Application Report
SLVA837–November 2016

Relay Replacement for Brushed DC Motor Drive in Automotive Applications

Ishtiaque Amin, Philip Beard

ABSTRACT

Many modern automotive applications use relays for driving different loads for power distribution. Such applications include power outlets, AC clutch, seat heaters, sunroofs, rear windshield defrost, and HVAC blowers. Some of these applications use brushed DC (BDC) motors to drive a load. This application report describes how Texas Instrument's automotive gate driver devices, in addition to MOSFETs, can be used to replace the mechanical relays in applications with a BDC motor. This document also highlights some of the benefits of using solid-state devices (SSDs).

When used as intended, SSDs have a high lifetime of survival, usually outlasting the equipment in which they are installed. These devices operate silently because they have no mechanical moving parts, which helps reduce electrical interference. SSDs can typically function over a wide range of input voltages, can drive a wide range of motors, and consume little power even at a high supply voltage. These device do not produce any arc which makes them suitable for use in extreme environments. SSDs have no moving parts, so physical shock, vibration, and other environmental conditions have a limited effect on the device integrity. SSDs are often used in applications requiring high frequency switching, where mechanical relays fail to perform, to improve efficiency.

Contents

List of Figures

Trademarks

All trademarks are the property of their respective owners.

1 Motor Control and Applications

Today's automotive industry is experiencing an increasing number of motors used in a car because of automation, enhanced safety, and luxury benefits. Motors are found in applications such as electric power steering, brakes, engine and transmission, body, and trunk. Figure 1 shows an overview of the areas where BDC motors can be used in a car.

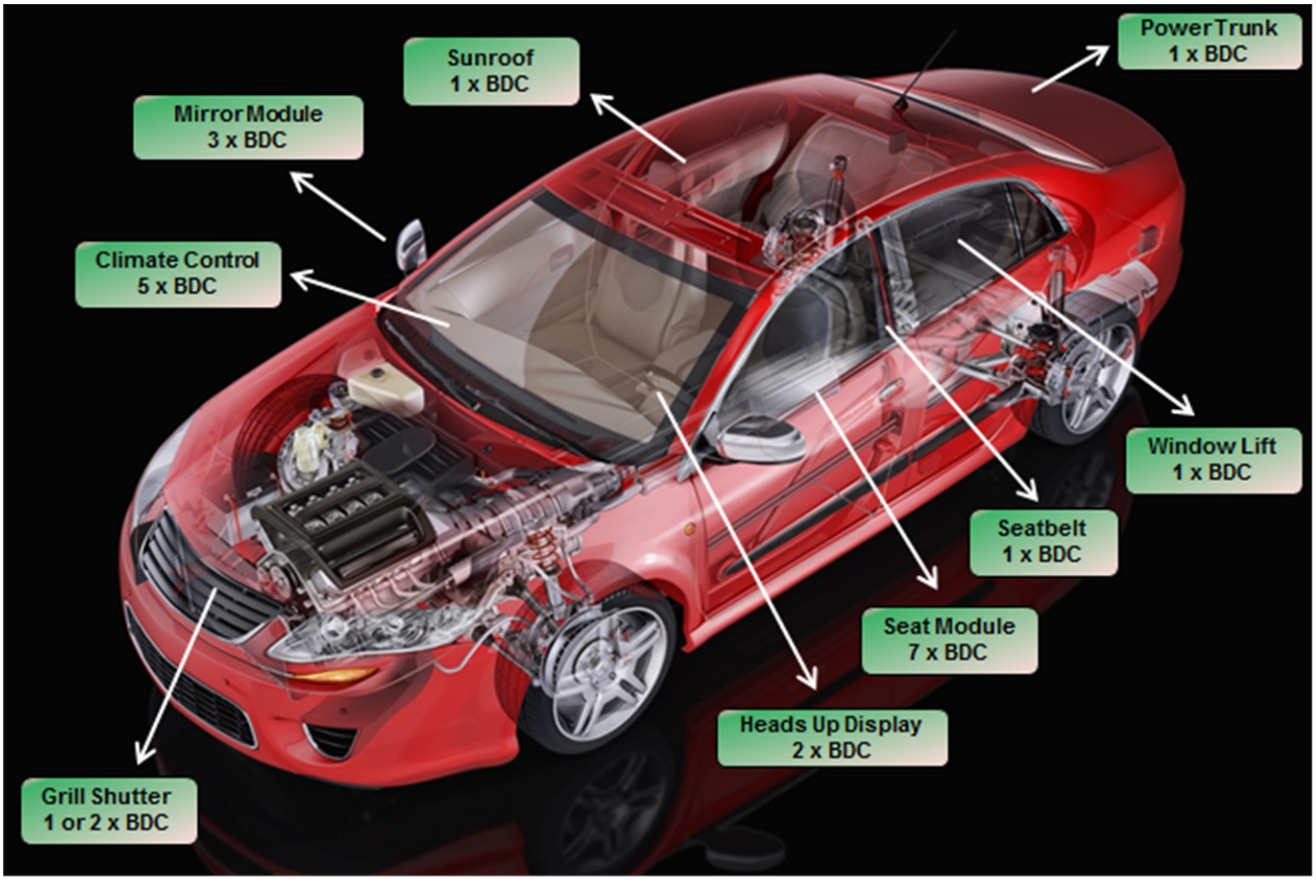


Figure 1. BDC Motor Applications in a Vehicle

A BDC motor can be driven in one of two ways. One way to drive a BDC motor is with mechanical relays and the other is with solid-state electronic devices such as MOSFETs and a gate driver integrated circuit (IC). If the motor size is small, the FETs can be integrated with the motor driver IC in one device. The following sections explore both these design methods.

1.1 Typical Relay Applications

A relay is an electromagnetic switch that turns on or off based on an external electrical signal, and is used to drive a high current load. Relays isolate low power circuits (for example, the microcontroller) from high power circuits (for example, the BDC motor). Relays are activated by energizing a coil wound in a soft iron core. In automotive applications, the most common type of relay used is the single-pole double-throw (SPDT) as shown in Figure 2. Other relay configurations include single-pole single-throw, double-pole single-throw, and double-pole single-through.

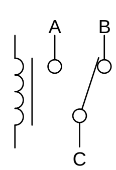


Figure 2. SPDT Configuration

The working principle of such a relay is simple: when the coil is not energized, the points B and C are connected. When electricity passes through the coil, the points A and C are connected thereby driving the load the relay is connected with.

A common automotive application for mechanical relays is to drive a BDC motor in an H-bridge topology. This type of configuration allows for bidirectional motor rotation by changing the direction of current through the motor. Figure 3 shows an example of an H-bridge configuration using two SPDT relays.

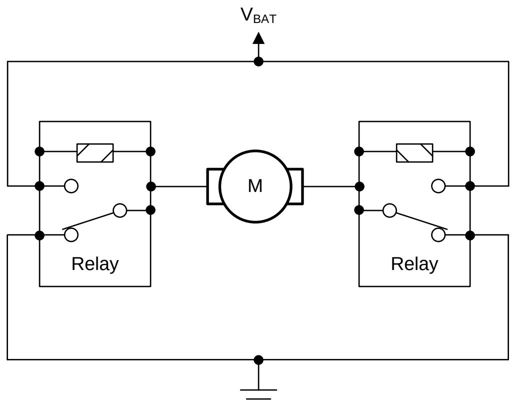


Figure 3. H-Bridge Control of BDC Motor Using Relays

By using two relays the motor can go into brake (decay) mode by shorting the motor terminals together. When both terminals are shorted the energy stored in the motor is quickly dissipated and the motor will come to a complete stop. Each relay essentially acts as a switch by connecting each of the motor phase leads to either power supply (usually vehicle battery) or ground (GND). While this topology is simple, the amount of board space required by relays can be significantly high compared to the SSD solution. With an increasing need for smaller boards by automotive customers, SSDs are the more attractive option.

1.2 Solid-State Design Considerations

By using an IC as the motor driver and discrete MOSFETs for the four switching positions in an H-Bridge, relays can be replaced in most automotive applications. Figure 4 shows how such electronic components can be used to drive a BDC motor with four external power MOSFETs in an H-bridge configuration.

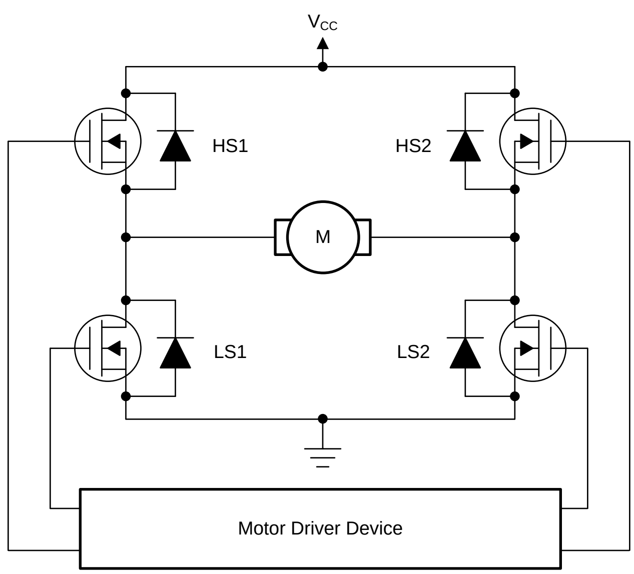


Figure 4. H-Bridge Control

In an H-bridge configuration, the following occurs:

- When HS1 and LS2 are on at the same time, the motor rotates in one direction, or *forward drive*.
- When HS2 and LS1 are on at the same time, the motor rotates in the opposite direction, or *reserve drive*.
- When LS1 and LS2 are on simultaneously, the phase terminal of the motor is shorted to (slowly) decay the energy stored in the windings. A similar way of power dissipation can be achieved by switching on both HS1 and HS2 simultaneously and the energy stored in the motor will decay faster.
- A faster decay mode can be achieved by *flip* stating the drive configuration. For example, if the motor is in forward drive, the faster decay mode can be obtained by switching on LS1 and HS2 simultaneously to dissipate energy stored in the motor faster.

The rate of switching of the MOSFETs is determined by the host microcontroller (MCU) which commands the motor driver to perform pulse-width modulation (PWM) at a given frequency. MOSFETs switch on or off at a much faster rate than mechanical relays which helps with electromagnetic interference (EMI) reduction and improves on switching losses.

2 Design Constraints

While choosing between a relay and SSD solution, a designer must consider multiple design factors, some of which are highlighted in this section. Both solutions have their advantages in a given system, however, the SSD solution tends to provide more flexibility and reliability.

2.1 Coil Suppression

Rapidly de-energizing relays forces the collapsing magnetic field to produce a significant voltage spike because it must dissipate all the stored energy caused by the rapid change of the current flow. These large voltage transients create noise in the system and produce EMI. Therefore, an external circuitry is required in a relay system to suppress high voltage transients.

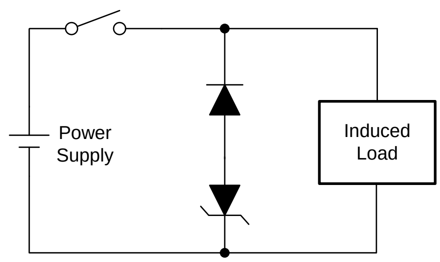


Figure 5. Suppression Circuit for High-Voltage Transients

Such relay coil suppression can be implemented by using external components which are a reversed biased rectifier in series with a Zener diode, both in parallel with the relay coil as shown in Figure 5.

2.2 Switching Time

Because of the pitting that results from high-voltage switching, the on/off times of the device are mechanically limited to the voltage limit created by the coil suppressor. This may not be an ideal solution in systems that require faster switching of the output. The high voltage breakdown created by switching between relay contacts results in high temperatures that pool metal and damage relay contacts over time.

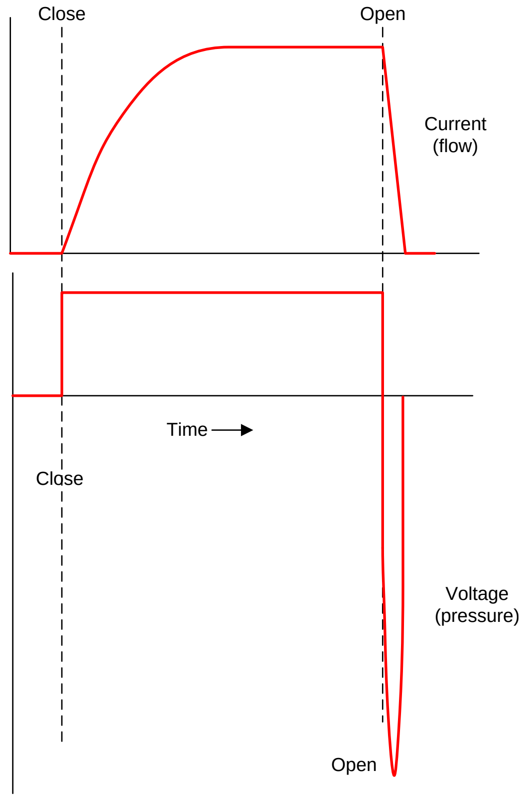


Figure 6. Relay Switching Time and High-Voltage Breakdown

One of the limitations for using relays is that they have much higher switching time. When compared to MOSFETs relays are slow devices typically having switching and settling time in the range of 5 to 15 ms. Such a range may be too slow for many automotive applications as it contributes to additional power losses during the switching intervals. Looking at MOSFETs with similar drive capability (CSD18540Q5B) we find the following information regarding switching times.

Table 1. MOSFET Switching Time

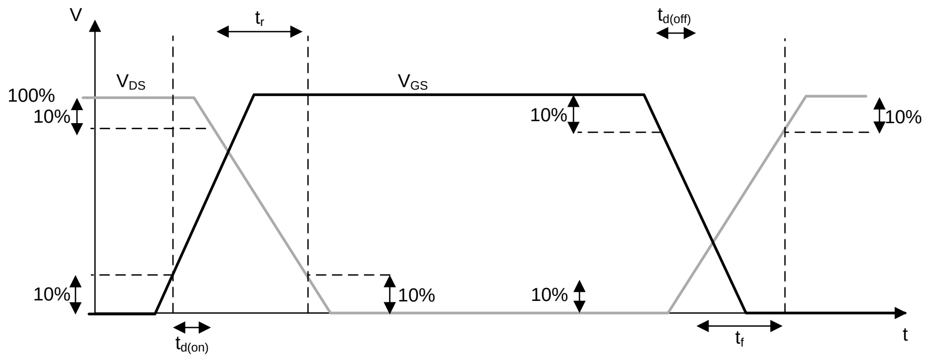
Parameter		Description	Test Conditions	Typical Value	Unit
$t_{d(on)}$	Turnon delay time	Turnon delay time is the time taken to charge the input capacitance of the MOSFET before the drain current conduction can start.	V_{DS} = 30 V, V_{GS} = 10 V, I_{DS} = 28 A, R_G = 0 Ω	6	ns
t_r	Rise time	During the rise time (t_r) the MOSFET gate voltage rises to a sufficient level to drive the MOSFET, and the drain current rises from zero to full-on current.		9	ns
$t_{d(off)}$	Turnoff delay time	Turnoff delay ($t_{d(off)}$) is the time taken to discharge the gate capacitance after the MOSFET has been switched off.		20	ns
t_f	Fall time	The fall time (t_f) is the time required for the drain current fall to zero.		3	ns

Use Equation 1 to calculate the MOSFET turnon time (t_{on}). Use Equation 2 to calculate the MOSFET turnoff time (t_{off})

$$t_{on} = t_{d(on)} + t_r = 6 \text{ ns} + 9 \text{ ns} = 15 \text{ ns} \quad (1)$$

$$t_{off} = t_{d(off)} + t_f = 20 \text{ ns} + 3 \text{ ns} = 23 \text{ ns} \quad (2)$$

Figure 7 shows the timing diagram for a MOSFET switching on and off.



(1) V_{GS} is the gate-to-source voltage.

(2) V_{DS} is the drain-to-source voltage.

Figure 7. MOSFET Switching Time

The comparison table (Table 2) shows the difference is switching times between relays and MOSFETs. For detailed information on how a MOSFET operates, refer to *Understanding IDRIVE and TDRIVE in TI Motor Gate Drivers* (SLVA714).

Table 2. Switching Time Comparison

Relay	MOSFET	
	Turnon Time	Turnoff Time
5 to 15 ms	15 ns	23 ns

The faster switching time for a MOSFET provides designers with the advantage of reducing switching losses in the system. This is particularly beneficial when doing variable speed control of a motor by pulse width modulation (PWM). Changing the duty cycle of the PWM signal will vary the motor speed; the higher the duty cycle, the faster the motor with rotate in a given direction. For a relay to perform a similar operation it must engage and disengage the metal contacts which raise reliability concerns of the part (as described in Section 3.3). Also, each engaging or disengaging cycle of the contacts results in 5 to 15 ms of switching time loss making the systems less thermally efficient. As a result, the SSD solution provides a major advantage for speed control of a motor by varying the duty cycle of the PWM pulse to drive the external MOSFETs in the H-bridge.

2.3 Bounce Factor

When an electromagnetic relay switches on, a bounce time is present. The bounce is an internal, undesired event where the contacts open and close intermittently for a period of time. As with any mechanical component, constant bouncing produces contact wear, such as metal degradation between contacts, or even contact welding or arching during these making-and-breaking events. This wear impacts the overall integrity and can reduce longevity of the device.

2.4 Integrated Protection

Relay based systems require protection features to be implemented with discrete circuitry. This additional circuitry requires additional board space because of the external components being added to the solution. The addition of components adds more failure points which can have adverse effect on reliability and safety of the application. Also, a higher component count increases the cost of the overall system and typically requires a larger controller board size. With the SSD approach, numerous protection features can be integrated within the motor driver IC that puts fewer burdens on the host microcontroller for fault detection. Such integrated protection features can include overcurrent, overvoltage, and overtemperature protection. For more details on some of these protection features, see Section 5.1.

2.5 Interfacing With the Microcontroller

In the SSD solution, the motor driver IC can be directly connected to the MCU with a digital interface. The motor driver IC amplifies the signal from the MCU to drive external MOSFETs to energize a motor.

If a relay is used, it should not be directly connected to a MCU because the MCU cannot able to source enough current to energize a relay. Also, a relay is activated by energizing the coils during which the MCU can receive negative voltage transients caused by the back-EMF of the relay. These negative will make the MCU stop working and, in some cases, may damage the MCU.

As a result, relays are typically interfaced to the MCU by a circuit similar to the one shown in Figure 8.

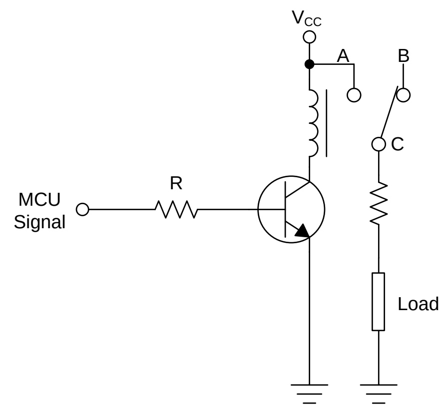


Figure 8. Relay Interface Circuit With MCU

The circuit requires two more components, at a minimum, which translates to more board space and additional failure points.

3 Environmental Constraints

In addition to design constrains, special attention must be given to environmental factors when selecting a relay-based solution. While some of these constraints can be aesthetic in nature, others can have an impact on the device performance and safety.

3.1 Shock and Vibration Limitations

In automotive body applications relays are susceptible to physical vibration and shock (both electrical and mechanical) and therefore designers must carefully consider the placement, packaging, and orientation of relays on a controller board. If abnormal vibration or shock is received, it will cause the relay to malfunction and can result in damage or component deformation.

3.2 Audible Noise

When a relay switches on and off, the contacts are engaged and disengaged rapidly which causes a clicking sound. Depending on the application, this clicking sound could be undesired, especially in high-end vehicles. An SSD solution provides a noise-free and fast switching operation because no mechanical parts move inside. As a result, hardware designers may prefer to go with an SSD approach to eliminate the clicking noise made by relays.

3.3 Reliability

Most mechanical relays are typically rated for 100,000 cycles for electrical endurance. Beyond these rated number of cycles, damage on the contacts can occur which increases the risk of failure. When switching off inductive loads, electrical arc discharge occurs between the relay contacts resulting in wear and fatigue over time.

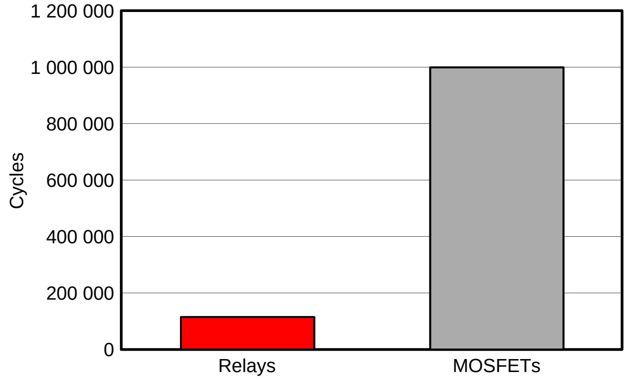


Figure 9. Switching Cycle Comparison

The graph in Figure 9 provides a rough comparison of switching cycles between the solutions. MOSFETs can typically have 10 times more switching cycles over lifetime. The effectively lifetime of an SSD solution can be infinite in comparison to the lifetime of the mechanical parts in a car. Silicon is very robust and has a much longer life cycle compared relays. The ICs are subjected to harsh test conditions for AEC-Q100 qualification requirements that ensure high reliability and longer life cycle. Also, an SSD can be used in high-frequency switching circuits because they typically have much higher switching cycles over lifetime compared to mechanical relays (see Table 2 for comparison).

4 Solution-Size Comparison

4.1 Typical Relay-Solution Size

The solution size can vary significantly depending on the type of application. For the purpose of this application report, the solution size for Figure 3 will be explored in more details. For a given application, set the parameters as follows:

- Supply voltage = 13.5 V
- Motor current = 15 A (rms)
- Temperature = 25°C

With these settings, a suitable automotive-SPDT relay can be one with 15-A continuous current rating. Figure 10 shows the mechanical dimensions of such a device.

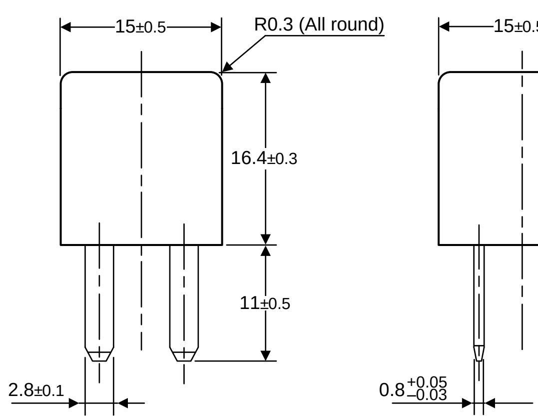


Figure 10. Typical Relay Dimensions

To drive a BDC motor, two of these relays is required. Each relay requires approximately 232.5 mm^2 of the area of the controller board area. Therefore, the total board area for just two relays is 2 × 232.5 mm^2 = 465 mm^2.

Additional components for high-voltage transient suppression and protection circuits for system diagnostics will be required. These components have not been considered in the board area calculation. Some relays can be larger (or smaller) in size than the one discussed with a similar continuous-current rating.

The height of the relays could be of another disadvantage because mechanical CAD designers must consider at least a 16.4-mm vertical keep-out distance when designing board covers and enclosures. Most electronic components will be less than 1.5 mm in height providing the benefit of better packaging.

4.2 Typical Motor Driver Solution Size

Keeping the same parameters listed in Section 4.1, this example uses the DRV8702-Q1EVM components for comparison.

The DRV8702-Q1EVM has one DRV8702-Q1 motor driver device and four CSD18540Q5B FETs for driving a BDC motor. The EVM configuration is similar to the one shown in Figure 4. Figure 11 shows the mechanical dimensions of the FETs. The DRV8702-Q1 driver comes in a 5-mm × 5-mm QFN package.

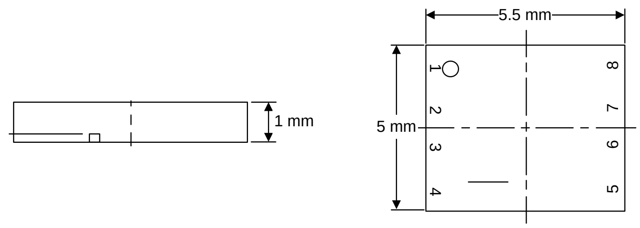


Figure 11. Typical MOSFET Dimensions

Using the footprint area, the following areas can be calculated:

- Area of each MOSFET = 27.5 mm^2
- Total area of all 4 MOSFETs = 27.5 mm^2 × 4 = 110 mm^2
- Area of one DRV8702-Q1 motor driver device = 25 mm^2

Total controller board area required is therefore 25 mm^2 plus 110 mm^2, which equals 135 mm^2 for the solid-state solution.

Figure 12 shows the solution size of SSD with DRV8702-Q1 gate driver IC on a DRV8702-Q1EVM. The white box marks the DRV8702-Q1 gate driver IC, and the yellow box outlines the MOSFETs.

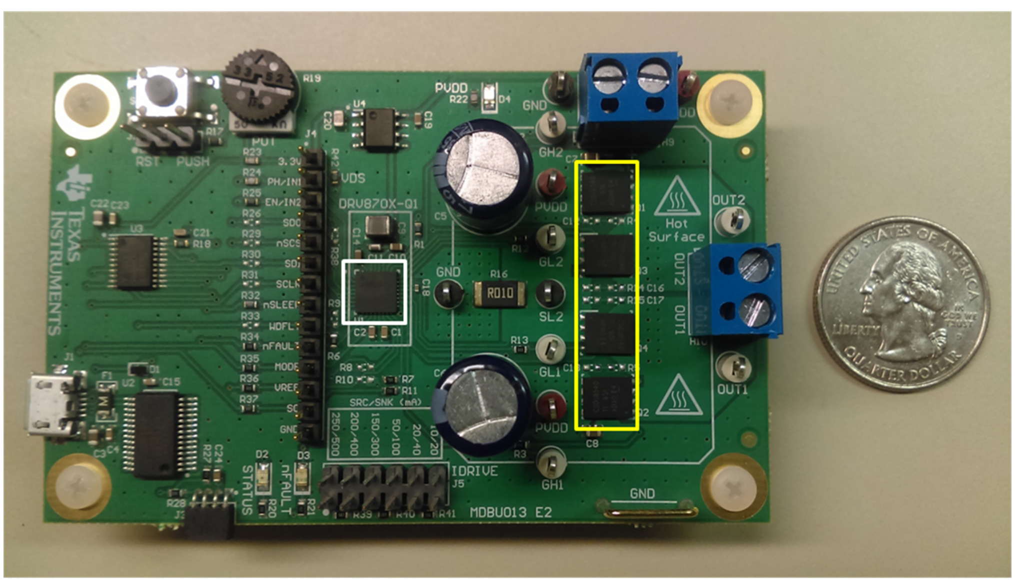


Figure 12. DRV8702-Q1EVM With MOSFETs and Motor Driver IC

4.3 Comparison

At a quick glance, the relay-based solution requires at least three times more board space compared to the SSD solution without even considering the additional components required for diagnostic and protection features. Also, the relay is 16 times taller than the CSD18540Q5B FET. The 135-mm^2 area is inclusive of numerous integrated protection features that can reduce external components to lower the cost of the overall system and save board space.

5 Motor Drivers by Texas Instruments

Relay based direction control of a BDC motor can be replaced with TI's solid-state devices listed as follows:

- DRV8702-Q1
- DRV8703-Q1

The DRV8702-Q1 and DRV8703-Q1 devices are H-bridge gate drivers (also called gate drivers or controllers). The device integrates FET gate drivers to control four external N-channel MOSFETs in H-bridge configuration, as shown in Figure 4. The device is also capable of driving each half-bridge independently which can be useful to drive two unidirectional motors. The device can be powered by a wide supply voltage between 5.5 V and 45 V. The device significantly reduces external component count of discrete motor driver systems by integrating the required MOSFET drive circuitry into a single device. Also, the DRV870x-Q1 device adds protection features above traditional discrete implementations, such as undervoltage lockout, overcurrent protection, gate-driver faults, and thermal shutdown. These integrated features are always missing when using relays, and must be implemented externally by adding components.

In addition, the DRV8703-Q1 driver incorporates a serial-peripheral interface (SPI) module that provides added flexibility to the customer to program different parameter settings for optimal motor drive operation. The SPI register also provides detailed reporting of fault conditions. For detailed information about these devices, refer to *DRV870x-Q1 Automotive H-Bridge Gate Driver* (SLVSDR9).

5.1 Integrated Diagnostics

This section highlights some of the protection features available in the DRV870x-Q1 motor driver device.

5.1.1 Overcurrent protection (OCP)

The voltage across each external MOSFET is monitored by the device and compared with a threshold that the customer can select to trigger an overcurrent condition. The DRV8702-Q1 device provides 5 settings using hardware interface, and the DRV8703-Q1 device provides 8 settings through SPI for the overcurrent threshold. These settings provide the customer flexibility to set different overcurrent trip points for different BDC motor sizes by keeping the same gate driver IC and external MOSFETs.

Figure 13 shows how the OCP feature is implemented inside the device. When an overcurrent event is triggered, the H-bridge is disabled to protect the motor, MOSFETs, and the gate driver device.

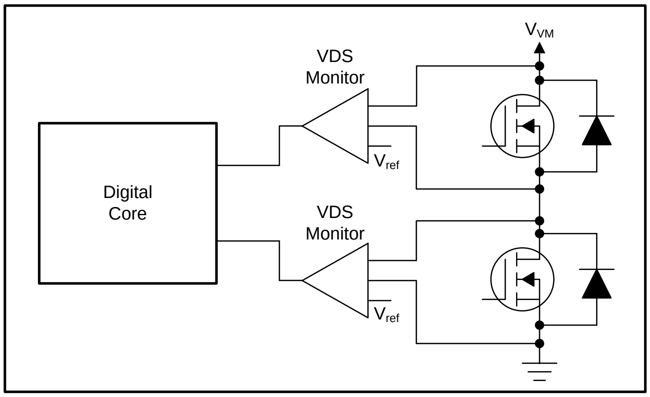


Figure 13. OCP Implementation in DRV870x-Q1

5.1.2 Thermal Shutdown

A temperature sensor inside the device constantly monitors the die temperature to prevent the device from overheating and causing an overtemperature event. When the die temperature exceeds the recommended operation condition, the H-bridge is disabled to protect itself from permanent damage.

5.1.3 Undervoltage Lockout

At any time during operation if the supply voltage drops below the recommended operating voltage, the device goes into a lockout state and disables the external H-bridge. This lockout occurs to prevent overdriving the charge pump inside the device. The power supply is constantly monitored by the device to ensure that it is not driving a load under extremely low voltages.

5.2 Slew-Rate Control

The DRV870x-Q1 device includes the IDRIVE feature that allows adjustable slewing of the external MOSFETs at any moment without adding external components to or removing them from the system. This feature allows the customer to fine tune the switching performance of the MOSFETs with regards to radiated emissions, efficiency, and the MOSFETs body-diode recovery inductive spikes. Mechanical relays will always switch at a given frequency, so if the customer wants improve system-level efficiency by reducing switching losses, the relays must be replaced.

5.3 Current Regulation With Integrated Current-Sense Amplifier

The DRV870x-Q1 device features an integrated current-sense amplifier (CSA) for measuring low-side current. This amplifier provides feedback to the MCU on how much current is being drawn by the load during normal operation. With the CSA, the device can perform current regulation based on an analog voltage reference which reduces dependency on the MCU to regulate the motor current. To use the CSA, the source pins of both the low-side MOSFETs in the H-bridge must be connected to a power (shunt) resistor as shown in Figure 14.

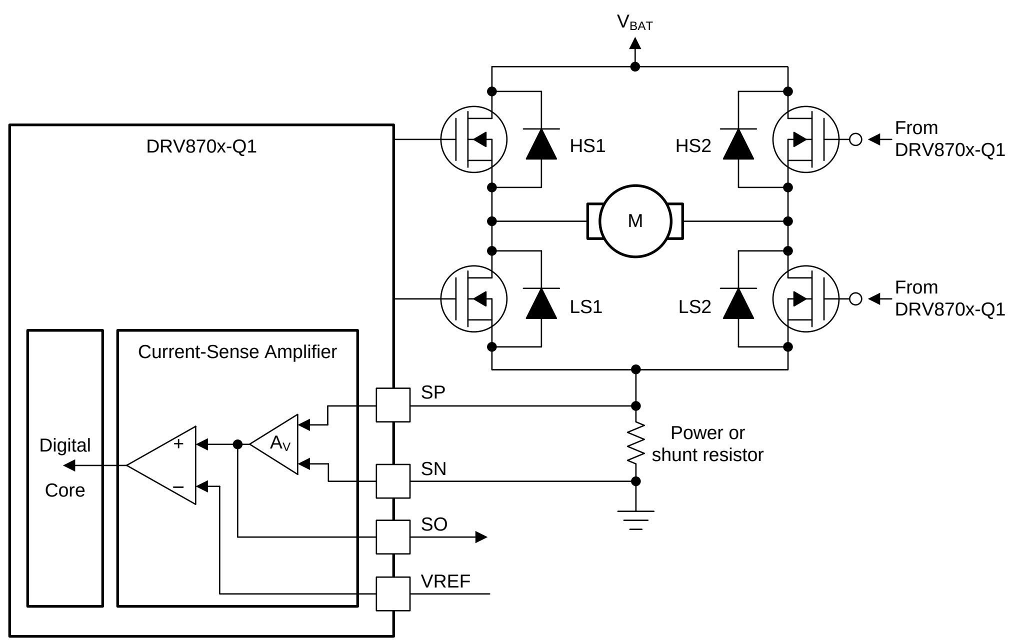


Figure 14. Current Regulation With DRV870x-Q1

When the voltage across the power resistor exceeds the reference voltage (V_{ref}), the H-bridge enters brake mode and energy stored in the motor is dissipated through the low-side MOSFETs. To implement such a feature with relays, external CSA devices must be implemented to monitor motor current, which adds to the cost of the system, introduces additional failure points, and requires more board space.

Glossary

A.1 Nomenclature Used in this Document

The following acronyms and initialisms are used in ths document:

BDC — Brushed direct current

CSA — Current-sense amplifier

IC — Integrated circuit

MCU — Microcontroller unit

MOSFET — Metal-oxide semiconductor field-effect transistor

OCP — Overcurrent protection

PWM — Pulse width modulation

SPDT — Single pole double throw

SSD — Solid state device

For a more comprehensive list of terms, acronyms, and definitions, refer to the *TI Glossary* (SLYZ022).

IMPORTANT NOTICE

Products		**Applications**	
Audio	www.ti.com/audio	Automotive and Transportation	www.ti.com/automotive
Amplifiers	amplifier.ti.com	Communications and Telecom	www.ti.com/communications
Data Converters	dataconverter.ti.com	Computers and Peripherals	www.ti.com/computers
DLP® Products	www.dlp.com	Consumer Electronics	www.ti.com/consumer-apps
DSP	dsp.ti.com	Energy and Lighting	www.ti.com/energy
Clocks and Timers	www.ti.com/clocks	Industrial	www.ti.com/industrial
Interface	interface.ti.com	Medical	www.ti.com/medical
Logic	logic.ti.com	Security	www.ti.com/security
Power Mgmt	power.ti.com	Space, Avionics and Defense	www.ti.com/space-avionics-defense
Microcontrollers	microcontroller.ti.com	Video and Imaging	www.ti.com/video
RFID	www.ti-rfid.com		
OMAP Applications Processors	www.ti.com/omap	**TI E2E Community**	e2e.ti.com
Wireless Connectivity	www.ti.com/wirelessconnectivity		

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265