TI Designs
Current Controlled Driver for AC Solenoids

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Design Resources

TIDA-00284	Tool Folder Containing Design Files
DRV110APW	Product Folder
TLV271IDBVR	Product Folder
DRV5023AJQDBZT	Product Folder

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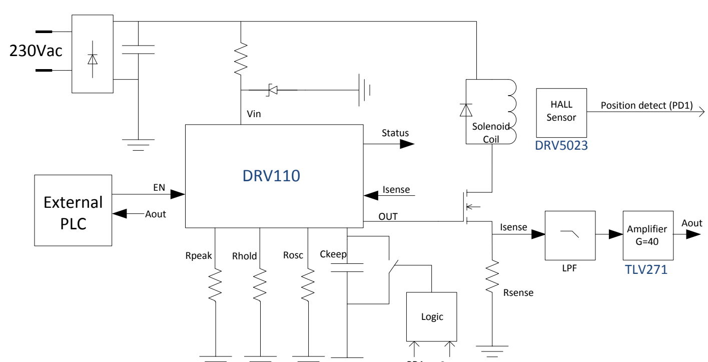
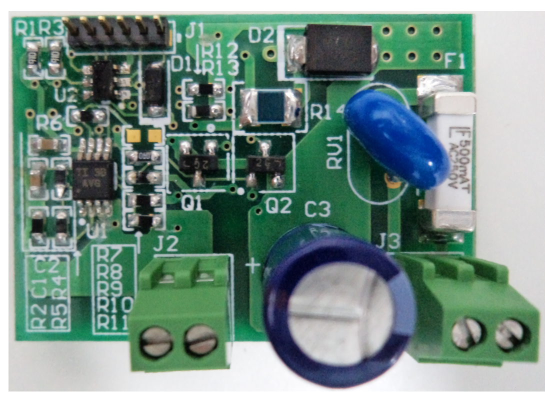
Design Features

- Uses DRV110 solenoid current controller with power-saving capability and an integrated supply regulation
- Control of solenoid current during peak and hold modes for lower power and thermal dissipation using the pulse width modulation (PWM) technique with an external MOS field effect transistor (MOSFET)
- Peak current, KEEP time at peak current, hold current, and PWM clock frequency are adjustable through external components
- Features an interface Hall sensor to detect plunger movement and switch to hold mode
- Provides a logic EN pin for the programmable logic controller (PLC) to activate or deactivate the solenoid
- Provides a 0- to 10-V analog output that is proportional to solenoid current (to interface with the PLC)

Featured Applications

- Electromechanical driver: solenoids, valves, and relays





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1 System Description

Overcurrent protection devices, such as circuit breakers, protect equipment from drawing excessive current. The design of overcurrent protection devices keep the flow of current in a circuit at a safe level to prevent the circuit conductors from overheating. Relays are integral parts of any switchgear equipment because relays connect or disconnect the mains to or from the protected equipment through coil energization and contacts.

The primary use of contactors is to make (connect) or break (disconnect) contact in the conducting element. Contacters are used in systems where the make-and-break connection is either frequent or unchanged for long periods of time. Direct online starters are one such example of contactors.

Valves are used in a variety of applications such as refrigeration, air conditioning, and hydraulic systems to control the flow of fluid and air.

Valves, relays, and contactors all use electromechanical solenoids to operate. Solenoid coils are rated to operate from 12-V DC to 24-V DC and 110-V AC to 230-V AC systems with a power consumption ranging from 8 W to 20 W. Solenoid coils require more current only during actuation. In a steady state the solenoid coil requires an approximate 30% of the nominal current. The continuous operation of a solenoid coil with nominal current results in an increased temperature in the coil due to higher power dissipation.

This reference design provides a solution to control the solenoid current using a PWM-based controller along with a Hall sensor to detect plunger movement and switch from peak current to hold current mode.

1.1 Characteristics of Solenoid Coils

Electromechanical solenoids consist of an electromagnetically inductive coil wound around a movable steel rod or iron slug known as the armature or plunger. The shape of the coil allows movement of the armature in and out of the center of the coil. This movement alters the inductance of the coil and changes the magnetic field associated with the coil. The armature provides a mechanical force to activate the control mechanism, for example, the opening and closing of a valve.

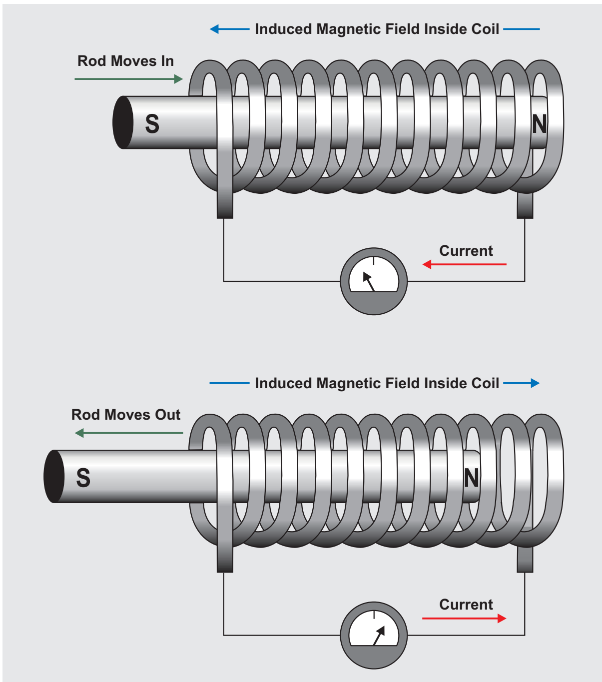


Figure 1. Function of a Solenoid Coil

The main electrical characteristic of a solenoid is that of an inductor, which opposes any change in current. Due to this characteristic, the current does not immediately reach a maximum level when energizing a solenoid. Instead, the current rises at a steady rate until the DC resistance of the solenoid limits the current. An inductor, (in this case a solenoid), stores energy in the form of a concentrated magnetic field. Whenever a current is present in a wire or conductor, a magnetic field, however small, creates around the wire. Winding a wire in many turns into a coil, such as a solenoid coil, creates a high concentration in the magnetic field. This electromagnetic field can be used to control a mechanical valve through an electrical signal. Upon energizing the solenoid, the current increases causing the magnetic field to expand until the magnetic force is strong enough to move the armature. The armature movement increases the concentration of the magnetic field as the magnetic mass of the armature moves farther into the magnetic field.

A magnetic field changing in the same direction of the current creating the field induces an opposing voltage into the windings. The magnetic field quickly expands when the armature strokes, causing a brief reduction in the current through the solenoid windings. After the armature strokes, the current continues on the normal upward path to a maximum level. View a typical current waveform in Figure 2. Notice the prominent dip in the rising portion of the current waveform.

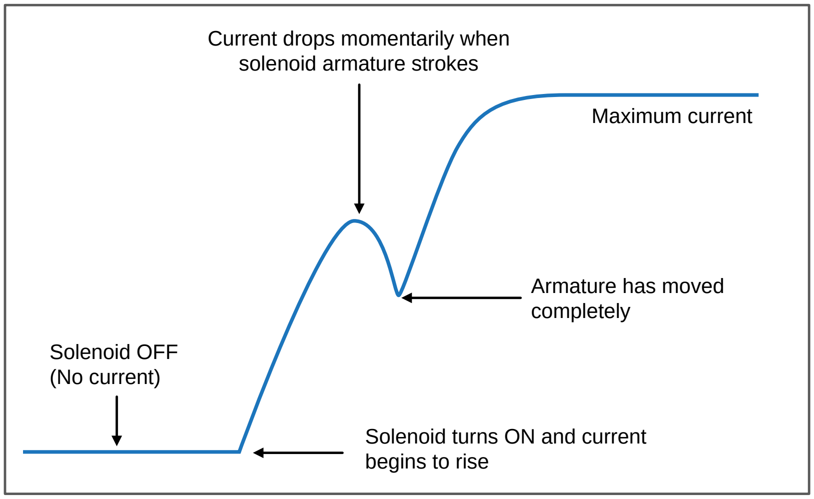


Figure 2. Solenoid Current

1.2 Driving the Solenoid Coil: Voltage or Current Drive?

The armature of a solenoid provides a mechanical force to activate the control mechanism. The force applied to the armature is proportional to the change in inductance of the coil due to the change in position of the armature.

The electromagnetic force of a solenoid directly relates to the current. Traditionally, use of a voltage drive to energize the solenoid coils causes a continuous power consumption in the coil. The heating of the coil, which subsequently heats the entire relay, is a negative effect of this power consumption. The coil temperature is a result of several factors: ambient temperature, self-heating due to the power consumption of the coil (of V × I), heating induced by the contact system, magnetization losses due to eddy currents, and other heat sources such as components in the vicinity of the relay. Coil resistance increases due to the coil heating. The resistance at elevated temperature is expressed by Equation 1:

$$R_{COIL\_T°C} = R_{COIL\_2\text{-}°C}[1 + k_{R\_T}(T°C – 20°C)]$$

where

- $R_{COIL\_20°C}$ is the resistance of the coil at 20°C
- k_{R_T} is the thermal coefficient of copper (= 0.00404 per °C)
- (1)

Based on $R_{COIL\_20°C}$, typically given in the datasheet of a solenoid coil, calculate the worst-case coil resistance at high temperature.

During circuit design, be sure to calculate for worst-case conditions, such as the highest possible coil temperature at the operating pick-up voltage. Also note that for any given coil the pick-up current remains the same at any condition. The pick-up current depends on the relationship between the pick-up voltage and the coil resistance ($I_{PICK\text{-}UP} = V_{PICK\text{-}UP} / R_{COIL}$). Most relay coils consist of copper wire. Due to the increase in coil temperature, the coil resistance increases as per Equation 1. Therefore, the pick-up voltage for the hot coil should be increased to generate the required pick-up current. For example, if the pick-up voltage of a 12-V DC relay is 9.6-V DC and the coil resistance is 400 Ω at 20°C, then $I_{PICK\text{-}UP}$ = 24 mA. When the coil temperature increases to 40°C, the coil resistance increases to 432 Ω, which results in a pick-up voltage of 10.36-V DC. The pick-up current remains the same. An increase in temperature by 20°C increases the pick-up voltage by 0.76-V DC. In relays operating with higher duty cycles, the pick-up voltage may increase slightly for each successive cycle due to the temperature rise of the coil. Figure 3 shows that the user may have to overdesign the coil if using voltage drive.

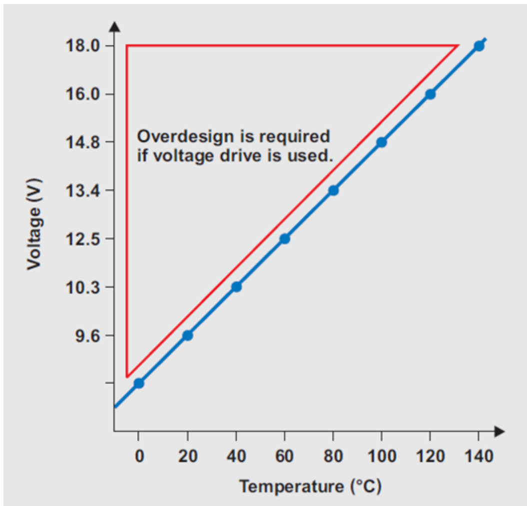


Figure 3. Overdesign for a Solenoid Voltage Drive

Voltage drive forces overdesign because the current changes with variations to coil resistance, temperature, supply voltage, and so on. Using current drive is optimal for many devices with solenoids.

1.3 Optimizing Power Consumption

Closing a relay or valve requires a lot of energy. The instantaneous current that activates the solenoid actuator, called the peak current (I_{PEAK}), can be high. However, once the relay or valve is closed, the current required to keep the relay or valve closed, called the hold current (I_{HOLD}), is significantly less than the peak current. During the use of voltage drive, the current flow through the solenoid coil is continuous and greater than that of the current drive. Unlike voltage drive, current drive requires no margin for parameter changes caused by temperature or solenoid-resistance variations. The design requires separate values for the peak current, which may be in the range of amperes. The design also requires separate values for the steady-state hold current, which may only be a fifth of the peak-current value.

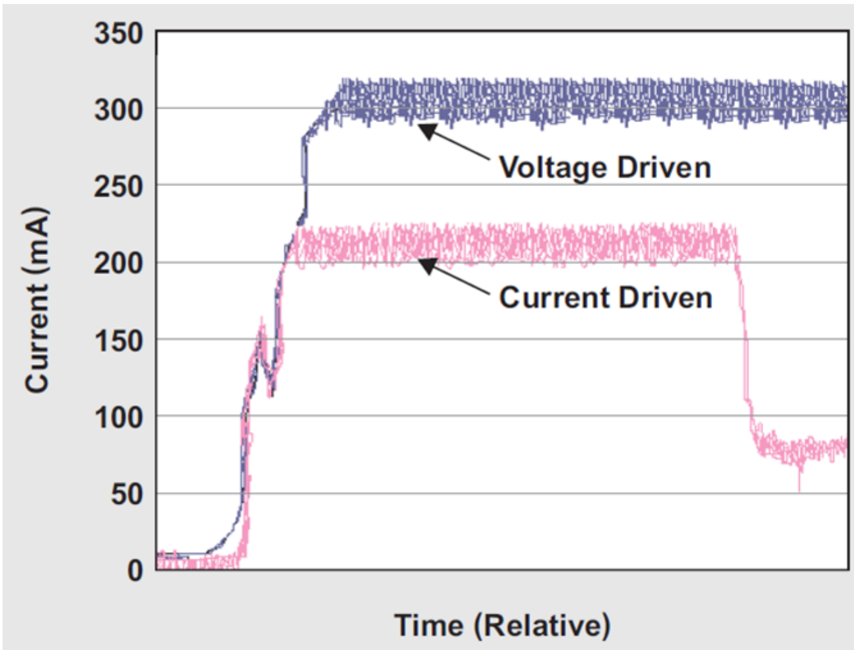
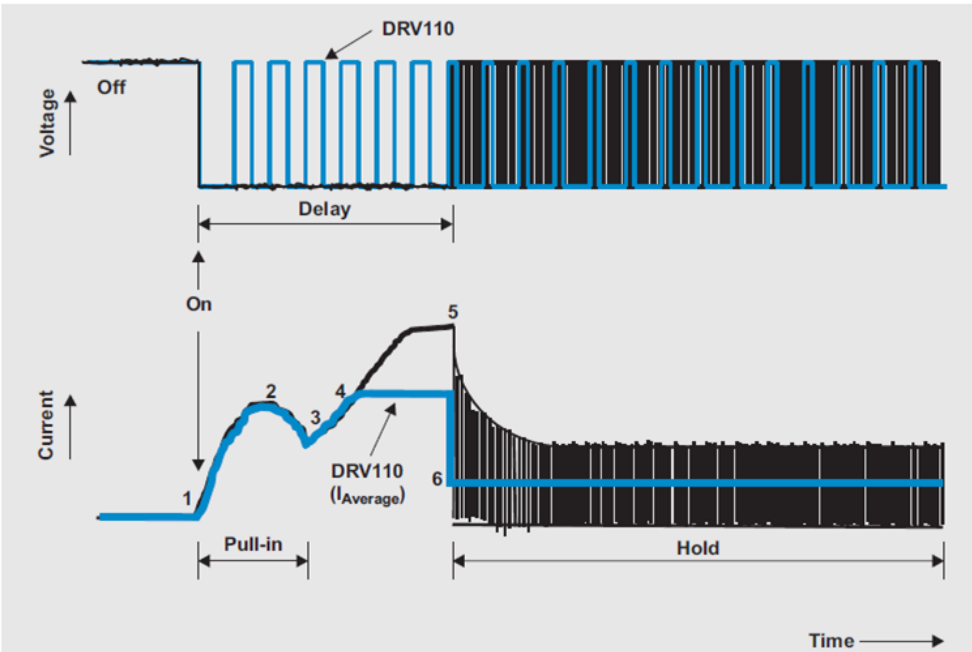


Figure 4. Solenoid Current With Voltage Drive and Current Drive

1.4 Current-Control Implementations for Driving a Solenoid Coil:

Traditionally, the general-purpose inputs and outputs (GPIOs) of the microcontroller (MCU) control the solenoid coil through the external bipolar junction transistor (BJT) or MOSFET. A newly developed driving system uses PWM to control the current waveform. The duty cycle of the PWM determines the average current through the coil. The design of the DRV110-based system regulates the current with a well-controlled waveform to reduce power dissipation. After the initial ramping, the solenoid current remains at a peak value to ensure correct operation. To avoid thermal problems and reduce power dissipation, the solenoid current is reduced to a lower hold level. The graphs in Figure 5 compare the operation of a conventional driver with that of the DRV110. Note that other methods reduce voltage but must have an overhead to guarantee that the hold current is constantly maintained across the temperature.



Step 1: Relay driver is enabled.

Step 2: Start of mechanical movement. This movement generates a back-EMF that counters the solenoid flux, reducing current.

Step 3: End of mechanical movement. (Current increases again.)

Step 4: DRV110 limits pull-in current, saving power.

Steps 5 and 6: Hold mode is entered after a delay. The DRV110's hold-current value is the lowest possible.

Figure 5. Operation of a Conventional Driver Versus DRV110

2 Design Features

The primary objective of this design is to provide a current-controlled drive for a solenoid or valve excitation with an optimum power consumption using a minimum number of components. This design objective leads to a reduced power loss in the solenoid and increases durability.

2.1 Design Requirements

The system-level requirements for this design include:

- Operation of the solenoid from an input voltage of 230-V AC ±15%
- A PWM current controller to scale the current drawn by the solenoid during excitation peak and hold period
- Peak current, KEEP time at peak current, hold current, and PWM clock frequency should be programmable through external components
- A rectifier stage to power up the driver with a DC supply
- A digitial input to control the driver from a PLC or control unit
- A signal conditioning and amplification circuit to provide a 0- to 10-V analog output, scaled to solenoid current to interface with a PLC
- A provision to interface a Hall sensor which detects the complete movement of the plunger

3 Block Diagram

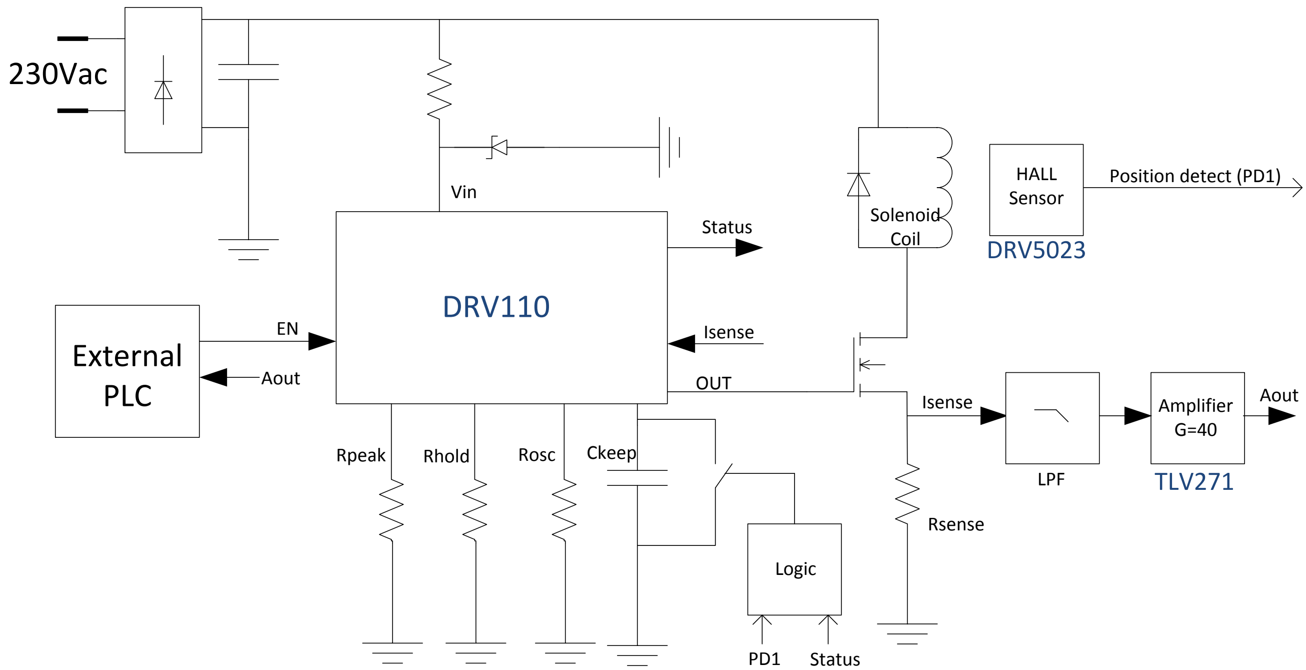


Figure 6. Block Diagram of the Solenoid Driver Using DRV110

The main parts of the design include the DRV110 controller, a suitable MOSFET, analog op-amp circuits, and a digital input for operating the DRV110. Operate the solenoid coil by applying an input voltage or by using a digital input signal (EN). The PLC units can control the operation of the DRV110 through the EN pin.

The OUT pin of the DRV110 delivers the gate pulses to the external MOSFET.

The use of R_{PEAK}, R_{HOLD} and R_{SENSE} resistors set the peak and hold current references of the DRV110. R_{OSC} determines the switching frequency and C_{KEEP} determines the duration of the peak current period.

The R_{SENSE} resistor senses the solenoid current. A low pass filter filters the solenoid current. The filter then sends the solenoid current to the amplifier TLV271 to generate A_{OUT}.

Use the Hall sensor DRV5023 to detect the position of the plunger.

The STATUS output pin of the DRV110 is a logic signal which corresponds to undervoltage and over temperature detection.

An external switch (BJT) shorts the C_{KEEP} until the plunger moves to the intended position. Upon moving to the intended position, C_{KEEP} will be allowed to charge there by transitioning from peak current to hold current.

4 Component Selection and Circuit Design

This reference design features the following devices:

- DRV110A (power-saving solenoid controller)
- TLV271
- DRV5023

For more information on each of these devices, see the respective product folders at www.TI.com or click on the links for the product folders in Design Resources.

4.1 Component Selection

4.1.1 DRV110A

The DRV110 is a PWM current controller for solenoids. The designed function of the DRV110 is to regulate the solenoid current with a well-controlled waveform to reduce power dissipation. The solenoid current ramps up fast to ensure the opening of the valve or relay. After initial ramping the solenoid current is kept at peak value to ensure the correct operation, after which the current is reduced to a lower hold level to avoid thermal problems and reduce power dissipation.

The peak current duration is set with an external capacitor. The current ramp peak and hold levels, as well as the PWM frequency, can be set independently with external resistors. External setting resistors can also be omitted if the default values for the corresponding parameters are suitable for the application.

The DRV110 device limits its own supply at V_{IN} to 15 V, which is also the gate drive voltage of an external switching device. A MOSFET that is driving the solenoid is an example of an external switching device. If an external switching device requires a gate drive voltage that is lower, use an external supply of at least 6 V.

Device features:

- Drives an external MOSFET with the PWM to control the solenoid current using an external sense resistor
- Guarantees activation through the fast ramping up of a solenoid current
- Reduces the solenoid current in the hold mode to reduce power consumption and thermal dissipation
- Regulates internal supply voltage to 15 V using an external pull-up resistor

4.1.2 TLV271

The TLV271 is a 3-MHz rail-to-rail dual operational amplifier in a 5-pin SOT-23 package. This amplifier allows work from a wide supply voltage of 2.7-V to 16-V DC. The low-supply current of 550 uA per channel and low-offset voltage also make this device suitable for the application.

The TLV271 takes the minimum operating supply voltage down to 2.7 V over the extended industrial temperature range while adding the rail-to-rail output swing feature. The TLV271 device also provides 3-MHz bandwidth from only 550 μA.

The TLV271 meets the full specifications for 5-V and ±5-V supplies. The maximum recommended supply voltage is 16 V, which allows operation of the devices from a variety of rechargeable cells (±8-V supplies down to ±1.35-V supplies).

The complementary metal-oxide semiconductor (CMOS) inputs enable use in high-impedance sensor interfaces and with a lower voltage operation. The TLV271 features a slew rate of 2.4 V/µs.

4.1.3 DRV5023

The DRV5023 device is a chopper-stabilized Hall effect sensor that offers a magnetic sensing solution with superior sensitivity stability over temperature and integrated protection features. The DRV5023 offers the high sensitivity option of 6.9 / 3.3 mT. This high sensitivity option allows the detection of flux linkage in the solenoid when the plunger is in the closed position. When the applied magnetic flux density exceeds the operating point (B_{OP}) threshold, the DRV5023 open-drain output goes low. The output remains low until the field decreases to less than release point (B_{RP}) and then the output goes to high impedance. The capability of the output current sink is 30 mA. The DRV5023 supports a wide voltage range from 2.5 V to 38 V. A reverse polarity protection up to –22 V enables the use of this device for a wide range of industrial applications. Internal protection features are provided for reverse supply conditions, load dump, and output short circuit or over current.

4.2 Circuit Design

4.2.1 Input Supply and Voltage Regulation for DRV110

Figure 7 shows the input supply and voltage regulation circuit for the DRV110. J4 is the input connector for the 230-V AC input supply. A protective fuse is used at the AC supply input and is followed by the metal oxide varistor for surge protection. The input supply is then rectified and filtered by the capacitor C4. The design of capacitor C4 allows for a minimum amount of ripple during the peak current mode of the solenoid. The components R25, R16, R4, and D1 are for voltage regulation of the DRV110.

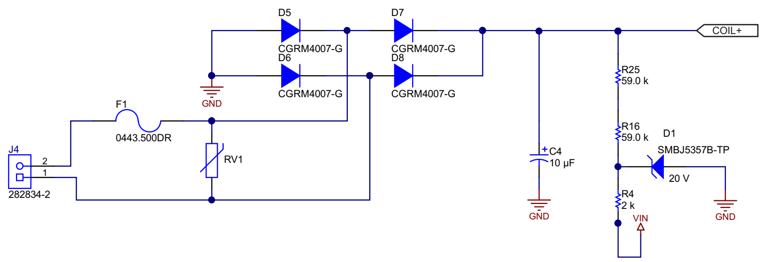


Figure 7. Input Supply and Voltage Regulation Circuit for DRV110

4.2.1.1 *Calculating the Current Limiting Resistor to Regulate V_{IN}*

The DRV110 is able to regulate V_{IN} voltage to 15 V from a higher external supply voltage. This regulation occurs due to an internal bypass regulator, which replicates the function of an ideal Zener diode. This regulation requires the supply current to be sufficiently limited by an external resistor between the external supply and the V_{IN} pin. C6, the external capacitor connected to V_{IN}, is used to store enough energy to charge the external switch gate capacitance at the OUT pin. Calculate the size of the limiting resistor (R_S) to keep quiescent current less than 1 mA with Equation 2.

$$R_S = \frac{V_{S\_MIN(DC)} - 15\ V}{1\,mA + I_{GATE\_AVG} + I_{AUX}}$$

where

- $V_{S\_MIN(DC)}$ is the minimum for DC supply voltage after the rectifier
- I_{GATE_AVG} is the average gate current required for driving the MOSFET in milli-ampere
- I_{AUX} is the current drawn by all the other circuits which derive current from V_{IN} (2)

To limit the power dissipation in the internal bypass regulator of the DRV110 an additional Zener D1 is provided externally in the circuit. D1 is a 20-V Zener. Use R25 and R16 to drop the voltage down to 20 V. The use of R4 drops the voltage down to 15 V.

Calculating I_{GATE_AVG}

The selected switching device Q2 has a total gate charge requirement of Q_G = 11 nC at 10 V (V_{GS}).

Gate voltage, V_G	= 15 V	
Switching frequency, F_{SW}	= 20 kHz	
Total gate capacitance, C_{GATE}	$= Q_G / V_{GS}$ = 1.1 nC	
Average gate power, P_{GATE}	$= 0.5 \times C_{GATE} \times V_G^2 \times f_{SW}$	(3)
	= 2.475 mW	
Average gate current, I_{GATE_AVG}	$= P_{GATE} / V_G$	(4)
	= 0.165 mA	

Calculating I_{AUX}

The devices that draw power from the regulated voltage V_{IN} include the op-amps, the Hall sensor, and the entire resistive divider network. The supply current of the Hall sensor is approximately 3 mA and the current taken by the other circuits is approximately 1 mA.

Calculating the value of R_S without considering the source current required for the Hall sensor

In the reference design, R_S	= R25 + R16 + R4
Minimum input voltage	= 195-V AC
Peak value of the rectified voltage	= 276 V
Total current requirement	= 1 mA + I_{GATE_AVG} + I_{AUX} = 2.165 mA
Therefore, R_S	= (276 – 15) V / (1 + 0.165 + 1) mA (5)
	= 121 kΩ

The Zener diode D1 clamps the voltage to 20 V using the series resistors R25 and R16. The maximum value of the resistor R4 then drops 5 V when 2.165 mA flows through the R4, resulting in R4 = 2.3 kΩ.

To total 121 k, select R25 and R16.

The power dissipation in resistors R25, R16, and R4 becomes maximum at the maximum input voltage. Design the power rating of these resistors to reach the maximum input AC voltage.

At the 265-V AC input, the peak value of the rectified DC voltage is 375 V, leading to total power dissipation in R16 and R25 to 1.05 W.

Therefore the power dissipation in each resistor is approximately 0.5 W. Similarly, the power dissipated in R4 is 17 mW.

Calculating the value of R_S considering the source current required for the Hall sensor

The supply current required for the Hall sensor is 3 mA at 25°C.

At an input voltage of 230-V AC, using Equation 5, R_S must be less than 52 kΩ.

4.2.2 DRV110 Circuit and Solenoid Current Control Circuit

Figure 8 shows the DRV110 circuit, the solenoid connections, and the power switching device.

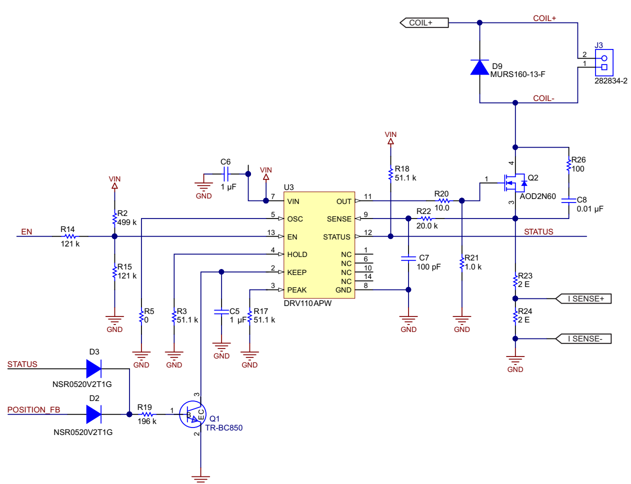


Figure 8. DRV110 Circuit and Solenoid Current Control Circuit

J3 is the connector for solenoid terminals. D9 is the freewheeling diode. Q2 is the power switching device. R23 and R24 sense the switch current.

4.2.2.1 ENABLE Signal

The DRV110 controls the current through the solenoid as shown in Figure 9. The DRV110 activates when the EN pin voltage is pulled high either by an external driver or an internal pull-up. At the start of activation, the DRV110 allows the load current to ramp up to the peak value I_{PEAK}. The DRV110 then regulates the load current at the peak value for the time, t_{KEEP}, before reducing the load current to I_{HOLD}. The load current is regulated at the hold value as long as the EN pin is kept high. The ramp-up time for the initial current depends on the inductance and resistance of the solenoid. As soon as the EN pin is driven to the ground (GND), the DRV110 allows the solenoid current to decay to zero.

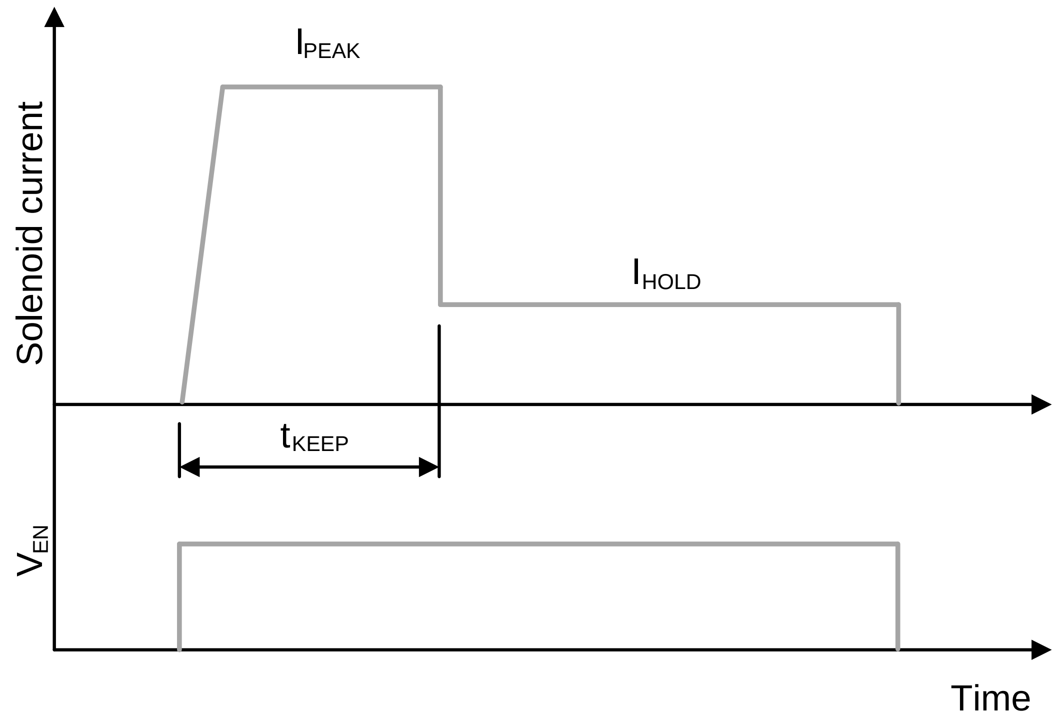


Figure 9. EN Signal Controlling DRV110

Table 1. Parameter Specification of the EN Input of DRV110

PARAMETER		MIN	TYP	MAX
VIL	Input low level			1.3 V
VIH	Input high level	1.65 V		
REN	Input pull-up resistance	350 kΩ	500 kΩ	

The resistive divider supplies the enable pin, consists of R2 and R15, and is operated from V_{IN} as shown in the circuit in Figure 10.

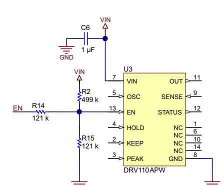


Figure 10. EN Signal Control Circuit

The R2 and R_{EN} now form a parallel path and the equivalent resistance, which is given by Equation 6.

$$R_{EQVT} = \frac{R_2 \times R_{EN}}{R_2 + R_{EN}} \quad (6)$$

The DRV110 enables when V_{EN} reaches 1.65 V which is V_{IH} of the EN pin and is given by Equation 7.

$$V_{EN} = V_{IN} \times \frac{R15}{R15 + R_{EQVT}} \quad (7)$$

Alternatively, the DRV110 enables when V_{IN} reaches a value given by Equation 8

$$V_{IN} = 1.65 \times \frac{R15 + R_{EQVT}}{R15} \quad (8)$$

In the reference design R2 = 499 k, R15 = 121 k.

The DRV110 will turn on at approximately V_{IN} = 5 V.

When an external source supplies the EN logic signal, populate R14 and do not populate R2. Calculate the value of R14 and R15 accordingly when considering the internal pull-up resistor of DRV110.

The EN pin of the DRV110 has an absolute maximum rating of 7 V. To ensure safe operation, confirm that the EN pin voltage is less than 5 V. When the PLC has 0 to 5 V, the EN pin directly supplies the voltage.

When the PLC has an output voltage of 0 to 10 V, design R14 and R15 so that the EN pin voltage is at a maximum of 5 V.

4.2.2.2 *Current Control*

The current control loop regulates cycle by cycle. The solenoid current is regulated by sensing voltage at the SENSE pin and controlling the external switching device gate through the OUT pin. During the ON-cycle, the OUT pin voltage is driven and remains high (equal to V_{IN} voltage) as long as the voltage at the SENSE pin is less than V_{REF}, which allows the current to flow through the external switch. As soon as the voltage at the SENSE pin is above V_{REF}, the OUT pin voltage is immediately driven and kept low until the signal from the internal PWM clock triggers the next ON-cycle. In the beginning of each ON-cycle, the OUT pin voltage is driven and kept high for at least the time determined by the minimum of the PWM signal duty cycle, D_{MIN} (7.5%).

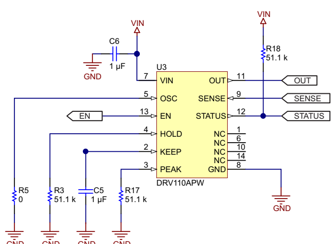


Figure 11. DRV110 Circuit With Reference Setting Resistors

Determining I_{PEAK} and I_{HOLD} of the DRV110

The ON resistance of the solenoid coil determines the activation (peak) current of the DRV110 in addition to the pick-up voltage the solenoid coil requires. This resistance value at maximum temperature ($R_{COIL\_T(MAX)}$) and the relay nominal operating voltage (V_{NOM}) can be used to calculate the I_{PEAK} value required at maximum temperature:

$$I_{PEAK} = \frac{V_{NOM}}{R_{COIL\_T(MAX)}} \quad (9)$$

The hold current of the DRV110 is determined by the ON resistance of the coil and by the voltage required to keep the relay from dropping out. To prevent the relay from dropping out, manufacturers provide the recommended voltage values in datasheets. Add a margin for vibration and other contingencies when considering voltage values. Many relay manufacturers list 35% of the nominal voltage as a safe limit. Assuming this voltage to be enough, the $R_{COIL\_T(MAX)}$ value and the nominal operating voltage of the relay (V_{NOM}) can be used to calculate the I_{HOLD} value that works over the temperature:

$$I_{HOLD} = \frac{0.35 \times V_{NOM}}{R_{COIL\_T(MAX)}} = 0.35 \times I_{PEAK} \quad (10)$$

V_{PEAK} and V_{HOLD} depend on the fixed resistance values of R_{PEAK} and R_{HOLD}. If the PEAK pin connects to the ground, the peak current reference voltage, V_{PEAK}, is at the default value (internal setting). An alternative way to set the V_{PEAK} value is by connecting an external resistor to the ground from the PEAK pin. For example, if a 50-kΩ (= R_{PEAK}) resistor connects between the PEAK pin and GND, and R_{SENSE} = 1 Ω, then the externally set I_{PEAK} level is 900 mA. If R_{PEAK} = 200 kΩ and R_{SENSE} = 1 Ω, then the externally set I_{PEAK} level will be 300 mA.

In situations where R_{SENSE} = 2 Ω instead of 1 Ω, then I_{PEAK} = 450 mA (when R_{PEAK} = 50 kΩ) and I_{PEAK} = 150 mA (when R_{PEAK} = 200 kΩ). The external setting of the HOLD current, I_{HOLD}, works similar to the I_{PEAK} reference setting, but the current levels are a sixth of the I_{PEAK} levels. The external settings for I_{PEAK} and I_{HOLD} are independent of each other. If R_{PEAK} is decreased below 33.33 kΩ (typ value), then the reference is clamped to the internal setting voltage of 300 mV. The same is valid for R_{HOLD} and I_{HOLD}. The values for I_{PEAK} and I_{HOLD} can be calculated by using the formulas in Equation 11 and Equation 12.

$$I_{PEAK} = \frac{1\,\Omega}{R_{SENSE}} \times \frac{900\text{ mA}}{R_{PEAK}} \times 66.67\text{ k}\Omega\ ;\ 66.67\text{ k}\Omega < R_{PEAK} < 2\text{ M}\Omega \quad (11)$$

$$I_{HOLD} = \frac{1\,\Omega}{R_{SENSE}} \times \frac{150\text{ mA}}{R_{HOLD}} \times 66.67\text{ k}\Omega\ ;\ 66.67\text{ k}\Omega < R_{HOLD} < 333\text{ k}\Omega \quad (12)$$

The variation of the peak and hold current references (with R_{PEAK} and R_{HOLD} resistance values) is shown in Figure 12.

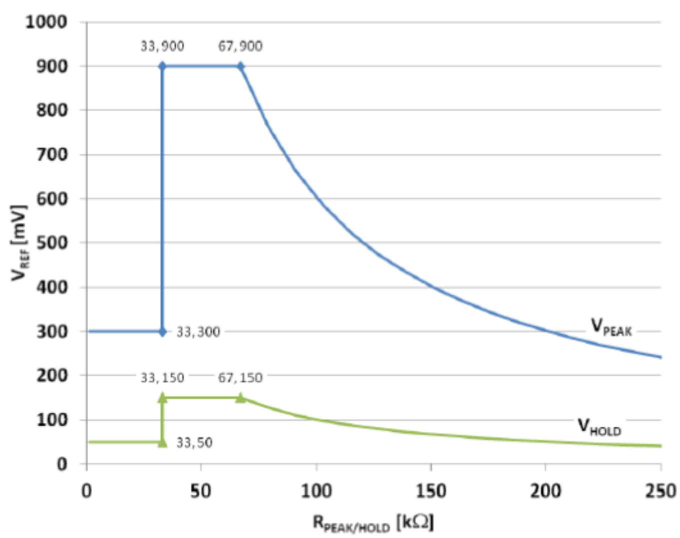


Figure 12. PEAK and HOLD Mode V_{REF} Settings for DRV110

When driven directly from a 230-V AC, the solenoid coil used for testing has a peak-to-peak steady-state current of 230 mA at 25°C.

By properly sizing the sense, peak, and hold resistors in this reference design, the peak and hold current values are selected as 200 mA and 50 mA respectively.

I_{PEAK} = 200 mA

I_{HOLD} = 50 mA

In the reference design R23 and R24 form the sense resistor.

R_{SENSE} = R23 + R24 = 4 Ω,

R_{PEAK} = R17 = 51.1 k and R_{HOLD} = R3 = 51.1 k

4.2.2.3 Determining the Value of KEEP Time

Connecting a capacitor to the KEEP pin externally sets the time, t_{KEEP}. The KEEP pin supplies a constant current which is driven into an external capacitor, resulting in a linear voltage ramp. When the KEEP pin voltage reaches 100 mV, the regulation reference voltage of the current, V_{REF}, switches from V_{PEAK} to V_{HOLD}. Calculate the dependency of t_{KEEP} on the external capacitor size from Equation 13.

$$t_{KEEP}\left[S\right] = C_{KEEP}\left[F\right] \times 10^{5}\left[\frac{S}{F}\right] \tag{13}$$

To get t_{KEEP} = 100 ms, C_{KEEP} = 1 µF

Table 2. Capacitance Value for Different KEEP Time

CAPACITANCE (µF)	KEEP TIME (ms)
0.01	1
0.02	2
0.03	3
0.04	4
0.05	5
0.06	6
0.07	7
0.08	8
0.09	9
0.1	10
0.2	20
0.3	30
0.4	40
0.5	50
0.6	60
0.7	70
0.8	80
0.9	90
1	100

4.2.2.4 Determining the Oscillator Frequency

An external resistor, R_{OSC}, which connects between the OSC and the GND, can adjust the frequency of the internal PWM clock signal (PWMCLK), which triggers each OUT pin ON-cycle. When the OSC connects directly to the GND a default frequency is used. Equation 14 shows the PWM frequency as a function of the value of an external resistor with a fixed adjustment (greater than 66.67 kΩ).

$$F_{PWM} = \frac{60\ \text{kHz}}{R_{OSC}} \times 66.67\ \text{k}\Omega\ ;\ 66.67\ \text{k}\Omega < R_{OSC} < 2\ \text{M}\Omega \quad (14)$$

Figure 13 shows the variation of switching frequency with R_{OSC}.

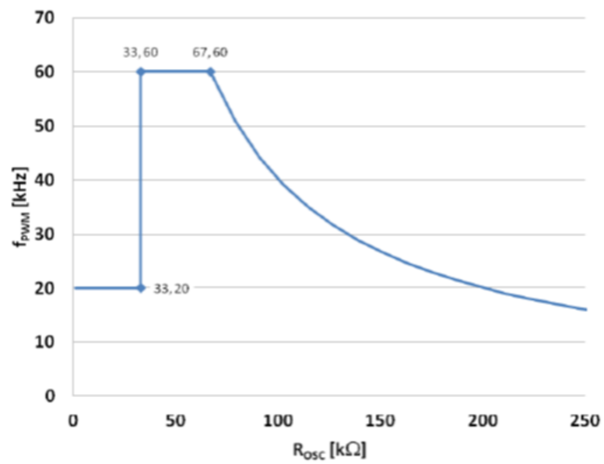


Figure 13. PWM Clock Frequency Setting for DRV110

This reference design uses a 20-kHz frequency. Therefore R_{OSC} = 0 Ω.

4.2.2.5 STATUS Pin

An open-drain pull-down path at the STATUS pin deactivates if either the undervoltage lockout or thermal shutdown blocks are triggered. Connect a pull-up at the STATUS pin to obtain the digital signal output.

The threshold levels are

- Threshold of undervoltage lockout (UVLO) = 4.6 V
- Thermal shutdown - junction temperature startup threshold = 140°C
- Thermal shutdown - junction temperature shutdown threshold = 160°C

In the reference design, R18 is the pull-up resistor connected to the status pin. The STATUS pin output is logic high when V_{IN} is less than the UVLO threshold. When V_{IN} is more than the UVLO threshold, the STATUS pin output is logic low. When the DRV110 detects undervoltage the STATUS pin output will be logic high or V_{IN}.

4.2.2.6 Selection of the Power Switching Device

The reference design is used to drive solenoids rated at 230-V AC ±15%. The nominal current of the solenoid is approximately 0.25 A. With regard to safety margin, select any MOSFET rated for 1 A or more at the operating junction temperature. With an operating junction temperature of 100°C, the MOSFET must be rated for a continuous current rating greater than 1 A at 100°C.

The maximum DC operating voltage of the switch (at 230-V AC +15% input supply) is 375 V. With regard to the safety margin, select a switch with a 600-V rating.

To allow proper switching, select a device with a gate charge less than 10 nC at 10 V.

4.2.3 Signal Conditioning and Amplifier Stage

In this reference design, a differential amplifier is used to provide the solenoid current information to the external interface. The solenoid current can be derived by sensing the switch current. The switch current is sensed across R24 and amplified. R9, C2, and R12 form a low-pass filter.

Selecting R9 = R12, R8 = R10 and R11 = R13

Gain of the differential amplifier U2 A = R13 / (R8 + R9) (15)

Output of the differential amplifier = I_{SENSE} × R24 × R13 / (R8 + R9)

where

- I_{SENSE} is the solenoid current sensed by R24 (16)

I_{SENSE} has switching current ripples at the PWM frequency; therefore, tracking the peak of I_{SENSE} gives the solenoid current. D4, R7, C1, and R6 form the filter network to constantly track the peak output of the differential amplifier.

A_{OUT} is the filtered current available at the interface for monitoring.

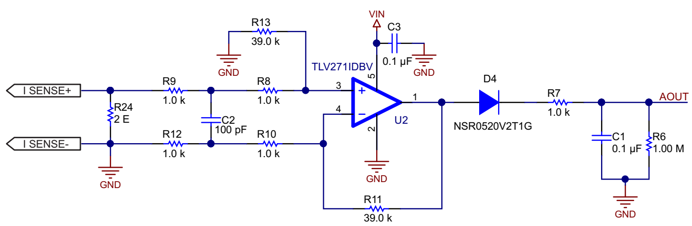


Figure 14. Solenoid Current Amplification Stage

In the reference design, the gain of the differential amplifier	= 20
Output of the differential amplifier	= I_{SENSE} × 2 × 20
	= 40 × I_{SENSE}
Therefore,	
A_{OUT}	= 40 × solenoid current
Therefore, when the solenoid current is 0.2 A, A_{OUT}	= 8

4.2.4 Plunger Position Detection Using Hall Sensor

The user can mount the DRV5023 device on the side of the solenoid where the plunger tip makes contact. View the experimental setup in Figure 15. When the plunger is open and the solenoid coil is supplied with current, the magnetic flux density produced by the coil is minimum. The Hall sensor detects this magnetic field as a weak field and provides logic high at the output due to the pull-up resistor. When the plunger closes, the flux linkage is maximum value and the Hall sensor pulls the output to logic low. When mounting the Hall sensor on the solenoid, a 0.01-μF (minimum) ceramic capacitor rated for V_{CC} must be placed as close to the DRV5023 device as possible.

If position detection using the Hall sensor is not required, do not populate D2, R1, and R19.

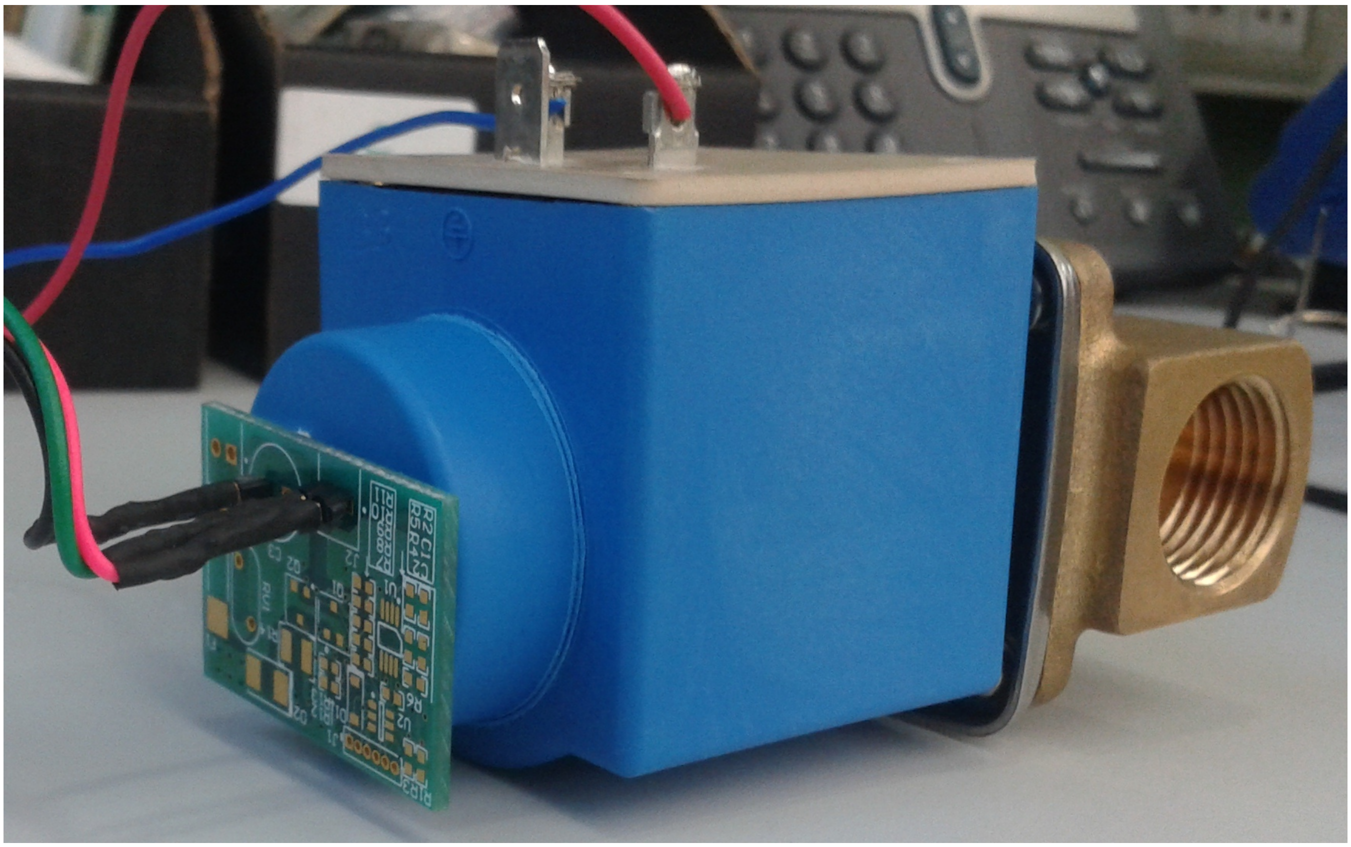


Figure 15. Mounting of the Hall Sensor on the Solenoid Coil for Testing Purposes

The Hall sensor can be connected to the board through the connector J1. To detect the solenoid plunger position, use the latch type Hall sensor, DRV5023. R1 is the pull-up resistor for the open drain output of the DRV5023 device.

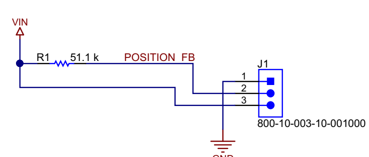


Figure 16. Hall Sensor Connector Circuit

The DRV5023 output stage uses an open-drain n-channel metal oxide semiconductor (NMOS) that is rated to sink up to 30-mA of current. For proper operation, calculate the value of the pull-up resistor R3 using Equation 17.

$$\frac{V_{IN\_MAX}}{30\text{ mA}} \leq R3 \leq \frac{V_{IN\_MIN}}{100\ \mu A}$$

where

- V_{IN_MAX} and V_{IN_MIN} are the maximum and minimum values of V_{IN} (17)

The size of R1 is a trade-off between the OUT rise time and the current when OUT is pulled low. A lower current is ideal; however, faster transitions and bandwidth require a smaller resistor for faster switching.

In the reference design R1 = 51.1 kΩ.

4.2.5 External Interface

J1 and J2 provide the external interface. The external signal at J2 includes the STATUS, A_{OUT}, and EN. Connector J1 forms the Hall sensor connections as explained in Figure 16. The U1, which is a four-channel 15-V unidirectional TVS diode, protects all of the signals from electro-static discharge (ESD). A_{OUT} is an output signal, which is the scaled solenoid current as explained in Section 4.2.3. EN is an input signal, which is the ENABLE signal for turning ON the controller DRV110 (this results in the excitation of the solenoid). The user can control the turn ON and OFF functions of the DV110 device and solenoid coil by using this EN input signal.

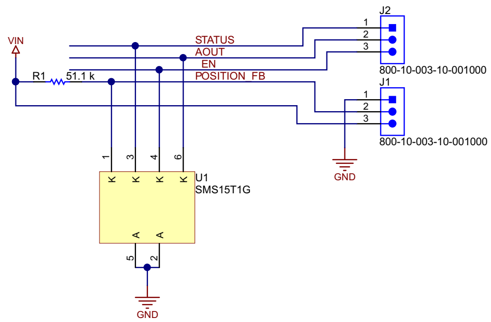


Figure 17. External Interface

4.3 *Design of the Circuit for 110-V AC Input*

The reference design is configured for 230-V AC, 50/60 Hz, and functions in the input voltage supply range of 230-V AC ±15%.

If the design requires modification for any other voltage, such as 110-V AC, a few components must be redesigned. The main components that require a redesign are the R25, R16, and R4. Use the same calculation as Section 4.2.1 to find the values of these resistors.

For example, if the input voltage is 110-V AC ±15%,

$$R_S = \frac{V_{S\_MIN(DC)} - 15\text{ V}}{1\text{ mA} + I_{GATE\_AVG} + I_{AUX}} \quad (18)$$

If the average gate current and the auxiliary circuit remain the same, then design the R_S at the minimum input voltage. Then R_S= 52 k.

The following can be chosen: R25 = R16 = 24.9 k and R4 = 2 k.

Check the nominal current of the solenoid and select the switching device and the power devices accordingly. Select the sense, peak, and hold resistors to set the peak and hold current appropriately.

5 Test Setup

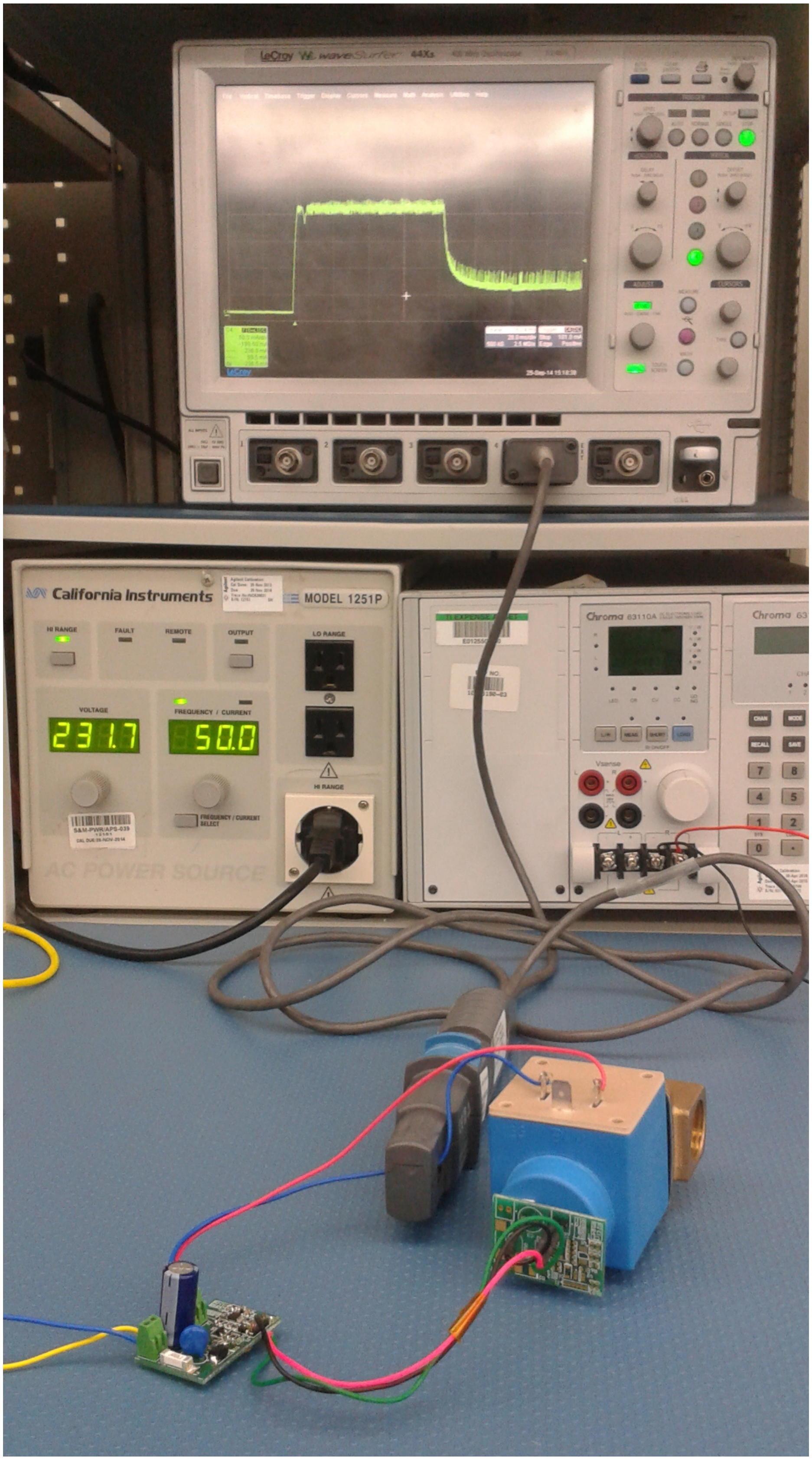


Figure 18. Test Setup

6 Test Results

6.1 Characterization of the Solenoid

The solenoid is characterized using a 230-V AC, 50-Hz supply. Figure 19 shows the current characterization curve of the AC solenoid. The peak-to-peak value of the current waveform is 230 mA with an RMS value of 77 mA.

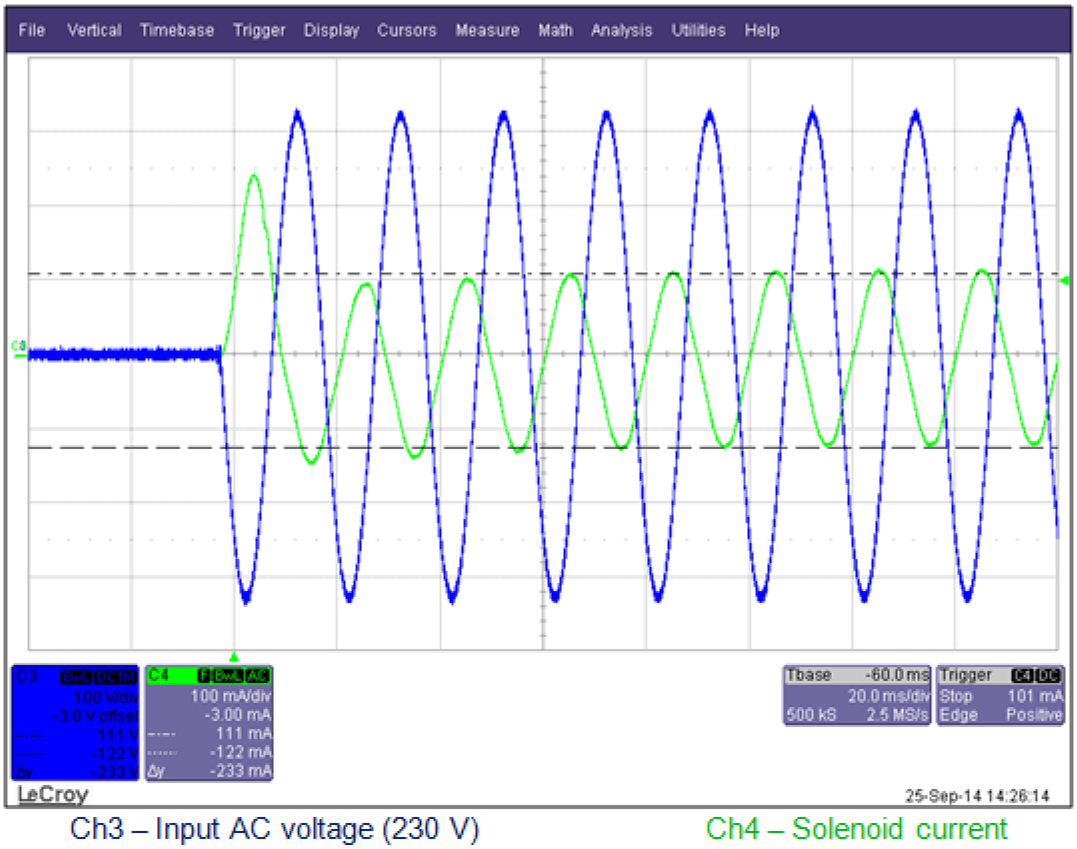


Figure 19. AC Solenoid Current Characteristics

6.2 Functional Test

Figure 20 shows the regulated power supply voltage (V_{IN}), the EN-pin voltage of the DRV110, and the gate signal from the OUT pin of the DRV110. The EN pin voltage increases proportionally to V_{IN}. When V_{IN} reaches 5 V, the DRV110 device enables and supplies the gate signal through the OUT pin.

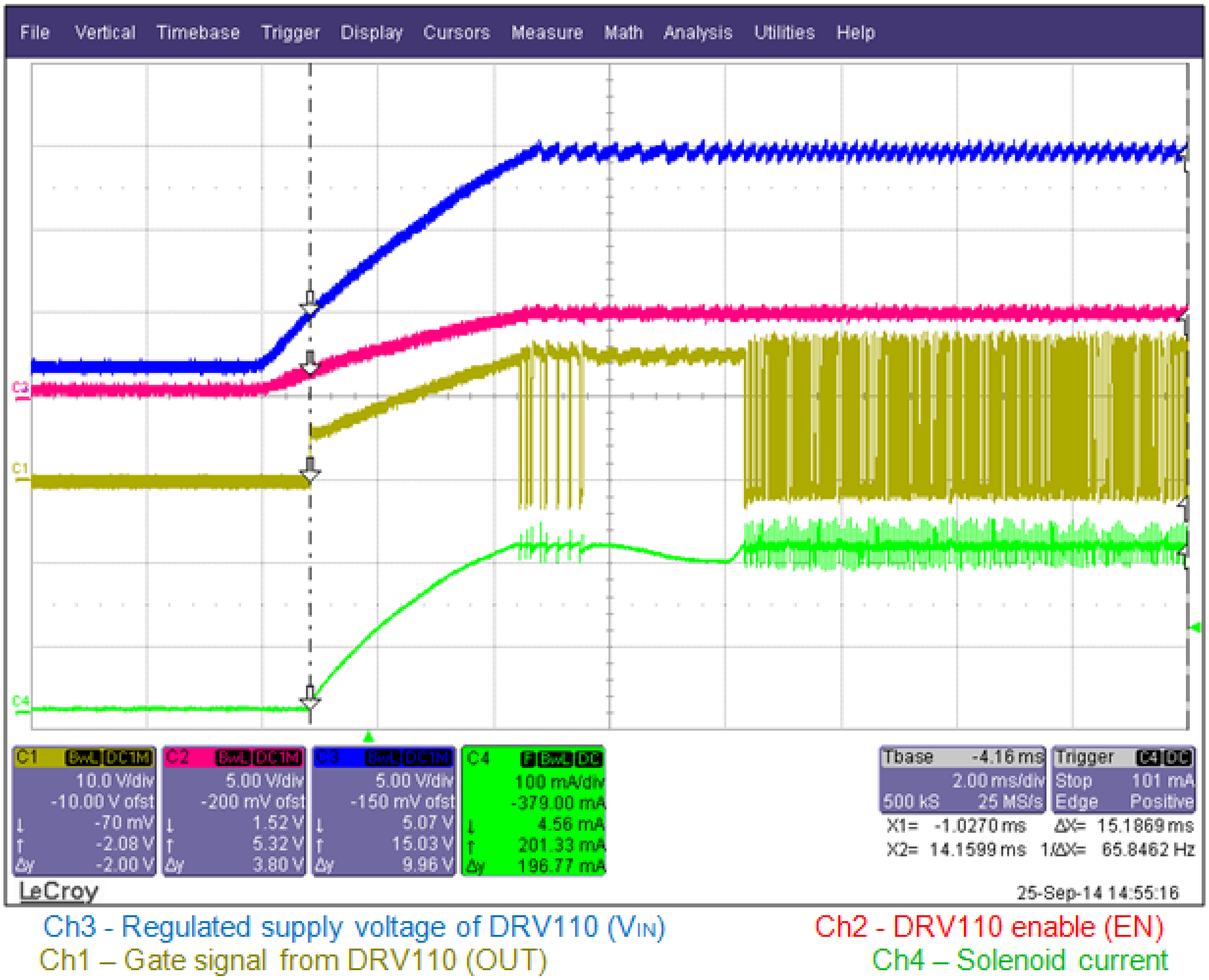


Figure 20. DRV110 Enable and Gate Voltage

Figure 21 shows the solenoid current and the gate signal originating from the DRV110. When the gate signal becomes high, MOSFET turns ON and the solenoid current increases from zero. The limit reference of the peak current in the DRV110 is set to 200 mA. The solenoid current reaches the maximum current of 200 mA and remains there for a time period determined by the KEEP capacitor. During the hold mode, the DRV110 is limiting the current to a lower value determined by the hold current reference. The DRV110 limits the current by reducing the duty cycle of the PWM, controlling the hold current to 50 mA. Figure 22 shows the variation of the gate signal originating from the DRV110 during the peak and hold modes.

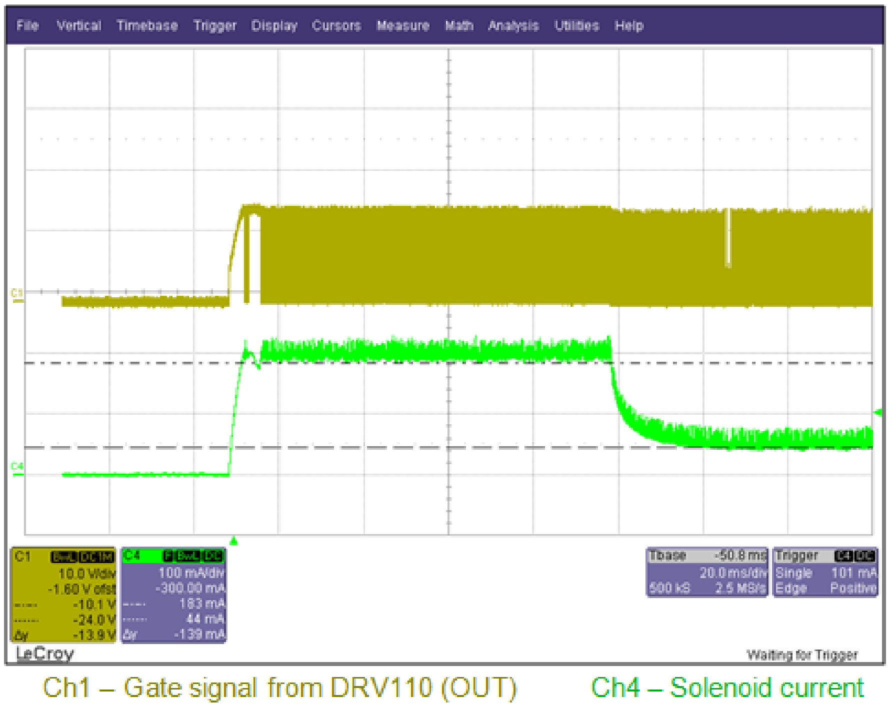


Figure 21. Solenoid Current and Gate Voltage from DRV110

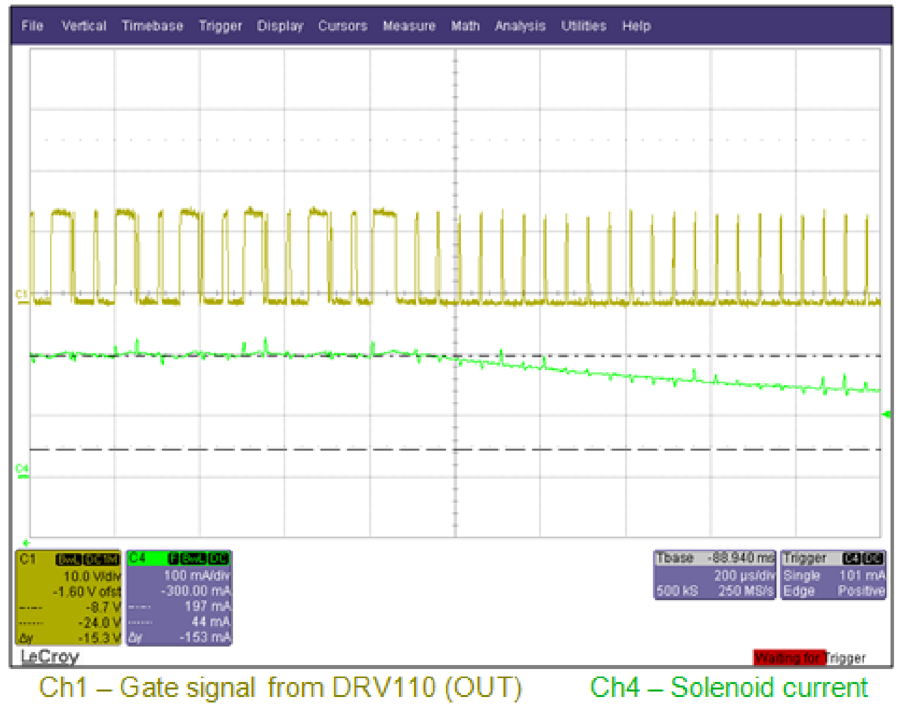


Figure 22. Variation of the Duty Cycle During the Transition from Peak Current Mode to Hold Current Mode

Figure 23 shows the regulated input supply voltage of the DRV110, the DC bus voltage, and the solenoid current. The supply voltage V_{IN} of the DRV110 regulates to 15 V. The rectified DC voltage has a peak-to-peak ripple of 90 V during the peak current mode and this voltage reduces to 25 V during the hold current mode.

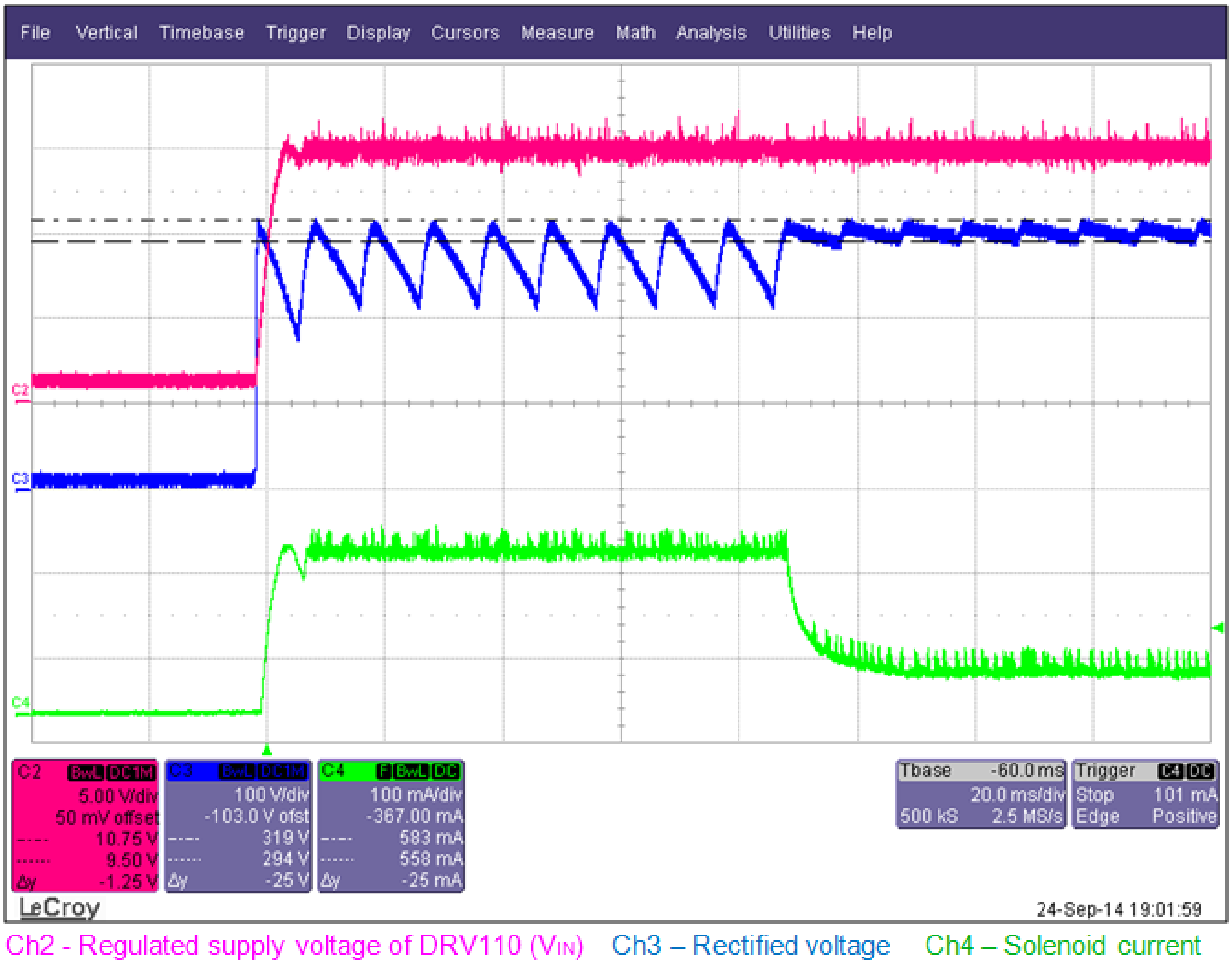


Figure 23. Solenoid Current and the DC Bus Voltage

Figure 24 shows the ripple content in the regulated supply voltage V_{IN} of the DRV110. The ripple content is approximately 735 mV.

Figure 24. Ripple in the Regulated Voltage V_{IN} of DRV110

Figure 25 shows the variation of A_{OUT} (amplified solenoid current). During the peak mode, the solenoid current is 200 mA and the corresponding A_{OUT} is 8 V. During the hold mode, A_{OUT} reduces to 1.8 V and corresponds to the hold current of 50 mA.

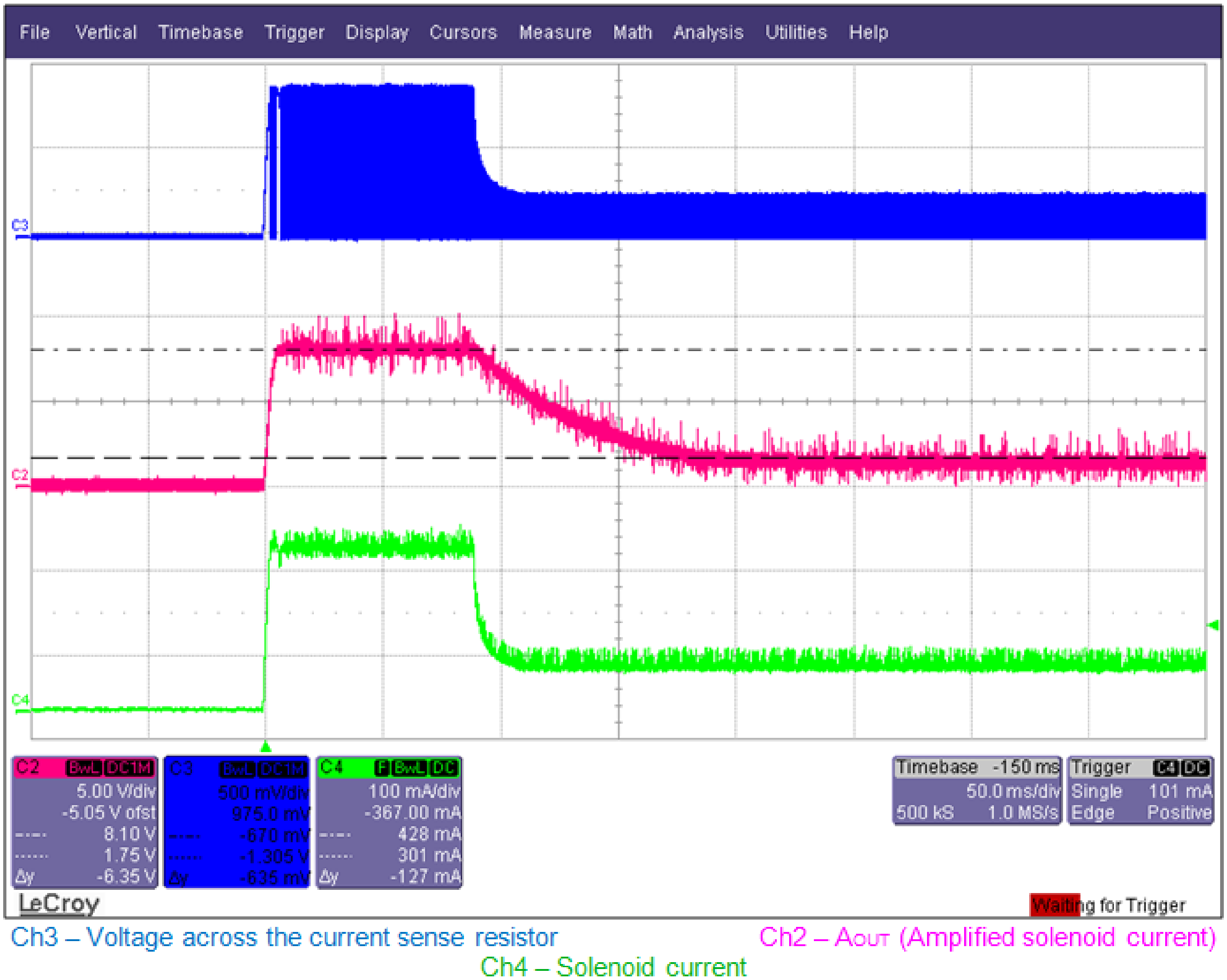


Figure 25. Solenoid Current and A_{OUT}

[Figure 26](#) shows the test result of the plunger position detection using the Hall sensor. When the plunger moves completely, the Hall sensor output is pulled low and the KEEP capacitor begins to charge. Once the KEEP capacitor voltage reaches 100 mV (which is an internal reference of the DRV110 to move into the hold mode), the DRV110 enters the hold current mode causing the solenoid current to decrease. The KEEP capacitor value used in tests is 1 µF; therefore, the KEEP time is 100 ms.

Figure 26. Plunger Position Detection Using Hall Sensor

Figure 27, Figure 28, and Figure 29 show the test results at different input voltages. The tests are conducted at 230-V AC, 265-V AC, and 195-V AC. The test result waveforms also show the solenoid current waveforms and the Hall sensor outputs.

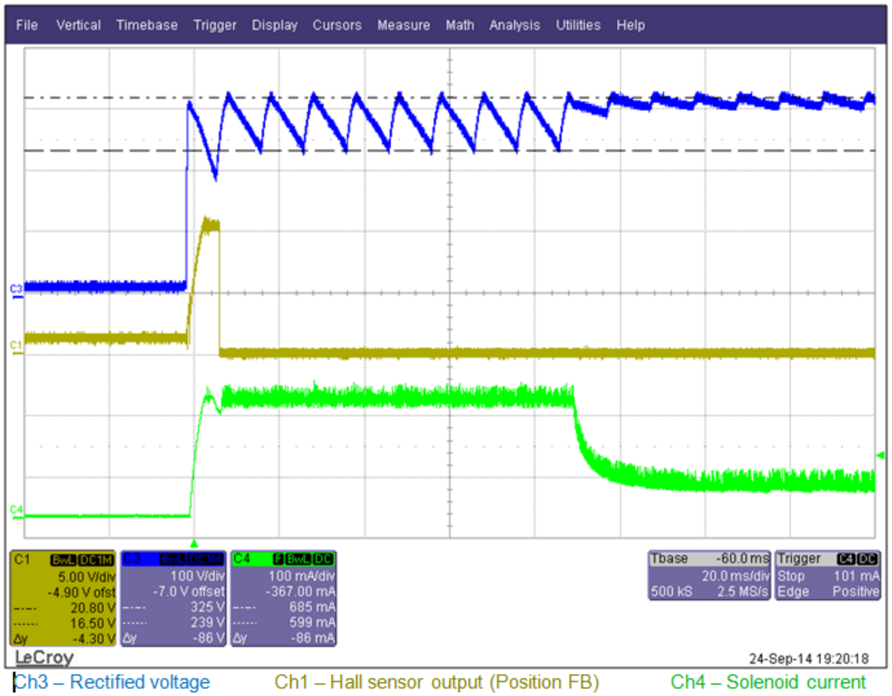


Figure 27. Test Results at the 230-V AC Input

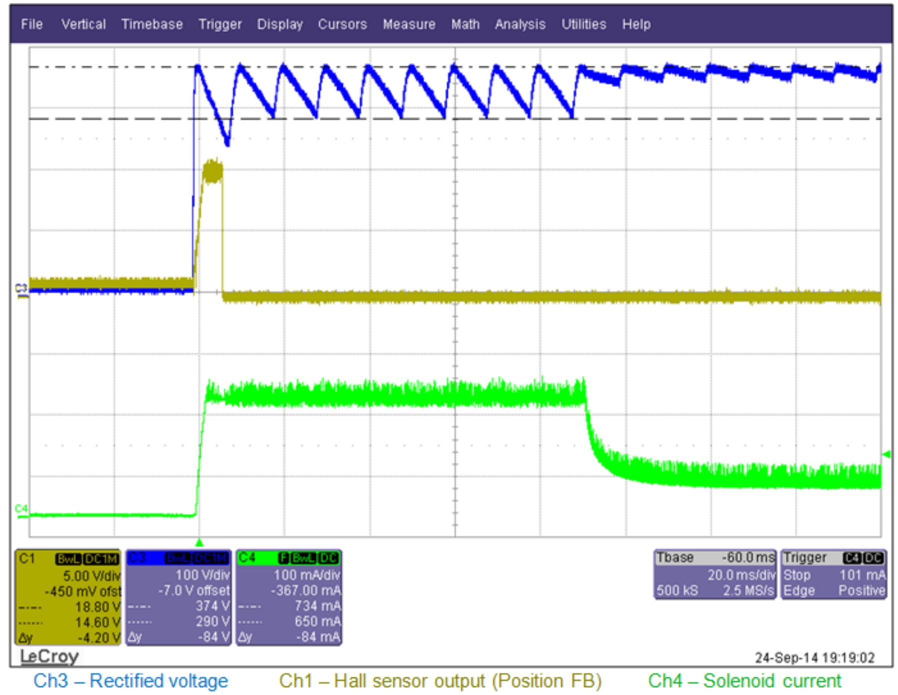


Figure 28. Test Results at the 265-V AC Input

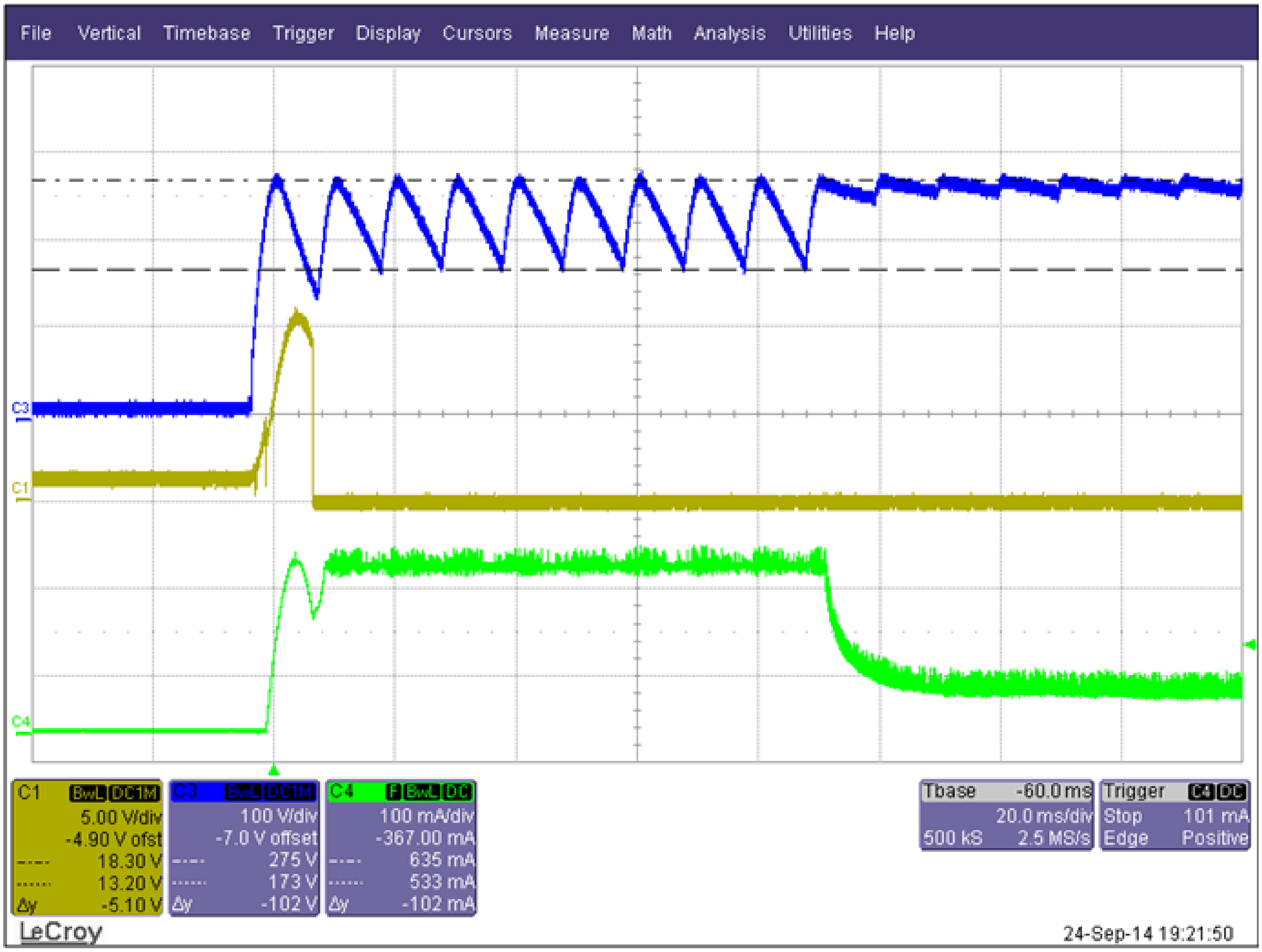


Figure 29. Test Results at the 195-V AC Input

6.3 Conducted Emission Test Results

This reference design has been tested for conducted emissions as per the EN55011 Class-A limits. For the CE test, Figure 30 adds a filter in the voltage line of the DC bus. Figure 31 and Figure 32 show test results. The margin can be further optimized based on the solenoid valve and by fine tuning filter components.

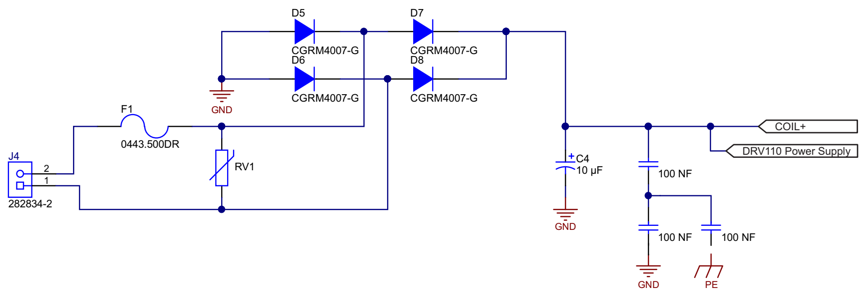


Figure 30. EMC Filter Connected Across the DC Bus

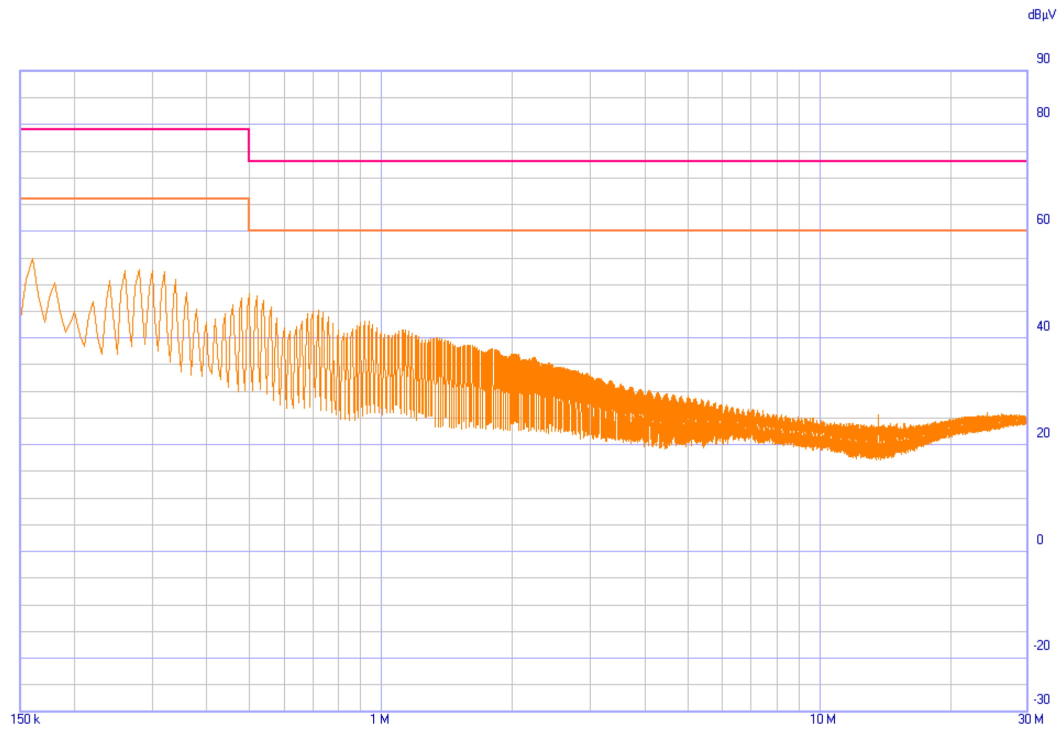


Figure 31. EMC Test Results — Average Detector Output

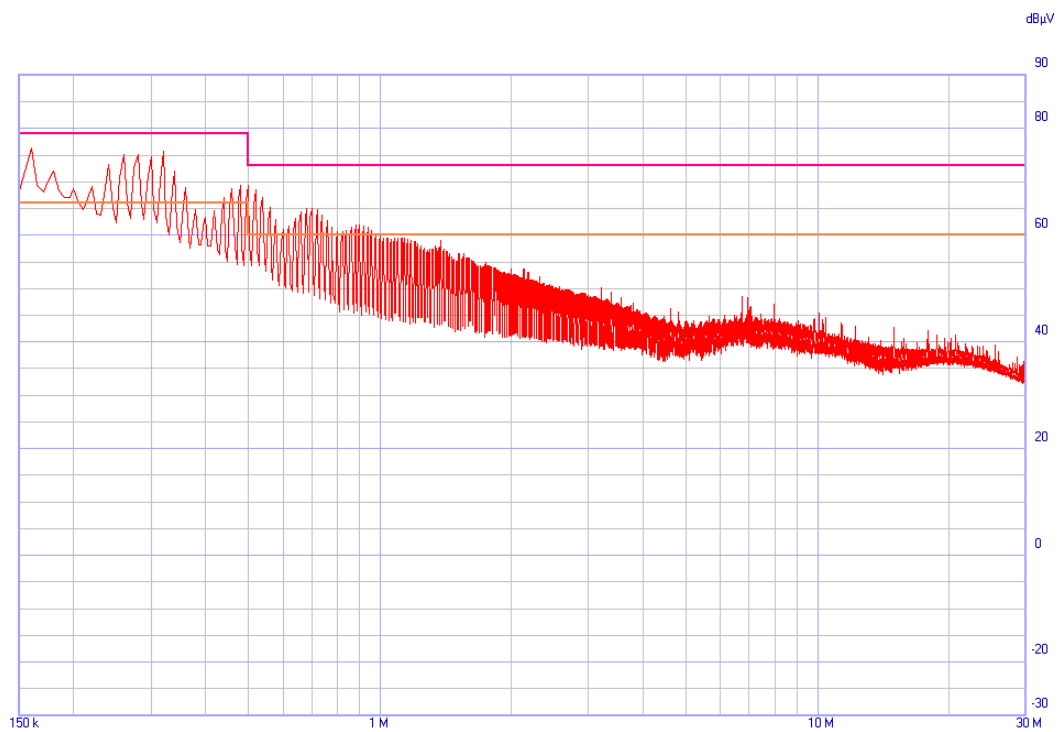


Figure 32. EMC Test Results — Quasi Peak Detector Output

7 Design Files

7.1 Schematics

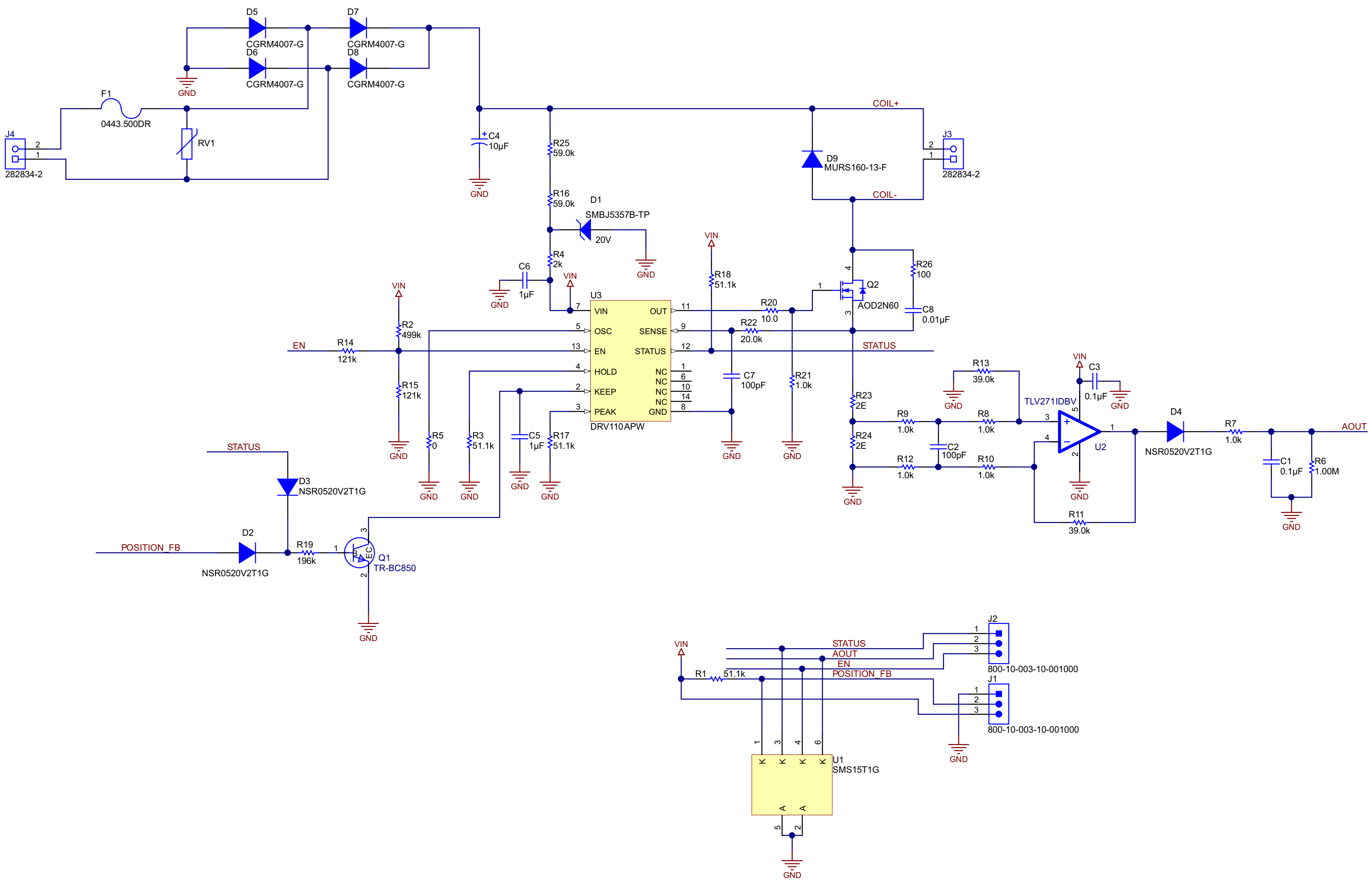


Figure 33. Main Schematic

7.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-00284.

Table 3. BOM

QTY	REFERENCE	PART DESCRIPTION	MANUFACTURER	MANUFACTURER PART NUMBER	PCB FOOTPRINT	NOTE
2	C1, C3	CAP, CERM, 0.1 uF, 25 V, ±10%, X7R, 0603	MuRata	GRM188R71E104KA01D	0603	Fitted
2	C2, C7	CAP, CERM, 100 pF, 50 V, ±5%, C0G/NP0, 0603	AVX	06035A101JAT2A	0603	Fitted
1	C4	CAP ALUM 10 µF 400 V, 20% RADIAL	Nichicon	UVC2G100MPD	RCAP, TH, 10 × 20 mm	Fitted
1	C5	CAP, CERM, 1 uF, 10 V, ±10%, X5R, 0603	Kemet	C0603C105K8PACTU	0603	Fitted
1	C6	CAP, CERM, 1 uF, 35 V, ±10%, X5R, 0603	Taiyo Yuden	GMK107BJ105KA-T	0603	Fitted
1	D1	Diode, Zener, 20 V, 5 W, SMB	Micro Commercial Components	SMBJ5357B-TP	SMB	Fitted
3	D2, D3, D4	DIODE SCHOTTKY 20 V, 0.5 A, SOD523	Diodes Inc.	NSR0520V2T1G	SOD-523	Fitted
4	D5, D6, D7, D8	Diode, P-N, 1000 V, 1 A, 3.9 × 1.7 × 1.8 mm	Comchip Technology	CGRM4007-G	3.9 × 1.7 × 1.8 mm	Fitted
1	D9	Diode, Ultrafast, 600 V, 1 A, SMB	Diodes Inc.	MURS160-13-F	SMB	Fitted
1	F1	Fuse, 0.5 A, 250 V, SMD	Littelfuse	0443.500DR	FUSE 10.1 × 3.12 × 3.13 mm	Fitted
2	J1, J2	Header, 100 mil, 3 × 1, TH	Mill-Max	800-10-003-10-001000	Header, 3 × 1, 100 mil, TH	Fitted
2	J3, J4	Terminal Block, 2 × 1, 2.54 mm, TH	TE Connectivity	282834-2	Terminal Block, 2 × 1, 2.54 mm, TH	Fitted
1	Q1	TRANS NPN LP 100MA 45V SOT23	ON Semiconductor	BC850CLT1G	SOT-23-3	Fitted
1	Q2	MOSFET, N-CH, 600 V, 2 A, DPAK	AOS	AOD2N60	DPAK	Fitted
4	R1, R3, R17, R18	RES, 51.1 k, 1%, 0.1 W, 0603	Vishay-Dale	CRCW060351K1FKEA	0603	Fitted
2	R11, R13	RES, 39.0 k, 1%, 0.1 W, 0603	Yageo America	RC0603FR-0739KL	0603	Fitted
2	R14, R15	RES, 121 k, 1%, 0.1 W, 0603	Vishay-Dale	CRCW0603121KFKEA	0603	Fitted
2	R16, R25	RES, 59.0 kΩ, 1%, 1 W, 2512	Vishay-Dale	CRCW251259K0FKEG	2512	Fitted
1	R19	RES, 196 k, 1%, 0.1 W, 0603	Vishay-Dale	CRCW0603196KFKEA	0603	Fitted
1	R2	RES, 499 k, 1%, 0.1 W, 0603	Vishay-Dale	CRCW0603499KFKEA	0603	Fitted
1	R22	RES, 10.0 kΩ, 0.1%, 0.1 W, 0603	Yageo America	RT0603BRD0710KL	0603	Fitted
2	R23, R24	RES 2.0 Ω, ½ W, 1%, 1210 SMD	Vishay Dale	CRCW12102R00FKEA	1210	Fitted
1	R4	RES 2.0 kΩ, ¼ W, 1%, 1210 SMD	Rohm Semiconductor	MCR25JZHF2001	1210	Fitted
2	R5, R20	RES, 0 Ω, 5%, 0.1 W, 0603	Vishay-Dale	CRCW06030000Z0EA	0603	Fitted
1	R6	RES, 1.00 M, 1%, 0.1 W, 0603	Vishay-Dale	CRCW06031M00FKEA	0603	Fitted
5	R7, R8, R9, R10, R12	RES, 1.0 kΩ, 5%, 0.1 W, 0603	Vishay-Dale	CRCW06031K00JNEA	0603	Fitted
1	RV1	Varistor, 300 V, 1.75kA, 7 mm, Radial, TH	EPCOS Inc	B72207S2301K101	Varistor, TH, 7mm	Fitted

Table 3. BOM (continued)

QTY	REFERENCE	PART DESCRIPTION	MANUFACTURER	MANUFACTURER PART NUMBER	PCB FOOTPRINT	NOTE
1	U1	TVS DIODE 15 vwm, 29 vc, SC746	Texas Instruments	SMS15T1G	SC-74	Fitted
1	U2	IC, 550 µA single Chan, R-R Output Op-Amp	Texas Instruments	TLV271IDBV	SOT23-5	Fitted
1	U3	Power Saving Solenoid Controller With Integrated Supply Regulation, PW0014A	Texas Instruments	DRV110APW	PW0014A	Fitted
0	C8	CAP, CERM, 0.01 uF, 100 V, ±10%, X7R, 0805	AVX	08051C103KAT2A	0805	Not Fitted
0	R21	RES, 1.0 kΩ, 5%, 0.1 W, 0603	Vishay-Dale	CRCW06031K00JNEA	0603	Not Fitted
0	R26	RES, 100 Ω, 0.1%, 0.125 W, 0805	Yageo America	RT0805BRD07100RL	0805	Not Fitted

7.3 PCB Layout

To download the layer plots, see the design files at TIDA-00284.

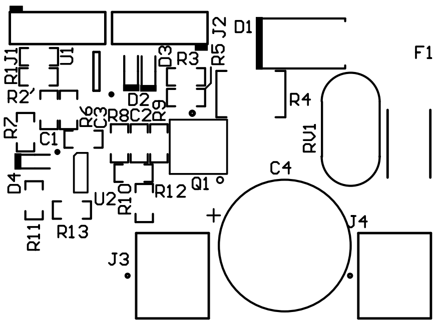


Figure 34. Top Overlay

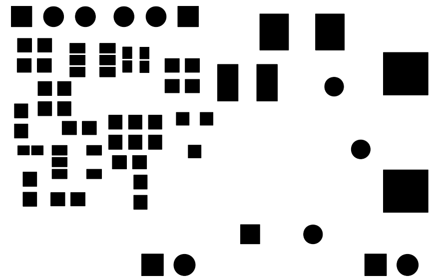


Figure 35. Top Solder

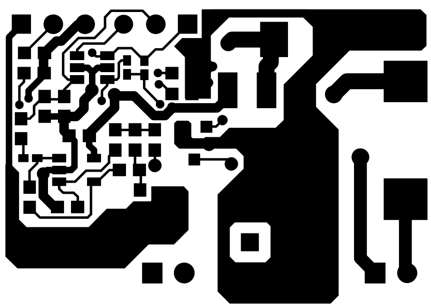


Figure 36. Top Layer

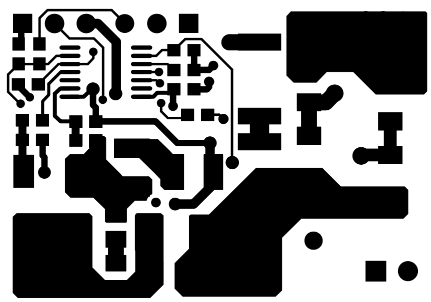


Figure 37. Bottom Layer

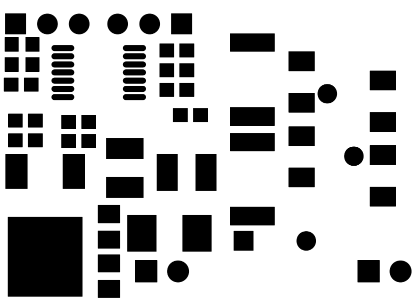


Figure 38. Bottom Solder

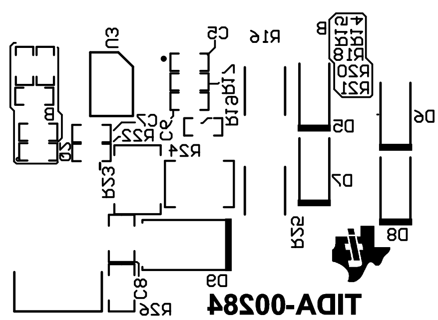


Figure 39. Bottom Overlay


Figure 40. MI Board Outline

7.4 Altium Project

To download the Altium project files, see the design files at TIDA-00284.

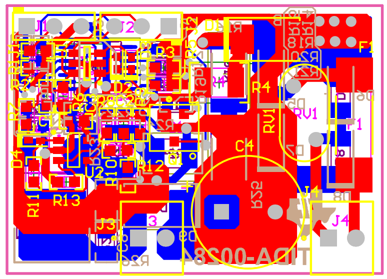
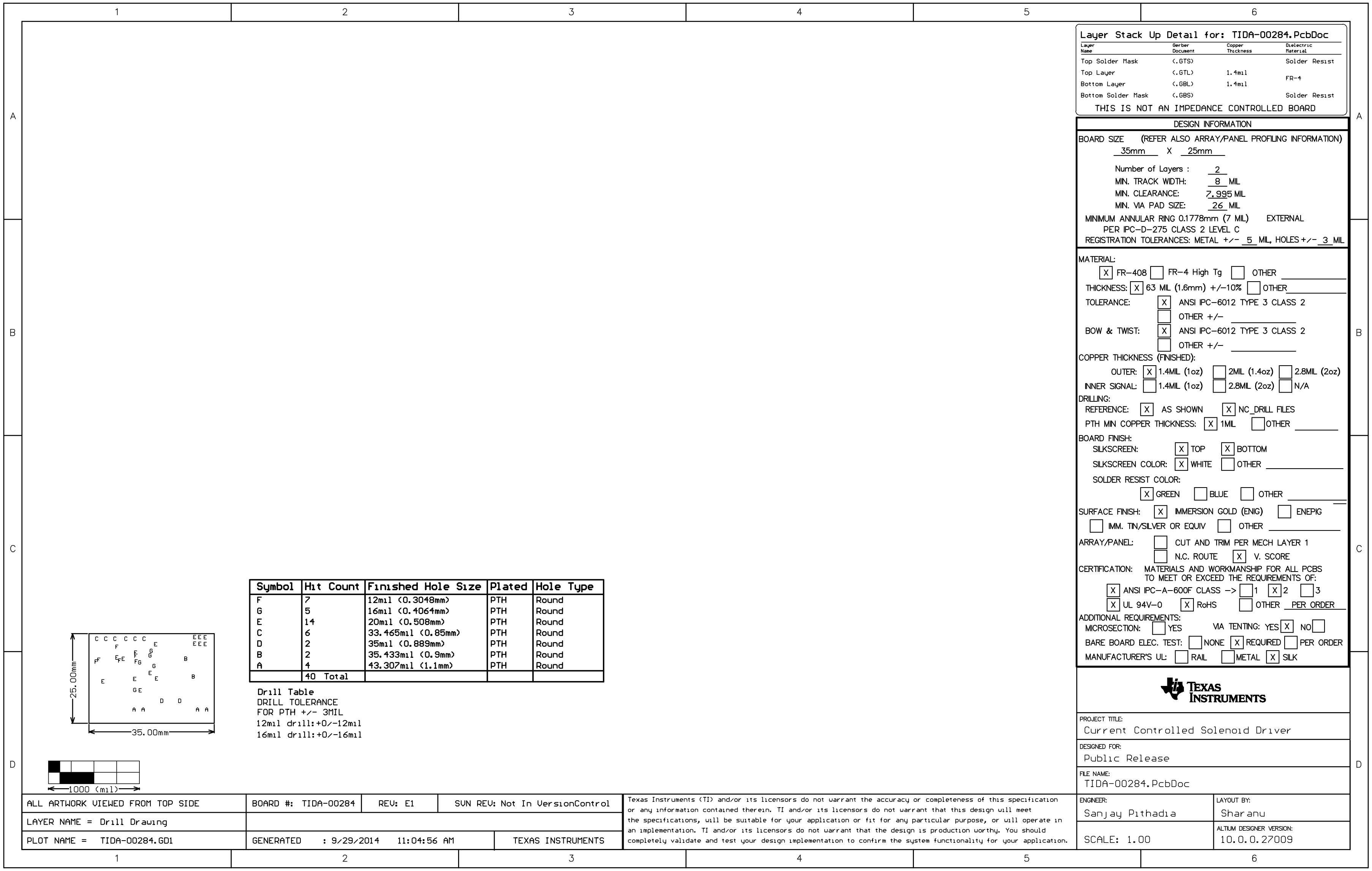


Figure 41. Multilayer Composite Print

7.5 Gerber Files

To download the Gerber files, see the design files at TIDA-00284.



Symbol	Hit Count	Finished Hole Size	Plated	Hole Type
F	7	12mil (0.3048mm)	PTH	Round
G	5	16mil (0.4064mm)	PTH	Round
E	14	20mil (0.508mm)	PTH	Round
C	6	33.465mil (0.85mm)	PTH	Round
D	2	35mil (0.889mm)	PTH	Round
B	2	35.433mil (0.9mm)	PTH	Round
A	4	43.307mil (1.1mm)	PTH	Round
	40 Total			

Figure 42. Fabrication Drawing

7.6 Assembly Drawings

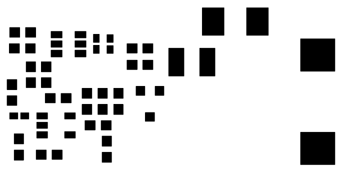


Figure 43. Top Paste Assembly

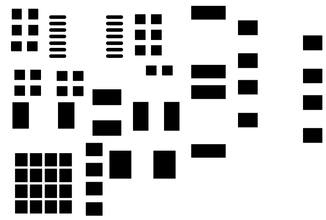


Figure 44. Bottom Paste Assembly

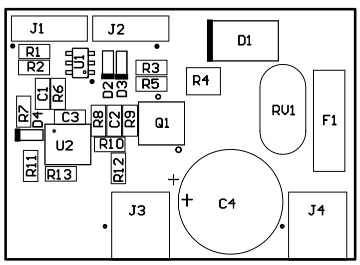


Figure 45. Top Assembly

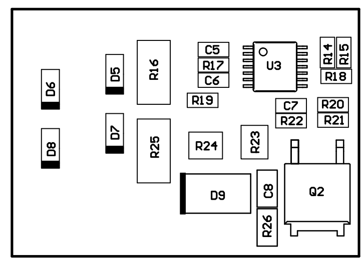


Figure 46. Bottom Assembly

7.7 Software Files

To download the software files, see the design files at TIDA-00284.

8 References

1. Texas Instruments, *Power Saving Solenoid Controller With Integrated Supply Regulation*, DRV110 Datasheet (SLVSBA8A)
2. Texas Instruments, *Driving solenoid coils efficiently in switchgear applications*, Application Note (SLYT544)

8.1 Trademarks

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9 About the Author

MANU BALAKRISHNAN is a systems engineer at Texas Instruments where he is responsible for developing subsystem design solutions for the Industrial Motor Drive segment. Manu brings to this role his experience in power electronics, analog, and mixed signal designs. He has experience in system level product design in permanent magnet motor drives. Manu earned his bachelor of technology in electrical and electronics engineering from the University of Kerala and his master of technology in power electronics from the National Institute of Technology, Calicut.

N. NAVANEETH KUMAR is a systems architect at Texas Instruments where he is responsible for developing subsystem solutions for motor controls within Industrial Systems. N. Navaneeth brings to this role his extensive experience in power electronics, EMC, analog, and mixed-signal designs. He has system-level product design experience in drives, solar inverters, UPS, and protection relays. N. Navaneeth earned his bachelor of science in electronics and communications engineering from Bharathiar University, India and his master of science in electronic product development from Bolton University, UK.

Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Original (November 2014) to A Revision	Page
• Changed *Equation 12* to updated version	14

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