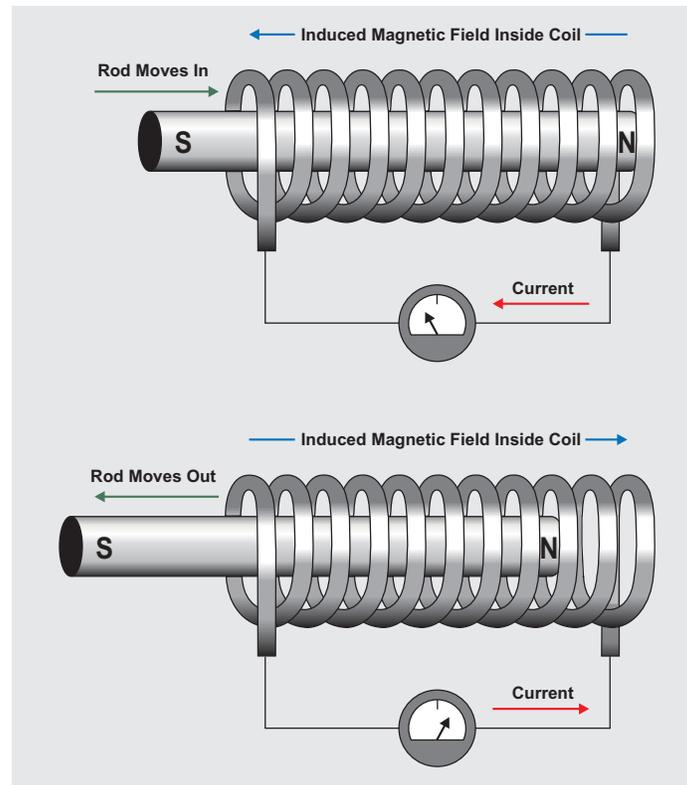


图 2. Working Solenoid

The 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 upon energizing a solenoid. Instead, the current rises at a steady rate until the DC resistance of the solenoid imposes a limit. 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, which causes the magnetic field to expand until it becomes strong enough to move the armature. The amount of current is proportional to the amount of magnetic field, which, in turn, is proportional to the solenoid movement.

### 2.3.2 Closed-Loop Control of Proportional Solenoid

图 3 shows the mechanism to control the proportional solenoid in a closed-loop fashion. The inner loop represents the current control and outer loop represents the pressure control. Using a varied duty cycle, the current set point has a value with which to operate  $G1(s)$ .  $G1(s)$  translates current into armature motion. A high-accuracy current sensor detects solenoid movement, which adjusts the current set point to give the next instruction to the  $G1(s)$ . This order of events forms a closed loop and achieves precise control of the solenoid. This criteria similarly applies to pressure loops.

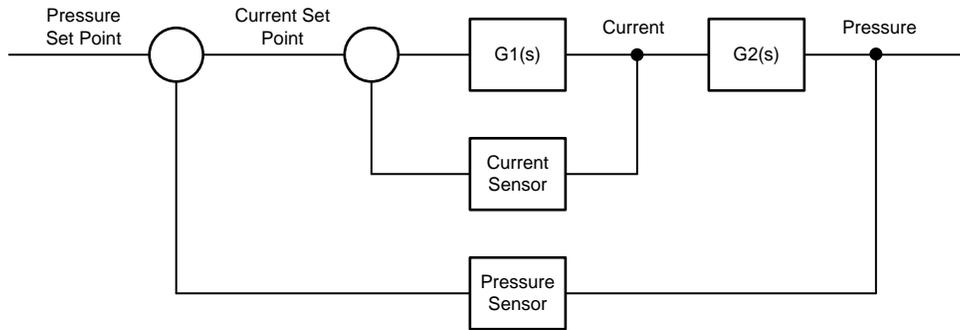


图 3. Closed-Loop Solenoid Control

One function of a feedback loop is to control the position of a linear solenoid. For example, the designer can monitor the downstream pressure of a valve, use it as a feedback signal to compare with the setpoint, and adjust the PWM duty cycle to control the solenoid. However, measuring the downstream pressure may be difficult, impractical, or very costly.

A practical alternative to measuring the downstream pressure is to establish the position of the solenoid by measuring the current through the solenoid. This measurement is possible because the force imposed by the mechanical load on a solenoid is directly proportional to the magnetic field, which, in turn, is directly proportional to the current through the coil. Proportional control of the solenoid is achieved by a balance of the forces between the spring-type load and the magnetic field of the solenoid, which the designer can determine by measuring the current through the solenoid.

### 2.3.3 Sensing Solenoid Current

As previously addressed, high-accuracy current sensing provides precise control for proportional solenoids. This focus of this section is on current sensing and its mechanisms.

The amount of current which flows through a solenoid is directly proportional to the measured change in position of the solenoid. Therefore, by detecting the amount of current, the designer may be able to estimate the exact movement of the solenoid. This process works by inserting a shunt in the path of the solenoid currents and using current shunt monitors to monitor the voltage drop across shunt, which detects any solenoid movement. The current measurement path has non-linearities due to the temperature and linearity effects around the solenoid. Selecting a suitable architecture and components solves this problem and improves the current sense accuracy.

#### 2.3.3.1 Operation

During operation, High side switch applied 12V when PWM is on and applied zero when PWM is off. The PWM frequency is generally in the range of 1 KHz to 2 KHz for a proportional solenoid. Use an MCU to generate this PWM signal, which travels to the high-side switch, during which the PWM-averaged current wave form is applied to the solenoid. According to the basic principles of solenoids, the amount of current is directly proportional to the amount of magnetic field around the coil which, in turn, relates to the movement of the solenoid. The high-side switch is typically a FET. Control the FET gate using a PWM signal. When the FET is on, the solenoid is connected to the 12 V and produces a current which charges the solenoid coil. When the FET turns off, the solenoid current discharges through the freewheeling diode and shunt resistor. By regulating the PWM frequency and duty cycle, the designer is able to determine the resulting average ripple current in the solenoid.

To detect the current that flows through the solenoid from the switch, a shunt is inserted in the path of the high-side switch and solenoid. The shunt value to choose depends on the solenoid selected. This reference design uses a 100-mΩ shunt, which is a four-wire shunt with two wires connected to the high-side switch source and solenoid positive and the other two wires differentially connected to the current shunt monitor. The current shunt monitor amplifies a low value of dropped voltage across the shunt and provides the analog output voltage. While operating the current sensors in a high-side configuration, the common-mode voltages at the shunt terminals must be located beyond the battery rails to accommodate for the freewheeling diode and common-mode voltage levels.

### 2.3.3.1.1 Current Sense Circuit

As 图 4 shows, one terminal (Out\_Switch) is connected to the FET source and the other terminal (Solenoid\_1) is connected to the solenoid positive. As this is a four-wire terminal shunt, the other two terminals connect to the INA240-Q1 differential input terminals. Depending on the next signal processing chain, the designer can choose from different types of gain variants for the INA240-Q1: 20, 50, 50, 100, and 200. For this reference design, select the 20-V/V gain version. Two capacitors on the 5-V signal line (VCC\_5V) help to buffer the action. The output of the INA240-Q1 amplifier is an analog signal. The output has an RC filter section where the designer can select the frequency based on the required averaging. In 图 4, the chosen R1, C1 values are around 30 KΩ to show the exact current waveform on the INA output. The designer can choose lower frequencies for further signal processing to meet the averaging requirements.

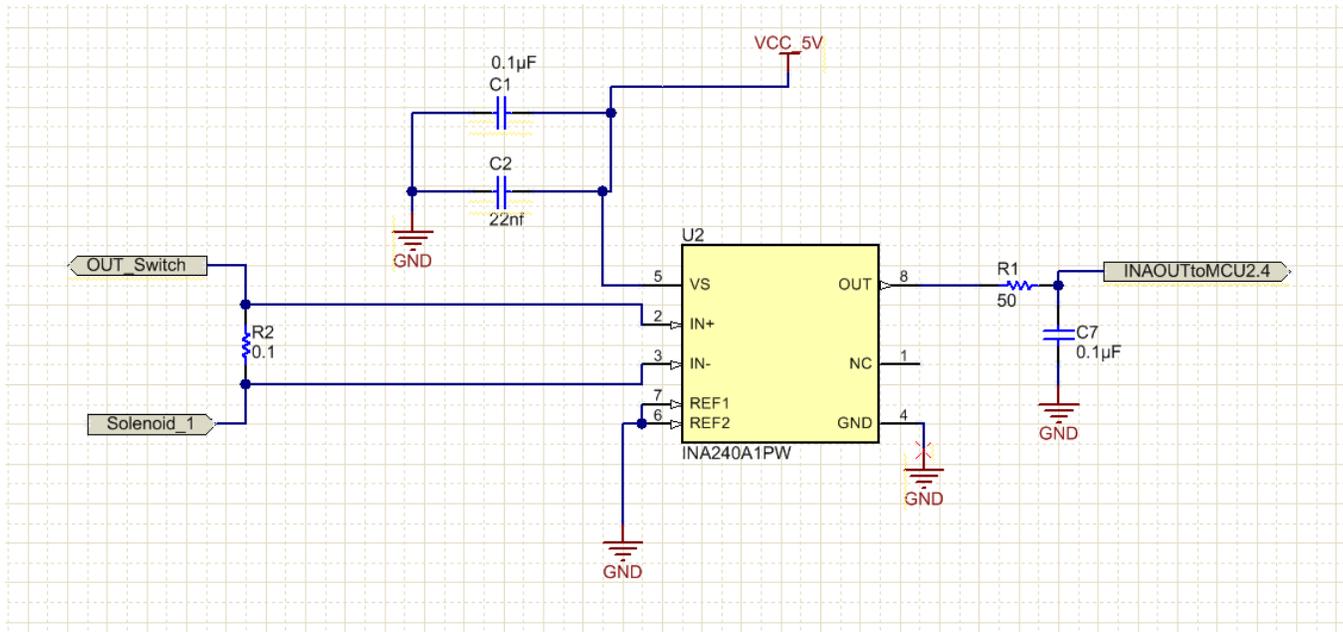


图 4. Current Shunt Monitor Schematics

### 2.3.3.1.2 High-Side Switch Circuit

The TPS1H100-Q1 provides 100 mΩ of  $R_{DS(ON)}$  resistance. As 图 5 shows, the PWM signal is given at the IN pin.

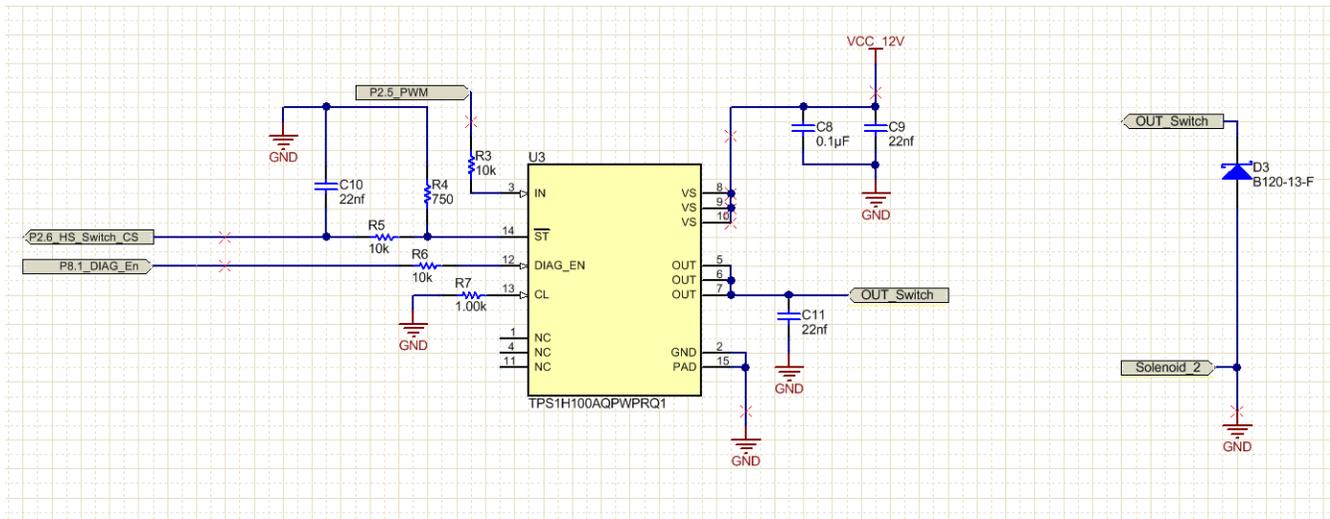


图 5. High-Side Switch Schematics

According to the data sheet specifications from *TPS1H100-Q1 40-V, 100-mΩ Single-Channel Smart High-Side Power Switch*, the TPS1H100-Q1 switch is only allowed to give a maximum PWM frequency of 2 KHz. 表 2 lists the switching characteristics of the TPS1H100-Q1 per the data sheet specifications. The high-side switch has a turnon delay of 50 μs, maximum.

表 2. TPS1H100-Q1 Switching Characteristics

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
$t_{d,ON}$	Turnon delay time	IN rising edge to $V_{OUT} = 10\%$ , DIAG_EN high	20	—	50	μs
$t_{d,OFF}$	Turnoff delay time	IN falling edge to $V_{OUT} = 90\%$ , DIAG_EN high	20	—	50	μs
$dV/dt_{ON}$	Slew rate on	$V_{OUT} = 10\%$ to $90\%$ , DIAG_EN high	0.1	—	0.5	V/μs
$dV/dt_{OFF}$	Slew rate off	$V_{OUT} = 90\%$ to $10\%$ , DIAG_EN high	0.1	—	0.5	V/μs
—	Slew rate on and off matching	—	-0.15	—	0.15	V/μs

图 6 shows the TPS1H100-Q1 switching characteristics diagram.

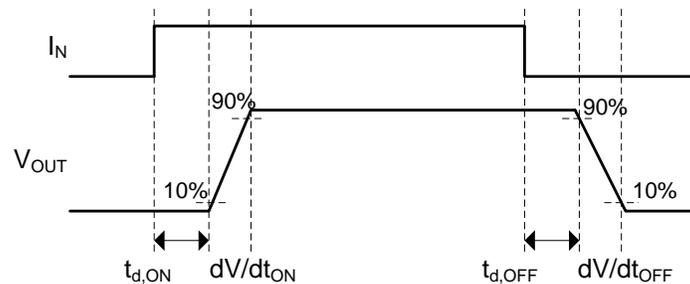


图 6. TPS1H100-Q1 Switching Characteristics Diagram

This high-side switch also provides current sensing and current limiting features. For example, if the current limit value chosen is 2.5 A for a nominal current of 1 A, then the calculations for the resistor values are as follows.

The current limit internal threshold is set at 1.233 V. To set the programmable current limit value to 2.5 A, calculate the R7 as shown in [公式 1](#):

$$R7 = \frac{V(\text{th}) \times K_{\text{CL}}}{I_{\text{OUT}}} = \frac{1.233 \times 2000}{2.5} = 986.4 \, \Omega \quad (1)$$

where,

- V(th) is the internal threshold,
- $K_{\text{CL}}$  is 2000 (as per the TPS1H100-Q1 data sheet),
- $I_{\text{OUT}}$  is the current limit value.

As indicated by [公式 1](#), R7 yields 986.4  $\Omega$ , A selected value of 1 K $\Omega$  is fairly close; so, for a 2.5-A current limit, choose 1 K $\Omega$  for R7.

TI recommends R6 = 10 k $\Omega$  for a 5-V MCU. Install two buffer capacitors on the 12-V power line. The solenoid recirculation current flows through the Schottky diode (20 V, 1 A). When the PWM cycle is in the OFF mode (switch closes), the solenoid discharges the currents through this recirculation diode.

Several methods are available for configuring this current measurement for solenoids. The customer can identify the particular architecture based on the chosen topology. The INA240-Q1 has a wider common-mode voltage range, so the designer can fit the device within any of the below architectures. This reference design uses the architecture for high-side current sensing with a high-side switch.

- Low-side current sense with a high-side drive
- High-side current sensing with a low-side switch
- High-side current sensing with a high-side switch

### 3 Hardware, Software, Testing Requirements, and Test Results

#### 3.1 Required Hardware

The required hardware is as follows:

- Oscilloscope
- Function generator
- Digital multimeter (DMM)
- Solenoid
- Power supply
- TIDA-01506 board

##### 3.1.1 Hardware Setup

Connect the required equipment as 图 7 shows for performing solenoid testing.

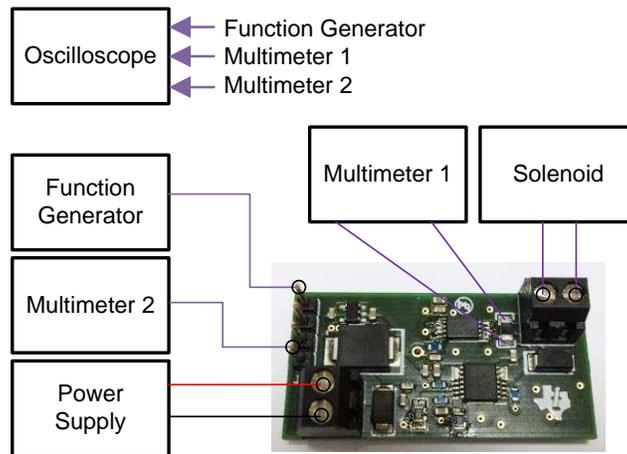


图 7. TIDA-01506 Hardware Setup

### 3.2 Testing and Results

For the purposes of testing, the TIDA-01506 design was connected to an emulated solenoid. This solenoid was emulated using a 4.2-mH inductor with a series resistance of 8.78 Ω. The 100-mΩ current shunt sense resistor was placed in series with the solenoid. Another series resistance of 10 Ω was placed in series with the solenoid for current-limiting purposes—note that this additional series resistor is virtual and does not exist in a real solenoid circuit.

After connecting the TIDA-01506 design to an emulated solenoid, two types of measurements were taken on the circuit: PWM operation of the solenoid and accuracy estimation of the solenoid.

#### 3.2.1 PWM Operation of Solenoid

At a frequency of 1 KHz, the PWM signal operates the high-side switch. With varied duty cycles of the PWM signal, various amounts of current pass through the solenoid. A set of figures in the following [节 3.2.1.1](#) show the variation of solenoid current for duty cycle variation. Choose the inductor and resistor value to be time constant. The amount of current that flows through the solenoid varies based on the capability of the solenoid.

##### 3.2.1.1 Hardware Setup for PWM Operation

图 8 shows the hardware setup for verifying the PWM operation of the solenoid.

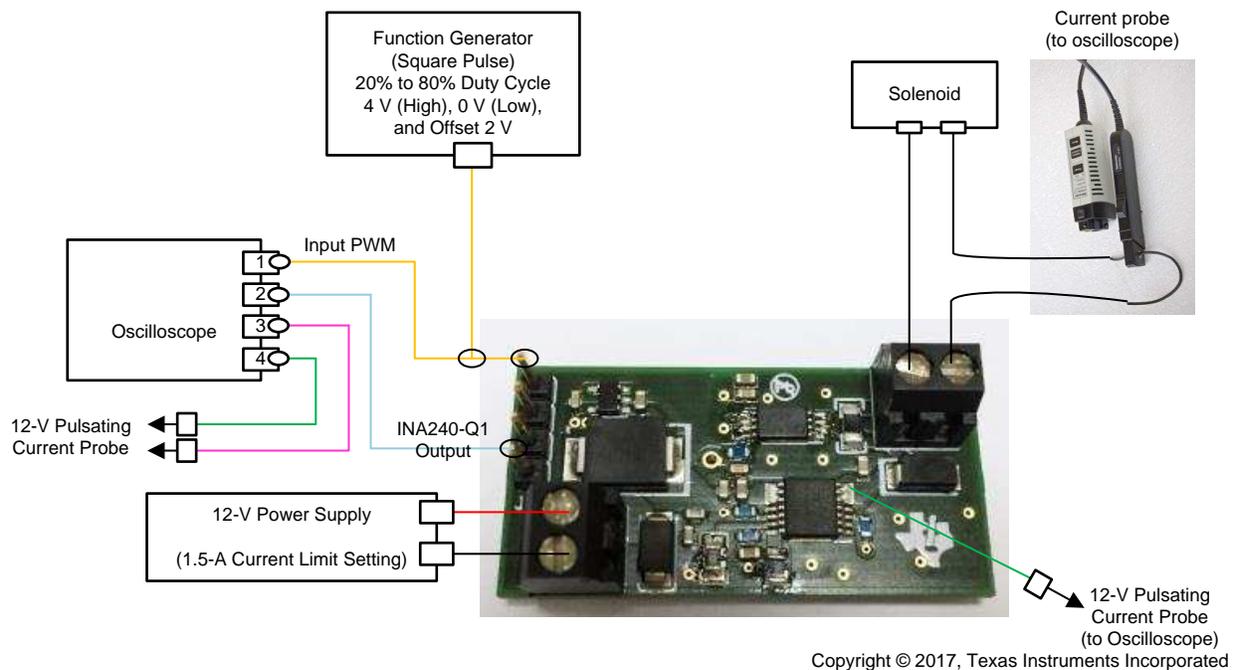
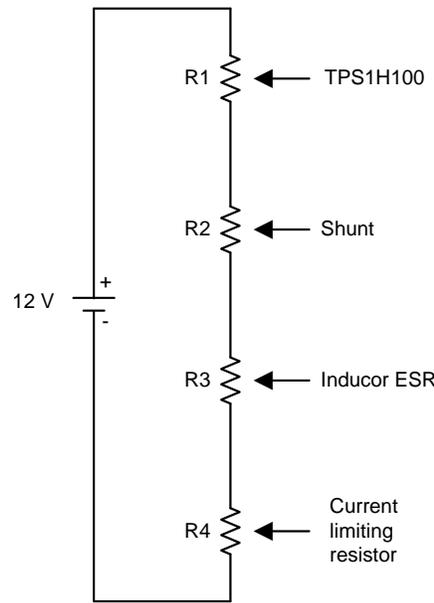


图 8. PWM Operation of Solenoid

As the following [图 9](#) shows, four types of resistors are available in a solenoid circuit for PWM operation.

1. R1: High-side switch  $R_{DS(ON)}$  resistance of 100 mΩ
2. R2: Shunt resistance of 100 mΩ
3. R3: Inductor equivalent series resistance (ESR) of 8.780 Ω
4. R4: Current-limiting resistor of 10 Ω (does not exist in a real solenoid)



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图 9. Resistors in Solenoid Current Path

With four resistors in series, the ESR of the resistance ladder is 18.980 Ω. The solenoid is connected to the 12-V supply and, according to Ohm's law, 0.6322 A of current flows through the network in a 100% duty cycle mode. With a varied duty cycle, differing amount of current flows through the circuit; thus, the solenoid moves with respect to the amount of current which flows through it.

As 图 10 through 图 15 show, a lower PWM cycle results in lower current and a higher PWM duty cycle results in higher current.

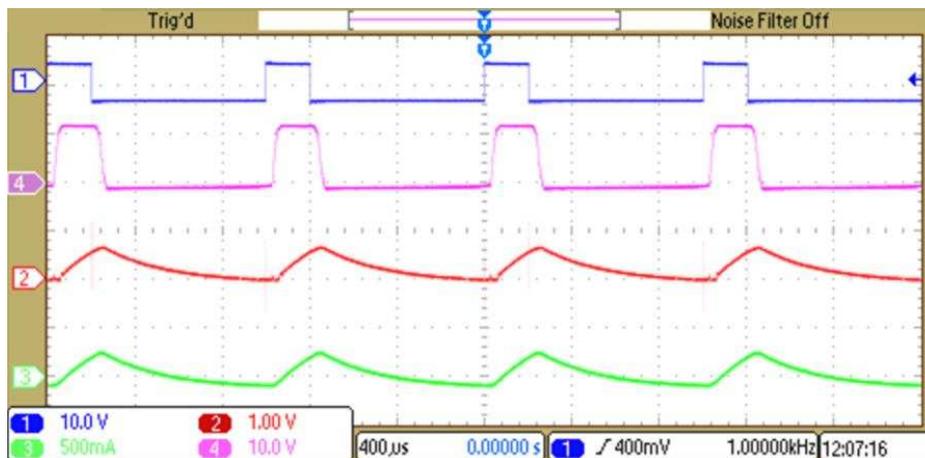


图 10. 20% Duty Cycle—Ch 1: Input PWM, Ch 2: INA240-Q1 Output, Ch 3: Current Probe Output, Ch 4: 12-V Pulsating

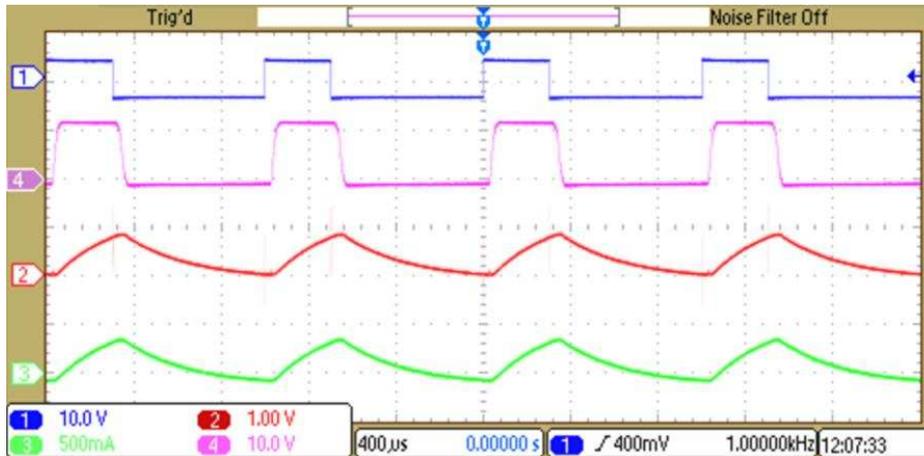


图 11. 30% Duty Cycle—Ch 1: Input PWM, Ch 2: INA240-Q1 Output, Ch 3: Current Probe Output, Ch 4: 12-V Pulsating

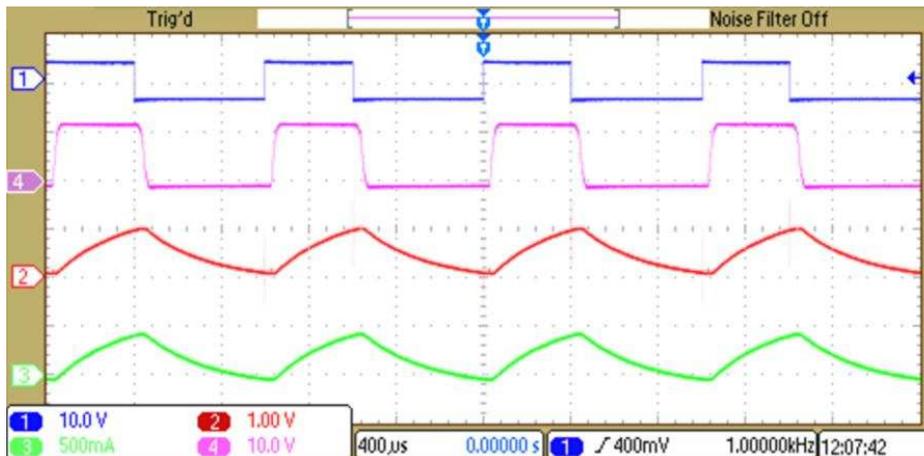


图 12. 40% Duty Cycle—Ch 1: Input PWM, Ch 2: INA240-Q1 Output, Ch 3: Current Probe Output, Ch 4: 12-V Pulsating

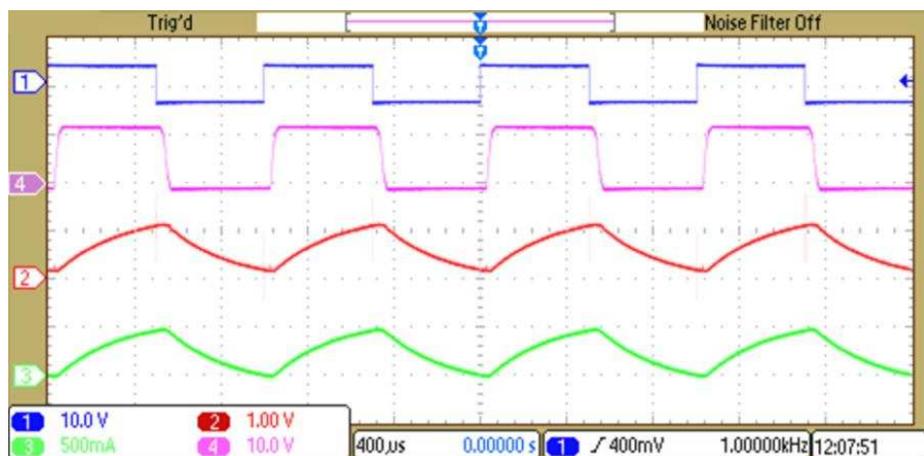


图 13. 50% Duty Cycle—Ch 1: Input PWM, Ch 2: INA240-Q1 Output, Ch 3: Current Probe Output, Ch 4: 12-V Pulsating

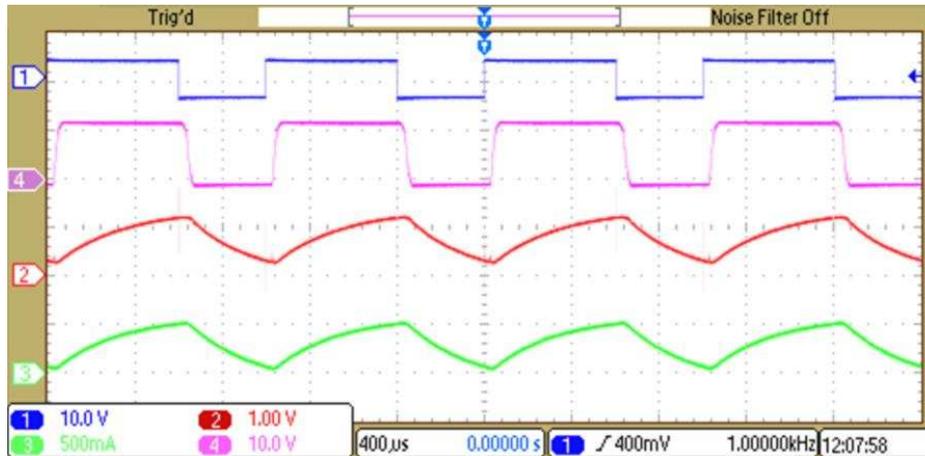


图 14. 60% Duty Cycle—Ch 1: Input PWM, Ch 2: INA240-Q1 Output, Ch 3: Current Probe Output, Ch 4: 12-V Pulsating

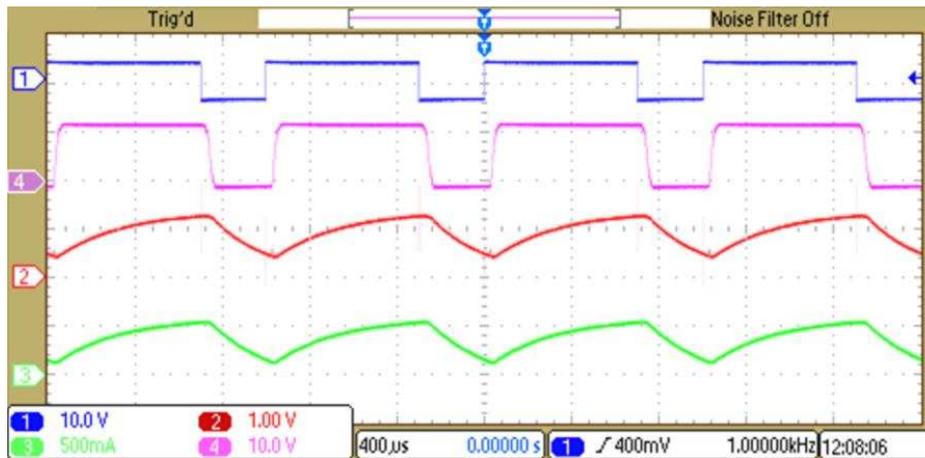


图 15. 70% Duty Cycle—Ch 1: Input PWM, Ch 2: INA240-Q1 Output, Ch 3: Current Probe Output, Ch 4: 12-V Pulsating

From the previous figures, observe that the magnitude of current changes proportionally with the varied duty cycles.

图 16 through 图 18 show the PWM signal at the drain of the FET versus the solenoid current (measured with a current probe). These waveforms show that the duty cycles vary from 20% to 60%. When the duty cycle is 20%, the magnitude of current is 250 mA. When the duty cycle reaches 60%, the magnitude of current changes to 500 mA.

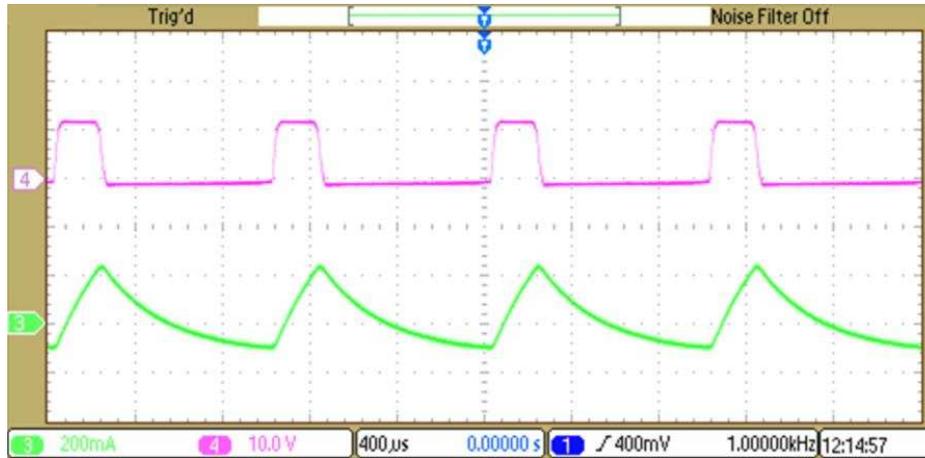


图 16. 20% Duty Cycle—Ch 4: Pulsating DC, Ch 3: Current Through Solenoid

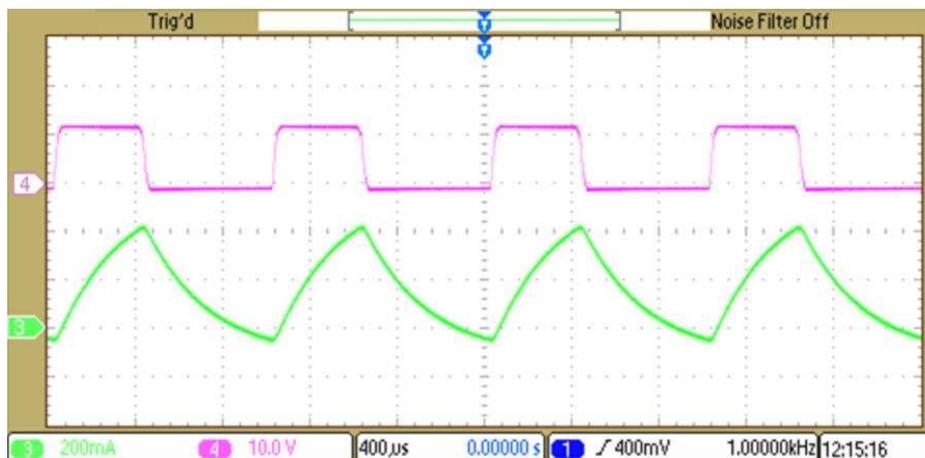


图 17. 40% Duty Cycle—Ch 4: Pulsating DC, Ch 3: Current Through Solenoid

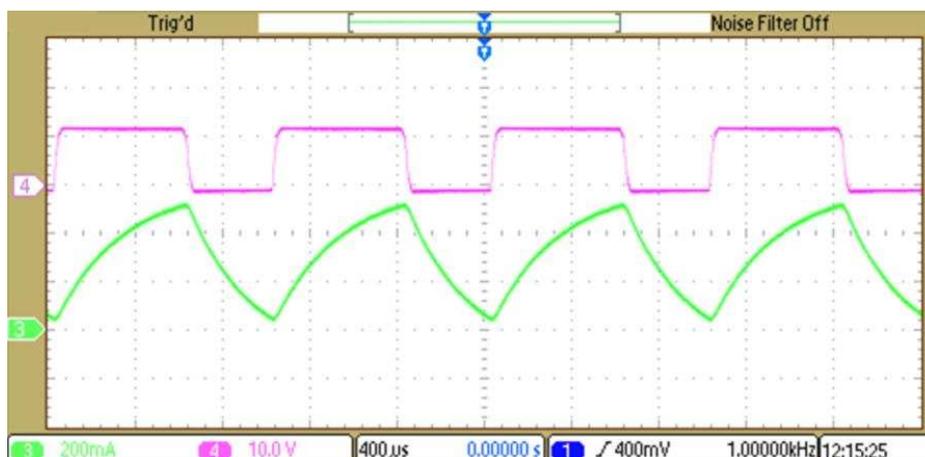


图 18. 60% Duty Cycle—Ch 4: Pulsating DC, Ch 3: Current Through Solenoid

图 19 through 图 23 show the input PWM versus the output of the current sense amplifier. When the duty cycle is 20%, the magnitude of voltage output for the INA240-Q1 device is 700 mV, which changes linearly as the duty cycle increases (meaning that it reaches 1000 mV when the duty cycle is approaching 70%).

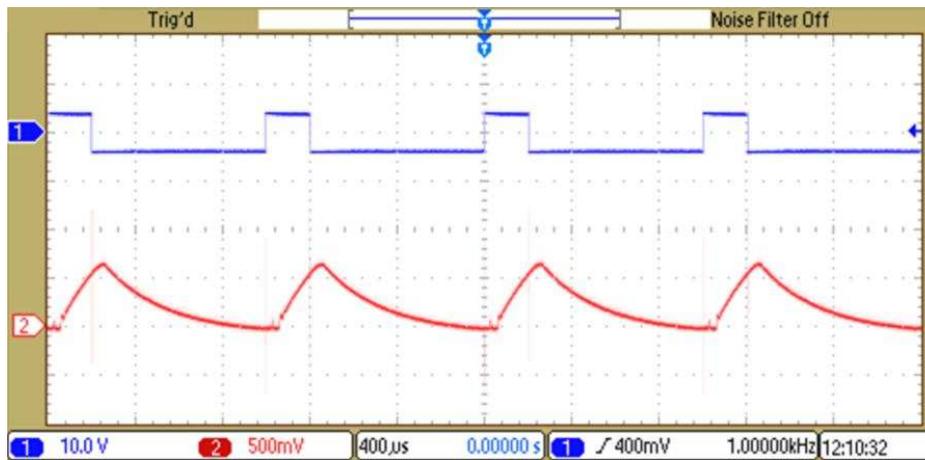


图 19. 20% Duty cycle—PWM Input versus Current Shunt Output, Ch 1: PWM Input, Ch 2: INA240-Q1 Output

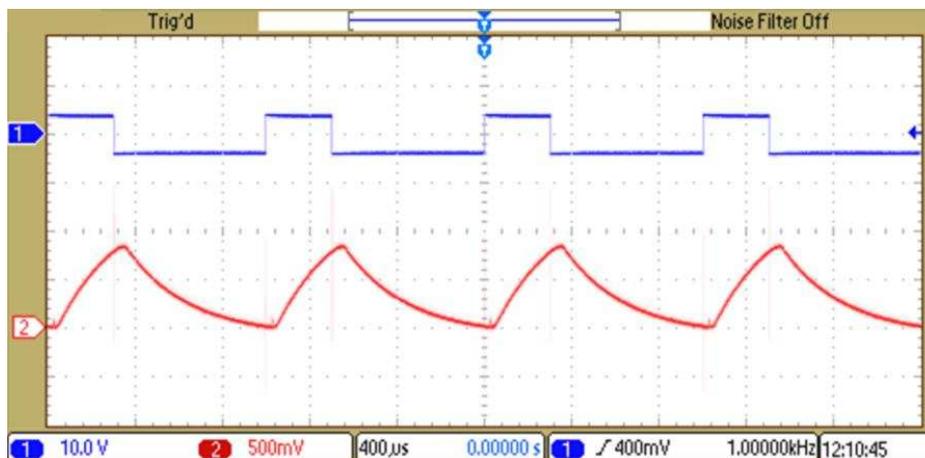


图 20. 40% Duty cycle—PWM Input versus Current Shunt Output, Ch 1: PWM Input, Ch 2: INA240-Q1 Output

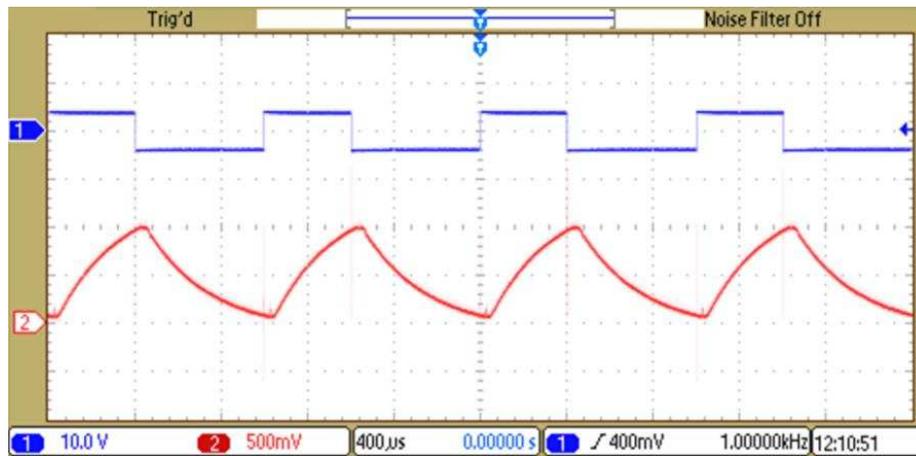


图 21. 50% Duty cycle—PWM Input versus Current Shunt Output, Ch 1: PWM Input, Ch 2: INA240-Q1 Output

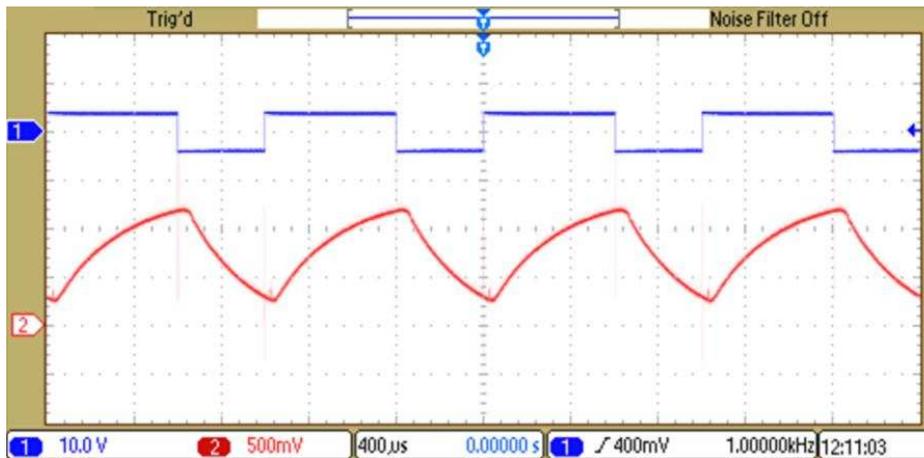


图 22. 60% Duty cycle—PWM Input versus Current Shunt Output, Ch 1: PWM Input, Ch 2: INA240-Q1 Output

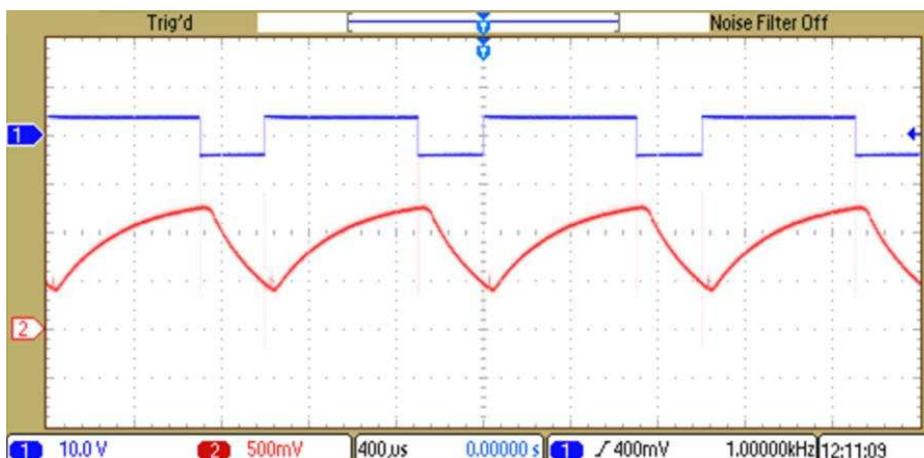


图 23. 80% Duty cycle—PWM Input versus Current Shunt Output, Ch 1: PWM Input, Ch 2: INA240-Q1 Output

### 3.2.1.2 Accuracy Estimation

As mentioned in previous sections, to facilitate the precise control of a solenoid, current sensor feedback information is essential and must be accurate. This section describes the accuracy calculations and results. With the chopper-stabilized front end, significantly less offset, and less gain drift, the INA240-Q1 amplifier performs outstanding for measuring the accuracy of a solenoid current.

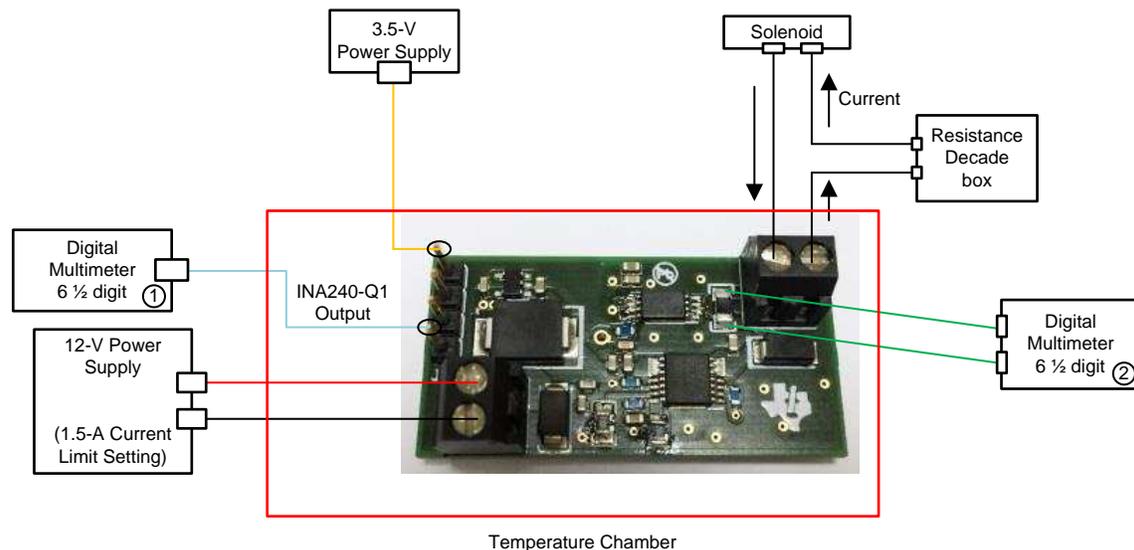
For the accuracy estimation connect the equipment to the TIDA-01506, as 图 24 shows.

The following steps are required to connect the circuit for accuracy estimation:

- Power up the board with a 12-V power supply.
- The 3.5-V power supply always keeps the high-side switch ON so that current through the shunt flows in continuous mode.
- Use a resistance decade box to vary the current through the solenoid. The resistance value is varied in the decade box so that the varied amount of currents flow through the solenoid.
- To monitor the exact amount of current that passes through the shunt, connect a digital multimeter (DMM) across the 100-mΩ shunt.
- Connect the INA output to another DMM.
- Compare two multimeter outputs to estimate the accuracy using the following formulae:

$$\text{Accuracy} = \frac{\text{Expected Output (V)} - \text{Measured Output (V)}}{\text{Expected Output (V)}} \times 100 \quad (2)$$

- where,
  - Expected Output = Voltage Across Shunt × DMM 2 Reading × 20 (Amplifier Gain)
  - Measured Output = Output Voltage of INA × DMM 1 Reading



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图 24. Accuracy Estimation Setup

Especially in solenoid applications, accuracy mainly degrades because of the temperature variations. Temperature variations cause accuracy to drift with large amounts. As the setup diagram in 图 24 shows, the total setup is placed in a temperature chamber, which runs from -40°C to 125°C.

The accuracy is calculated at different temperatures and plotted against the different currents at different temperatures; 图 25 shows this plot.

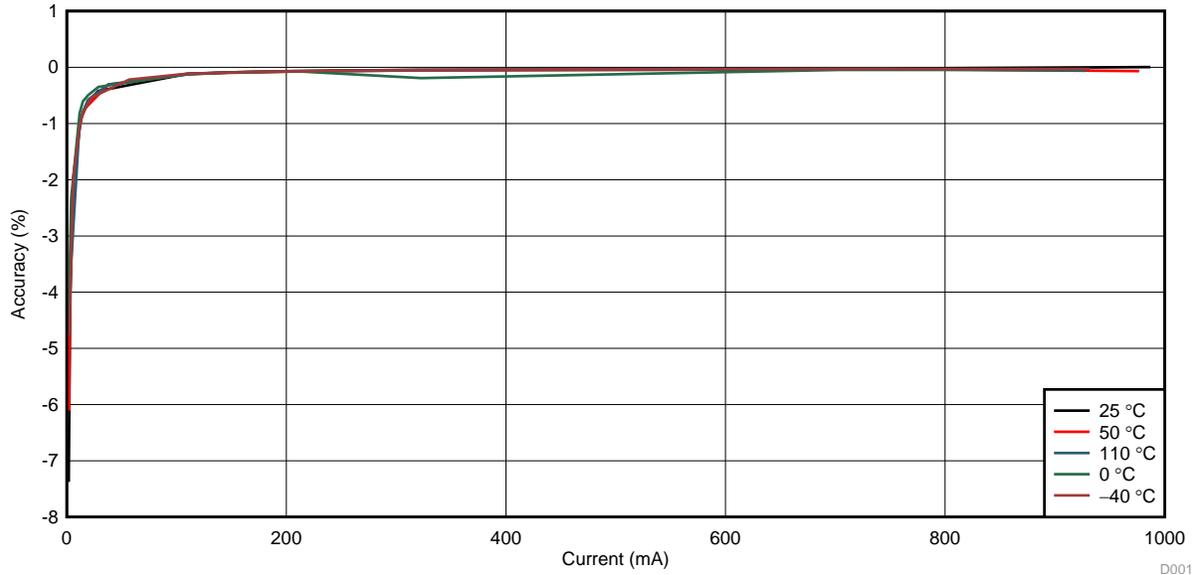


图 25. FS Accuracy at Different Temperatures

As the previous 图 25 shows, the accuracy varies quite less for the various temperatures because of the reduced drift of the INA240-Q1 device.

Use the temperature chamber to maintain the temperature at 25°C and use the resistance decade box to vary the resistance to deliver the different amounts of current through the shunt. Apply a current from 1 A down to 0 mA across the shunt. 表 3 shows the values at 25°C. 表 3 shows the accuracy figures across the current range from 2 mA to 1 A.

表 3. Accuracy at 25°C

TEMPERATURE (°C)	VOLTAGE ACROSS SHUNT (mV)	EQUIVALENT CURRENT (mA)	EXPECTED OUTPUT (V)	MEASURED OUTPUT (INA OUTPUT) (V)	ABSOLUTE ACCURACY (%) AT 25°C
25	97.673	976.73	1.95346	1.9548	-0.068596234
25	78.808	788.08	1.57616	1.5767	-0.034260481
25	69.493	694.93	1.38986	1.3904	-0.038852834
25	32.075	320.75	0.6415	0.64185	-0.054559626
25	20.809	208.09	0.41618	0.41649	-0.074487001
25	13.511	135.11	0.27022	0.2705	-0.103619273
25	10.974	109.74	0.21948	0.21975	-0.123018043
25	3.789	37.89	0.07578	0.076014	-0.308788599
25	1.649	16.49	0.03298	0.033222	-0.733778047
25	1.162	11.62	0.02324	0.023468	-0.981067126
25	0.588	5.88	0.01176	0.011996	-2.006802721
25	0.303	3.03	0.00606	0.006295	-3.877887789
25	0.208	2.08	0.00416	0.004414	-6.105769231

Similarly, temperature measurements were taken for various temperatures: 50°C, 110°C, 0°C, and -40°C. 表 4 through 表 7 show the respective results. Observe from these results that the error caused by the temperature variations is significantly less. *The results shown here are the uncalibrated results.* The advantage of using a 25- $\mu$ V offset for the INA240-Q1 is that the user can obtain outstanding accuracy results which are best in class within the industry.

**表 4. Accuracy at 50°C<sup>(1)</sup>**

TEMPERATURE (°C)	VOLTAGE ACROSS SHUNT (mV)	EQUIVALENT CURRENT (mA)	EXPECTED OUTPUT (V)	MEASURED OUTPUT (INA OUTPUT) (V)	ABSOLUTE ACCURACY (%) AT 50°C
50	92.753	927.53	1.85506	1.8562	-0.061453538
50	74.412	744.12	1.48824	1.4887	-0.030908993
50	70.375	703.75	1.4075	1.408	-0.035523979
50	32.27	322.7	0.6454	0.64575	-0.054229935
50	20.898	208.98	0.41796	0.41828	-0.07656235
50	15.302	153.02	0.30604	0.30631	-0.088223762
50	11.006	110.06	0.22012	0.2204	-0.127203344
50	3.798	37.98	0.07596	0.076191	-0.304107425
50	1.937	19.37	0.03874	0.038964	-0.578213733
50	1.456	14.56	0.02912	0.029352	-0.796703297
50	1.166	11.66	0.02332	0.023552	-0.994854202
50	0.305	3.05	0.0061	0.006332	-3.803278689
50	0.21	2.1	0.0042	0.00439	-4.523809524

<sup>(1)</sup> The results shown here are the uncalibrated results.

**表 5. Accuracy at 110°C<sup>(1)</sup>**

TEMPERATURE (°C)	VOLTAGE ACROSS SHUNT (mV)	EQUIVALENT CURRENT (mA)	EXPECTED OUTPUT (V)	MEASURED OUTPUT (INA OUTPUT) (V)	ABSOLUTE ACCURACY (%) AT 110°C
110	92.909	929.09	1.85818	1.859	-0.044129202
110	79.848	798.48	1.59696	1.5977	-0.046338042
110	70.302	703.02	1.40604	1.4067	-0.046940343
110	32.282	322.82	0.64564	0.64688	-0.192057493
110	20.94	209.4	0.4188	0.4191	-0.071633238
110	15.323	153.23	0.30646	0.30673	-0.088102852
110	12.156	121.56	0.24312	0.24338	-0.106943073
110	11.03	110.3	0.2206	0.22085	-0.113327289
110	2.89	28.9	0.0578	0.058002	-0.349480969
110	1.944	19.44	0.03888	0.039073	-0.496399177
110	1.463	14.63	0.02926	0.029438	-0.608339029
110	1.172	11.72	0.02344	0.023632	-0.819112628
110	0.406	4.06	0.00812	0.008309	-2.327586207
110	0.254	2.54	0.00508	0.005269	-3.720472441
110	0.187	1.87	0.00374	0.003916	-4.705882353

<sup>(1)</sup> The results shown here are the uncalibrated results.

**表 6. Accuracy at 0°C<sup>(1)</sup>**

TEMPERATURE (°C)	VOLTAGE ACROSS SHUNT (mV)	EQUIVALENT CURRENT (mA)	EXPECTED OUTPUT (V)	MEASURED OUTPUT (INA OUTPUT) (V)	ABSOLUTE ACCURACY (%) AT 0°C
0	93.151	931.51	1.86302	1.8636	-0.031132248
0	74.614	746.14	1.49228	1.4927	-0.028144852
0	44.119	441.19	0.88238	0.88272	-0.038532152
0	25.346	253.46	0.50692	0.50721	-0.057208238
0	17.758	177.58	0.35516	0.35544	-0.078837707
0	10.989	109.89	0.21978	0.22003	-0.113750114
0	5.685	56.85	0.1137	0.11395	-0.219876869
0	2.303	23.03	0.04606	0.046305	-0.531914894
0	1.451	14.51	0.02902	0.029255	-0.809786354
0	1.161	11.61	0.02322	0.023473	-1.08957795
0	0.589	5.89	0.01178	0.012012	-1.969439728
0	0.249	2.49	0.00498	0.005217	-4.759036145

<sup>(1)</sup> The results shown here are the uncalibrated results.

**表 7. Accuracy at -40°C<sup>(1)</sup>**

TEMPERATURE (°C)	VOLTAGE ACROSS SHUNT (mV)	EQUIVALENT CURRENT (mA)	EXPECTED OUTPUT (V)	MEASURED OUTPUT (INA OUTPUT) (V)	ABSOLUTE ACCURACY (%) AT -40°C
-40	98.703	987.03	1.97406	1.974	0.003039421
-40	79.041	790.41	1.58082	1.5811	-0.017712327
-40	69.671	696.71	1.39342	1.3939	-0.034447618
-40	32.02	320.2	0.6404	0.64068	-0.043722673
-40	20.793	207.93	0.41586	0.41614	-0.067330352
-40	15.21	152.1	0.3042	0.30447	-0.088757396
-40	10.948	109.48	0.21896	0.21922	-0.118743149
-40	2.863	28.63	0.05726	0.057501	-0.420887181
-40	1.925	19.25	0.0385	0.038739	-0.620779221
-40	1.282	12.82	0.02564	0.025874	-0.912636505
-40	1.157	11.57	0.02314	0.023398	-1.114952463
-40	0.586	5.86	0.01172	0.011959	-2.039249147
-40	0.301	3.01	0.00602	0.006269	-4.136212625
-40	0.179	1.79	0.00358	0.003844	-7.374301676

<sup>(1)</sup> The results shown here are the uncalibrated results.

## 4 Design Files

### 4.1 Schematics

To download the schematics, see the design files at [TIDA-01506](#).

### 4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at [TIDA-01506](#).

### 4.3 PCB Layout Recommendations

The following three bullet points list the three primary tasks to accomplish when doing the layout for a solenoid current sensor (see [图 26](#)).

- Ensure a Kelvin connection for the 100-Ω shunt.
- The solenoid, high-side switch, and shunt must be very close in proximity (the loop distance is very small).
- Use thicker lines for the solenoid current (calculate line thickness based on the current capability of the solenoid).

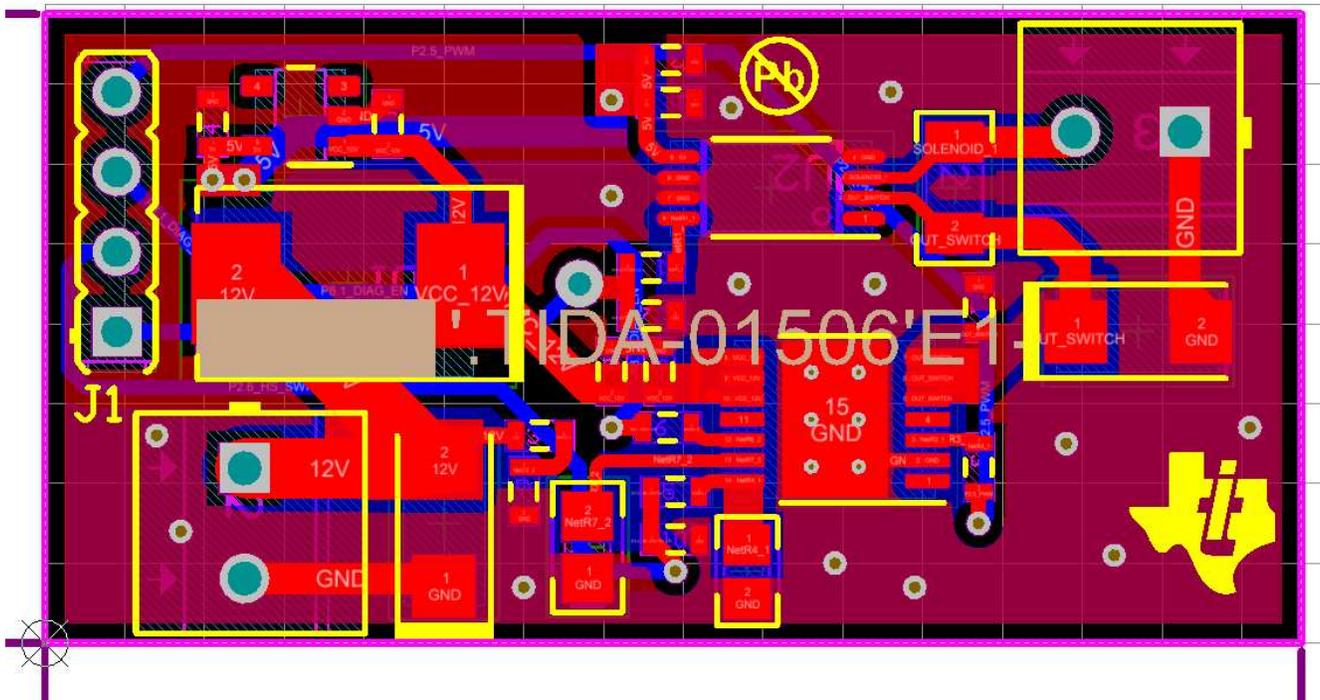


图 26. PCB Layout

#### 4.3.1 Layout Prints

To download the layer plots, see the design files at [TIDA-01506](#).

### 4.4 Altium Project

To download the Altium project files, see the design files at [TIDA-01506](#).

#### 4.5 Gerber Files

To download the Gerber files, see the design files at [TIDA-01506](#).

#### 4.6 Assembly Drawings

To download the assembly drawings, see the design files at [TIDA-01506](#).

### 5 Related Documentation

1. Texas Instruments, [High-Side Drive, High-Side Solenoid Monitor With PWM Rejection](#)
2. Texas Instruments, [Current Controlled Driver for 24-V DC Solenoid With Plunger Fault Detection](#)

#### 5.1 商标

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### 6 About the Author

**SANDEEP TALLADA** is a systems engineer at Texas Instruments. As a member of the Automotive Systems Engineering team, Sandeep focuses on HEV/EV, powertrain end-equipments and creating subsystem reference designs. He brings to this role experience in sensor systems technology. Sandeep earned his master of science in sensor systems technology from the University of Applied Sciences Karlsruhe, Germany.

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