Application Note
Using Motor Drivers to Drive Solenoids

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ABSTRACT

Solenoids are electromagnetic actuators that convert electrical current to linear or rotational motion with a coil of wire. A key difference from other motors is that the solenoid has a sliding iron plunger within the coil. Solenoid assemblies, which may be referred to as solenoids, solenoid valves, solenoid switches, or "metal can" relays, have become more frequently used in automotive and industrial applications for actuation of loads, valves, and as electro-mechanical switches. Driving a solenoid is similar to driving a motor. However, its unique physical characteristics and varying configurations bring new challenges for the electronics driving them. This application report describes key parameters of solenoids, what power stage architectures can be used to drive them, and how Texas Instruments motor driver solutions can simplify solenoid driving systems.

Table of Contents

List of Tables

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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. There are several types of solenoids, but generally their main use is to displace objects or maintain a specific state or position, much like a traditional relay. These 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.

Within each application, solenoids and relays are driven in different configurations. Some example solenoid applications include home appliances, printers, HVAC, irrigation systems, engine and transmission control.

This application report categorizes and describes a few types of solenoids, discusses driver configurations, and highlights semiconductor solutions from TI that can simplify solenoid driver solutions.

1.1 Types of Solenoids

There are three main categories of solenoids; push/pull, latching/bistable, and proportional.

The first type, push/pull or monostable, is used to displace an object by energizing and de-energizing the coil, or where "in and out" movement is needed. Push/pull solenoid is made up of an iron frame, iron plunger, copper coil, and return spring. Figure 1-1 shows a cross-sectional view of a pull-type solenoid. This type of solenoid can be found in applications such as electronic door locks, valves, and robotics.
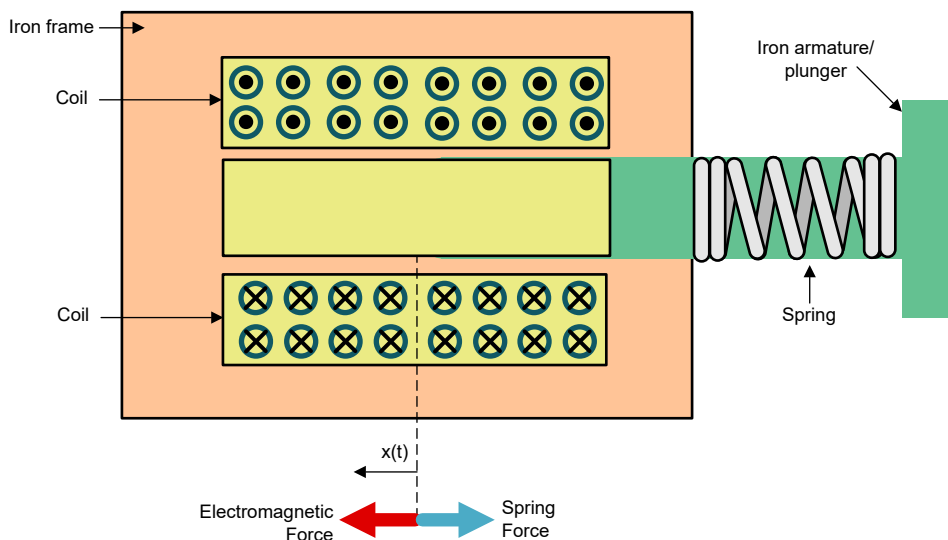
Figure 1-1. Cross-Sectional View of a Push/Pull Solenoid

The second type is the latching/bistable solenoid. The latching/bistable is similar in use to the push/pull, but the latching solenoid can maintain its position after power is off. When off, the position of latching solenoid is maintained by a permanent magnet, as opposed to a spring for push/pull solenoid. Energizing the coil with a pulse of current will change the position of the solenoid.

Proportional solenoids are solenoids that generate a force proportional to the current flowing through it, as opposed to solenoids changing between two positions or states. By adding a spring, the solenoid can generate a displacement which is proportional to current. In applications such as hydraulics, these solenoids can also be constructed with an air gap, so that fluid pressure does not affect force characteristics of the solenoid. This allows for very fine force and positioning control.

2 Solenoid Driving Typologies

Most systems today use motor drivers to actuate and de-actuate solenoid. The key to driving a solenoid is which FETs to switch on and off, and when to switch them.

There are three basic driver configurations, low-side, high-side, and half-bridge/full-bridge, each with their trade-offs. Choosing which configuration depends on the system requirements, such as switching speed and fault protection. The high-side driver can protect against short to ground fault, whereas a low-side driver protects against short to battery fault.
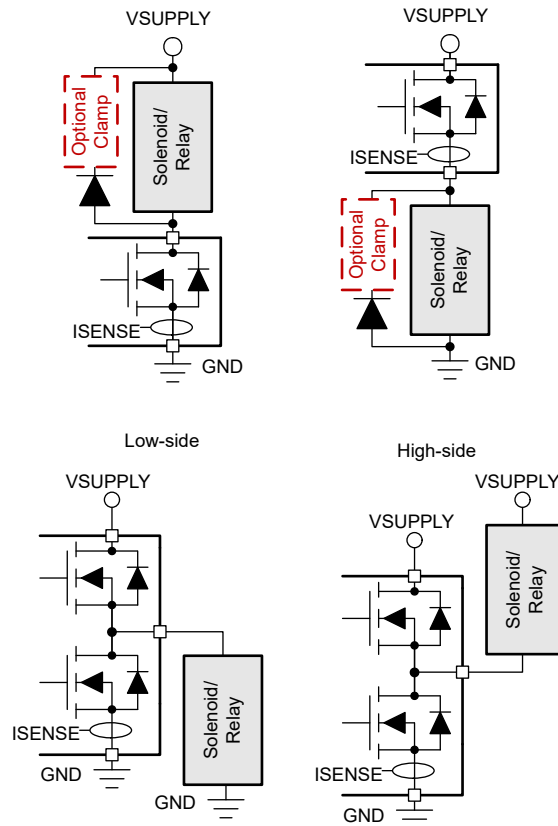

Figure 2-1. Configurations for Basic Low-Side, High-Side, and Half-Bridge Drivers

2.1 Low-Side and High-Side Configuration

The typical low-side or high-side driver configuration uses a single MOSFET with enough current handling capability to drive the solenoid. High- and low-side drivers are good choices for push/pull solenoids with a return spring. Figure 2-2 shows the LS/HS configuration, with optional external clamp.
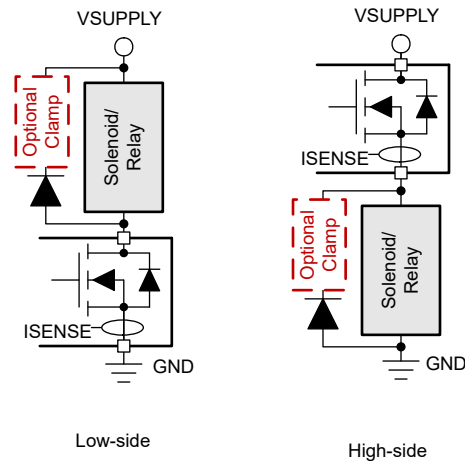
Figure 2-2. Low-Side and High-Side Configurations

When the MOSFET is enabled, it conducts all the current needed to energize the solenoid. When the MOSFET is disabled, the current in the solenoid must freewheel through a diode, or be allowed to continue flowing or decay to zero, otherwise the MOSFET can see large voltage spikes. The freewheeling diode across the solenoid provides this low impedance path for solenoid current to flow. Figure 2-3 shows a low-side driver.

Figure 2-3. A Power MOSFET Transistor and a Freewheeling Diode Used to Drive a Solenoid

2.2 Half-Bridge and H-Bridge Driver Configurations

The half-bridge driver uses two MOSFETs to control the current through a solenoid; one MOSFET to forward drive the solenoid and the other to recirculate current.

The H-bridge driver uses four MOSFETs, or two half-bridges joined by a load, to control current through a solenoid. With four MOSFETs, bidirectional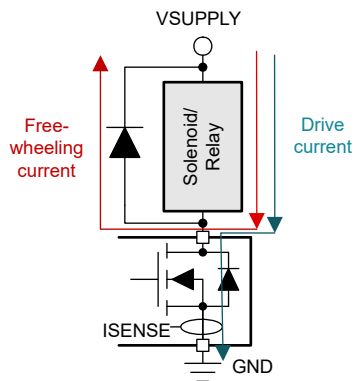 current control is possible. This makes H-bridge drivers a good choice for single-coil and latching or dual-coil relays.

The H-bridge and half-bridge configurations can be seen in Figure 2-4 and Figure 2-5.

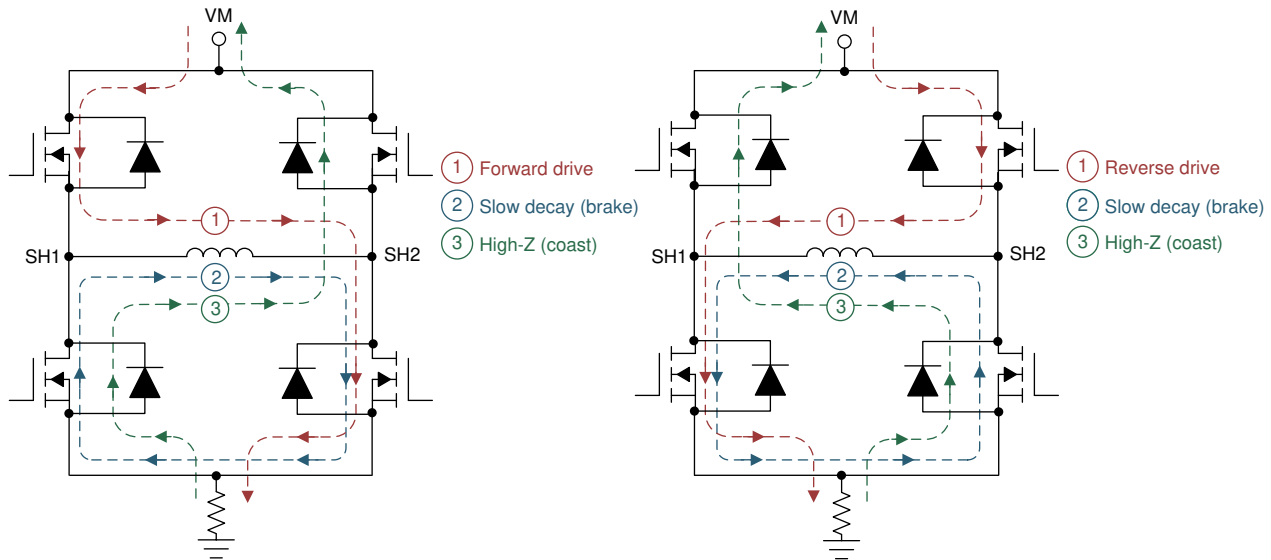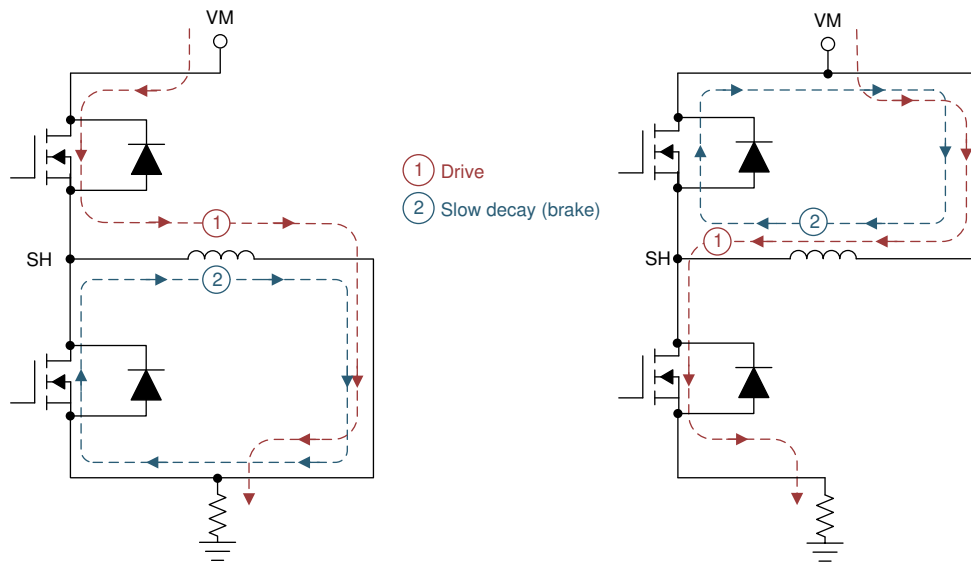**Figure 2-4. H-Bridge Drive and Recirculation Current Paths**

Figure 2-5. Half-Bridge Drive and Recirculation Current Paths

While the half-bridge can only enable slow decay, the half-bridge integrates the freewheeling diode, which is typically an external component. This further reduces the solution size. There is also the benefit of flexibility between driving high- or low-side loads with the half-bridge.

The H-bridge driver can enable both slow and fast decay (coast) by recirculating current with either high- or low-side MOSFETs. Figure 2-6 shows how an H-Bridge can be utilized to drive a conventional solenoid valve with high-side recirculation.
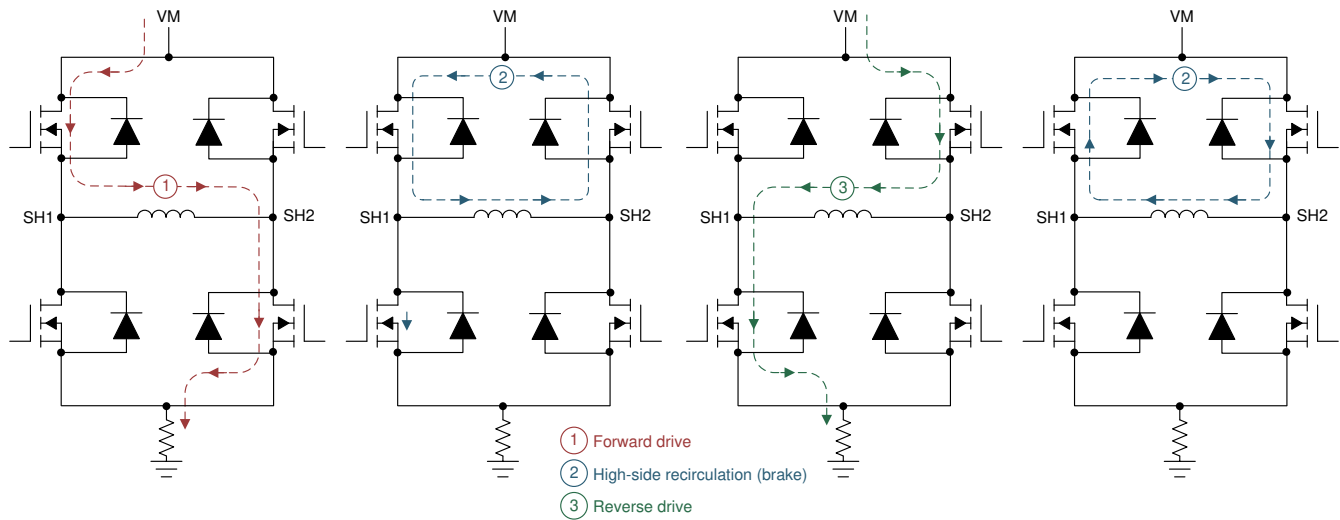
Figure 2-6. H-Bridge Configuration Utilized to Drive a Solenoid Valve

An H-Bridge can also be used as an effective fast discharge circuit. Fast decay can be accomplished by turning off the MOSFETs and allowing current to flow through the body diodes. This results in an opposing voltage to the solenoid current equal to VM plus the forward voltage of the two body diodes. Figure 2-7 shows current flow for fast decay with H-Bridge.
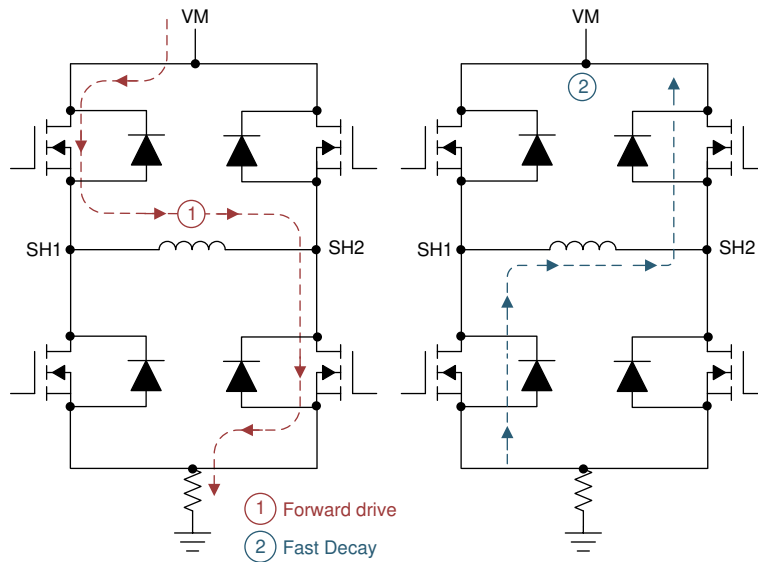
Figure 2-7. H-Bridge Fast Decay

If fast decay and improved system thermal performance are desirable, an H-Bridge configuration could be a good fit.

3 Basics of Driving Solenoid Loads

Because solenoids are inductive loads, they store energy in the magnetic field when current flows through the coil. Whether disabling the solenoid or using PWM to maintain a specific current level, any circuitry used to drive a solenoid must never abruptly stop the flow of current. Doing so will cause a large voltage spike due to the energy leaving the solenoid. This is apparent from the expression that defines the voltage characteristic of inductors: V = L*di/dt.

As mentioned in the previous sections, freewheeling diodes allow for the current to recirculate when the driving FET disables. This keeps the voltage across the solenoid equal to the forward voltage drop of the diode. When disabling a solenoid, the current will recirculate until the energy stored in the inductor dissipates as heat in the series resistances of the diode and solenoid. Because the current decreases slowly, freewheeling diodes should be used in systems when PWM or current regulation schemes are used to implement peak and hold control for power savings.

Some circuits require solenoids to disable quickly to minimize latency in the system for valves or actuators. Clamping circuits may be integrated into the driver or added externally to help dissipate the energy. For instance, adding a Zener diode in series with the freewheeling diode will help to dissipate energy quickly from the solenoid. In this case, the voltage drop across the solenoid when the driving FET is disabled will be equal to the Zener clamping voltage plus the diode drop. Because this voltage is much higher than the freewheeling diode alone, it will dissipate the stored inductive energy much fast.

3.1 Current Control

Driving solenoids with current control requires two things: current sense and current regulation. The advantages of current control are improved efficiency and reliability across 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 can provide some measure of protection from higher than rated supply voltage. Solenoids have voltage ratings because they can be destroyed by too much current going through the coil, which happens when driving at higher voltages. This problem can be managed with current-sense feedback, and 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 load current feedback from motor driver IC to a microcontroller. One method is from a current shunt amplifier using an external sense resistor that is connected either in line with the load, or on the high- or low-side. The other is from a current mirror, which provides a proportional current to load current to pin output, removing the need for an external sense resistor. This proportional current output method is available for motor driver ICs with integrated MOSFETs. One limitation here is that generally, both high- and low-side sense output may not always be available for a given integrated motor driver IC.

To regulate current and energize and de-energize most solenoids, peak-and-hold drive is desired. Figure 3-1 below shows an example of this expected peak-and-hold current.
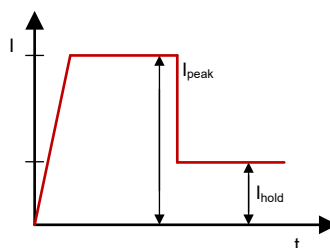

Figure 3-1. Expected Current Waveform for Peak and Hold

The charging current is drawn or driven into the solenoid, called the peak current. The current in the solenoid will ramp to its peak, at which point the magnetic field will depress the plunger into the spring. To maintain the solenoid in this position, current must still be drawn or driven into the solenoid. This is referred to as hold current. However, this current is far lower than the peak current. To further minimize power dissipation through the solenoid during hold phase, the hold current can be regulated.

Just as pulse width modulation (PWM) is used to drive other types of 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 or maximum duty cycle to pull in the solenoid, and then a shorter duty cycle to hold it in place, optimizing the power consumption. Figure 3-2 shows the current and voltage driving outputs for the PWM implementation.
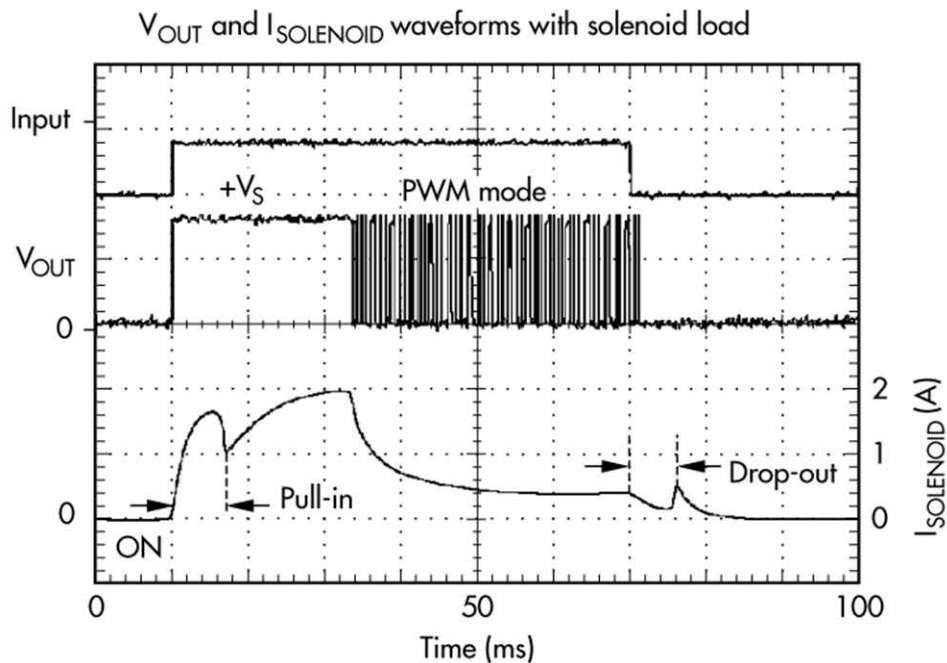

Figure 3-2. Solenoid Voltage and Current Outputs Using PWM

This reduces power consumption of the solenoid solution, due to the lower current in the coil. If the drive current is not reduced, power dissipation will heat up the solenoid further. With the increase in temperature the solenoid initial resistance will also increase, all of which can lead to unintentional de-actuation or failing to actuate the solenoid. Note in the above screenshot that the drop-out or de-actuation time is roughly 10 ms.

3.2 Fast Discharging Circuits

Some applications require fast turn on/off rates of a solenoid. Recirculating load current in opposing MOSFET may not be enough to decay the current fast enough, which can cause a delay in the plunger releasing.

To implement a fast discharge circuit, the driver circuit must generate a large voltage opposite to the solenoid 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 an H-bridge, Zener or Transient-voltage-suppression (TVS) diode, a Voltage Dependent Resistor (varistor).

3.2.1 Freewheeling and Clamping

Freewheeling and clamping are both strategies to dissipate energy stored in the solenoid inductance when the FET turns off. A key difference is current decay speed. Clamping very quickly decays solenoid current by creating a large voltage spike opposite in polarity to solenoid current, voltage larger than with opposing MOSFET recirculation, as in fast decay. Freewheeling is slowly decaying solenoid current by recirculating current through a parallel diode, slowly decaying current. Figure 3-3 shows both freewheeling and clamping implementations.
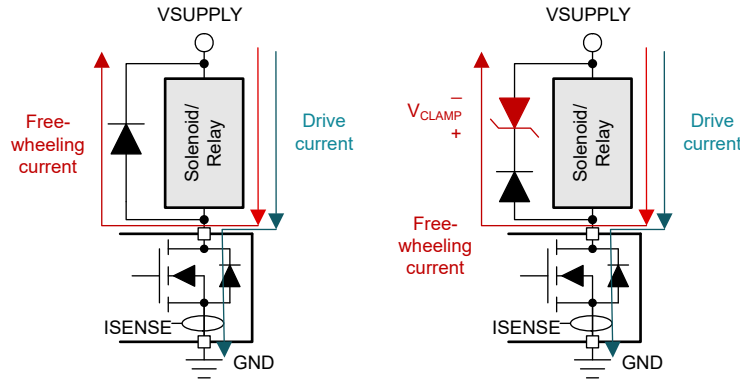

Figure 3-3. Freewheeling, Driving, and Clamping

Clamping involves using as a zener diode or transient voltage suppression diode to rapidly decay current through an inductive load such as solenoid. This can be required for control systems where de-actuation delays are intolerable. The clamping circuit creates a very large voltage opposing the solenoid drive current, and quickly decays current. Figure 3-4 shows expected waveforms when disabling a solenoid using active clamping compared with freewheeling.
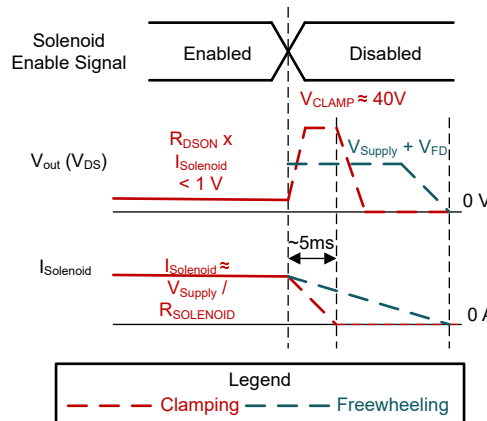

Figure 3-4. Expected Voltage and Current During Clamping vs Freewheeling

When the solenoid is enabled, V_{out} is low, below 1 V, while solenoid is in the hold phase. When the solenoid is disabled, V_{out} quickly jumps up to around 40 V (or 3-4 times supply voltage), and the solenoid current quickly drops to 0 A. Also shown above is roughly what the freewheeling voltage and current waveforms would look like. What is not shown is the back EMF generated by the armature when changing state. Figure 3-5 shows an oscilloscope screenshot demonstrating actual voltage and current waveforms during a quick turn-off for a solenoid.
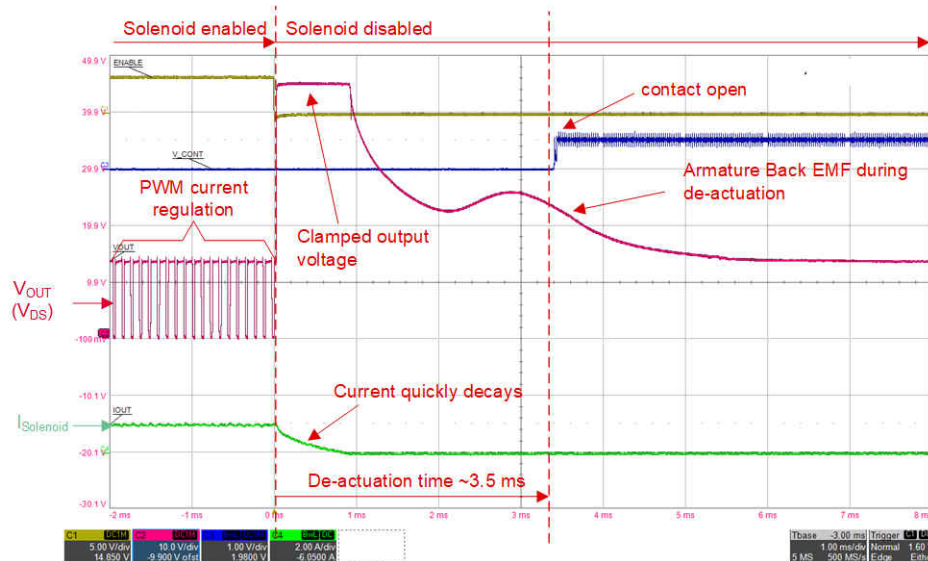

Figure 3-5. Waveforms Demonstrating Quick Turn-Off

At the start of the scope shot, the solenoid is in the hold phase. Note the V_{OUT} waveform shows PWM current regulation with V_{SUPPLY} of around 13 V and the steady solenoid current leading up to the disabling of the solenoid. When the solenoid is disabled, V_{OUT} is clamped at roughly 45 V, and the solenoid current decays to zero within one millisecond. After the current has decayed to zero, the armature generates a back EMF during de-actuation. Total time from solenoid disable to de-actuation is about 3.5 milliseconds. Recall in the previous section, the de-actuation time with freewheeling was roughly 10 milliseconds.

3.2.2 Passive Voltage Clamping

Common passive components used for voltage clamping of inductive loads are zener diodes or TVS diodes. The voltage across an inductive load can be described by Equation 1. During recirculation, the voltage across the inductor is mainly due to any changes in current, minus the voltage drop due to load current through internal resistance of solenoid.

$$V = L\frac{\Delta i}{\Delta t} - i \times R \tag{1}$$

To simplify further, internal resistance of the solenoid is ignored, the decay time can be estimated by Equation 2.

$$\Delta t = L \times \frac{\Delta i}{V} \tag{2}$$

Assuming inductance and current are constant during recirculation, this shows that the decay time is inversely related to voltage across inductive load; the larger the voltage, the smaller the decay time. For the case of freewheeling or slow decay, this voltage would just be the forward voltage of diode. Again, for fast decay with full-bridge, this voltage would be V_{SUPPLY} plus forward voltage of two diodes. For quick turn-off or clamping with a zener diode, this voltage would be forward voltage of diode plus V_{ZENER}, where V_{ZENER} can be much larger than V_{SUPPLY}.

Figure 3-6 shows the recirculation path when using a Zener diode for fast discharging. Note that the voltage on one node of the solenoid is VM, and the other node is $V_{DIODE} + V_{ZENER} + VM$, making the total voltage across the solenoid equal to $V_{DIODE} + V_{ZENER}$.
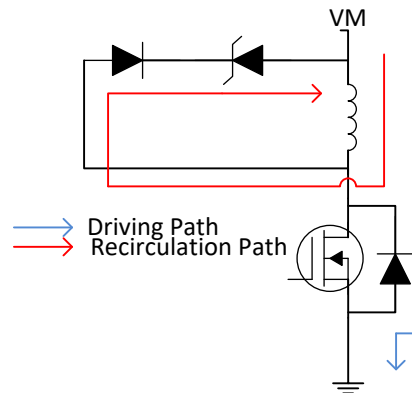

Figure 3-6. Zener Diode Fast Discharging Circuit

4 DRV Motor Driver Features for Solenoid Driving

While Texas Instruments has a large portfolio of motor drivers, this section highlights several devices and their features related to the topics mentioned in this application report.

4.1 Current Sensing and Regulation Solutions

Most motor drivers from Texas Instruments support current sense. First, motor gate drivers, such as the DRV8714-Q1 multi-channel gate driver or DRV8343-Q1 three-phase gate driver, have integrated current shunt amplifiers which provide inline current sensing to continuously measure motor current, even during recirculation. Figure 4-1 shows a simplified version of the current shunt amplifier circuit as an example.
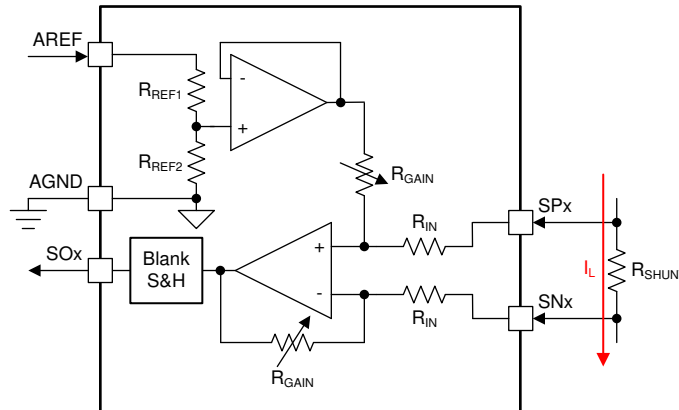

Figure 4-1. Amplifier Simplified Block Diagram

The integrated MOSFET motor drivers like the DRV8243-Q1 and DRV8873-Q1 have a current mirror architecture which sources a current on IPROPI pin that is proportional to load current. The current can be converted to voltage with an external resistor. This voltage can be used by a microcontroller.

Figure 4-2 shows a generic diagram of IPROPI implementation. It is important to note that both the DRV8243-Q1 and DRV8873-Q1 have high-side sensing, and that DRV8243-Q1 does not have pin for external voltage reference.
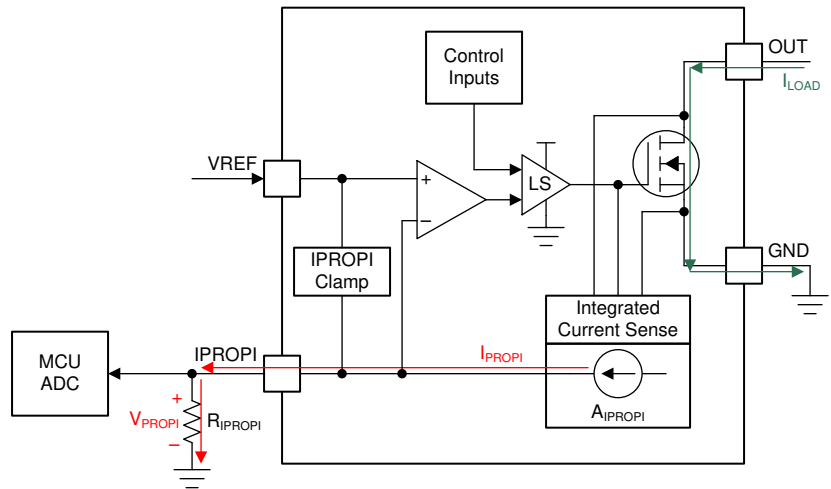
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Figure 4-2. Integrated Current Sensing

Another feature in some motor drivers that can be used to control the amount of current through the solenoids is integrated current regulation. The integrated full-bridge drivers DRV824x-Q1, and DRV887x-Q1 have this feature. When the current hits the configured current limit, the bridge enters a brake mode until the toff time expires, or the next control input edge.

Integrated current regulation on the DRV887x-Q1 and DRV824x-Q1 can be set using the VREF/ITRIP and IPROPI pins. For the DRV8873-Q1, the integrated current regulation can either be set to use a fixed off-time, or cycle-by-cycle PWM current chopping scheme. DRV8243-Q1 only supports fixed off-time.

For details on how to configure current limits, see the device-specific data sheets.

4.2 Independent Low-/High-Side Driving

For high-side and/or low-side driving, some devices have an independent FET mode that can drive separate high-side and low-side loads. Both the DRV8714-Q1 and DRV8343-Q1 gate drivers support several drive configurations.

The DRV8714-Q1 has a split high-side and low-side control feature which enables connecting a floating load in between HS and LS FETs. The diagram below shows DRV8714-Q1 driving a solenoid load in this configuration.
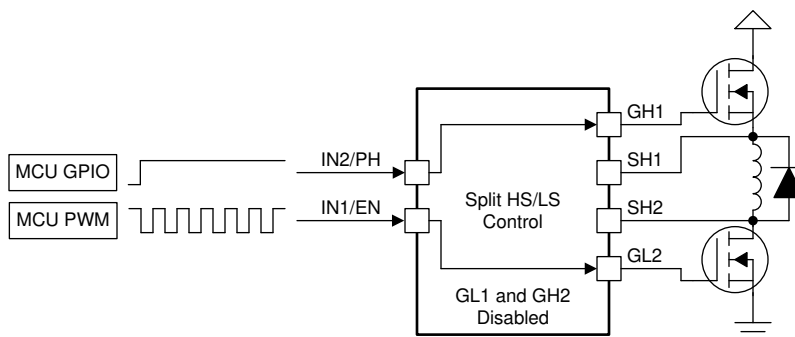

Figure 4-3. DRV8714-Q1 Split HS/LS Control

In this mode, the HS FET can be controlled as a switch, and the LS FET can be controlled by PWM.

The highly configurable DRV8343-Q1 can support several configurations of phases, for example, where one phase of three could be a half-bridge and others are independent FETs, one is PH/EN and others are PWM, and so forth.

For the Independent MOSFET drive mode, the INHx and INLx pins control the outputs, GHx and GLx, respectively. This control mode. 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 4-1. Truth Table for Independent MOSFET Mode

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

Figure 4-4 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. Note that if a half-bridge is used to only implement a high-side or low-side driver, the unused does not need to be connected. VDS monitors can still monitor for overcurrent condition.
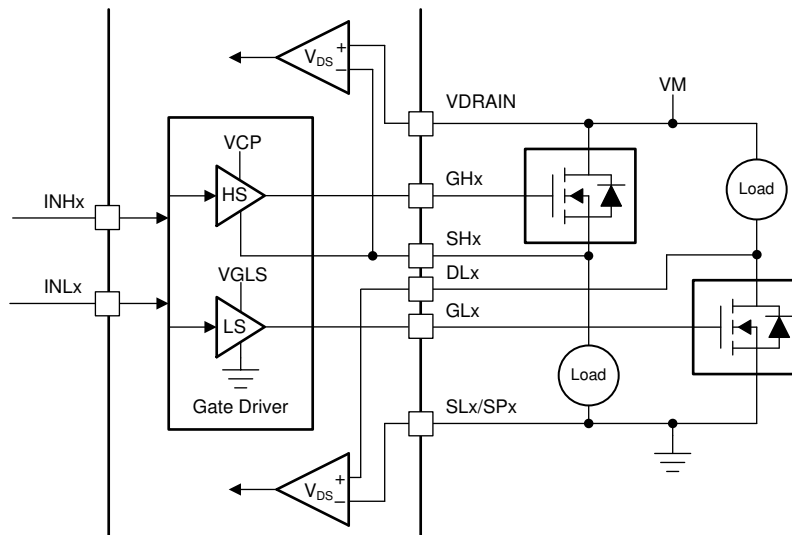

Figure 4-4. Independent PWM High-Side and Low-Side Drivers

4.3 Half-Bridge Driving

Half-bridge driving can be very useful as it provides flexibility in load configuration, and H-bridge solutions can be configured as multiple half-bridges to drive multiple solenoids. As mentioned before, the DRV8714-Q1 and DRV8718-Q1 gate drivers support this configuration, along with PWM mapping feature, as shown in Figure 4-5

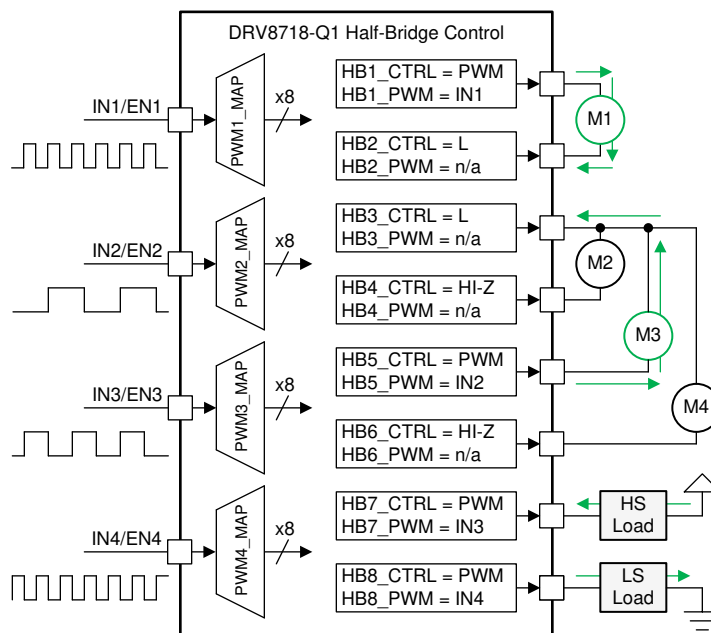**Figure 4-5. Half-Bridge Control**

The DRV8343-Q1 can control up to three different solenoids in a high-side PWM and low-side cutoff 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 . 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 4-2. 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 four solenoids to be driven at the same time individually, two in push-pull configuration, one in high-side configuration, and one in low-side configuration. In these modes, the two 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.

For lower current applications, the DRV824x-Q1 and DRV887x-Q1 are device families of integrated H-Bridge drivers which scale by R_{DSON}. These drivers can also be configured to drive two solenoids in Independent Half Bridge mode. The MOSFETs are built into the devices to simplify the design and decrease board space.

The DRV824x-Q1 family can support independent half-bridge mode to drive several load configurations. A low-side configuration example is shown in Figure 4-6.
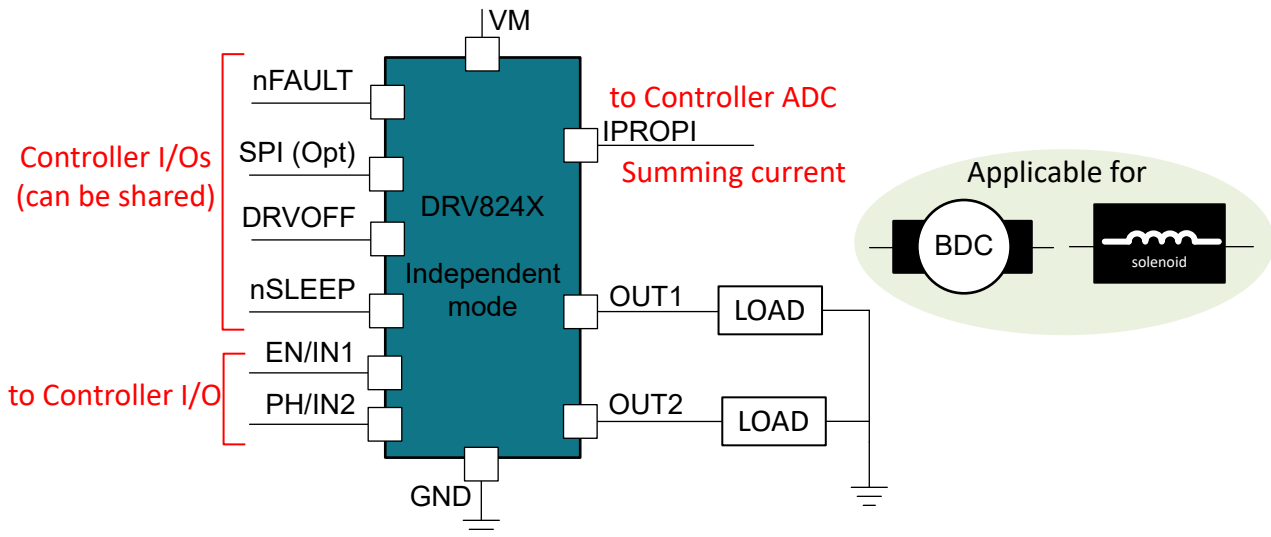
Figure 4-6. DRV824x Independent Half-Bridge Low-Side Loads

Figure 4-7 shows the application schematic configured to drive two solenoids in Independent Half-Bridge mode.
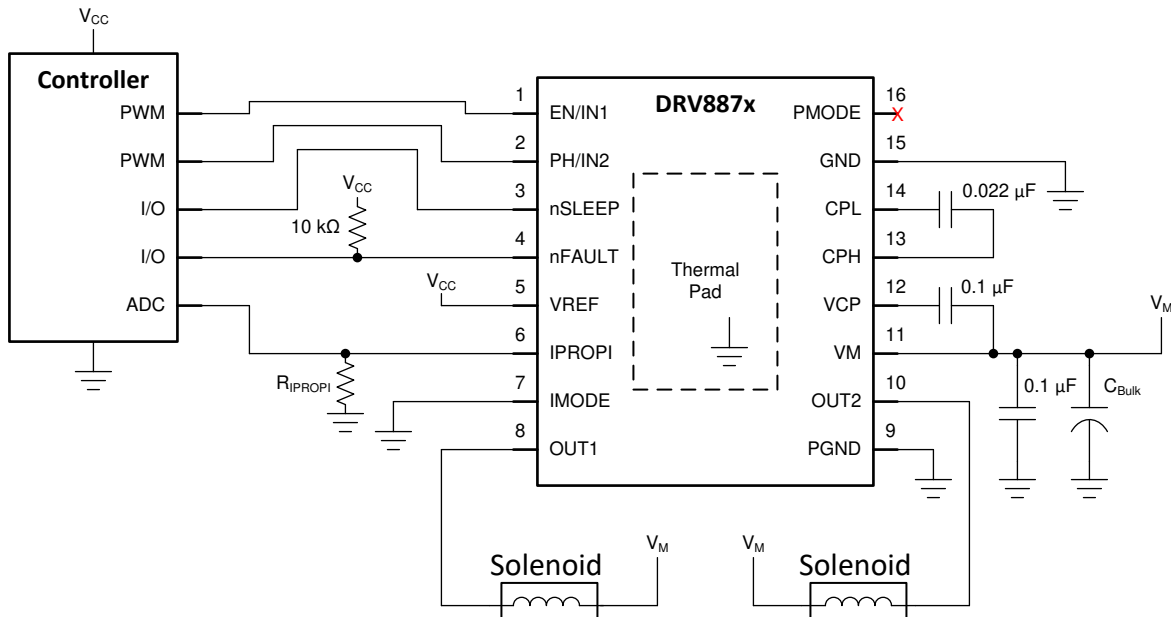

Figure 4-7. Application Schematic for DRV887x to Drive Two Solenoids

Table 4-3 shows the truth table for Independent Half-Bridge mode.

Table 4-3. 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

The DRV8706-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 4-8 shows control of Independent Half Bridge mode. Table 4-4 shows the control table for DRV8706-Q1 in Independent Half Bridge mode. In this mode, the device does not perform PWM current regulation or current chopping.

Table 4-4. Independent Half Bridge Mode Truth Table

nHIZx	IN1x	GHx	GLx	SHx
0	x	L	L	Z
1	0	L	H	L
1	1	H	L	H
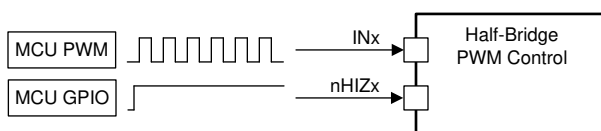
Figure 4-8. Half-Bridge Control

4.4 Integrated and Gate Driver H-Bridges

TI motor drivers can also support H-bridge driving with integrated gate drivers or gate driving solutions. Some drivers, such as DRV8714-Q1 and DRV8718-Q1 gate drivers, have H-Bridge control mode, which can enable driving two to four H-bridges. If PWM control is not required, the two H-bridge gate drivers can even be controlled directly through SPI control registers. In this mode, the active freewheeling recirculation path (low-side or high-side) is configurable in SPI register.
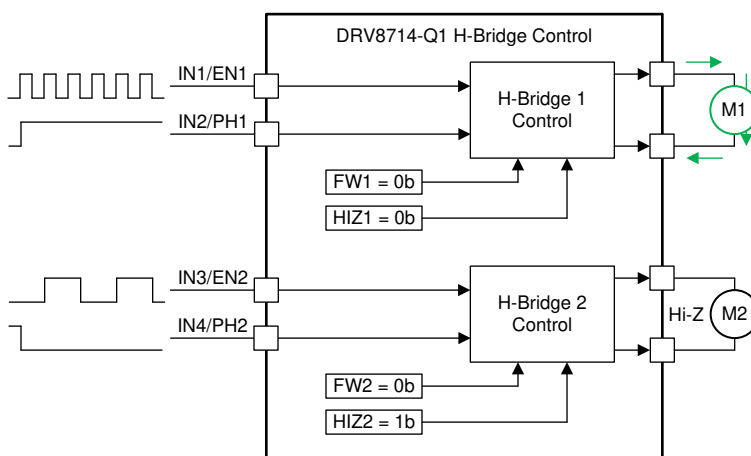

Figure 4-9. H-Bridge Control Example

For space-constrained solenoid applications, the DRV8243-Q1 integrated H-bridge driver can be configured as a single H-bridge driver or as two independent half-bridge drivers. This device can also control bridges through SPI specific register bits. Additionally, the user can configure between an AND/OR logical combination of each external input with their equivalent register bit. For example, pin input can be ANDed with SPI_IN register bit, for certain configuration bit.

The DRV8243-Q1 device is part of device family, pin to pin compatibility, scalable R_{DSON} to support different loads, and also includes the DRV814x-Q1 integrated half-bridge drivers with half R_{DSON} of DRV824x-Q1 devices.

The DRV887x-Q1 integrated H-bridge driver family, which includes the DRV8873-Q1, includes H-bridges that can support up to 10-A.

5 Summary

Table 5-1 summarizes the devices and features that are discussed.

Table 5-1. Devices and Features

Device	Description	Current Sense	Mode Support
DRV8243-Q1	Integrated full-bridge	High-side; IPROPI	Independent and full-bridge
DRV8873-Q1	Integrated full-bridge	High-side; IPROPI	Independent and full-bridge
DRV8714-Q1	Multi-channel gate driver	2xCSA	Independent half-bridge, independent MOSFET, and full-bridge
DRV8706-Q1	H-bridge gate driver	CSA	Independent half-bridge and full-bridge
DRV8343-Q1	three-phase gate driver	3xCSA	Independent half-bridge and independent MOSFET

While there are many types of solenoids with many configurations, DRV motor driver ICs from Texas Instruments simplify solutions to drive solenoids not only by reducing size, but by integrating more control and diagnostic features. With all the integrated features and pin-to-pin packaging, one or a small subset of DRV motor drivers can be used to drive one or multiple solenoids from a single device, and leverage a single design for different solenoid loads.

6 Revision History

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

Changes from Revision * (February 2019) to Revision A (April 2022)   **Page**

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