DRIVING INDUCTIVE LOADS

By Imhotep Baptiste and Alistair Wood
Allegro MicroSystems, Edinburgh, UK

INTRODUCTION

Motors generate torque by passing an electric current through a coil of wire. Torque may be used in solenoids for valves and locks, actuators for positioning and holding, motors to produce rotating movement for fans, pumps and driving wheels in vehicles, or inductors in power converters.

In each application, current in the coil must be controlled to set the torque generated. The various techniques available for current control can be grouped into three primary categories: open-loop control, closed-loop linear control, and closed-loop switched control.

Open-loop control and closed-loop linear control employ in-circuit series resistors to limit the current flowing through the inductor. However, both techniques dissipate large amounts of energy as heat and high heat loss results.

In contrast, closed-loop switched control provides the advantages of less energy loss and more-precise current control. Pulse width modulation (PWM) techniques in particular are simple to implement and are widely employed.

This application note outlines common techniques and challenges in the employment of a single half-bridge driver configuration to control current in a simple two-terminal inductive load.

DRIVING INDUCTIVE LOADS

For a purely inductive load, the voltage across the load (*V*) is directly proportional to the rate of change of current through the load (*dI*/*dt*), with a constant of proportionality defined as the inductance (*L*):

Equation 1: $$V = L(dI/dt)$$

If a fixed value of voltage is applied across an inductor, the current in that inductor will ramp linearly per Equation 1, with ramp direction dependent on voltage polarity.

Current flow in an inductor cannot be stopped instantaneously. If an external attempt is made to stop current flow, a circuit path must be provided to allow that current to continue to flow and decay (recirculate) in a controlled manner. As indicated by Equation 1, the rate of decay of current is proportional to the voltage at which the circuit path clamps the differential voltage across the inductor terminals.

Failure to provide a circuit path to allow inductor current to decay in a controlled manner leads to generation of a high voltage across the inductor, rapid current decay, and possible circuit damage.

Consequently, when applying PWM (on-off switching) control techniques to an inductive load, the load current must be controlled and a suitable path for current decay must be provided.

A basic switching circuit and its corresponding voltage and current waveforms are shown in Figure 1. As can be observed, when switch A is closed, fixed voltage V_L is applied across inductor L, and the resultant inductor current I_L ramps in a positive direction. When the switch is open, the voltage source is removed from the inductor. Because flow of the inductor current cannot stop instantly and continues to flow in the same direction, the right-handed end of the inductor is driven to a positive voltage with respect to the left. The current flows to ground and returns to the inductor through diode D. The diode clamps the voltage across the inductor to a single diode drop (nominally 0.7 V) and the inductor current decays linearly at a rate determined by this voltage and the inductance as defined by Equation 1. When switch A is closed, the diode clamps the voltage across the inductor to a value lower than that applied to the inductor, which causes the rate of current decay to be less than the rate of current rise.

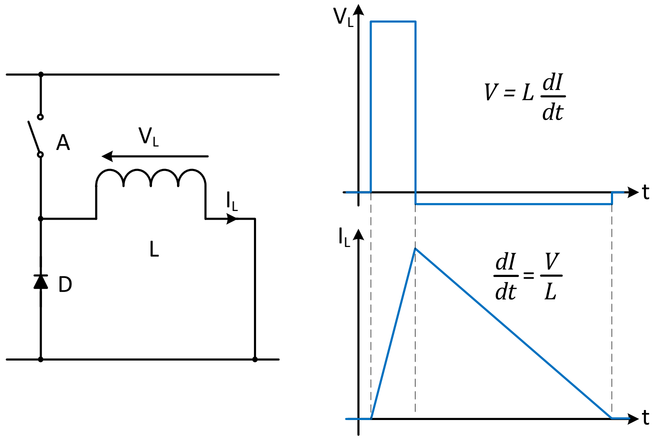

Figure 1: Driving inductive load.

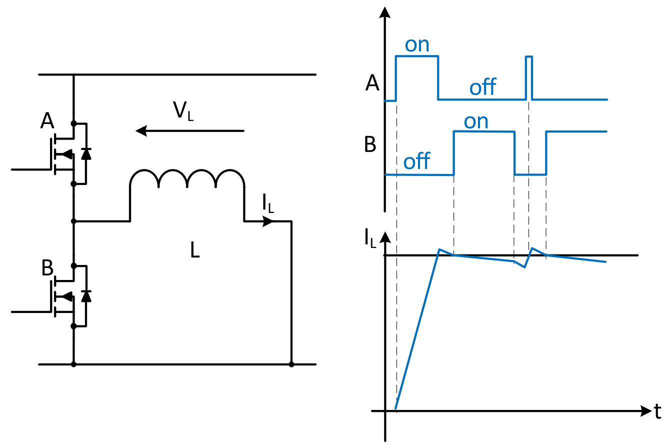

Figure 2: Complementary switching circuit.

Another option for control of inductive loads is to replace switch A and diode D with two MOSFETs. The vast majority of MOSFET types include a parasitic body diode between drain and source, as shown in Figure 2. This feature can be used to help manage current recirculation.

For example, with both MOSFETs in Figure 2 commencing in the off state, when MOSFET A is switched to the on state, the inductor current ramps in the positive direction as before. However, when MOSFET A is subsequently switched to the off state, the inductor current continues to circulate and is returned to the inductor through the body diode of MOSFET B (even though MOSFET B is in the off state). In this process, often referred to as ***diode rectification***, the rate of decay of the current is determined by the forward voltage of the body diode and the inductance from Equation 1.

The diode rectification process relies heavily on the MOSFET B body diode. To minimize this reliance, when MOSFET A is in the off state, MOSFET B is switched to the on state. This provides a recirculation path. In this process, often referred to as ***synchronous rectification***, the voltage across the inductor is clamped at a lower voltage, as dictated by the pull on resistance, MOSFET $R_{DS(ON)}$. Synchronous rectification typically reduces power dissipation in the circuit as well as the rate of decay of the inductor current from Equation 1.

Note that a time delay or ***dead time*** must be provided between the power off of MOSFET A and the power on of MOSFET B. This required time delay prevents MOSFET conductance overlap so as to prevent direct current flow from the supply to ground or from ***shoot-through***. In practice this means a short period of diode recirculation occurs during the dead time, prior to power on of MOSFET B and commencement of the synchronous rectification process.

GATE DRIVER CONFIGURATIONS

Examples of possible configurations to drive inductive loads, such as solenoids and relays, are illustrated in this section using the Allegro MicroSystems AMT49502 and A89503 gate drivers. Several key features of the gate drivers are described.

AMT49502

In the AMT49502, the high-side and low-side gate drivers are controlled independently. Any combination of the active high-side and low-side MOSFETs can be powered on individually or simultaneously. And, neither lock-out nor internally generated dead time occur. This feature allows the AMT49502 to be employed in a complementary half-bridge configuration or in an independent driver configuration to drive the high-side and low-side MOSFETs.

One way to drive loads independently is to use the low-side gate driver to enable current flow through the load to provide on-off control, and to use the high-side driver to provide PWM current control. This example is shown in Figure 3: Low-side MOSFET M2 enables or disables the flow of currentt, and high-side MOSFET M1 is used with low-side recirculation diode D2 to provide PWM current control.

Many features to detect the power bridge and load fault condition are integrated in the AMT49502. For fault protection, this configuration requires that the low-side VDS monitor be disabled (LO bit set to 1 in the Mask 1 register). This is necessary because, when high-side MOSFET M1 is in the on state, the reference voltage for the drain of Low-side MOSFET M2 is the S terminal, which would become pulled to the supply and would otherwise cause a false low-side VDS fault if the low-side VDS monitor were to be active.

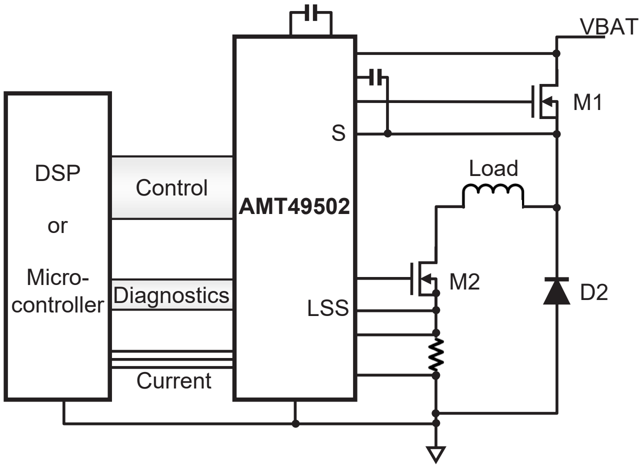

Figure 3: AMT49502 PWM load current control.

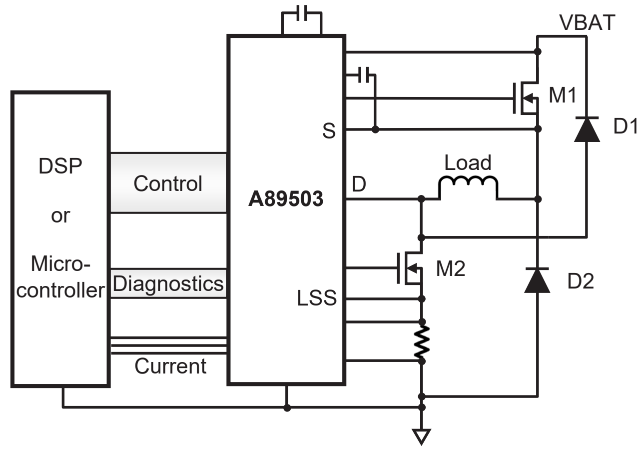

Figure 4: A89503 PWM load current control.

A89503

Similar to the AMT49502, the A89503 also allows independently driven loads. One configuration for independently driven loads in the A89503 is where high-side MOSFET M1 operates in conjunction with ow-side recirculation diode D2 to provide PWM current control, and low-side MOSFET M2 operates in conjunction with high-side recirculating diode D1 to provide on-off control. Because the low-side VDS overvoltage detector monitors the differential voltage between the D and LSS terminals, the D terminal must be connected to the drain of low-side MOSFET M2, as shown in Figure 4. This allows the low-side MOSFET VDS overvoltage detector to remain operational with a series-connected load, unlike the AMT49502.

Due to package pin-count limitations, inclusion of the D terminal in the A89503 precludes the use of a dedicated output offset (OOS) pin terminal on which to directly output the current sense amplifier pedestal voltage (V_{OOS}). However, V_{OOS} can be made available on the CSO terminal at any time (SAT bit in Config 5 register set to 1; further detail is available in the product datasheet).

DIODE CONFIGURATIONS

When using the AMT49502 and A89503, an appropriate path for inductor current circulation must be provided. When using low-side on-off control with high-side PWM, this path is achieved by the inclusion of diode D2, as shown in Figure 3 and Figure 4. During periods when high-side MOSFET M2 is in the off state, inductor current circulates and decays through MOSFET M2 and diode D2.

When stopping current flow through the load, regardless of whether the AMT49502 or the A89503 is employed, it is good practice to allow the inductive current to decay to a low value through MOSFET M2 and diode D2 before MOSFET M2 is switched to the off state. This decay is needed to prevent generation of a high positive voltage at the drain of MOSFET M2, which would otherwise force the device into avalanche breakdown. In the case of the A89503, this decay is also needed to prevent device damage, which would otherwise result if the absolute maximum rating of the D pin terminal were to be exceeded. An alternative method to protect the D pin terminal and MOSFET M2 is to add a second diode D1 between the drain of MOSFET M2 and the supply VBAT, as shown in Figure 4, to clamp the voltage across the load when the state is switched to off.

CONCLUSION

A circuit design that employs an inductive load driver must ensure that current flows are handled appropriately. The Allegro MicroSystems AMT49502 and A89503 gate drivers include features to support multiple inductive load configurations, including simultaneous power-on of high-side and low-side MOSFETs and, in the case of the A89503, the presence of a dedicated D pin terminal to allow the use of a low-side VDS overvoltage monitor.

Revision History

Number	Date	Description	Responsibility
–	June 22, 2021	Initial release	Imhotep Baptiste, Alistair Wood

955 PERIMETER ROAD • MANCHESTER, NH 03103 • USA
+1-603-626-2300 • FAX: +1-603-641-5336 • ALLEGROMICRO.COM