

# **Using DRV to Drive Solenoids - DRV8876/DRV8702-Q1/DRV8343-Q1**

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## **ABSTRACT**

This application report provides various methods on how to drive solenoids and relays using TI integrated motor driver ICs. This report will discuss solenoid fundamentals, basic configurations, and different driving methods.

## **Contents**

1	Introduction .....	2
2	Driving Typologies .....	2
3	Driving Multiple Solenoids .....	5
4	Efficient Solenoid Driving using DRV .....	8
5	Fast Discharging Circuits.....	11
6	Conclusion .....	12

## **List of Figures**

1	Cross-Sectional View of a Pull-Type Linear Solenoid .....	2
2	A Power MOSFET Transistor and a Freewheeling Diode Used to Drive a Solenoid.....	3
3	Sneak Path When VBAT is Disconnected from the Board .....	3
4	Configurations for Basic Low-side, High-side, and Push-Pull Drivers .....	4
5	H-Bridge Configuration Utilized to Drive a Solenoid Valve.....	4
6	Independent PWM High-Side and Low-Side Drivers .....	5
7	Solenoid Drive Configuration.....	6
8	Application Schematic for DRV8702-Q1 to Drive Two Solenoids .....	7
9	Application Schematic for DRV8876 to Drive Two Solenoids .....	8
10	Solenoid Voltage and Current Outputs Using PWM .....	9
11	Block Diagram for DRV8343S .....	10
12	Zener Diode Fast Discharging Circuit .....	11
13	H-Bridge Fast Decay .....	12

## **List of Tables**

1	Trade-offs of Different Driver Configurations .....	4
2	Truth Table for Independent MOESFET Mode .....	5
3	Independent Half-Bridge Mode Truth Table.....	6
4	Independent Half Bridge Mode Truth Table.....	6
5	Independent Half-Bridge Control Mode .....	8

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## 1 Introduction

A solenoid is a coil that produces a linear or rotational movement in a mechanical system by applying a current through the coil. Electromechanical solenoids consist of a copper inductive coil wound around a steel or iron armature sometimes called a “plunger”. The magnetic field of the energized coil pulls on the armature, and the armature transfers a mechanical force to an external mechanism. Similar to solenoids, electromagnetic relays are electrically operated switches typically used to connect or disconnect an electrical circuit. Typical applications of solenoids include home appliances, printers, HVAC, irrigation systems, engine and transmission control, and much more.

Solenoids and relays can be driven using either an H-Bridge or half-bridge motor driver IC. These ICs can be used to implement the most common configurations and driving methods to operate solenoids. These ICs can also be used to drive multiple solenoids simultaneously and independently.

### 1.1 Types of Solenoids

There are two main types of solenoids, the pull-type linear solenoid and the rotatory solenoid. The pull-type linear solenoid is used in applications where an “in and out” movement is needed. This type of solenoid can be found in applications such as electronic door locks, valves, and robotics. [Figure 1](#) shows a cross-sectional view of a pull-type linear solenoid.

The second main type is the rotary solenoid. These solenoids produce a rotational motion on a mechanism. Rotary solenoids can be used in applications where a small rotational movement is needed. Some application examples of rotary solenoids include camera shutters, document movement machines, and sorting systems.

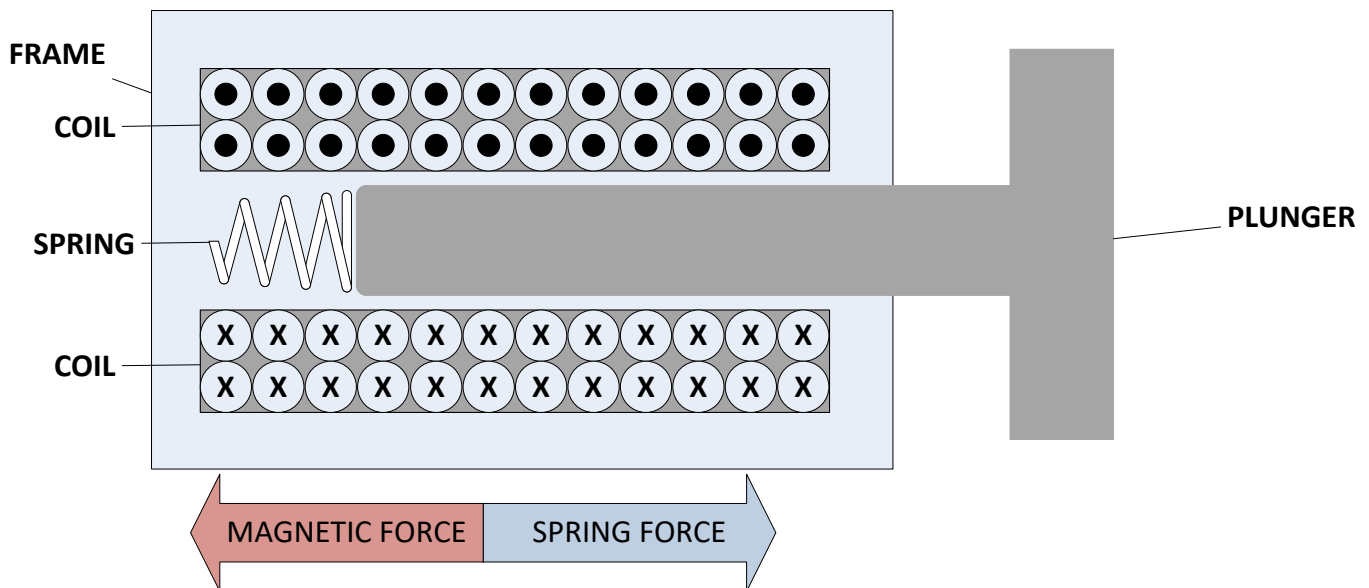


Figure 1. Cross-Sectional View of a Pull-Type Linear Solenoid

## 2 Driving Typologies

The fundamentals of driving a solenoid or relay starts with configuring one or more MOSFETs to switch on and off a driving current. While this can be very simple, other circuitry is needed to drive a solenoid efficiently. There are three basic driver configurations, low-side, high-side, and push-pull, each with their trade-offs. Choosing which configuration depends on the system requirements such as switching speed and necessary fault protection.

## 2.1 Low-Side and High-Side Configuration

The typical low-side or high-side solenoid driver uses a single MOSFET with enough current handling capability to drive a load, and a freewheeling diode which is forward biased when the MOSFET is disabled. When the MOSFET is enabled, it conducts all the current needed to energize the solenoid. When the MOSFET is disabled, the current flowing through the solenoid must be allowed to continue flowing or decay to zero. To do this, the freewheeling diode is forward biased taking this current to avoid damaging the power MOSFET. Figure 2 shows a low-side driver with the two possible states a solenoid will experience as it is energized. While the low-side and high-side drivers operate similarly, high-side drivers are more complex. This is because the high-side NMOS typically needs additional circuitry, such as a charge pump or bootstrap, to drive its gate voltage.

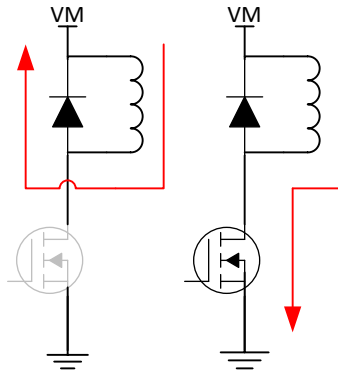


Figure 2. A Power MOSFET Transistor and a Freewheeling Diode Used to Drive a Solenoid

## 2.2 Push-Pull Driver Configuration

The push-pull driver type uses two MOSFET transistors in a half-bridge configuration to control the current through the solenoid. This driver type uses one MOSFET to forward drive the solenoid and another to recirculate current. This configuration is suited for high-speed operations (100kHz or higher), and allows for both high-side and low-side driving. Another advantage of using a push-pull driver configuration is that it protects both short to VBAT and short to GND scenarios.

Using a push-pull driver does add complexity due to having both high-side and low-side drivers. Along with the added complexities, a push-pull driver also allows for sneak paths. Sneak paths are unintended electrical current paths with the circuit and external components. This is an issue if a body diode is parallel to the load and particularly noticeable for multiple board systems where connectors can be disconnected when the load is still connected to the power supply. An example of a sneak path is shown in Figure 3. The basic configurations can be seen in Figure 4 along with their trade-offs in Table 1.

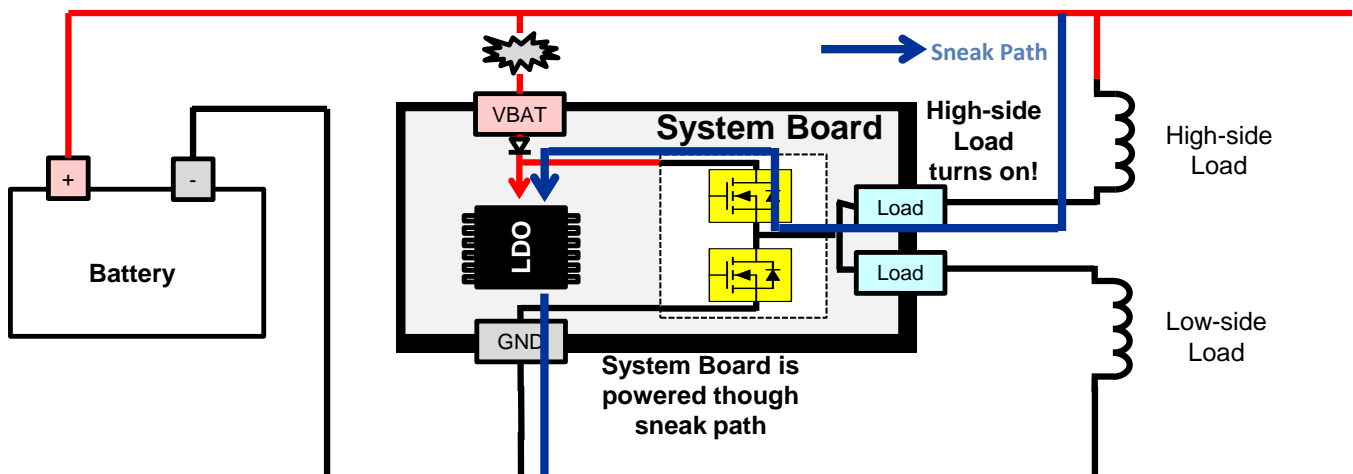


Figure 3. Sneak Path When VBAT is Disconnected from the Board

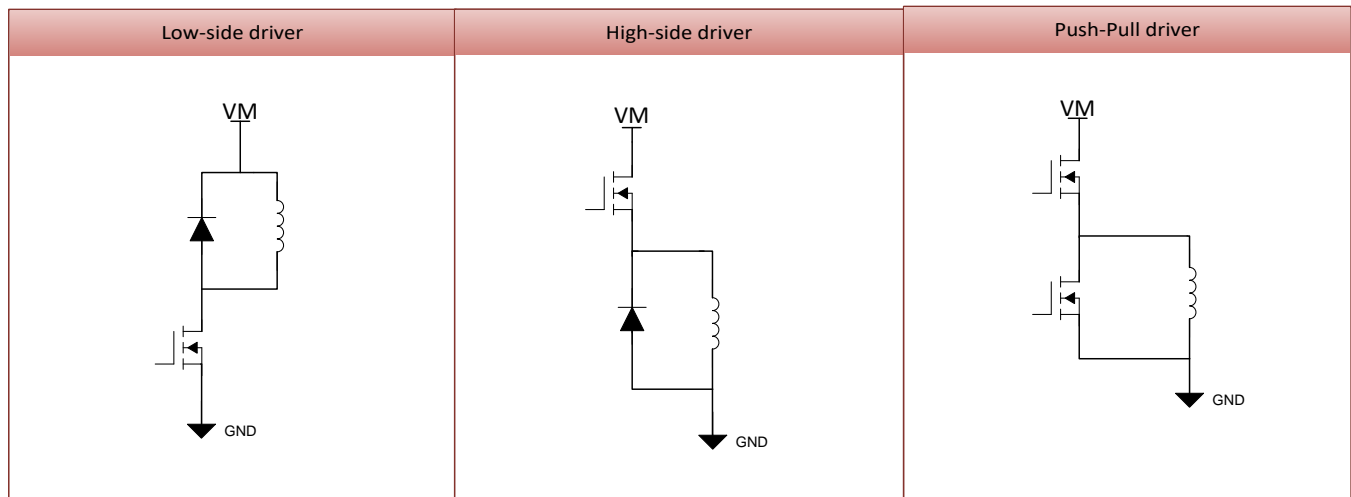


Figure 4. Configurations for Basic Low-side, High-side, and Push-Pull Drivers

Table 1. Trade-offs of Different Driver Configurations

Low-Side driver	High-side driver	Push-Pull driver
+ Easy to drive	- More Complex drivers	- Contains HS+LS driver
- HS load only	- LS load only	+ HS or LS loads
- No Short to GND Protection	+ Protects short to GND	+ Protects short to GND
+ Protects short to VBAT	- No short to VBAT protection	+ Protects short to VBAT
- Slower speed operation	- Slower speed operation	+ High speed operation
+ Sneak path prevented	+ Sneak path prevented	- Sneak path

### 2.3 H-Bridge Driver

Each solenoid driving typology can be implemented with an integrated H-Bridge motor driver IC. An H-Bridge is two half-bridges joined together by a load. This is mainly used in applications where the voltage or current polarity applied to the load needs to be switched such as a latching relay. An H-Bridge also allows the capability to recirculate current slower using the opposing MOSFET. Figure 5 shows how an H-Bridge can be utilized to drive a conventional solenoid valve.

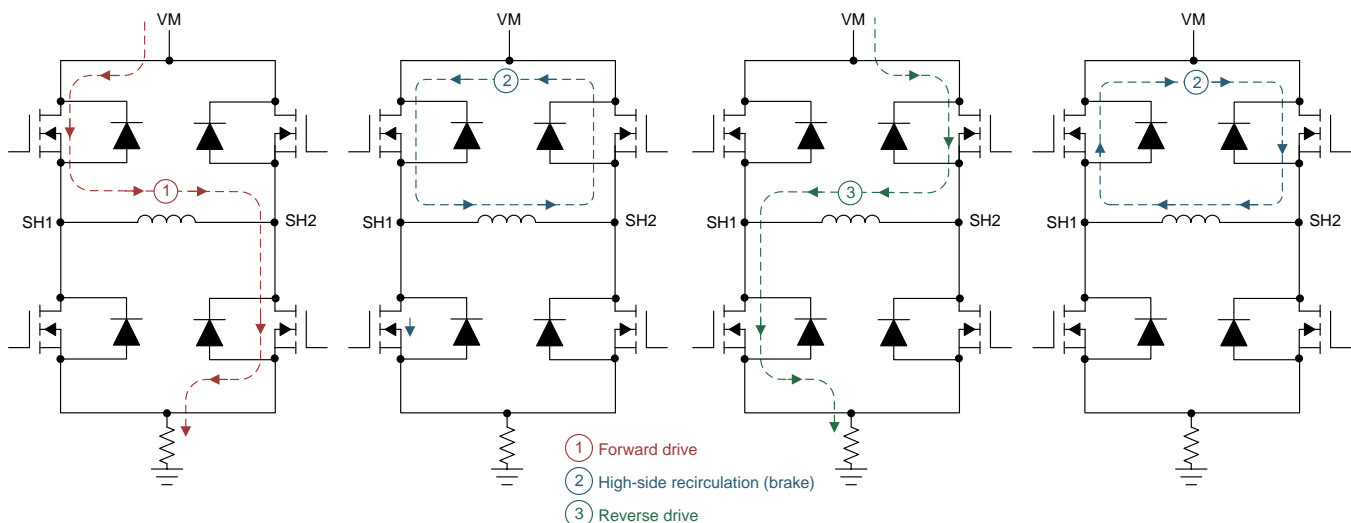


Figure 5. H-Bridge Configuration Utilized to Drive a Solenoid Valve

### 3 Driving Multiple Solenoids

Many motor driver ICs have the advantage of driving multiple solenoids with their multiple outputs. Devices such as the DRV8343-Q1, DRV8702-Q1, and DRV8876 all are able to drive two or more solenoids with a single device. For example, the DRV8343-Q1 can be configured to drive up to six solenoids individually, three high-side and three low-side. Using these motor driver ICs can simplify the design and decrease the board size needed to accomplish this task.

#### 3.1 DRV8343-Q1

The Independent FET mode and Independent Half-Bridge mode on the DRV8343-Q1 are easy solutions for driving multiple solenoids or relays with a single device. In Independent MOSFET Drive mode, the INHx and INLx pins control the outputs, GHx and GLx, respectively. This control mode lets the DRV8343-Q1 drive separate high-side and low-side loads with each half-bridge. In this mode, turning on both the high-side and low-side MOSFETs at the same time in a given half-bridge gate driver is possible. In this mode, the integrated dead time is bypassed. Table 3 shows the truth table for DRV8343-Q1 in independent PWM mode.

Table 2. Truth Table for Independent MOESFET Mode

INLx	INHx	GLx	GHx
0	0	L	L
0	1	L	H
1	0	H	L
1	1	H	H

Figure 6 shows how the DRV8343-Q1 device can be used to connect a high-side load and a low-side load at the same time with one half-bridge and drive the loads independently. In this mode, the VDS monitors are active for both the MOSFETs to protect from an overcurrent condition. This can be done for each of the 3 phases for a total of 6 different solenoids.

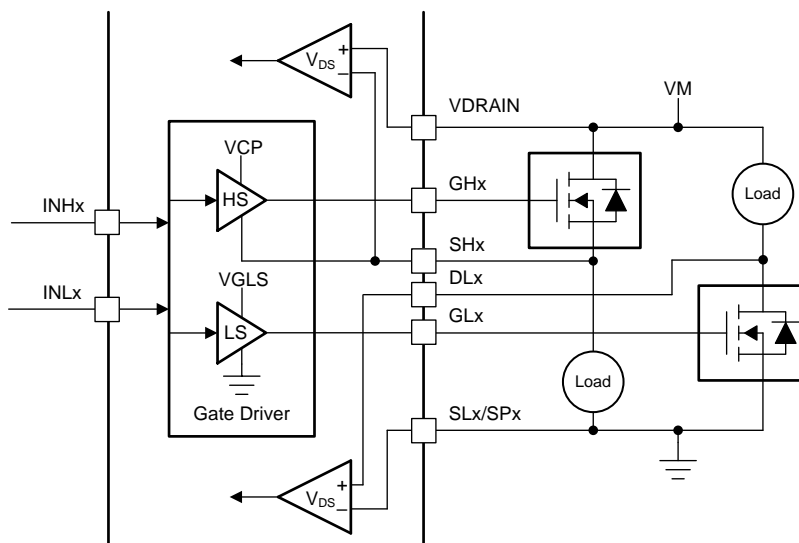
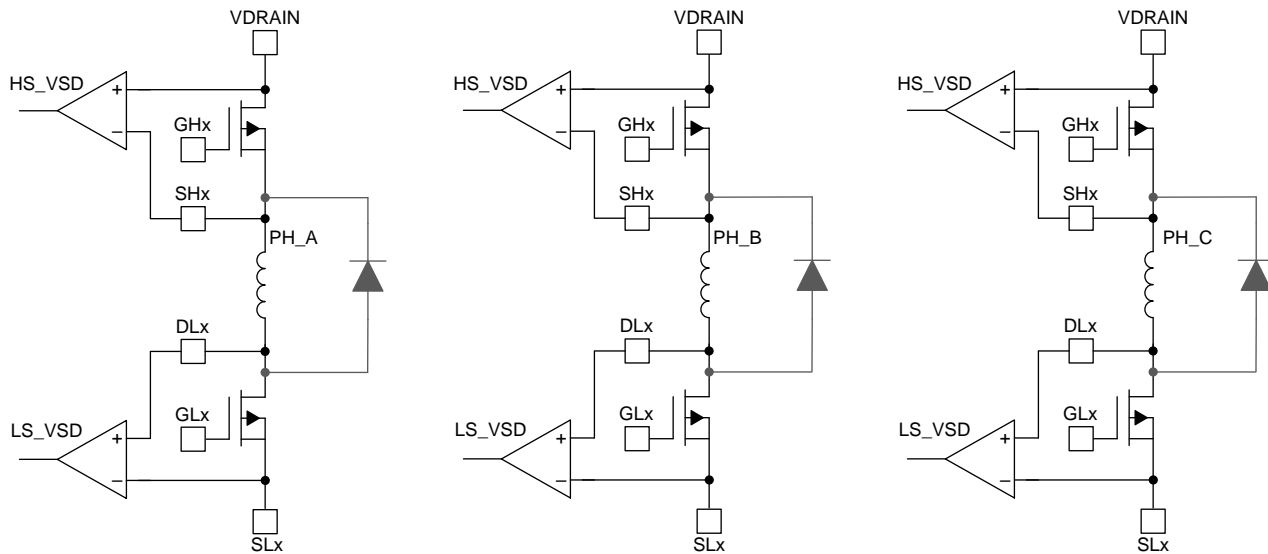


Figure 6. Independent PWM High-Side and Low-Side Drivers

Figure 7 shows how the DRV8343-Q1 device can be used to connect a solenoid load where both the high-side and low-side MOSFETs can be turned on at the same time to drive the load without causing shoot-through. TI recommends having the external diodes for current recirculation. If a half-bridge is not used, the gate pins (GHx and GLx) can stay unconnected and the sense pins (SHx and DLx) can be tied directly or through a resistor to GND.



**Figure 7. Solenoid Drive Configuration**

In the Independent Half-Bridge mode the DRV8343-Q1 can control up to 3 different solenoids in a Push-Pull configuration. In this mode the DRV8343-Q1 will automatically insert dead time when switching and handle the protections for over current protection (OCP), short to battery, and short to GND faults. In Independent Half-Bridge PWM mode, the INHx pin controls each half-bridge independently and supports two output states: low or high. The corresponding INHx and INLx signals control the output state as listed in Table 3. The INLx pin is used to change the half-bridge to high impedance. If the high-impedance (Hi-Z) state is not required, tie all INLx pins logic high.

**Table 3. Independent Half-Bridge Mode Truth Table**

INLx	INHx	GLx	GHx
0	x	L	L
1	0	H	L
1	1	L	H

Combinations of Half-Bridge and Independent MOSFET drive modes are available where two of the phases will be in Independent Half-Bridge mode and the last phase in Independent MOSFET mode. This allows a total of 4 solenoids to be driven at the same time individually, 2 in push-pull configuration, 1 in high-side configuration, and 1 in low-side configuration. In these modes, the 2 phases in independent Half-Bridge mode control the independent fault handling and dead time enforcement is done by the device. The dead time insertion by the device is bypassed for the phase in Independent MOSFET mode.

### 3.2 DRV8702-Q1

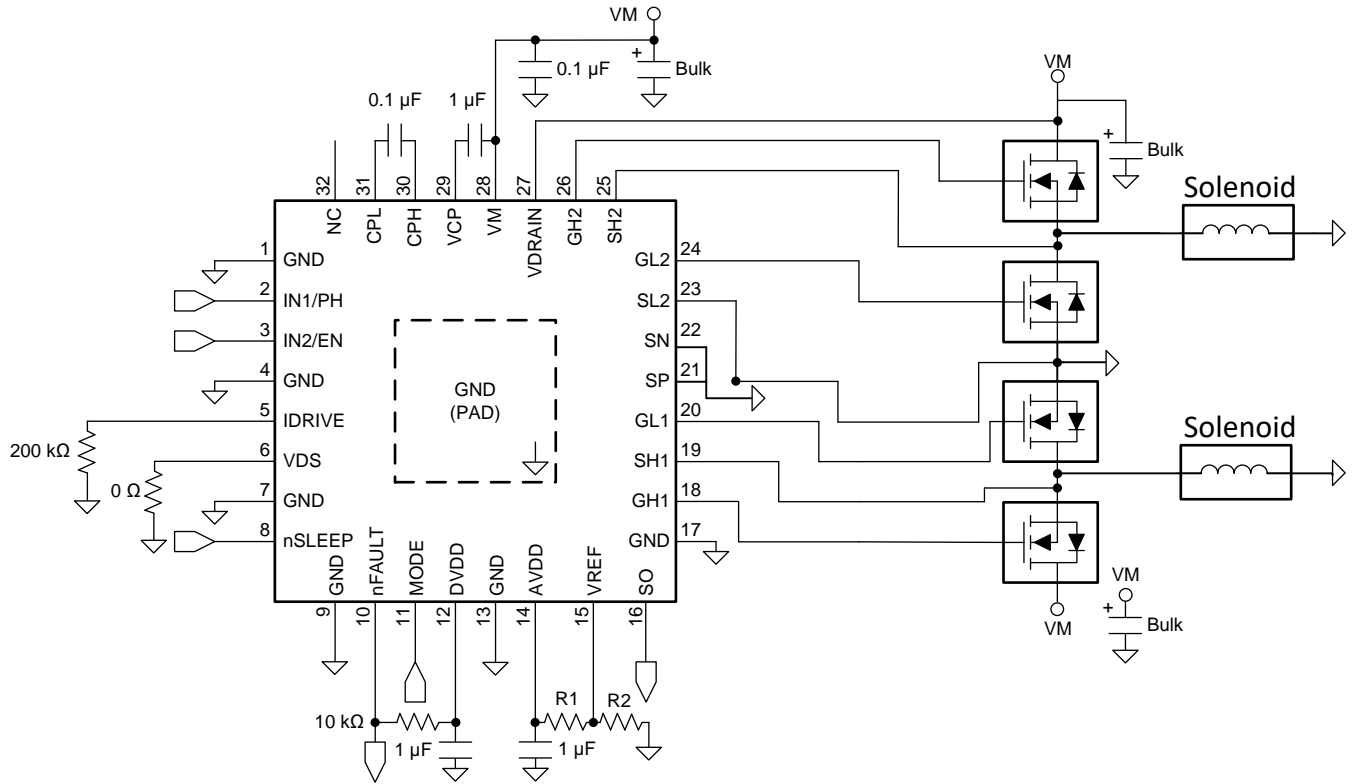
The DRV8702-Q1 is a small single H-Bridge gate driver that uses four external N-channel MOSFETs that can control up to two solenoids or relays independently. Figure 8 shows how to configure the DRV8702-Q1 in the Independent Half Bridge mode. Table 4 shows the control table for DRV8702-Q1 in Independent Half Bridge mode. In this mode the device does not perform PWM current regulation or current chopping.

**Table 4. Independent Half Bridge Mode Truth Table**

nSleep	IN1/PH	IN2/EN	GH1	GL1	SH1	GH2	GL2	SH2
0	x	x	x	x	Hi-Z	x	x	Hi-Z
1	x	0	x	x	x	0	1	L
1	x	1	x	x	x	1	0	H
1	0	x	0	1	L	x	x	x

Table 4. Independent Half Bridge Mode Truth Table (continued)

nSleep	IN1/PH	IN2/EN	GH1	GL1	SH1	GH2	GL2	SH2
1	1	x	1	0	H	x	x	x



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Figure 8. Application Schematic for DRV8702-Q1 to Drive Two Solenoids

### 3.3 DRV8876

For lower current applications the DRV8876 is an integrated H-Bridge driver that can also be configured to drive two solenoids in Independent Half Bridge mode. The MOSFETs are built into the DRV8876 to simplify the design and decrease board space. Figure 9 shows the application schematic configured to drive two solenoids in Independent Half-Bridge mode. Table 5 shows the control modes in Independent Half-Bridge mode.

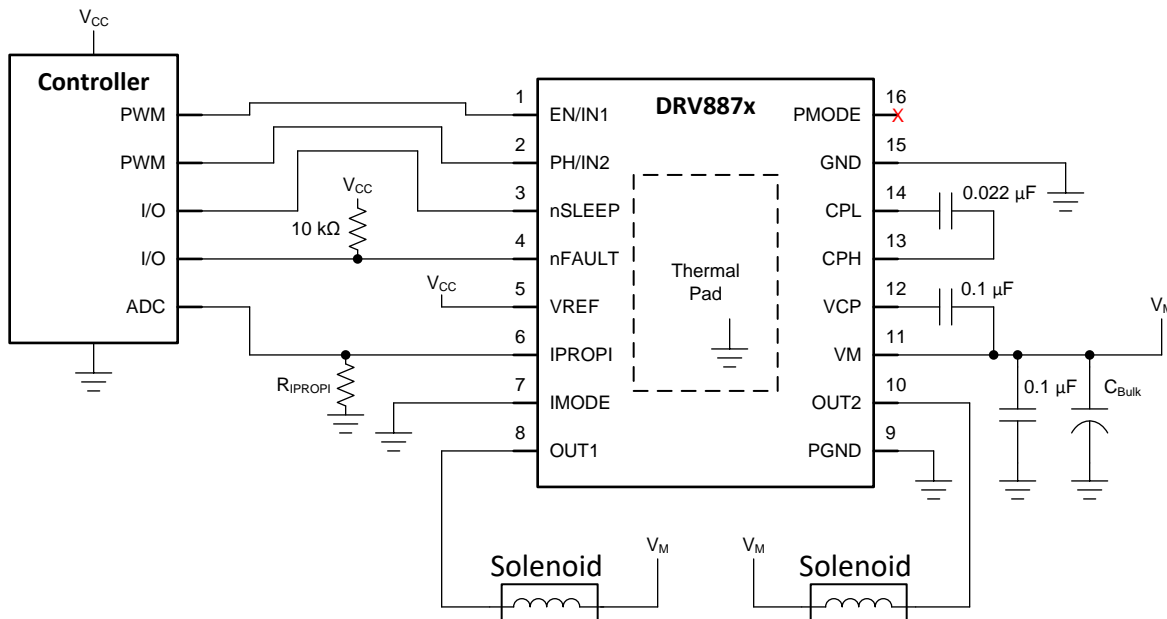


Figure 9. Application Schematic for DRV8876 to Drive Two Solenoids

Table 5. Independent Half-Bridge Control Mode

nSleep	INx	OUTx	Description
0	X	Hi-Z	Sleep, (H-Bridge, Hi-Z)
1	0	L	OUTx Low-side On
1	1	H	OUTx High-side On

## 4 Efficient Solenoid Driving using DRV

To drive solenoids efficiently and reliably more than just MOSFETs are required. Using motor driver ICs can optimize power efficiency without adding complex circuitry to the design. In most applications the full driving current is only needed initially to pull in the plunger. After the initial pull-in current can be regulated at a lower level to hold the solenoid in place. This allows for lower power consumption due to the lower current and less heat generated in the coil. If the drive current is not reduced, large and unnecessary power consumption will generate as well as large amounts of heat in the solenoid. With the increase in temperature the solenoid initial resistance will also increase. When applying a constant voltage, the increase in initial start up resistance will reduce the current in the solenoid, which reduces the magnetic force. This may cause the solenoid to de-actuate or for a relay to open its contacts if the current decreases too much.

### 4.1 Current Regulation using PWM

Just as pulse width modulation (PWM) is used to drive motors, it also can be used to drive solenoids. PWM can be used to regulate the current of a solenoid to different levels at different times by varying the duty cycle. This allows the user drive a longer duty cycle to pull in the solenoid and then a shorter duty cycle to hold it in place, optimizing the power consumption. Figure 10 shows the current and voltage driving outputs for the PWM implementation. Most DRV motor driver ICs, including DRV8343-Q1, DRV8876, and DRV8702-Q1, can use this method to regulate current.



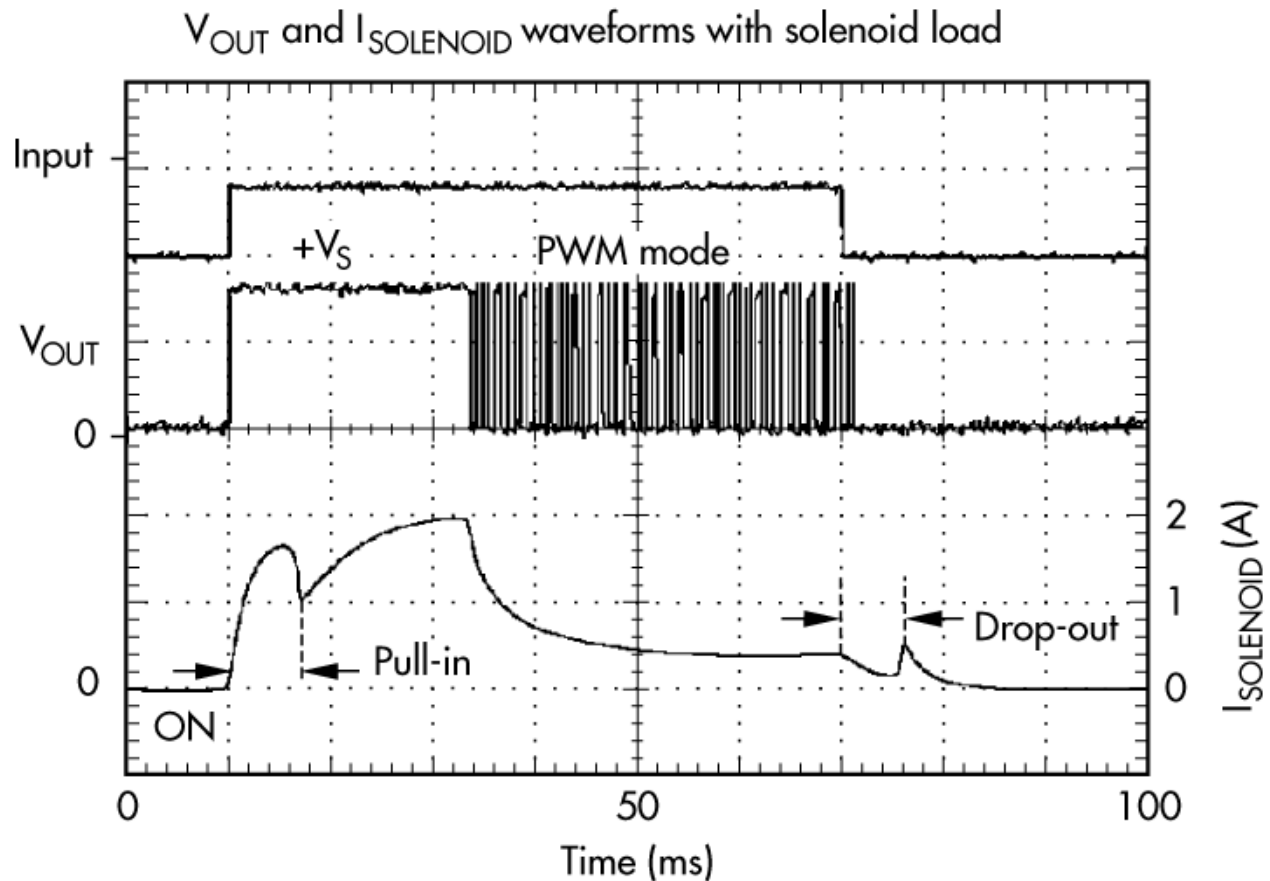
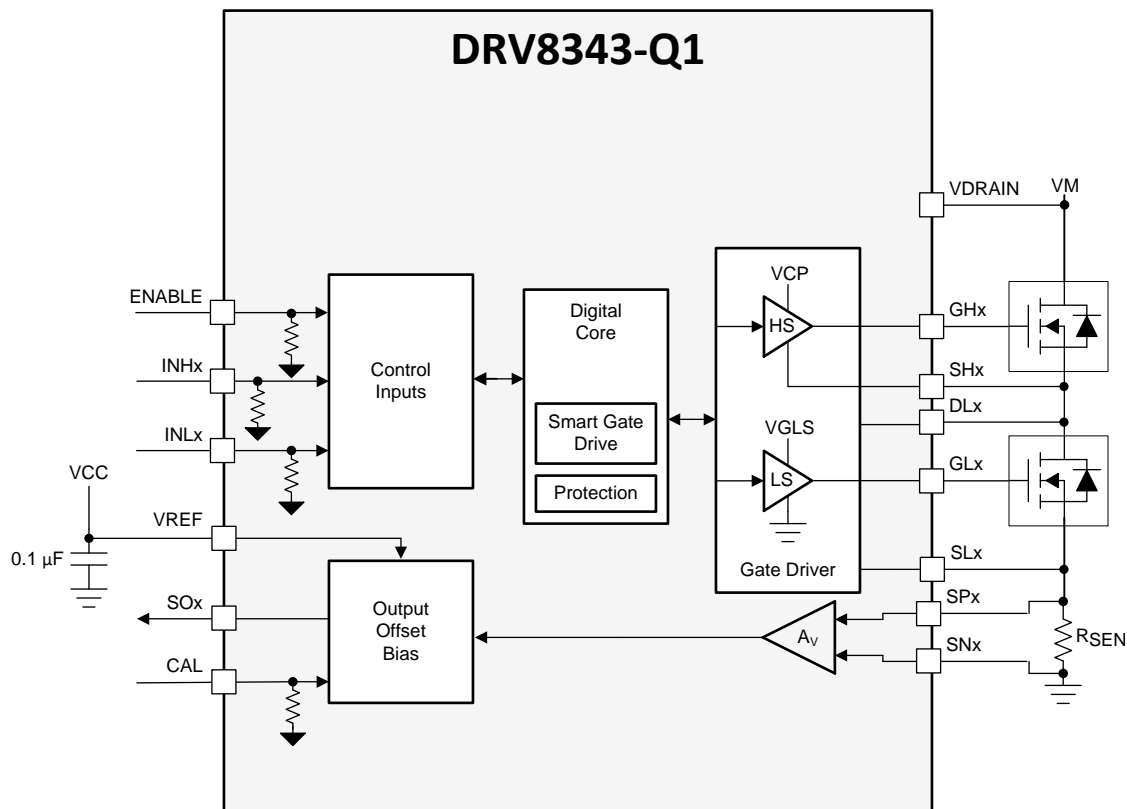


Figure 10. Solenoid Voltage and Current Outputs Using PWM

#### 4.2 Increase Efficiency with Integrated Current Regulation or Integrated Current Sense Amplifiers

To even further the efficiency and reliability of a solenoid driver circuit, current-sense feedback for the current control can be implemented. Current-sense feedback provides two main advantages. One advantage is efficiency and reliability over temperature. As the solenoid or relay coil heats up from  $I^2R$  losses or is warmed by its environment, the coil resistance increases. With the current-sense feedback, the current can be monitored and adjusted to produce a constant force even with the changes in resistance. The second advantage is that it allows operation regardless of supply voltage. At times a relay or solenoid will have good performance, but may not be rated for the available voltage rails in the system. Solenoids have these voltage ratings because they can be destroyed by too much current going through the coil which happens when driving at higher voltages. This issue is eliminated when using current-sense feedback by controlling the current going through the solenoid regardless of the supply voltage. This allows a single solenoid driver design to be reused on multiple products.

There are two methods for providing current feedback to a microcontroller, one through an integrated current shunt amplifier using an external sense resistor and the other through a current mirror where a proportional current is fed to the microcontroller without the need for an external sense resistor, saving cost and board space. Typically, in gate drivers you will find integrated current shunt amplifiers like in DRV8343-Q1 which has three current shunt amplifiers as shown in Figure 11. On the other hand, integrated MOSFET motor drivers like the DRV8876 have a current mirror architecture which provides a proportional current to the microcontroller through the IPROPI pin.


**Figure 11. Block Diagram for DRV8343S**

Another feature in some motor drivers that can be used to control the amount of current through the solenoids is integrated current regulation. TI Motor Drivers such as DRV8702-Q1, DRV8702D-Q1, and DRV8876 have this feature. The DRV8702-Q1's integrated current regulation can be used when put in a H-Bridge configuration. If only a half-bridge is needed, the DRV8702D-Q1 can be used. On the DRV8702-Q1 and DRV8702D-Q1, the maximum current through the motor winding is regulated by a fixed off-time PWM current regulation or current chopping. When the current hits the current chopping threshold, the bridge enters a brake (low-side slow decay) mode until the toff time expires. The PWM chopping current is set by a comparator that compares the voltage across a current-sense resistor connected to the SP pin, multiplied by a factor of  $A_v$ , with a reference voltage from the VREF pin. The factor  $A_v$  is the shunt-amplifier gain, which is 19.8 V/V for the DRV8702-Q1 device or configurable to 10, 19.8, 39.4, or 78 V/V for the DRV8703-Q1 device. Use Equation 1 to calculate the chopping current  $I_{\text{CHOP}}$ .

$$I_{\text{CHOP}} = \frac{V_{\text{VREF}} - V_{\text{IO}} \times A_v}{A_v \times R_{\text{(Sense)}}} \quad (1)$$

Integrated current regulation on the DRV8876 can be set using the VREF and IPROPI pins. The integrated current regulation can either be set to use a fixed off-time or cycle-by-cycle PWM current chopping scheme. Equation 2 can be used to size the appropriate IPROPI resistor to achieve the desired  $I_{\text{TRIP}}$  level. In the fixed off-time mode, the H-bridge enters a brake, low-side slow decay (both low-side MOSFETs ON) for  $t_{\text{OFF}}$  duration after  $I_{\text{OUT}}$  exceeds  $I_{\text{TRIP}}$ . After  $t_{\text{OFF}}$  the outputs are re-enabled according to the control inputs unless  $I_{\text{OUT}}$  is still greater than  $I_{\text{TRIP}}$ . If  $I_{\text{OUT}}$  is still greater than  $I_{\text{TRIP}}$ , the H-bridge will enter another period of brake/low-side slow decay for  $t_{\text{OFF}}$ . In cycle-by-cycle mode, the H-bridge enters a brake, low-side slow decay (both low-side MOSFETs ON) after  $I_{\text{OUT}}$  exceeds  $I_{\text{TRIP}}$  until the next control input edge on the EN/IN1 or PH/IN2 pins.

$$I_{\text{TRIP}} = \left( \frac{V_{\text{VREF}}}{R_{\text{IPROPI}}} \right) \times A_{\text{IPROPI}} \quad (2)$$

Since there is only 1 IPROPI pin on the device the current sensing on the IPROPI pin is the summation of the currents through the two low-side internal MOSFETs.

## 5 Fast Discharging Circuits

Some applications require very fast turn on/off rates of a solenoid. Due to the nature of solenoids, current flow cannot change instantaneously. Recirculating the current in either a freewheeling diode or opposing MOSFET is sometimes not enough to decay the current fast enough and will cause a delay in the plunger releasing. To do this, a fast discharging circuit is added into the application. The basic idea is to construct a circuit that can provide a large opposing voltage that can quickly decay the recirculation current to zero. The higher opposing voltage, the faster the current decay. These fast discharging circuits can be made using a Zener or TVS (Transient-voltage-suppression) diode, a varistor (Voltage Dependent Resistor), or an H-Bridge configuration.

### 5.1 Zener or TVS diode

When using a Zener diode to discharge the solenoid current, the opposing voltage will be equal to [Equation 3](#).

$$V = L \frac{\Delta i}{\Delta t} - i \times R \quad (3)$$

If the internal resistance of the solenoid is ignored the decay time can be estimated by [Equation 4](#).

$$\Delta t = L \times \frac{\Delta i}{V} \quad (4)$$

[Figure 12](#) shows an example of using a Zener diode for fast discharging.

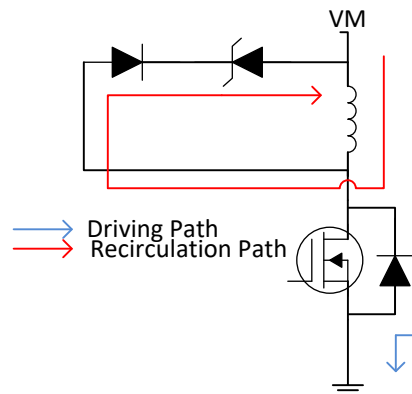
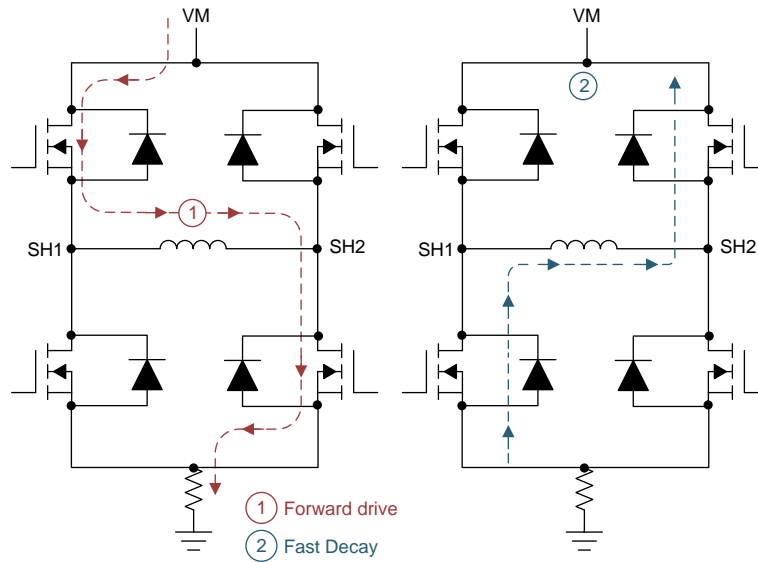


Figure 12. Zener Diode Fast Discharging Circuit

### 5.2 H Bridge with Fast Decay OFF Time

Using an H-Bridge can also be used as an effective fast discharge circuit. As shown in [Figure 13](#) fast decay can be used by turning off the MOSFETs and allowing current to flow through the body diodes. This will result in a opposing voltage equal to the  $V_M$  plus the forward voltage of the two body diodes. If frequency response and better thermal performance is desired an H-Bridge configuration can be used.



**Figure 13. H-Bridge Fast Decay**

## 6 Conclusion

Motor driver ICs can be an effective, efficient, and reliable solution to drive solenoids. With all the integrated features, using drivers such as DRV8343-Q1, DRV8702-Q1, and DRV8876, can be used to drive multiple solenoids with a single device, achieve greater efficiency using PWM, and increase reliability using current sense feedback.

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