Application Report

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Implementing a Battery Disconnect Switch Using 100-V Half-Bridge Gate Drivers

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ABSTRACT

The 12-, 24-, and 48-V Automotive and Industrial applications such as battery load balancing and power distribution commonly use relays as cutoff switches. Relays can control a high-voltage system from a low-power signal. However, they present many design constraints due to their mechanical nature, and size causing long-term reliability issues, slow switching speeds, and board space constraints. Semiconductors, like MOSFETs and gate drivers, can be used as a solid state relay to solve these issues, increasing lifetime reliability, and providing fast switching speeds. This solid state cutoff switch can be used in 12-, 24-, and 48-V DC/DC converters Figure 1 and safety applications such as EPS, chassis control, and engine fans, where a battery disconnect switch or circuit breaker is needed.

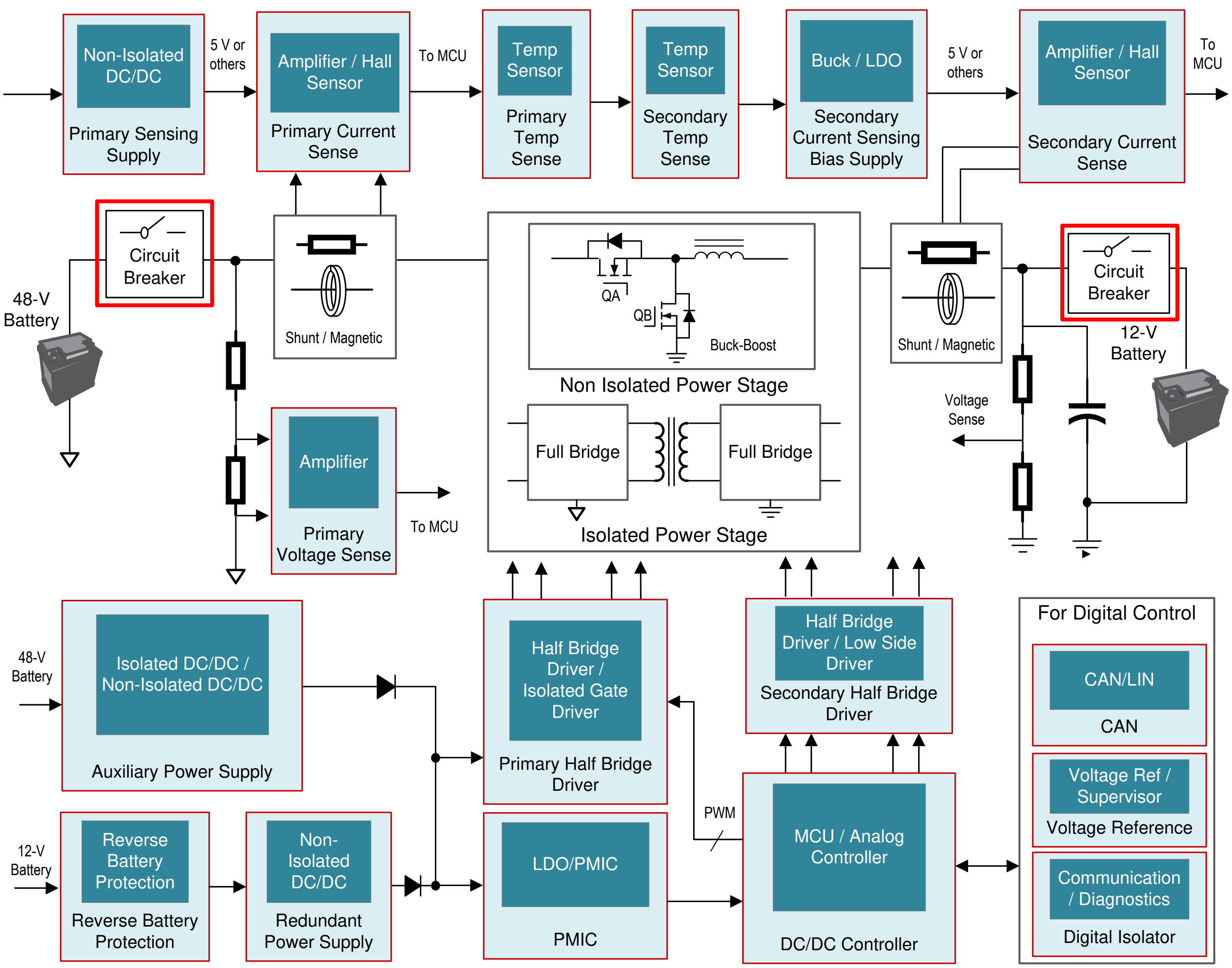

Figure 1. Block Diagram of Bidirectional 48-V to 12-V DC/DC Converter

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Trademarks

1 Basic Operation

A bidirectional cutoff switch is an active switch capable of supporting bidirectional current flow during the ON condition and bidirectional voltage blocking when it is turned OFF. Bidirectional cutoff switches also allow the conduction of positive or negative ON-state current and blocking of positive or negative OFF-state voltages.

Designers can implement the bidirectional power switch using MOSFETs to eliminate mechanical bounce of relays. MOSFETs are also attractive because of their faster response times due to their electrical nature and their low on resistance ($R_{DS(on)}$). **Figure 2** is a bidirectional switch using the UCC27212-Q1 gate driver + MOSFETs in a common source configuration of back-to-back N-MOSFETs. This solution allows the switch to conduct a 48-V supply to a load during the ON time of the FETs. During the OFF times, the body diodes of the back-to-back FETs block current flow in either direction of D_1 and D_2.

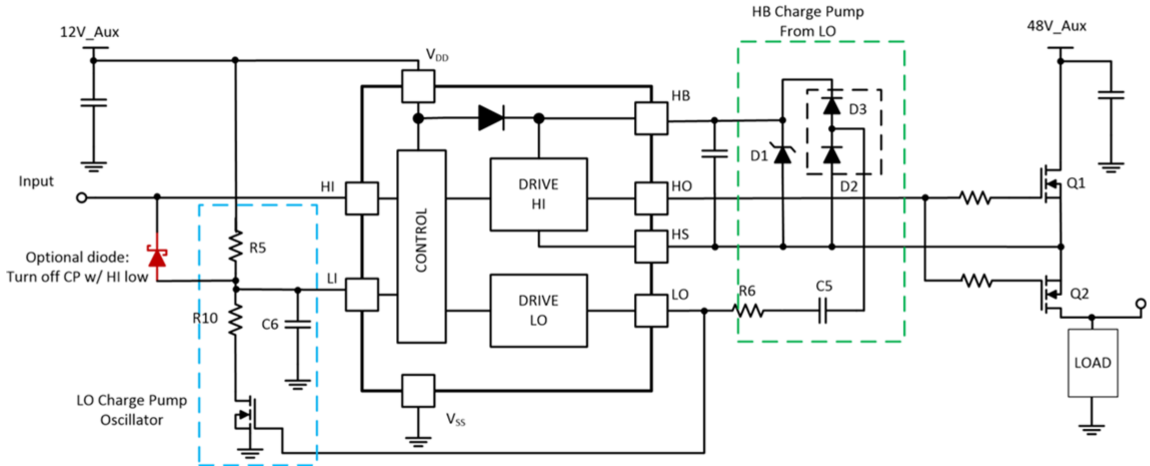

Figure 2. Bidirectional Switch With Back-to-Back N-MOSFETs in Common-Source Configuration

When the current is flowing from the supply (48V_Aux) to the load (VLOAD), the bus voltage will be higher than the load voltage due to voltage drop across the MOSFET due to $R_{DS(on)}$. With 48V_Aux higher than the VLOAD voltage, UCC27212-Q1 drives the gates to turn the MOSFETs "on" (conducting), and current flows through the $R_{DS(on)}$ of the FETs to VLOAD. This operation would be the same for opposite scenario where a load must charge the battery.

To turn-off the switch, the HO output of the driver goes low to set the gates at V_{GS} = 0 to turn "off" the MOSFET (non-conducting). The common source topology ensures that the body diodes block current flow when MOSFETs are not conducting.

2 Half-Bridge Gate Drivers to Drive a Bidirectional Switch

To effectively turn on and turn off the switch, a half-bridge gate driver must source and sink sufficient peak current to the gates. Because the MOSFETs are not referenced to earth GND (as Figure 3 shows) and long duty cycle (up to 100%) mode of operations where the driver IC operates in a standby mode for most of the application, bootstrap circuitry cannot be implemented to provide bias to the high-side channel (HO). It is therefore necessary to generate constant bias to maintain the high-side floating supply above the HB-HS UVLO of the driver during the long duty cycle operations.

3 Gate Driver Selection

Knowing the total gate charge of the switches, designers can select the appropriate driver based on desired application timing requirements. Table 1 shows how to determine a suitable driver based on gate charge and MOSFETs on and off times.

Table 1. Gate Charge

Gate Charge of the MOSFET	105 nC
Total back-to-FETs	8
Switch ON, switch OFF time	0.5 µs
Total gate charge	840 nC
Required driver peak current	1.68 A

The application requires a gate driver capable of sourcing and sinking 2.56-A current to turn on and turn off the MOSFETs in the bidirectional switch.

Figure 3 shows a bidirectional switch using UCC27212-Q1 (4-A source and 4-A sink) or UCC27284 (2.5-A source and 3.5-A sink) to drive 8 parallel FETs. The configuration shows the ICs driving high gate charge loads of a 48-V battery switch (840 nC gate charge). The low-side channel is used to generate an oscillator that charges the HB-HS pump through the 100-nF capacitor C_5. The HB-HS charge pump provides constant bias to the gates allowing the application to maintain the floating gates above the HB-HS UVLO thresholds.

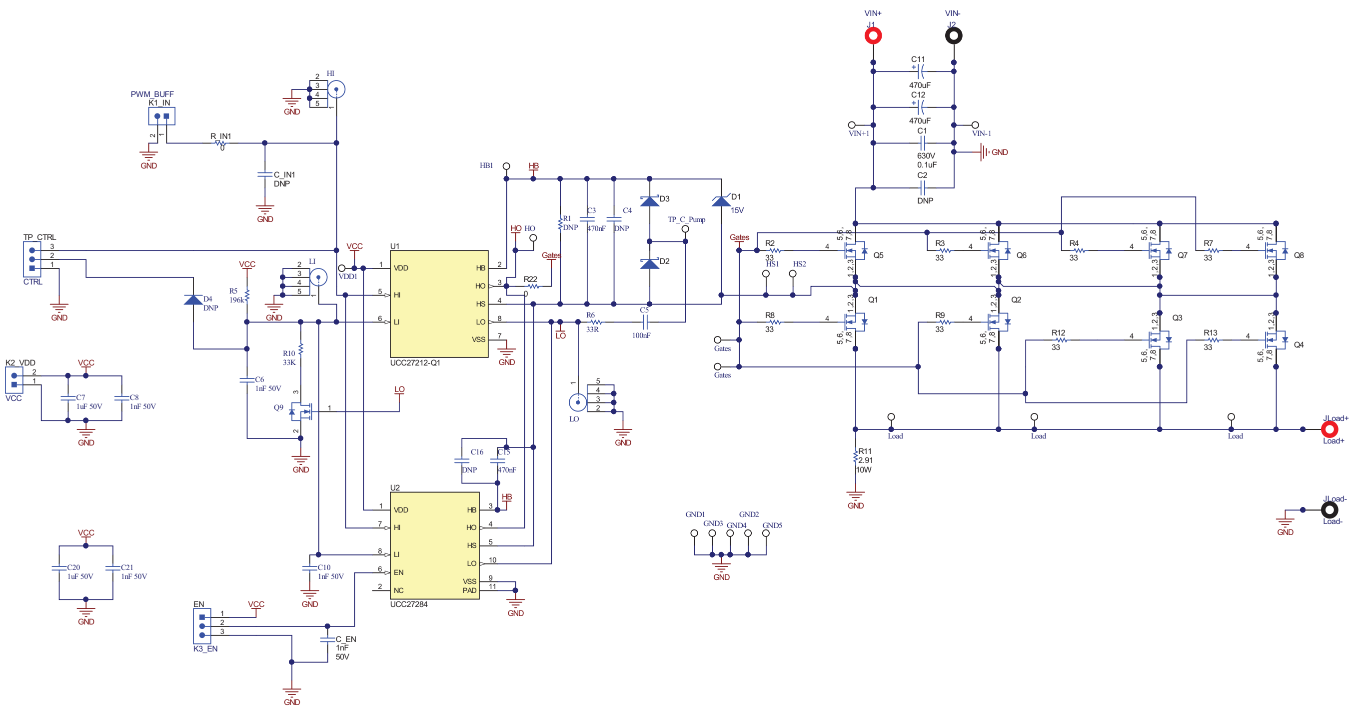

Figure 3. One Hundred Percent Duty-Cyle Capable Half-Bridge Gate Drivers for 48-Battery Cutoff Switch

This configuration requires a half-bridge driver with independent outputs on the low and high-sides (LO and HO) as both low-side and high-side outputs should be able to stay high simultaneously; drivers with an interlock feature will require different topology. The gate driver IC must also be rated above the bus voltage expected operating condition.

4 LO Oscillator

The low-side channel self generates the oscillator signal necessary to charge the HB-HS pump through the common V_{CC} supply. When sizing the components around the LO oscillator, there are several considerations to take into account including V_{CC} gate drive operating range, internal pulldown resistance of LI, worst-case V_{IH} and V_{IL} thresholds, charge pump switching frequency, and so forth.

From the schematic in Figure 3, when the charge pump is not running, R_5 and the IC's internal pulldown resistor (R_{int}) on LI form a voltage divider network where the output voltage of the divider network must be higher than the maximum VIH threshold of the IC. This ensures that the gate driver IC is fully on during a igh command therefore R5 should be sized with the minimum V_{DD} such that:

$$V_{LI} > V_{IH} \text{ therefore } \frac{V_{CC,\,min} \times R_{int}}{R_5 + R_{int}} > V_{IH} \quad (1)$$

Solving for R_5 yields Equation 2:

$$R_5 < \frac{V_{CC} \times R_{int}}{V_{IH}} - R_{int} \quad (2)$$

Using UCC27212-Q1 as an example, the internal pulldown of LI is specified at R_{int} = 68 kΩ and the maximum V_{IH} threshold is 2.6 V, V_{CC} = 10.5 V,

$$R_5 < 206\ k\Omega \qquad (3)$$

For the measurements that follow, chose R5 = 196 kΩ.

To turn off the charge pump, the voltage on the LI pin must cross the V_{IL} threshold of the device. This is accomplished by sizing R_{10} such that:

$$R_{pulldown} = \frac{V_{IL}}{I_{in}} = \frac{V_{IL}}{(V_{CC,max} - V_{IL}) / R_5} \qquad (4)$$

Where is the equivalent parallel resistance formed by the driver's internal pulldown on the LI pin and the external pulldown resistance R_{10}.

The time constant created with R_5 and C_6 will slow the LI rise and therefore influence the duty cycle of the oscillator. C_6 should be sized to meet acceptable current consumption from V_{CC} when the charge pump is running as a higher switching frequency on the charge pump will increase the I_{CC} current.

The optional diode connected to LI allows control of the oscillator to turn it off when shorted to GND. It can also be tied to HI in which case the oscillator will only run when HI is high.

C_5 is the coupling capacitor interfacing the oscillator and the charge pump. C_5 should be sized according to the expected switching frequency of the oscillator. For this application, our expected oscillator frequency is < 20 kHz; therefore, a 100-nF capacitor is sufficient for AC coupling of the oscillator signal.

Channels 1 and 2 from Figure 4, respectively, show the LI and LO behavior during the oscillator operation. LI oscillates above the V_{IH} and V_{IL} thresholds of the driver IC to generate the pulse train at the LO output. The pulse train charges the charge pump through the C_5 capacitor to maintain constant bias across the HB-HS capacitors (Channel 3).

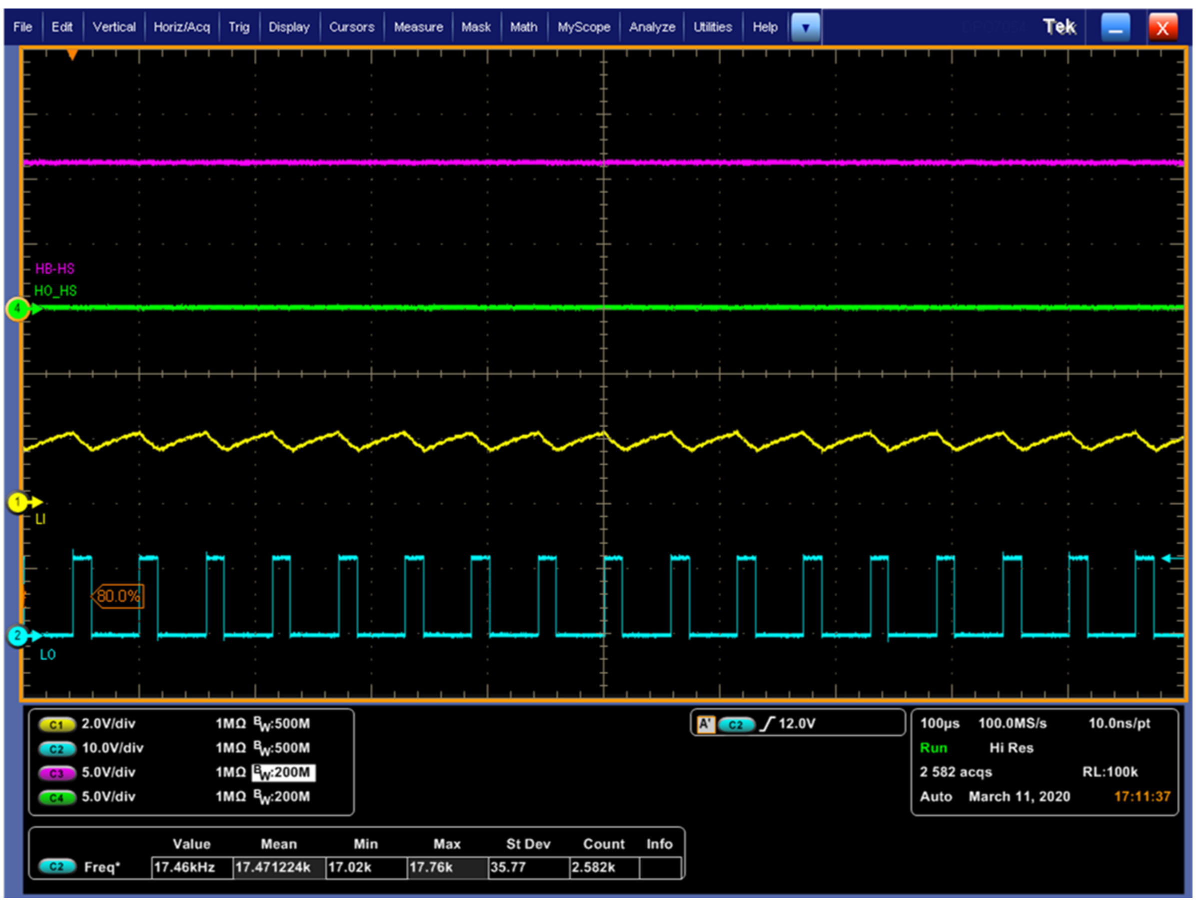

Figure 4. LO Oscillator at Test Conditions HI = GND, R_5 = 196 kΩ, D_4 Open, EN Tied to V_{CC}, V_{bus} = 48 V

During operation of the LO oscillator, **Figure 5** shows the bias current behavior of the UCC27212-Q1 and UCC27284 in standby mode with the charge pump oscillator in ON and OFF mode.

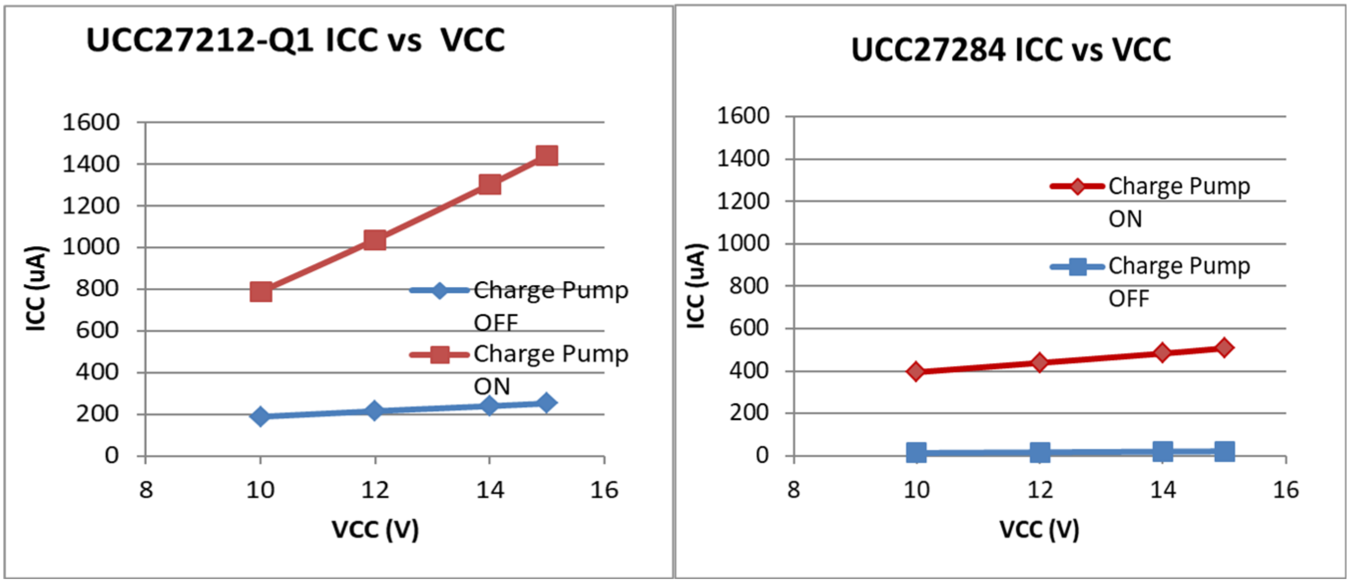

Figure 5. Test Conditions: Left: HI = GND, R_5 = 196 kΩ, D_4 floating, Vbus = 48 V Right: HI = GND, R_5 = 316 kΩ, D_4 open, EN tied to V_{CC}, V_{bus} = 48 V

5 HB-HS Charge Pump

The oscillator generates bias across the HB-HS capacitor C_4 from Figure 3 during the desired ON-time of the high-side switch. During the charging sequence of the pump, the low-side channel output LO charges the C_4 capacitor through the D_3 diode when LO is high. During the oscillator LO OFF times, C_5 is clamped to HS through the D_2 diode which charges C_5. The peak-to-peak voltage at the D_2 and D_3 junctions is the LO peak-to-peak amplitude. R_6 is added in series with C_5 to limit the current into the output of the driver when the high-side switch is turned on and off. The R_6 resistor is sized such that is within the driver's current rating. To size the HB_HS capacitor, designers should determine the minimum gate drive as well as the expected minimum voltage at the gate such that:

$$C_{HB\_HS} \geq \frac{Q_{g,total}}{\Delta V} = \frac{Q_{g,total}}{V_{DD,min} - V_{DH} - V_{Gs,min}}$$

where

- $V_{DD,min}$ = minimum supply voltage
- V_{DH} = charge pump diode drops
- $V_{GS,min}$ = expected minimum V_{GS} (5)

The HB-HS capacitance, represented in Figure 3 as C3 and C15, was sized such that:

$$C_{HB\_HS} \geq \frac{840nC}{11V - 1V - 9V} \geq 840 \ \ nF \quad (6)$$

A capacitance of 940 nF (equivalent parallel capacitance of C_3 and C_{15}) was used in Figure 3 to separately evaluate both the UCC27284 and UCC27712-Q1 devices, driving the switch.

The Zener diode D_1 from Figure 5 sets the maximum V_{DD} operating range; therefore, should be chosen to match the maximum recommended operating conditions of the HB-HS pins. The Schottky diodes D_2 and D_3 should have sufficient peak current ratings to account for transients occurring during the power switch initial turn-on and turn-off sequence. They provide the needed clamping protection for high-voltage transients to pass transient tests and typical battery line transients.

6 Performance Advantages for 48-V High-Side Switch Applications

High-side switch applications typically drive high gate charge loads where the FETs must be the switch must turn-off within 1 µs. To illustrate TI half-bridge drivers in such applications, the UCC27212-Q1 and UCC27284 devices were used to drive 8 parallel FETs with maximum total gate charge at 840 nC (typical) and 1280 nC (maximum).

Figure 6 shows the DC operation of the switch using the UCC27284 device. Channel 3 shows the charge pump supply constant above the driver's HB-HS UVLO threshold which allows the HO-HS (Channel 4, green) to provide constant bias to the gates of the MOSFETs for several milliseconds.

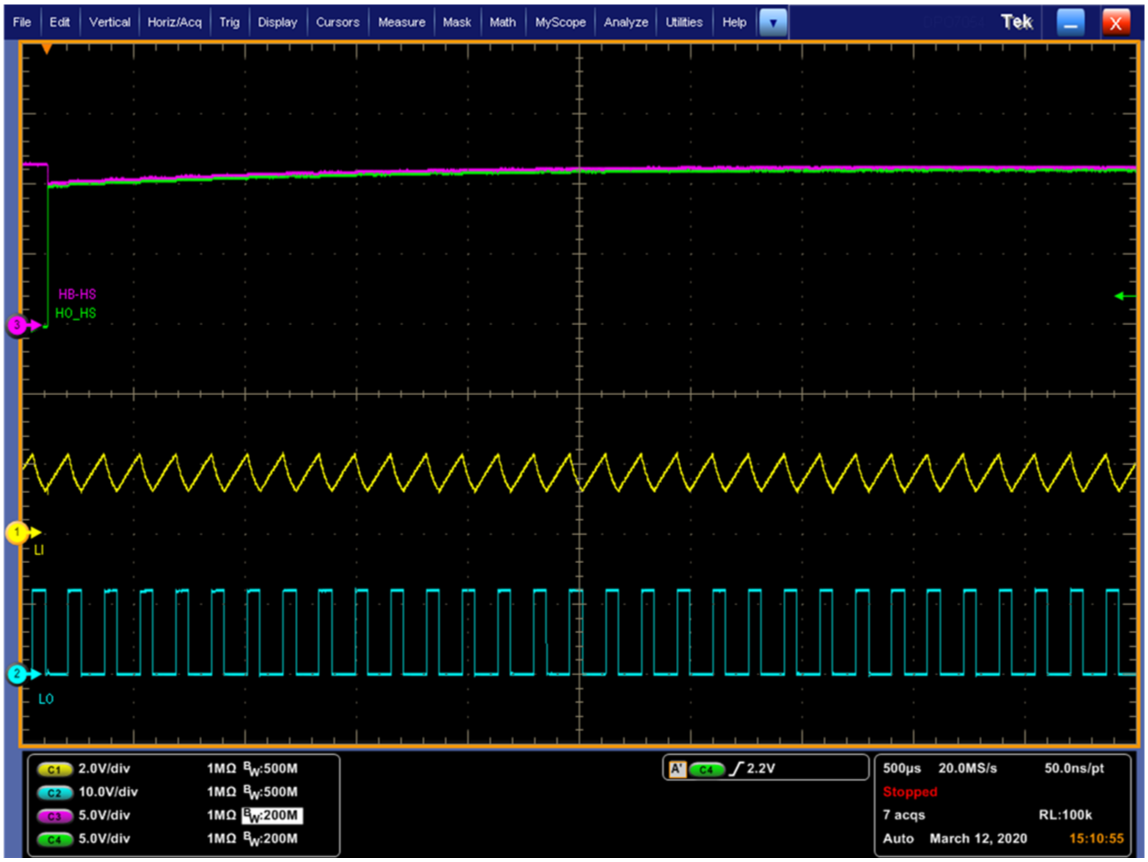

Figure 6. DC Operation of the Bidirectional Switch Using UCC27284

One of the key advantages of using gate drivers + MOSFETs over relay-based solution MOSFETs is the switching performance. Figure 6 and Figure 7 show the dynamic behavior of the bidirectional switch with a 3-Ω resistive load connected to a 48-V battery. The switch shows similar response times in both cases where the delay between controller signal to gate of the FETs are measured and the delay from controller signal to the load changing state. It is important to point out that there is no arcing, bouncing, or both, when the load switches states as commonly associated with mechanical relays.

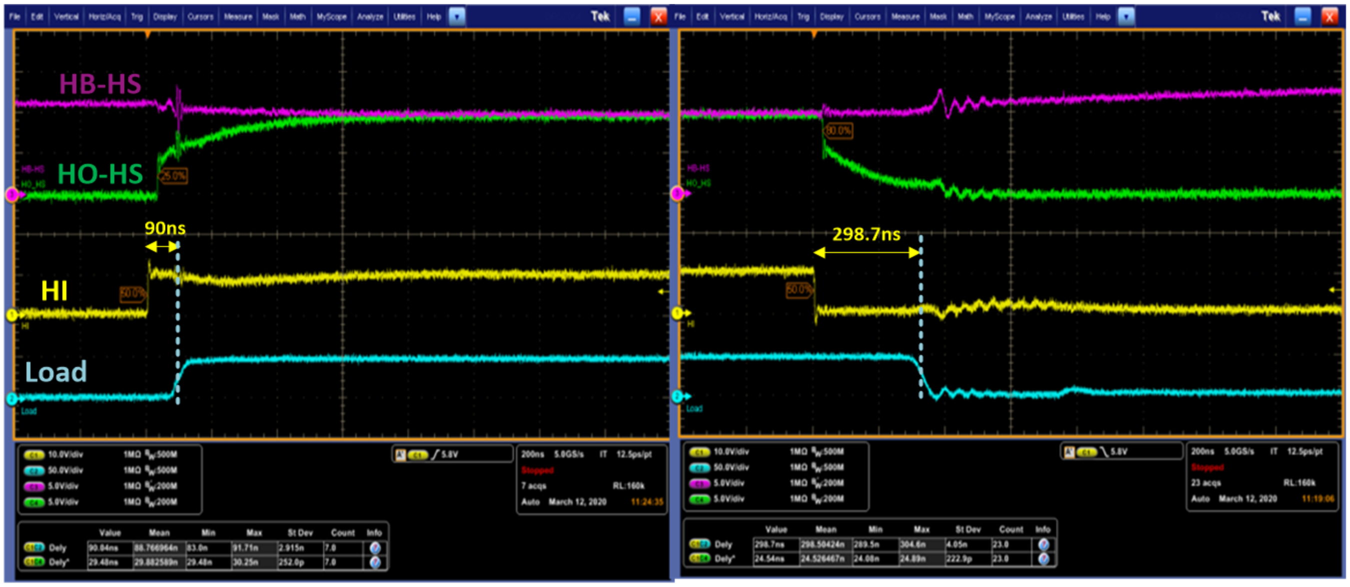

Figure 7. Response Time of the Bidirectional Switch Driver UCC27212-Q1

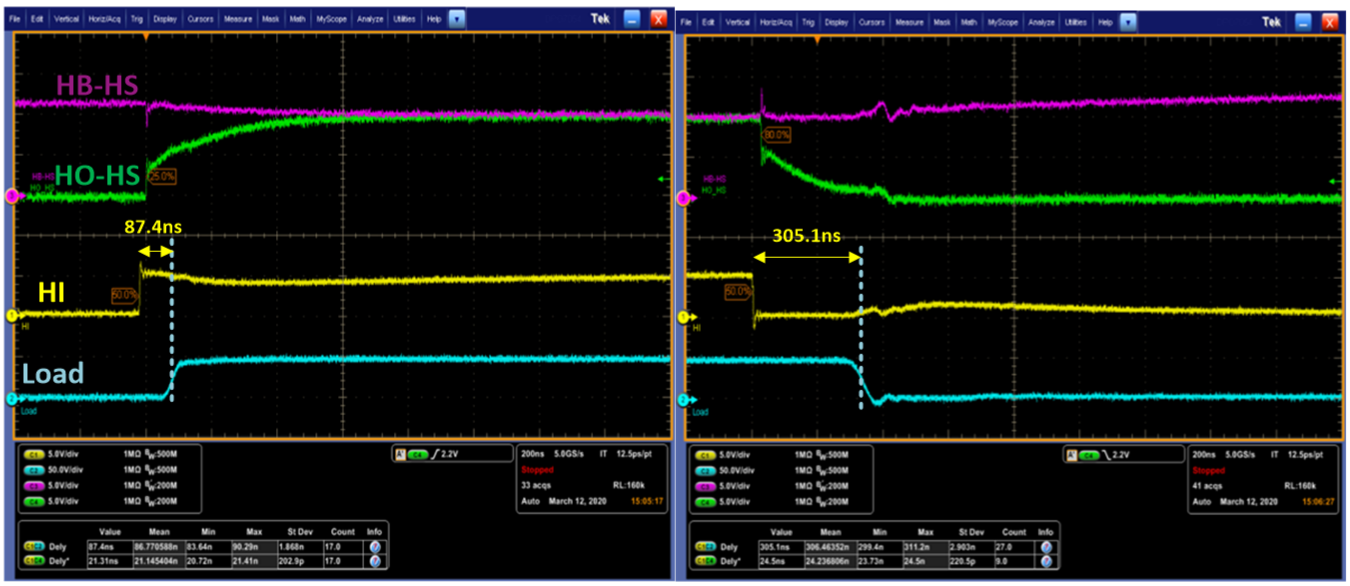

Figure 8. Response Time of the Bidirectional Switch Driver UCC27284

Both responses from the bidirectional switch using UCC27212-Q1 and UCC27284 are well below most applications requirements where designers are typically looking at 1-µs response times from the controller signal to load as Figure 8 shows.

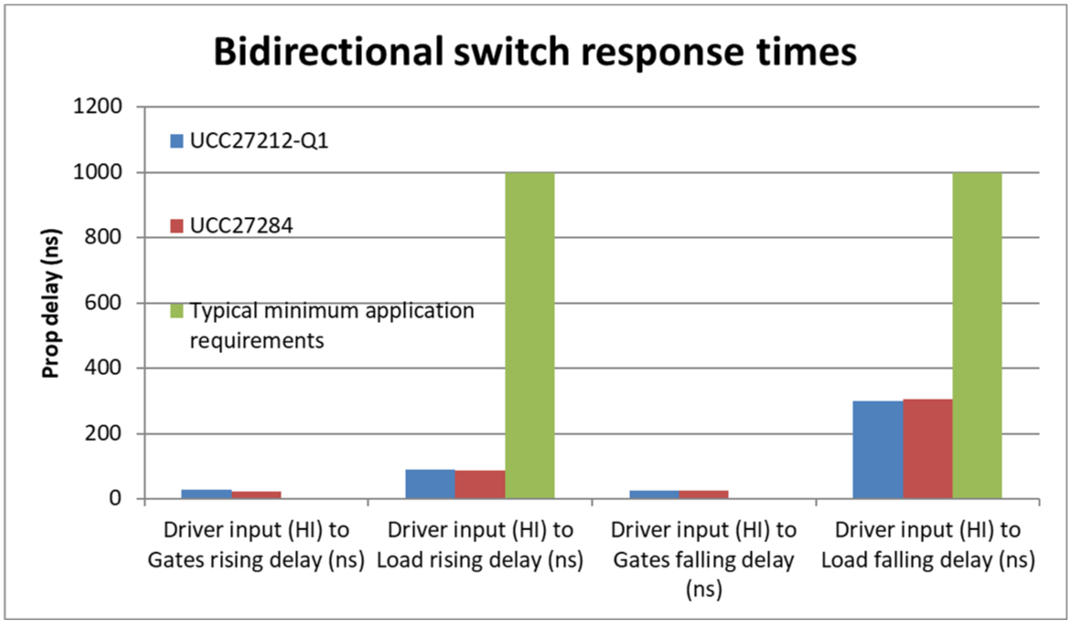

Figure 9. Response Time of the Bidirectional Switch vs Typical Requirements

7 Performance Trade-offs

Implementing the high-side switch using gate drivers have performance trade-offs including the oscillator's frequency dependency standby current for which higher current consumption when the oscillator is running at higher frequencies.

The Schottky diodes MUX the supplies at terminals 'A' and 'B' to power the charge pump circuit, which in turn provides enough gate drive to turn ON both the N-channel MOSFETs. Even though the implementation provides low $R_{DS(on)}$ with N-MOSFETs but the complex drive circuit of the component occupies more board space versus traditional dedicated high-side switches.

This solution also does not provide thermal protection for the FETs, so oversized FETs need to be considered for higher design margin.

When using the UCC27284 (Figure 10), the EN to OUT turn-on response is much longer than the HI to OUT delay, so if fast turn-on is required and using EN, the IC should be enabled before the expected HO turn-on response.

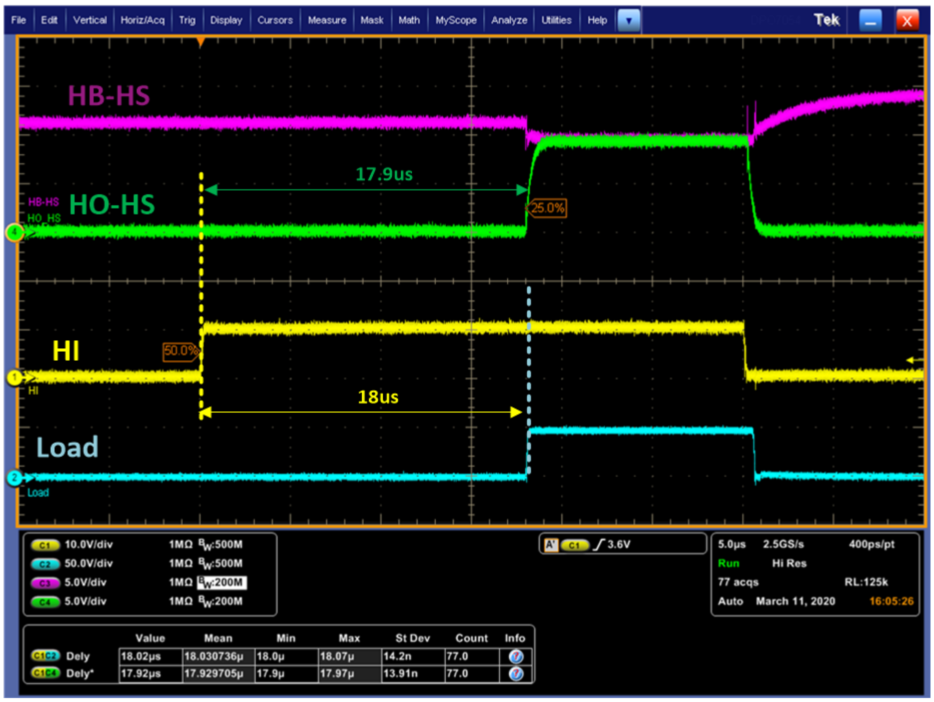

Figure 10. Response Time of the Bidirectional Switch Driver