TI Designs
Low-Cost AC Solid-State Relay With MOSFETs

Description

The low-cost AC solid-state relay (SSR) with MOSFETs reference design is a single relay replacement that enables efficient power management for a low-power alternative to standard electromechanical relays in thermostat applications. This SSR reference design is the base model of the self-powered SSR providing a low-cost solution for low-cost thermostats.

Resources

TIDA-01064	Design Folder
ATL431	Product Folder
LP339	Product Folder
SN74AUP1G74	Product Folder
CSD18541F5	Product Folder
TIDA-00377	Tools Folder
TIDA-00751	Tools Folder

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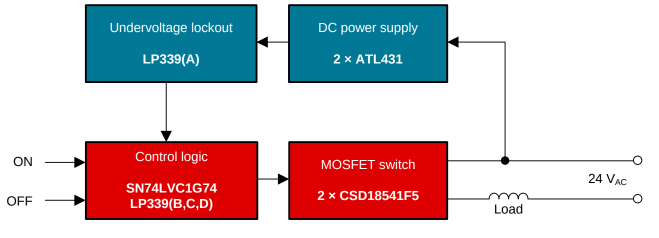
Features

- No Clicking Sound
- Low-Cost BOM
- MOSFET Based Design for Fast ON/OFF Switching
- Self-Powered
- Zero Power From Thermostat Battery
- Inherent Snubber Circuit Reducing Voltage Spike Created by Inductive Loads
- Low Power and Quiescent Current Components
- Undervoltage Protection

Applications

- Thermostats
- HVAC Systems
- Building Automation



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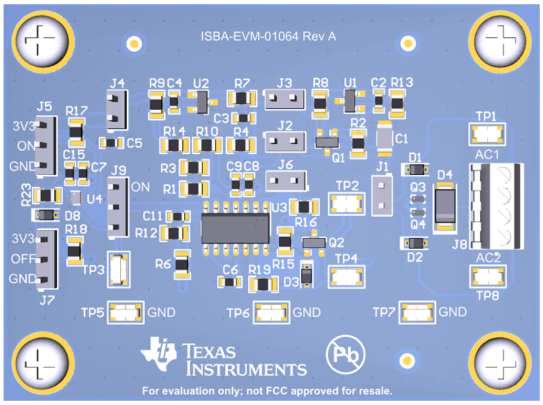

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1 System Overview

1.1 System Description

A solid-state relay (SSR) is an electronic switching device that switches on or off when a small external voltage is applied across its control terminals. SSRs consist of an input logic to respond to an appropriate input (control signal), a solid-state electronic switching device to switch power to the load circuitry, and a coupling mechanism to enable the control signal to activate this switch without mechanical parts. The SSR may be designed to control either an AC or DC voltage or current load. It serves the same function as an electromechanical relay, but has no moving parts.

SSRs use power semiconductor devices such as thyristors or transistors to switch currents up to 100 A. SSRs have fast switching speeds compared to electromechanical relays and have no physical contacts to wear out. To apply an SSR, the user must consider their lower ability to withstand momentary overload, compared to electromechanical contacts, and their initial higher "on" state resistance. Unlike an electromechanical relay, an SSR provides only limited switching arrangements (single-pole, single-throw switching).

This SSR is a low-cost reference design for a single mechanical relay replacement in low-cost thermostat applications, which only uses one switching relay. The SSR is self-powered through the AC line of the HVAC system and provides undervoltage lockout (UVLO). See Figure 1 for the block diagram.

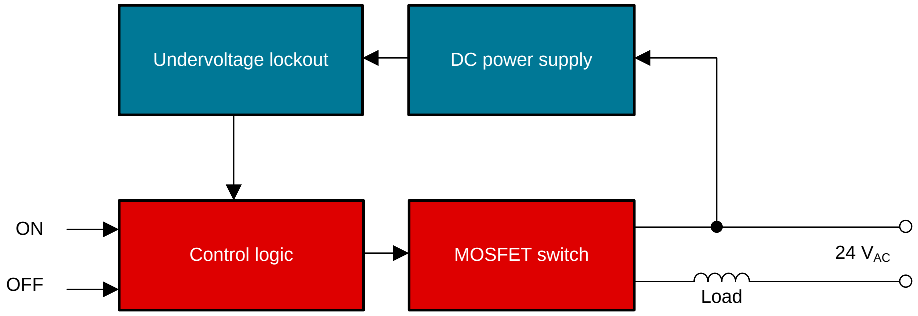

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Figure 1. TIDA-01064 SSR With MOSFETs Block Diagram

1.1.1 Choosing Between SSR Reference Designs

The TI Designs portfolio has three available SSR reference designs: the TIDA-00377, TIDA-00751, and TIDA-01064. They differ in terms of power consumption, galvanic isolation, voltage and current protection, and cost. See Table 1 for a feature comparison between the three designs.

Table 1. Comparison of SSR Reference Designs

PARAMETER	TIDA-00377	TIDA-00751	TIDA-01064
Self-powered	√		√
Isolation		√	
Snubber circuit	√	√	√
UVLO	√		√
OCP	√		
Low cost			√

1.1.1.1 Power Consumption

The TIDA-00377 and TIDA-01064 do not consume any power from the thermostat battery. They are self-powered and consume < 0.4 mA from the HVAC system. Alternatively, the TIDA-00751 consumes power from the thermostat battery during both on and off-states. The SSR consumes 1.2 mA from the battery during on-state and < 0.2-mA during off-state.

1.1.1.2 Galvanic Isolation

The TIDA-00751 includes galvanic isolation, whereas the TIDA-00377 and TIDA-01064 do not. The TIDA-00377 and TIDA-01064 are designed for single relay replacement in low-cost thermostats. Considering that it is replacing a single relay, isolation is not needed. If necessary, use a different TI Design for galvanic isolation.

1.1.1.3 Voltage and Current Protection

The TIDA-01064 includes UVLO, the TIDA-00377 includes both protection circuits, and the TIDA-00751 includes neither. The UVLO protects the low AC power supply, which also translates to the DC power supply of the SSR. This will enable the self-powering feature. The overcurrent protection (OCP) is to protect the MOSFET switch from overcurrent and to detect short circuits.

1.1.2 N-Channel Power MOSFET

In residential as well as commercial building automation application, 24 V_{AC} is used as the standard power supply voltage. When an SSR is used in thermostat applications as a replacement for the mechanical relay, the maximum operating voltage of the power switch is the peak voltage of one transformer. Taking into account the input voltage variations (20 to 30 V_{AC}), the peak DC voltage rises up to 43 V. For that reason, this design uses power MOSFETs with a breakdown voltage of 60 V.

1.1.3 Input Logic Control

In thermostat applications, power consumption is one of the main concerns. To ensure a long battery life, the control logic, in most cases a dedicated microcontroller, provides a control signal for a short period of time before it goes in a low power or sleep mode. Turnon and turnoff signals are two different signals that are active for short periods of the time. For that reason, the input control logic uses the Texas Instruments low-power AUP D-type flip-flop, SN74AUP1G74 with a 3.3-V supply voltage. This circuit will set the output signal high on a short, low-ON pulse and reset the output signal low when a short, low-OFF signal is applied.

1.1.4 Gate Driver

The fast turnon and turnoff time of the power MOSFETs are necessary for the self-powering function of the SSR. The time is controlled by the current flow during the gate-to-source capacitance charge and discharge of the MOSFETs. The open drain comparator cannot achieve a fast charge of the gate of the MOSFET so an additional NPN transistor is needed to speed up the process. The equivalent turnon gate resistance is the pullup resistor, divided by the h_{FE} of the transistor, in addition with the built-in internal series gate resistance of the MOSFETs. By pulling the output of two comparators to a negative DC voltage rail, the base of the NPN transistor will be negatively biased turning the transistor off, while the comparator will quickly discharge the gate capacitance allowing fast turnoff. In addition, the second comparator will keep the gate voltage of the MOSFET close to zero increasing the noise immunity. The low-power quad comparator LP339 was chosen for this function due to the low quiescent current and low cost. This part serves two purposes with two comparators used for the gate driver. The second purpose is for UVLO as explained in Section 1.1.6.

1.1.5 Power Management

Power consumption is another main concern in thermostat applications because the circuitry, which makes up the thermostat control, consumes its power from an onboard battery. To avoid additional power consumption and the lifetime of the battery, this SSR reference design is self-powered through the 24 V_{AC} power line. By using the body diodes of the power MOSFETs and two additional diodes, the 24 V_{AC} is rectified to 33 V_{DC}, which is further stepped down to provide power to the remaining of the SSR circuitry. The voltage regulation is performed by two low-power shunt regulators, ATL431, with a quiescent current of 25 μA.

1.1.6 Undervoltage Lockout

To properly regulate the voltage of the DC power supply, the input DC voltage must maintain a certain threshold level. If the AC voltage or rectified AC voltage of the load (V_{DC}) drops below the desired rail voltages, the shunt regulators will no longer be able to regulate, disabling the operability of the SSR. Due to the nature of the DC power supply during the ON time of the MOSFETs, the DC supply capacitor will want to fully discharge. To prevent this, a reference voltage is set on the UVLO to shortly turn off the MOSFETs when the minimum voltage is met and allows the DC supply capacitor to recharge without affecting the load. This will keep V_{DC} at a voltage where the shunt regulators can regulate properly. To perform this function, one of the comparators from the LP339 is used. To use the UVLO as a control signal, a second comparator from the LP339 is used to perform a logic AND function between the UVLO and input control signals.

1.2 Key System Specifications

Table 2. Key System Specifications

SPECIFICATION	VALUE	DETAILS
Logic input level	3.3 V	See Section 1.1.3
AC voltage input range	20 to 30 V	See Section 1.1.1
Maximum current	2 A[1]	—
Turnon and turnoff time	< 1 µs	See Section 4.2
On-state current consumption (typ)	190 µA	See Section 4.2
Off-state current consumption (typ)	370 µA	See Section 4.2
Operating temperature	0°C to 60°C	—
Working environment	Indoor building automation	—

[1] Typical $R_{\theta JA}$ = 245°C/W

1.3 Block Diagram

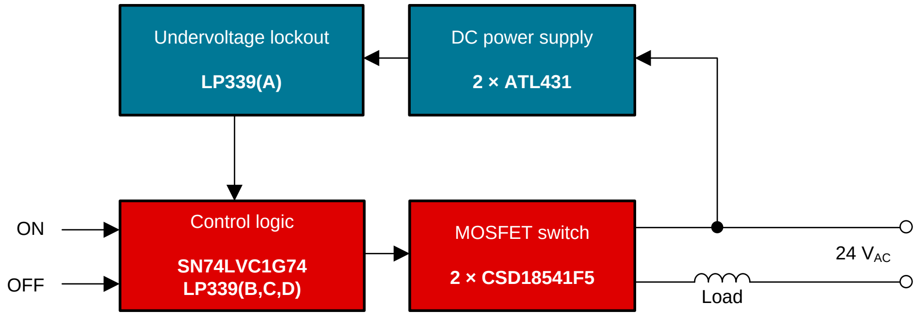

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Figure 2. TIDA-01064 SSR With MOSFET Block Diagram With Component List

1.4 Highlighted Products

The SSR reference design features the following devices:

- CSD18541F5: 60-V N-Channel FemtoFET Power MOSFET
- SN74AUP1G74: Low-Power Single Positive-Edge-Triggered D-Type Flip-Flop
- ATL431: 2.5-V Low I_Q Adjustable Precision Shunt Regulator
- LP339: Low-Power Quad Differential Comparators

2 System Design Theory

2.1 Basic SSR Theory

An alternative to the electromechanical switch is an SSR with a MOSFET. SSRs are integrated electrical circuits that act as a mechanical switch. The relays can be switched much faster and are not prone to wear because of the absence of moving parts. Another advantage is that less current and voltage is needed for SSRs to control high-voltage AC loads.

This design uses a two N-channel MOSFET topology serving two main functions. The first function is to perform the switching. By using two MOSFETs, both positive and negative current are allowed to flow during the ON time, as shown in Figure 3a. During the OFF time, the body diodes block the current flow because the top and bottom body diode become reverse bias, as shown in Figure 3b.

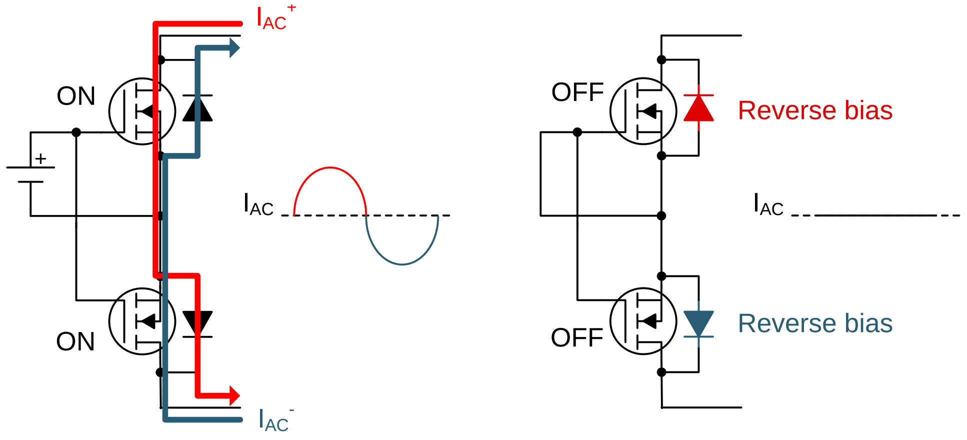

Figure 3. Functionality of MOSFETs for (a) ON and (b) OFF Times

The second function of the two N-channel MOSFET topology is to self-power the system by assisting in the AC voltage rectification. See Section 2.2 for more details.

2.2 Basic Power Management Theory

The two MOSFET body diodes of the switch and two external diodes create a full-wave rectification circuit that converts the AC power supply at the load to a DC voltage that can then be stepped down to desired levels. The control logic and gate driver are powered by the resulting DC voltage and therefore does not consume any power from the thermostat battery.

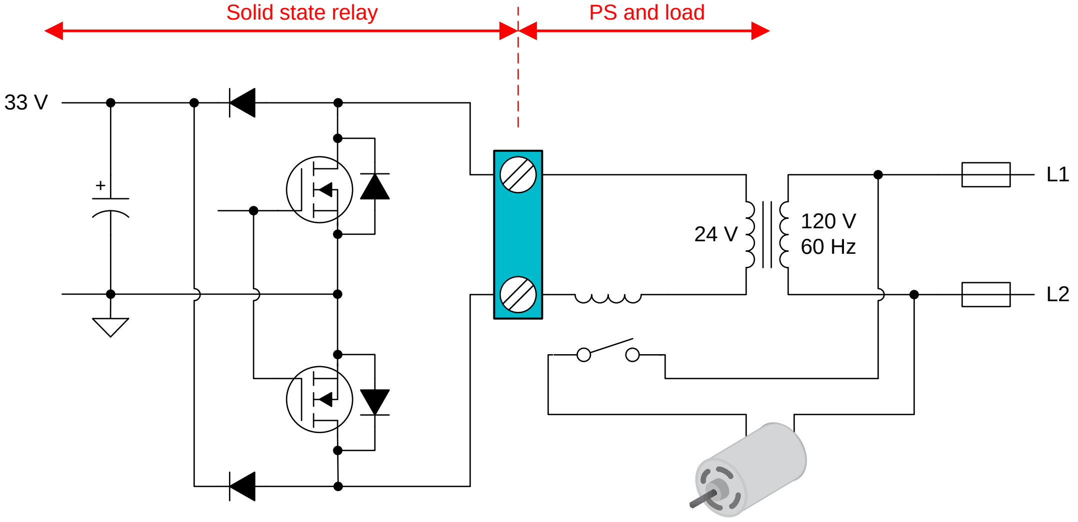

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Figure 4. Power Supply of SSR in HVAC System

2.2.1 Full-Wave Rectification

When the SSR is not active, the 24-V_{AC} voltage from the HVAC system across HV1 and HV2 is rectified using D1 and D2 in addition to the two body diodes of the MOSFETs. When the MOSFETs are off, the resulting full-wave rectified waveform has a peak DC voltage of 34 V, calculated by Equation 1.

$$V_{P\_DC} = \sqrt{2} \times V_{AC} - 2 \times V_F \tag{1}$$

With the addition of the capacitor, the rectified AC waveform is smoothed out providing a nominal average DC voltage. The ripple of the DC voltage is determined by the value of the capacitor and the current flowing through it over a period of time, as described in Equation 2.

$$\Delta V_{DC} = \frac{i \times \Delta t}{C_{DC}} \tag{2}$$

The resulting waveforms are shown in Figure 5.

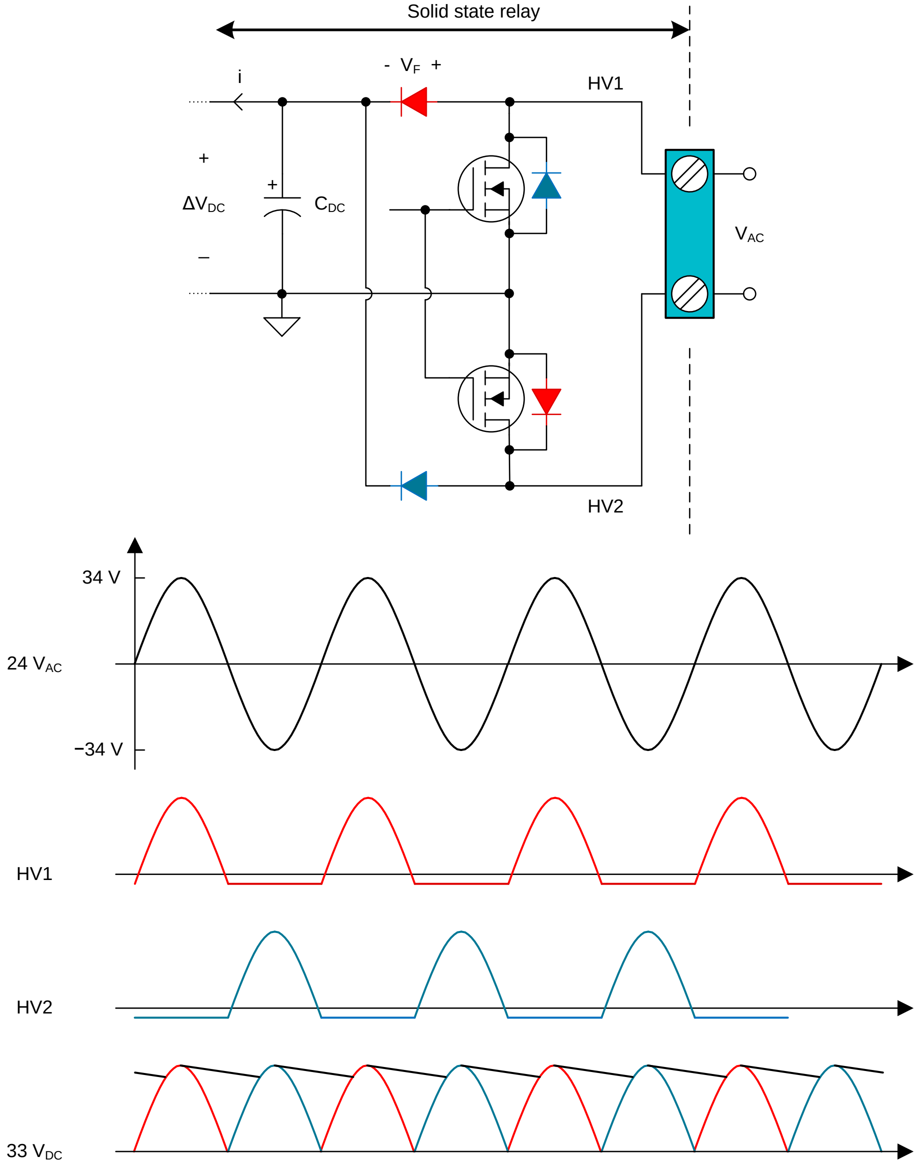

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Figure 5. Full-Wave Rectification Waveforms

2.2.2 DC Power Supplies

The two DC rail voltages used in this reference design are 10 V and 3.3 V. The 10-V supply rail is chosen based on the gate-to-source voltage on the MOSFETs to provide a low on-state resistance (Figure 6). The 3.3-V supply rail is chosen due to the required supply range of the logic components used in the logic control portion of this reference design.

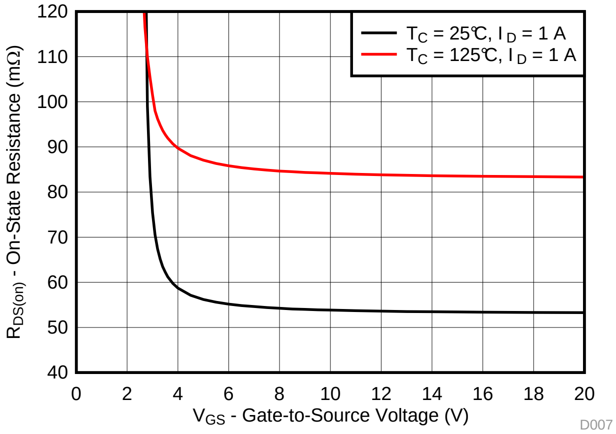

Figure 6. On-State Resistance as a Function of Gate-to-Source Voltage of CSD18541F5

2.2.2.1 *10-V Power Supply*

The 10-V supply uses the low I_Q adjustable precision shunt regulator, ATL431. Along with the regulator are three resistors with the DC supply voltage provided by the rectified AC input voltage. One of the resistors, R3, provides the cathode current, I_{KA}, and the other two creates a resistive divider to set the output voltage, V_{OUT}. The NPN transistor provides power to the 3.3-V supply, logic control, and protection blocks of the SSR, reducing the total power consumption of R3.

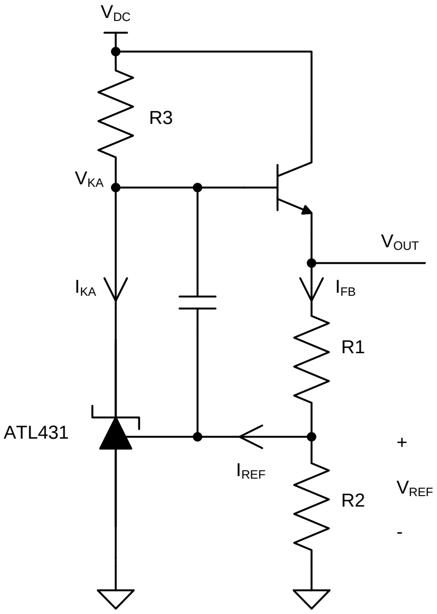

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Figure 7. Schematic of 10-V Supply

Table 3. ATL431 Electrical Characteristics Over Recommended Operating Conditions 25˚C

PARAMETER		TEST CONDITIONS		MIN	TYP	MAX	UNIT
V_{REF}	Reference voltage	$V_{KA} = V_{ref}$, I_{KA} = 1 mA		2475	2500	2525	mV
$V_{I(dev)}$	Deviation of reference input voltage over full temperature range	$V_{KA} = V_{REF}$, I_{KA} = 1 mA,	ATL43xAI; T_A = –40°C to 85°C		5	15	mV
			ATL43xAQ; T_A = –40°C to 125°C		6	34	
ΔV_{REF} / ΔV_{KA}	Ratio of change in reference voltage to the change in cathode voltage	I_{KA} = 1 mA	ΔV_{KA} = 10 V – V_{REF}		–0.4	–2.7	mV/V
			ΔV_{KA} = 36 V – 10 V		–0.1	–2	
I_{REF}	Reference input current	I_{KA} = 1 mA, R1 = 10 kΩ, R2 = ∞			30	150	nA
$I_{I(dev)}$	Deviation of reference input current over full temperature range	I_{KA} = 1 mA, R1 = 10 kΩ, R2 = ∞			20	50	nA
I_{MIN}	Minimum cathode current for regulation	$V_{KA} = V_{REF}$			20	35	µA
I_{OFF}	Off-state cathode current	V_{KA} = 36 V, V_{REF} = 0			0.05	0.2	µA
$\lvert z_{KA} \rvert$	Dynamic impedance	$V_{KA} = V_{REF}$, f ≤ 1 kHz, I_{KA} = 1 to 100 mA			0.05	0.3	Ω

Table 3 specifies when $V_{KA} = V_{REF}$ and I_{KA} is 1 mA the nominal V_{REF}, (labeled as V_{NOM}) is 2.5 V. The reference voltage varies with cathode voltage at two different rates: –0.4 mV/V from V_{REF} to 10 V, and –0.1 mV/V above 10 V. The reference pin current is 30 nA.

The Z_{KA} parameter offsets V_{REF} by ($I_{KA} - I_{NOM}$) × Z_{KA}. In addition, the $\Delta V_{REF}/\Delta V_{KA}$ parameter offsets V_{REF} by either –0.4 mV × (V_{KA} – 2.5 V) if V_{KA} ≤ 10 V, or –10.5 mV – 0.1 mV/V × (V_{KA} – 10 V) if V_{KA} > 10 V. The "–10.5 mV" constant is the V_{REF} offset as V_{KA} changes from V_{NOM} to 10 V, (10 V –2.5 V) × –0.4 mV/V.

For the 10-V supply, the parameters for V_{KA} > 10 V are used for Equation 3 because V_{KA} = 10.6 V due to the voltage drop across the NPN transistor.

$$V_{REF} = V_{NOM} + \left(I_{KA} - I_{NOM}\right) \text{x}\, Z_{KA} + \left(V_{KA} - 10\right) \times -0.1\,\text{mV/V} - 10.5\,\text{mV} \tag{3}$$

Now that V_{REF} is solved, R1 and R2 can be determined.

$$R1 = \frac{\left(V_{KA} - V_{REF}\right)}{I_{FB}} \tag{4}$$

$$R2 = \frac{V_{REF}}{\left(I_{FB} - I_{REF}\right)} \tag{5}$$

NOTE: R2 has less current than R1.

The design goal is to set the cathode of the ATL431 to 10.6 V by providing a minimum cathode current of 20 µA, and a feedback current and resistor bridge that will keep V_{KA} within a narrow supply range of ±2% to 3%. The following parameters are calculated using the formula derived in the general example for V_{KA} > 10 V.

$$V_{REF} = 2.5\text{ V} + \left(20\text{ µA} - 1\text{ mA}\right) \times 0.05\,\Omega + \left(10.6\text{ V} - 10\text{ V}\right) \times -0.1\,\text{mV/V} - 10.5\text{ mV}$$

$$V_{REF} = 2.4899\text{ V}$$

$$R1 = \frac{\left(10\text{V} - 2.4899\text{ V}\right)}{2\text{ µA}} = 3.755\text{ M}\Omega$$

$$R2 = \frac{2.4899\text{ V}}{\left(2\text{ µA} - 30\text{ nA}\right)} = 1.264\text{ M}\Omega$$

The closest standard 1% resistor value for R1 is 3.74 kΩ. A value of 1.3 MΩ is chosen for R2 to achieve the V_{KA} narrow supply range 10 V ± 2% to 3%.

To calculate R3, it is necessary to know the base current of the NPN transistor. Use the maximum required emitter current of 300 μA to sufficiently supply the 10-V load and 3.3-V supply and load current.

$$I_B = \frac{I_C}{h_{FE}} \tag{6}$$

$$I_B = \frac{300\ \mu A}{400}$$

$$I_B = 750\ nA$$

Use the maximum required base current, the minimum UVLO voltage of 18 V, the maximum cathode voltage, and the maximum value for the minimum cathode current of 35 μA to calculate the resistance R3.

$$R3 = \frac{\left(V_{DC} - V_{KA}\right)}{\left(I_{KA} + I_B\right)} \tag{7}$$

$$R3 = \frac{\left(18\ V - 10.7\ V\right)}{\left(35\ \mu A + 750\ nA\right)} = 204.196\ k\Omega$$

The closest standard 1% resistor value for R3 is 205 kΩ.

2.2.2.2 3.3-V Power Supply

The 3.3-V supply uses the same low I_Q adjustable precision shunt regulator, ATL431, as the 10-V supply. Along with the regulator are three resistors with the DC supply voltage of 10 V. One of the resistors, R3, provides the cathode current, I_{KA}, and the other two creates a resistive divider to set the output voltage, V_{KA}.

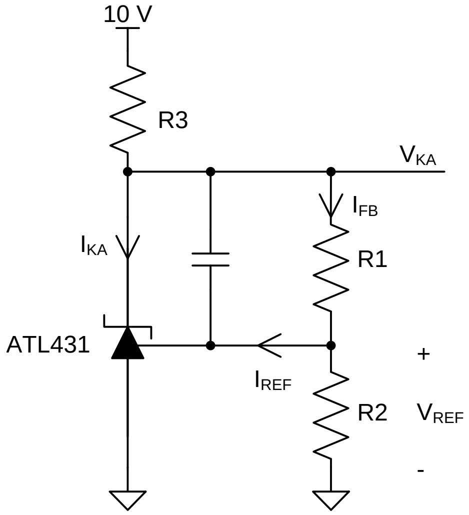

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Figure 8. Schematic of 3.3-V Supply

For the 3.3-V supply, the parameters for $V_{KA} \leq 10$ V are used for Equation 8.

$$V_{REF} = V_{NOM} + \left(I_{KA} - I_{NOM}\right) \times Z_{KA} + \left(V_{KA} - V_{NOM}\right) \times \Delta V_{REF} / \Delta V_{KA} \tag{8}$$

Now that V_{REF} is solved, R1 and R2 can be determined.

$$R1 = \frac{\left(V_{KA} - V_{REF}\right)}{I_{FB}} \tag{9}$$

$$R2 = \frac{V_{REF}}{\left(I_{FB} - I_{REF}\right)} \tag{10}$$

NOTE: R2 has less current than R1.

The design goal is to set the cathode of the ATL431 to 3.3 V by providing a minimum cathode current of 20 µA, and a feedback current and resistor divider that will keep V_{KA} within a narrow supply range of ±2%. The following parameters are calculated using Equation 8.

$$V_{REF} = 2.5\ V + \left(20\ \mu A - 1\ mA\right) \times 0.05\ \Omega + \left(3.3\ V - 2.5\ V\right) \times -0.4\ mV / V$$

$$V_{REF} = 2.4996\ V$$

$$R1 = \frac{\left(3.3\ V - 2.4996\ V\right)}{1\ \mu A} = 800.369\ k\Omega$$

$$R2 = \frac{2.4996\ V}{\left(1\ \mu A - 30\ nA\right)} = 2.577\ M\Omega$$

The closest standard 1% resistor value for R1 is 806 kΩ. A value of 2.8 MΩ is chosen for R2 to achieve the V_{KA} narrow supply range 3.3 V ± 2%.

With the standard resistor values for R1 and R2, the estimated V_{KA} and I_{FB} can calculated to determine the value of R3. Use the maximum parameters in the datasheet (SLVSCV5) to calculate the resistance.

$$V_{REF} = V_{NOM} + \left(I_{KA} - I_{NOM}\right) \times Z_{KA} + \left(V_{KA} - V_{NOM}\right) \times \Delta V_{REF} / \Delta V_{KA}$$

$$V_{REF} = 2.5\ V + \left(35\ \mu A - 1\ mA\right) \times 0.3\ \Omega + \left(3.3\ V - 2.5\ V\right) \times -2.7\ mV / V$$

$$V_{REF} = 2.523\ V$$

$$V_{KA} = V_{REF} \times \left(1 + \frac{R1}{R2}\right) + I_{REF} \times R1 \tag{11}$$

$$V_{KA} = 2.523\ V \times \left(1 + \frac{806\ k\Omega}{2.8\ M\Omega}\right) + 150\ nA \times 806\ k\Omega$$

$$V_{KA} = 3.370\ V$$

$$I_{FB} = \frac{\left(V_{KA} - V_{REF}\right)}{R1} \tag{12}$$

$$I_{FB} = \frac{\left(3.370\ V - 5.523\right)}{806\ k\Omega}$$

$$I_{FB} = 1.051\ \mu A$$

$$R3 = \frac{\left(V_{15V} - V_{KA}\right)}{\left(I_{LOAD} + I_{KA} + I_{FB}\right)} \tag{13}$$

$$R3 = \frac{\left(10\ V - 3.370\ V\right)}{\left(30\ \mu A + 35\ \mu A + 1.051\ \mu A\right)}$$

$$R3 = 100.382\ \Omega$$

The closest standard 1% resistor value for R3 is 100 kΩ.

For stability reasons, ceramic capacitors are placed in the feedback loop of each regulator between the cathode and reference nodes. The capacitors introduce a zero to each system, and when properly placed will increase the phase margin of each regulator as to avoid oscillation and decrease ringing on the output voltages.

2.3 MOSFET Selection

Low-cost thermostats can be connected up to two separate 24-V_{AC} connections. This low-cost SSR reference design is focused towards thermostats that are connected to a single transformer. For the connection of two transformers, see the TIDA-00377 design. A standard 24-V_{AC} power relay with a current rating of 40 A has a coil resistance of 660 Ω. The 120- to 24-V_{AC} transformer output voltage can range from 20 to 30 V_{AC}. Therefore, each MOSFET must be able to handle a drain-to-source voltage and current of 43 V_{DC} and 0.12 A, respectively. The CSD18541F5 was chosen for its 60-V drain-to-source voltage and package size and cost.

When the SSR is used to turn on and off the inductive load, take care to limit overvoltage spikes during the turnoff process. The DC supply capacitor and external rectification diodes create a snubber circuit to absorb the energy from inductive load during turnoff. When the switch is turned off, the current from the inductive load is interrupted, causing the voltage to spike. For additional precaution, a transient voltage suppression (TVS) diode is added across the MOSFETs. For the DC application, unidirectional TVS is sufficient where for AC application, a bidirectional TVS is needed.

2.4 Undervoltage Lockout Design Theory

When the relay is not active, the rectification circuit capacitor charges. When the relay is active, the voltage across the MOSFETs reduces down to zero, causing the rectification capacitor to start to discharge, as shown in Figure 9 and Figure 10. If the DC source voltage becomes too low, the two ATL431 shunt regulators will not regulate and the SSR will no longer be able to function. A UVLO circuit is included in this reference design to turn off the MOSFETs and allow the capacitor to recharge.

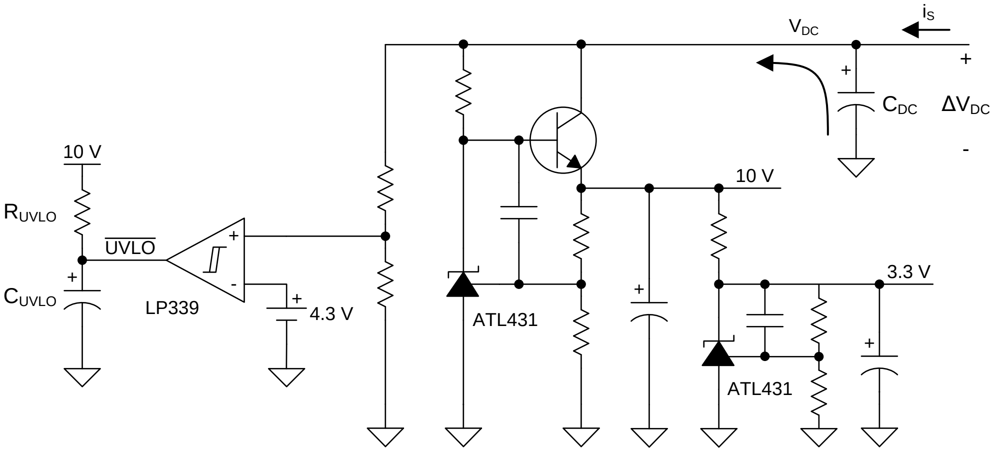

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Figure 9. Mode of DC Supply When MOSFETs are ON

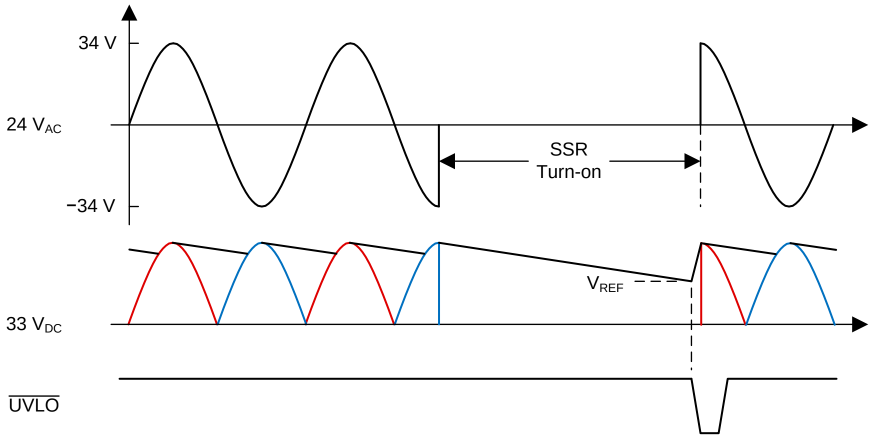

Figure 10. Resulting Waveforms for DC Supply and UVLO When SSR Cycles are ON and OFF

A minimum voltage of 18 V is chosen to maintain the DC source voltage above the ATL431 cathode voltage. When the DC source voltage goes below 18 V, the LP339 will output a logic low, which will be sent to the logic control to turn off the MOSFET.

To improve functionality and reduce the number of low pulses per AC cycle, place a capacitor at the output of the comparator (C_{UVLO}). The RC network will add a delay to the rise time of /UVLO and provide more time for the capacitor to recharge. To calculate the delay time, use the peak current provided from the HVAC load (typically the current through HVAC relay), the DC supply capacitor value calculated in Section 2.2.1, and the desired peak voltage for Equation 14.

$$\Delta t_{UVLO\_DELAY} = \frac{C_{DC} \times \Delta V_{DC}}{i_S} \tag{14}$$

To calculate values of the RC network, use the desired delay time and Equation 15 and Equation 16.

$$\tau = R_{UVLO} \times C_{UVLO} \tag{15}$$

$$V_{REF4V3} = V_{UVLO}(t) = 10\text{ V} \times \left(1 - e^{-\frac{t}{\tau}}\right) \tag{16}$$

2.5 Control Logic Design Theory

The control logic circuitry uses short, LOW logic level pulses at the inputs of the D-type flip-flop, SN74AUP1G74, to turn on and off the MOSFETs. See Table 4 for the logic levels on output Q in reference to the input levels of /PRE and /CLR. Output Q is sent to a comparator whose output is connected to the output of the UVLO comparator, as shown in Figure 11. The connection of the comparator outputs performs an AND function between the flip-flop and UVLO output signals. The resulting voltage level, EN, is sent to the two comparators of the gate driving network.

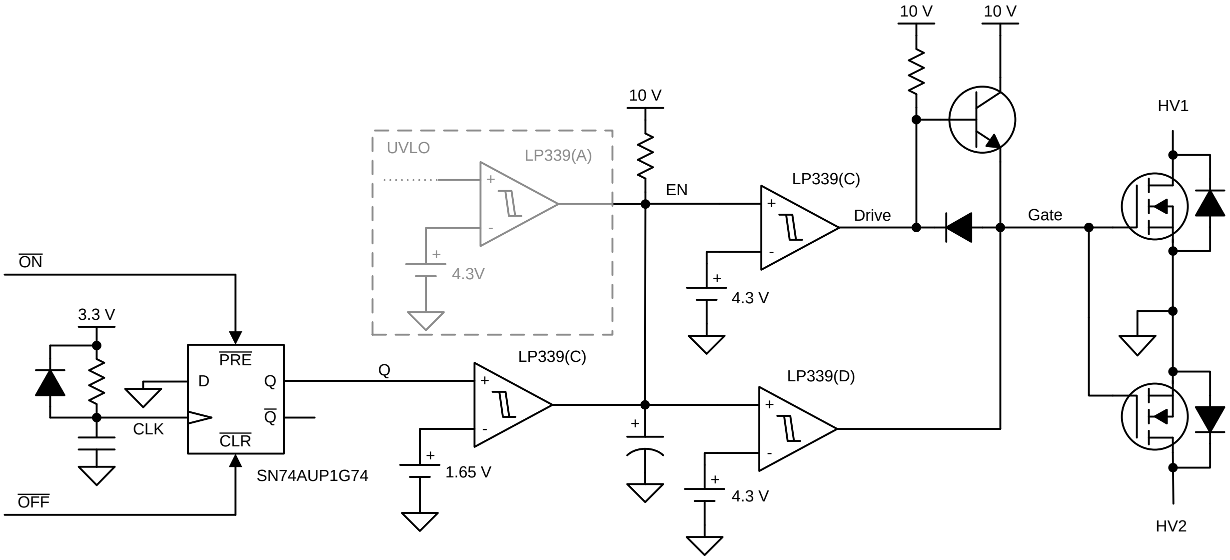

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Figure 11. Control Logic and Gate Driver Schematic

Table 4. SN74AUP1G74 Logic Levels for /PRE, /CLR, and Q

/PRE	/CLR	CLK	D	Q
L	H	X	X	H
H	L	X	X	L
H	H	↑	L	L

When the SSR is initially connected to the power source, the flip-flop will start in an unknown state. To initialize the flip-flop in the off-state, connect an RC network at the active rising edge CLK input and connect D to GND. After the rail voltages are stable, the signal at the CLK input will increase depending on the time constant of the network. When the RC signal passes the V_{IH} threshold of the CLK input, the Q output will be set to a logic level low setting the SSR in an off-state.

The function of EN is to drive the gates of the MOSFETs through the two comparators. For fast turnon time of the MOSFETs, a sufficient amount of current must be available to charge the gate-to-source capacitance (C_{GS}) as shown in Figure 12. When EN is high, the open collector outputs of the comparators are also high and the gate will be driven from the common collector circuit as shown. This configuration will amplify the current provided by R_{CB} at the base at the NPN transistor to provide the necessary current to C_{GS}.

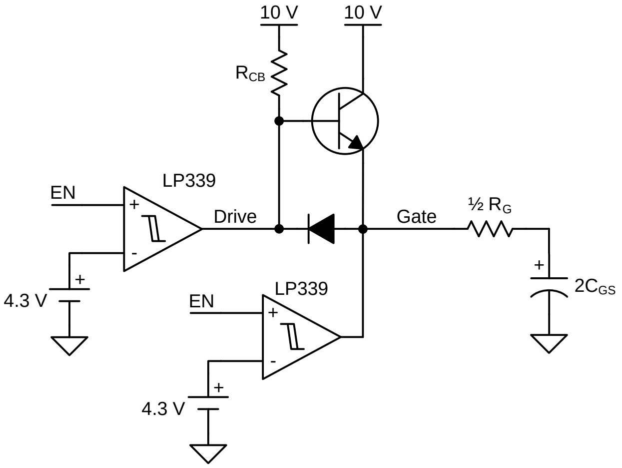

Figure 12. Gate Driver Schematic With Series Gate Resistance and Gate-to-Source Capacitance of MOSFETs

For fast turnoff time of the MOSFETs, a sufficient discharge path must be provided for C_{GS}. When EN goes low, the outputs of the comparators are pulled down to ground, which sinks current. To protect the base-emitter junction of the transistor from overvoltage, an additional diode is used to limit the V_{EB} voltage to the forward voltage of the diode, V_F.

For improved functionality and protection, a Zener diode can be connected to the gate of the MOSFETs. The Zener diode sets a peak voltage limit to the gate of the MOSFETs as to avoid overvoltage of the gate-source junction.

For the full logic sequence to turn on and off the switch through the D-type flip-flop, see Figure 13.

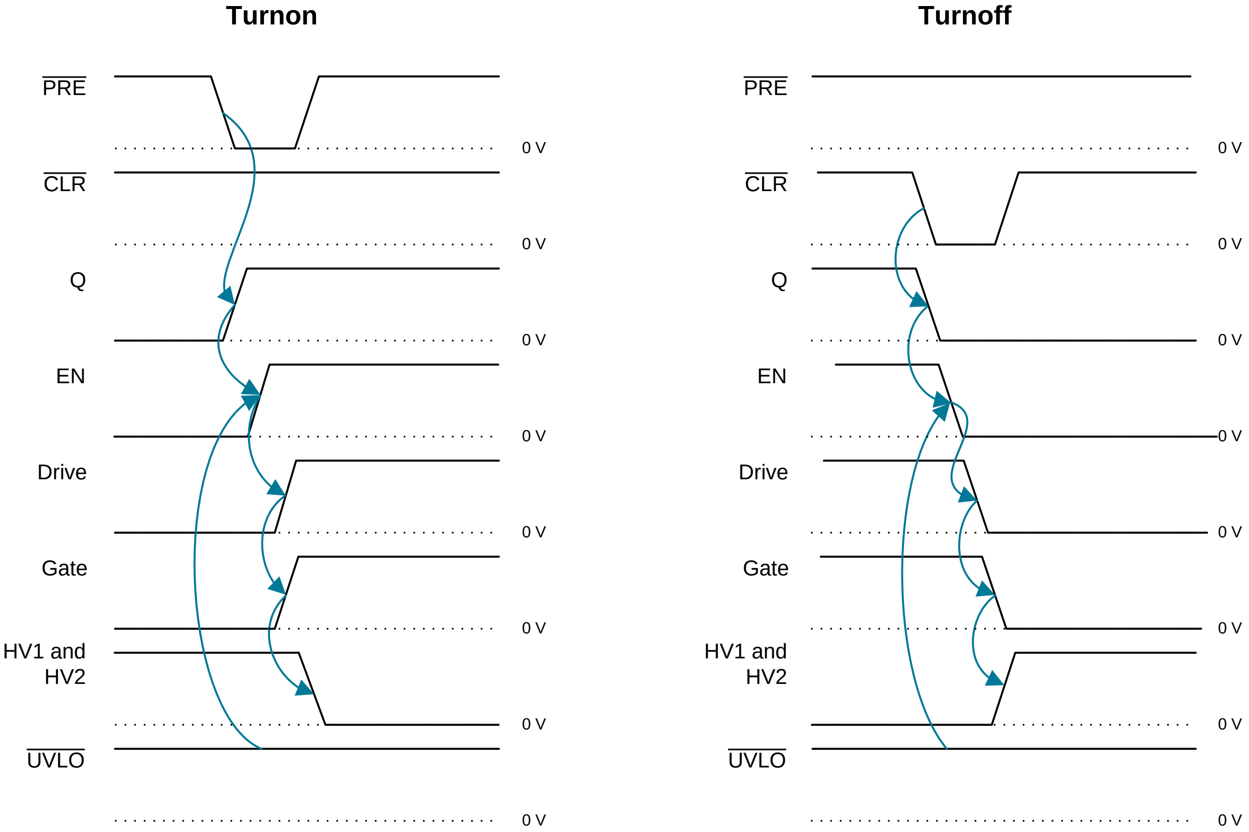

Figure 13. SSR Turnon and Turnoff Logic Sequence

3 Getting Started Hardware

3.1 Board Overview

For ease of use, all of the components, headers, and test points are located on the top side of the board, as shown in Figure 14. The signal chain starts on the left side of the board and moves to the right side of the board in a linear fashion. The input headers, J5 and J7, are located on the left edge of the board has connection points ON and OFF for active logic level LOW inputs of the D-type flip-flop. To the right of those two headers is J9, which provides the option to use the enable signal from the D-type flip-flop or an externally applied enable signal. The top-most headers connect the 3.3-V_{DC} supply (J4) and 10-V_{DC} supply (J3) rails to the corresponding loads. The three remaining two pin headers in the center of the board connect the rectified ac load voltage to the DC power supply (J2), rectified AC load voltage to the input of the UVLO (J2), and the output of the UVLO to the gate driver (J6). On the far right is the terminal block (J5), which connects the circuit to the 24-V_{AC} HVAC load. The eight surface mount test points provide access to the signal chain and ground.

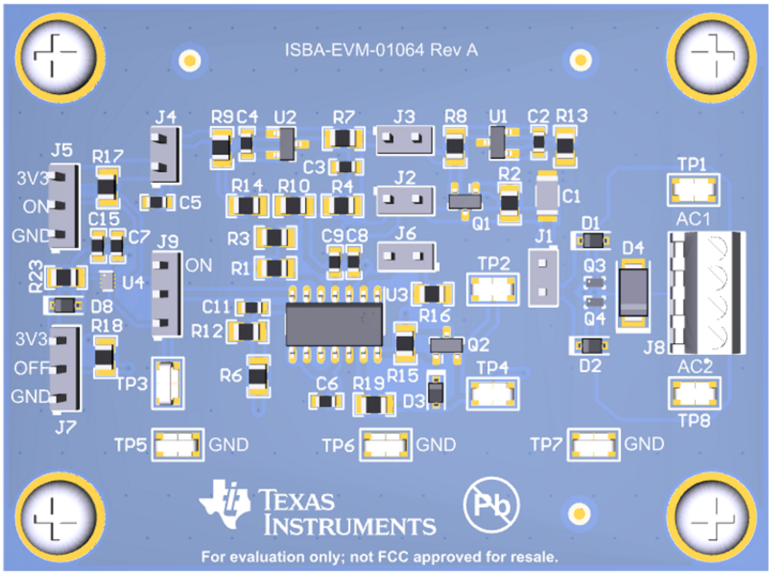

Figure 14. TIDA-01064 Reference Design Hardware

3.2 Operating the Circuit

Before powering the board, set the headers in the orientation described in Table 5. Connect the HVAC system load last to power the board.

Table 5. Header Connections at Start-up

HEADER	CONNECTION
J1	Short
J2	Short
J3	Short
J4	Short
J5	Short pins 2 and 3
J6	Short
J7	Short pins 1 and 2
J8	24-V_{AC} HVAC load
J9	Short pins 1 and 2

When the board is first powered on, the rectification diodes will provide the voltage to the DC power supply, which will enable the logic control and gate driver. The MOSFETs will not be active due to the short across pins 1 and 2 of J7. To turn on the MOSFETs, move the jumper from pins 1 and 2 on J7 to short pins 2 and 3. Next, provide a short, logic level LOW pulse to ON through pins 1 and 2 of J5. Because both inputs are active low and have pullup resistors, the pulse must pull down the signal to logic zero. The simplest way to do this is to short the pin to ground for a short period of time. The same method goes for the OFF signal; shorting the OFF pin to ground will turn on the MOSFETs.

4 Testing and Results

4.1 Test Setup

Following the header orientation listed in Table 5, the circuit is tested using a Honeywell 120- to 24-V_{AC} 40VA transformer, AT140B1214, similar to what is used in HVAC systems. A 24-V lightbulb is connected in series across terminal block J8 to provide 0.18 A, as shown in Figure 15. The initial testing procedure was to activate and deactivate the switch to see the light turn on and off. There was no flicker in the light, providing the initial results that the charging time of the DC supply capacitor was not too long.

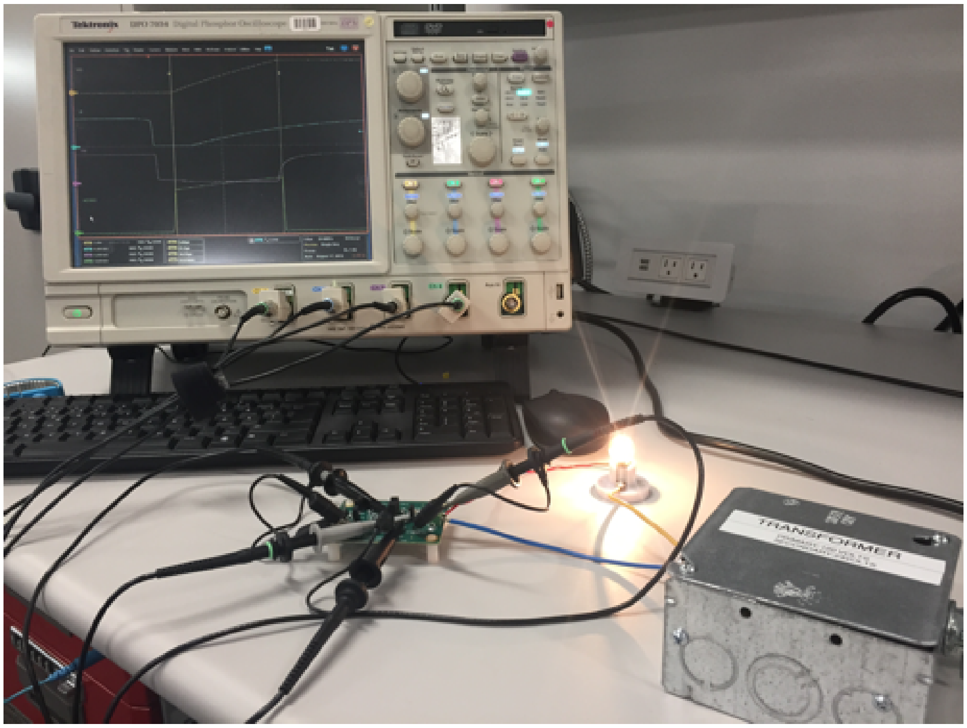

Figure 15. Test Setup of TIDA-01064 EVM, Light Bulb, and Transformer

To verify the specific functionality of this reference design, there are two necessary tests: the current consumption from the 24-V_{AC} line, and the timing of the signal chain waveforms to validate the low self-powering and fast switching. The first test performed is the current consumption. These values were collected measuring the current flow through available headers using an ammeter during on and off states. The data was then verified by calculating the current through resistors by means of voltage measurements in addition to current rating of components from their datasheets.

The second test is to measure the timing of the control signals, which includes four sets of signals. The first is charging time of the DC supply capacitor. This is seen by probing J1, J6, TP4, and AC1/AC2 as shown in Figure 16.

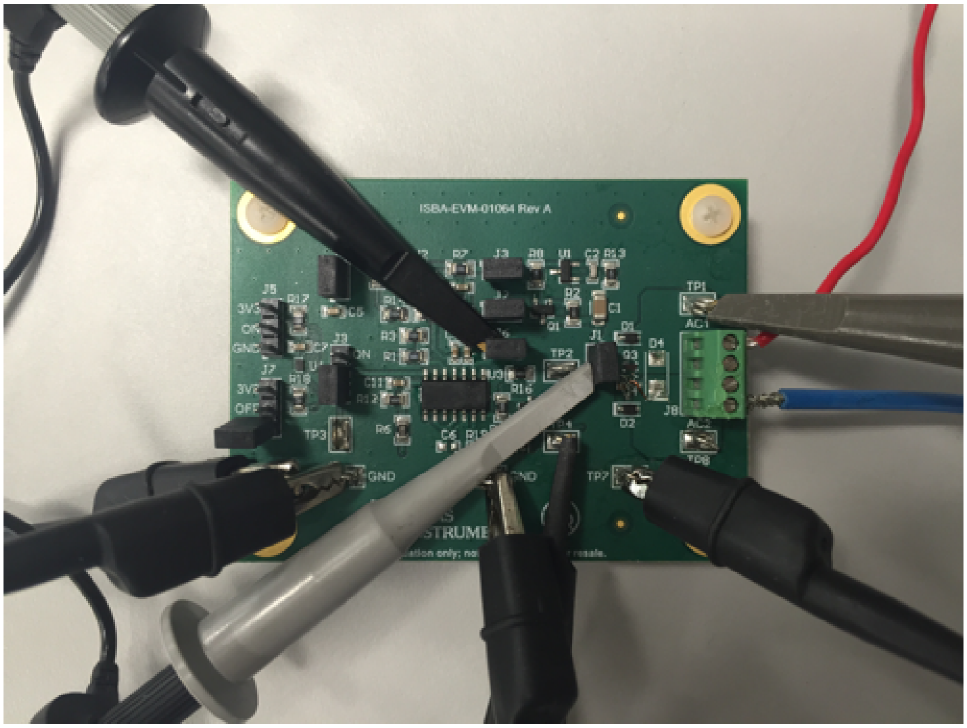

Figure 16. Probe Connections for Signal Chain Waveforms

The second and third signals are to check the turnon and turnoff delay of the MOSFETs. The turnon and turnoff functionality has been verified visually by the lightbulb, but it is important to verify the speed of the switching as to efficiently charge the DC supply capacitor during active time. The waveforms captured are ON, TP3, TP4, and AC1/AC2, which can be found in Figure 20 and Figure 21 in Section 4.2.

4.2 Test Data

The total steady-state current consumption for both on and off times are found in Table 6. The steady-state currents for each block of the SSR for both on and off times are shown in Figure 17 and Figure 18.

Table 6. Total Steady-State Current Consumption

STATE	CURRENT (µA)
ON time	186.63
OFF time	367.33

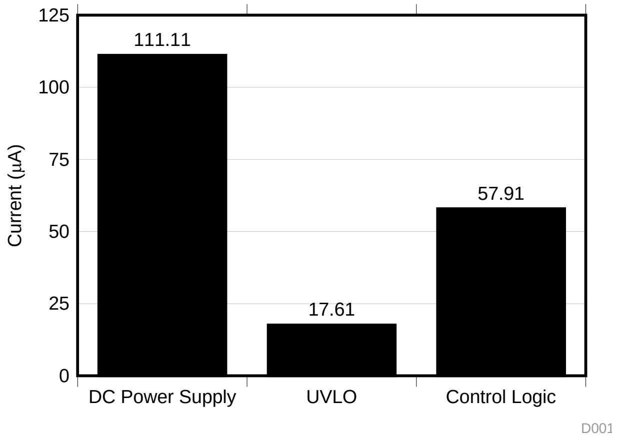

Figure 17. Steady-State Current Consumption During ON Time

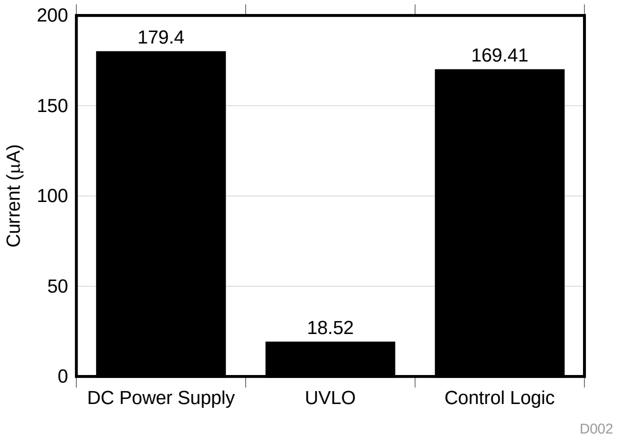

Figure 18. Steady-State Current Consumption During OFF Time

Figure 19 displays the charging time of the DC supply capacitor during the active time of the SSR. Active time of the SSR is when it is controlling the HVAC load and MOSFETs are on also cycling through on and off, recharging the DC supply capacitor. The time between the rising and falling edge of the AC1 and AC2 waveform corresponds with the V_{DC} charging time of ~19 μs, as shown in Figure 19. This also corresponds with the edges of J6 (UVLO) and TP4 (V_{GS}), with the consideration of delay.

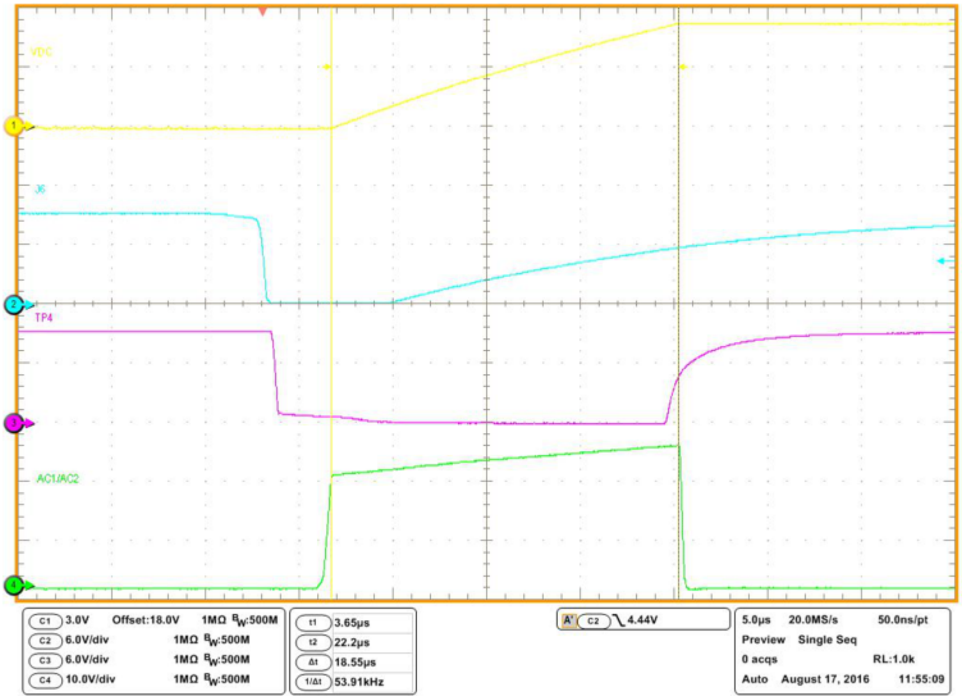

Figure 19. Charging Time of DC Supply Capacitor (Yellow) in Reference to J6 (Blue), TP4 (Purple), and AC1/AC2 (Green)

Figure 20 shows the turnon delay time through input pulse to the D-type flip-flop. From the falling edge of the ON# low pulse to the low transition of the voltage across the MOSFET is 12.1 µs. The turnon time of the MOSFETs (AC1/AC2 = V_{DS}) is 0.5 µs.

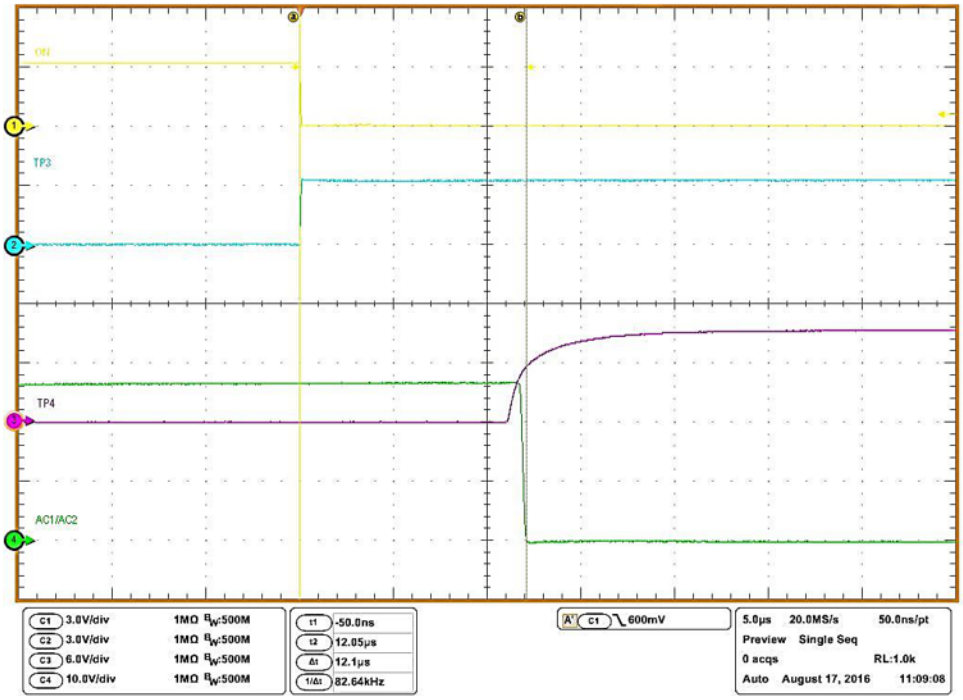

Figure 20. ON Delay Waveforms From /PRE Input (Yellow) to TP3 (Blue), TP4 (Purple), and V_{DS} of MOSFETs (Green)

Figure 21 shows the turnoff delay time through input pulse to the D-type flip-flop. The delay time from the falling edge of the OFF low pulse to the low transition of the voltage across the MOSFETs is 4.6 µs. The turnoff time of the MOSFETs (AC1/AC2 = V_{DS}) is 0.75 µs.

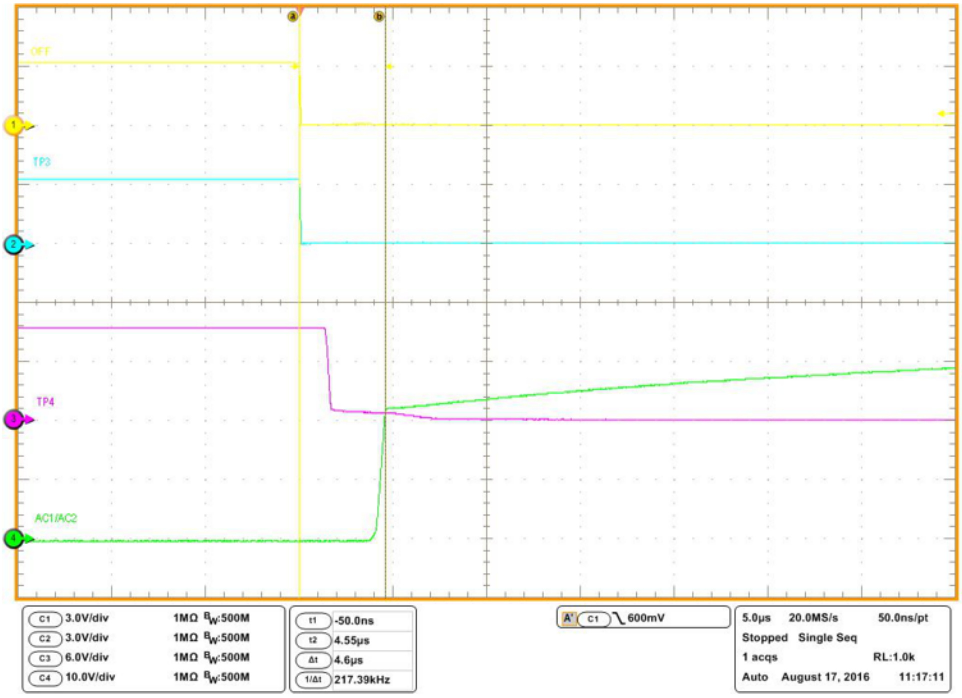

Figure 21. OFF Delay Waveforms From /CLR Input (Yellow) to TP3 (Blue), TP4 (Purple), and V_{DS} of MOSFETs (Green)

5 Design Files

5.1 Schematics

To download the schematics, see the design files at TIDA-01064.

5.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-01064.

5.3 PCB Layout Recommendations

A careful PCB layout is critical and extremely important in a high-current, fast-switching circuit to provide appropriate device operation and design robustness. As with all switching power supplies, pay attention to detail in the layout to save time in troubleshooting later on.

5.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-01064.

5.4 Altium Project

To download the Altium project files, see the design files at TIDA-01064.

5.5 Gerber Files

To download the Gerber files, see the design files at TIDA-01064.

5.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-01064.

6 Related Documentation

1. Texas Instruments, *Designing with the "Advanced" TL431, ATL431*, Application Report (SLVA685)
2. Texas Instruments, *Setting the Shunt Voltage on an Adjustable Shunt Regulator*, Application Report (SLVA445)
3. Texas Instruments, *Compensation Design With TL431 for UCC28600*, Application Report (SLUA671)
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7. JEDEC Solid State Technology Association. (2006). *Interface Standard for nominal 3 V/3.3 V Supply Digital Integrated Circuits (JESD8C.01)*. Arlington, VA : JEDEC Solid State Technology Association

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7 About the Authors

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Revision A History

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

Changes from Original (September 2016) to A Revision	**Page**
- Changed from preview draft	1

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