

Power Drive Circuits

By the Integrated Circuits Business Unit

Introduction

Power switching circuitry is required to complete the interface for electrical control signals between microcontrollers and system loads. The real-world function of a load may be in the form of motion, light, or sound. Depending on the complexity of the control system, the interface circuit may be required to control a simple action, to provide feedback signals, or to perform fault isolation.

To serve a wide range of requirements, Allegro® offers a complete portfolio of power interface circuitry. Manufactured using the Allegro ABCD3 process technology, the product line offers designers flexibility in both architecture

and power performance, enabling a variety of solutions for individual applications.

This new family of Allegro power ICs are power DMOS devices that feature multiple integrated transistors in surface-mount and DIP packaging. The devices include on-chip control logic, ESD protection, and clamping circuitry.

Due to the high level of integration, Allegro power ICs maintain significant cost advantages over discretes on a per-transistor basis. These advantages include reduced component count and board-space requirements, as well as minimized procurement and inventory expenses.

Power Applications		
...used in a wide variety of end equipment:		
EDP	Industrial	Automotive
HDDs	Automated test equipment	Powertrain
Tape back-ups	Process control systems	Body and chassis
Printers	Programmable machine tools	Instrumentation
Plotters	Robotics	Passive restraints
Copiers	Instrumentation panels	ABS
Scanners	Personal appliances	EFE
Fax machines	Telecom line cards	
	Electronic games	

Allegro power interface devices offer superior alternatives to discrete power MOSFETs and hybrids in many power switching applications, including: driving fractional horsepower motors, solenoids, valves, relays, and lamps.

In the market today, significant application areas include:

- EDP: *hard-disk drives, tape back-ups, printers, plotters, copiers, scanners, fax machines, and power distribution switching*

With their low on-resistance and minimized power dissipation, these power devices operate reliably in confined spaces. Their surface-mount packaging is well-suited for modules with limited headroom.

- Industrial: *automated test equipment, process control systems, programmable machine tools, robotics, instrumentation panels, personal appliances, telecom line cards, moving signs, and electronic games*

The ruggedness of these devices makes them very attractive for industrial environments. They offer power handling capabilities, extended temperature ranges, and avalanche energy absorption.

- Automotive: *powertrain (engine, transmission, and emission controls), body and chassis, instrumentation, passive restraints, anti-lock brake systems, and electronic fuel injectors*

For this cost-conscious segment and its extremely harsh operating environment, these devices offer wide operating ranges, a high level of integration, short cycle time to market, and cost-effectiveness. These are low-cost and low-risk catalog alternatives to custom solutions.

Types of Loads

There are several types of loads, such as: resistive, capacitive, and inductive. Resistive loads are the simplest, because sizing is largely a question of examining the current and voltage specifications, estimating dissipation, making allowance for duty cycle, and then allowing margins for safety. Capacitive loads are comparatively rare. Stray capacitance is the only capacitive element in an otherwise resistive load.

Inductive loads, however, are relatively common and can be complex to design because energy can be passed from the switch to the load and back again to the switch. This energy must be dissipated without damaging the load or switch. A well-specified avalanche energy value for the switch is helpful.

Inductive Load Switch Requirements

Motors, solenoids, lamps, and other assorted loads are generally specified by operating voltage and current. The information provided in manufacturer datasheets is sufficient for operating at continuous duty. However, in most applications, the load is being switched on and off. When switching loads, the operating requirements as well as transient conditions must be considered. The power requirements are often further influenced by dynamic operating conditions.

The easiest way to look at load requirements is to consider the example of a load operating from a battery and controlled by a low-side switch. The system power supply and load choice will determine:

- Current drawn from the battery, including transients when the switch is turned on and off
- Battery terminal voltage
- Energy output from the load (motion, sound, etc.)
- Energy dissipated from the load in the form of heat (I^2R loss, magnetic loss, and friction)
- Energy returned to the system (induction, regeneration, and cross-coupling)

These system load requirements must then be used to determine the switch requirements:

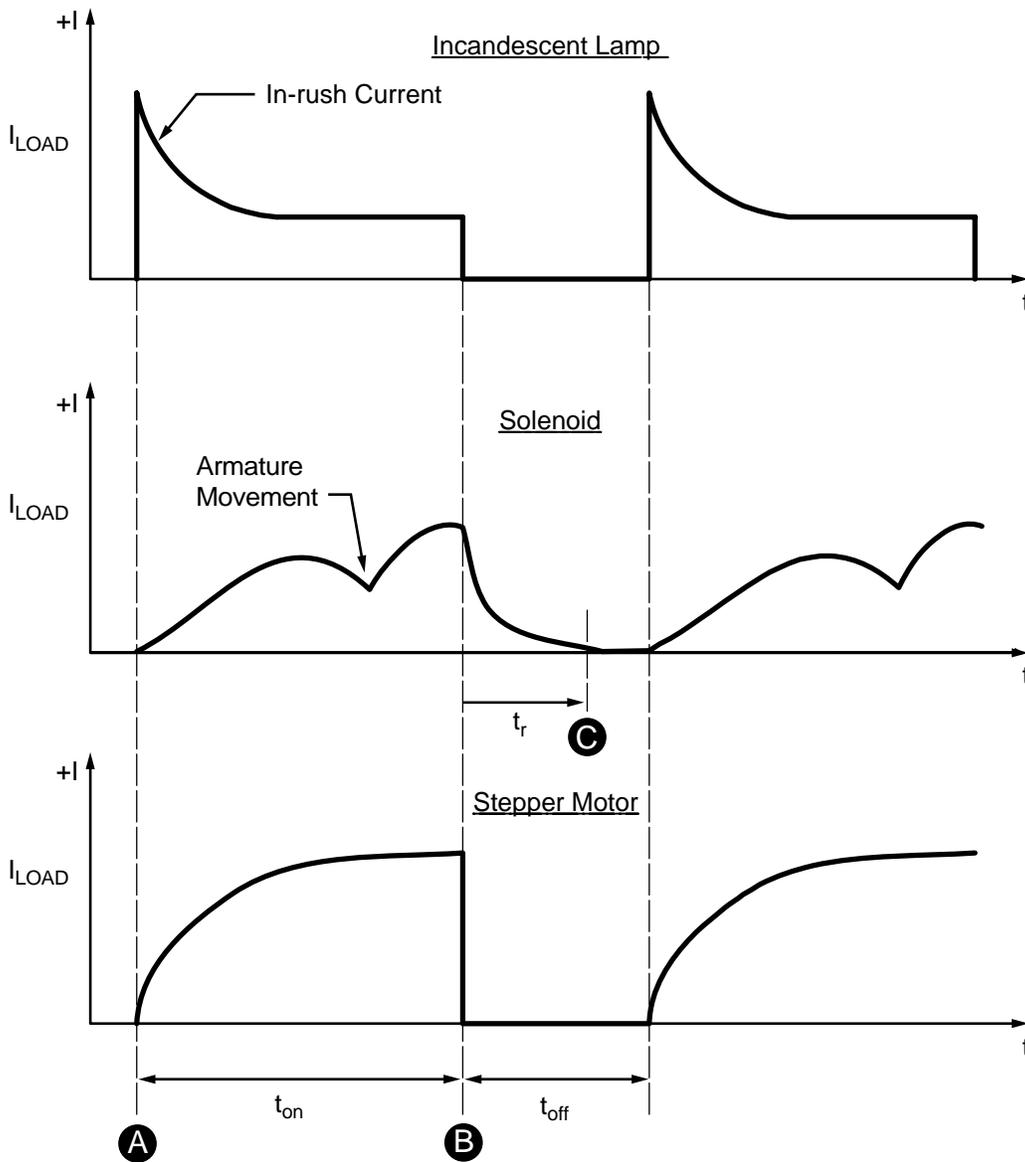
- Continuous drain-source current
- Pulsed drain current
- Continuous power dissipation at $T_A = 25^\circ\text{C}$
- Single-pulse avalanche energy (energy returned to the switch from back EMF)
- Drain-source voltage, V_{DS}
- Drain-source on-state resistance, $R_{DS(on)}$

Selecting or designing a switch is a three-step process:

1. Determine the total energy, current, and voltage required.
2. Select a switching device that will accommodate the energy.
3. Evaluate the system power dissipation to determine any heat-sinking requirements.

Load Switching Current Levels

Determining the total energy begins with evaluating the load current, both during operation and during switching. The diagram below shows the load current waveforms for an incandescent lamp, a solenoid, and a stepper motor. Each is depicted at steady state and at switching conditions such as those that must be considered in controlling a load.



Load switching current characteristics for three common power applications

The incandescent lamp current shows a high in-rush value at initial turn-on (A), due to the difference in filament resistance when cold and hot. During the on period, t_{on} , the current level decreases to a steady current value until turn-off (B). There is a clean turn-off, with no current flowing during the off period, t_{off} . A lamp control switch will need to withstand high peak currents or limit the current until the lamp filament warms up. The latter approach is preferable, because it extends the life of the filament.

The solenoid current starts rising at turn-on (A) and increases until turn-off (B), but after turn-off continues to flow during a period, t_r , until it dissipates fully (C). The change in current slope between turn-on and turn-off is caused by the solenoid armature moving closer to the coil and increasing the coil inductance. The current flow during t_r is a result of the magnetic field in the solenoid collapsing and returning energy to the system. A solenoid switch must be capable of conducting the coil operating current, and the system must provide a method of accommodating the energy returned to the system at turn-off. Several methods are employed to deal with the returned energy, which, when it is dissipated in the switch, is referred to as *avalanche energy*.

The stepper motor current waveform exhibits the exponential increase characteristic of an inductive load. Returned energy is a factor in stepper motor control. Additionally, stepper motor windings can produce currents as a result of cross-coupling from adjacent motor windings. This is particularly true for unipolar stepper motors. A control circuit for a stepper motor must accommodate the transient energy at turn-on (A) and the returned energy at turn-off (B).

When considering a switch for a stepper motor application, note that during normal commutation of a unipolar stepper motor, mutual coupling between the motor windings can force the outputs of the power switch below ground. This condition will cause forward biasing of the drain-to-substrate junction and source current from the output. For many L/R applications, this substrate current is high enough to adversely affect the logic circuitry and cause misstepping. External series diodes (Schottky type are recommended for

increased efficiency at low voltage operation) will prevent substrate current from being sourced through the outputs. Alternatively, external ground clamp diodes will provide a preferred current path from ground when the outputs are pulled below ground.

Energy and Power Calculations for an Inductive Load

After the load characteristics are determined, energy calculations can proceed. The energy calculations for an inductive load are presented in this section, along with calculations for the total power dissipated in a transistor type switch.

On-Time Power Dissipation While the switch is on, inductor current generally approximates a linear ramp, assuming that the inductor L/R_L time constant is much greater than the on-time, t_{on} . This would result in a mean square drain current of $1/3 I_P^2$, where I_P is the peak drain current. Therefore, the average power dissipated in the output MOSFET, $P_{ON(AV)}$, could be calculated as:

$$P_{ON(AV)} = \frac{1}{3} \times I_P^2 \times R_{DS(on)} \times d \quad (1)$$

where d is the duty cycle.

This assumption would be applicable to the stepper motor waveform shown earlier, but would not work for the solenoid. The solenoid L/R_L time constant is less than t_{on} ; therefore, P_{ON} would be greater than that calculated above.

Off-Time Power Dissipation Power dissipated during switch off-time is calculated as follows:

When the output MOSFET is turned off, the back EMF generated by the inductor raises the drain voltage, which must be clamped either externally or internally. External clamping is normally accomplished with a snubber diode. Internal clamping can be accomplished with a Zener diode. The clamp voltage, V_{CL} is also called the *avalanche voltage*.

The equation to define avalanche energy is:

$$E_T = \frac{3 \times L_H \times I_P^2 \times V_{CL}}{6 \times (V_{CL} - V_{SS}) + 4 \times R_L \times I_P} \quad (2)$$

as specified by JEDEC standard JESD10 [2002, sec. 3.2.5.1(3)], where:

E_T is the total turn-off transient energy absorbed

I_P is the peak output load current,

L is the load inductance,

R_L is the resistance of the inductor,

V_{CL} is the clamp voltage, and

V_{SS} is the load supply voltage.

This equation assumes a linear decay of the current in the inductor. A more accurate calculation of E_T can be derived by integrating the inductor current and clamp voltage for the load from turn-off until the inductor current decays to zero, as follows:

$$E_T = \int_t^0 V_{CL} \times I_L \times dt \quad (3)$$

$$I_L = \left(I_P + \frac{V_{CL} - V_{SS}}{R_L} \right) \exp \left[- \left(\frac{R_L}{L} t - \frac{V_{CL} - V_{SS}}{R_L} \right) \right] \quad (4)$$

$$I_P = \frac{V_{SS}}{R_L} \left\{ 1 - \exp \left[- \left(\frac{R_L}{L_H} \times \frac{d}{f} \right) \right] \right\} \quad (5)$$

$$t_1 = \frac{L}{R_L} \times \ln \left(1 + \frac{I_P \times R_L}{V_{CL} - V_{SS}} \right) \quad (6)$$

$$E_T = V_{CL} \times \frac{L_H}{R_L} \times \left(I_P - \frac{V_{CL} - V_{SS}}{R_L} \right) \times \ln \left(1 + \frac{I_P \times R_L}{V_{CL} - V_{SS}} \right) \quad (7)$$

where f is the switching frequency.

The power dissipated during the off-time can be equated to the product of E_T and the frequency of switching:

$$P_{OFF} = E_T \times f \quad (8)$$

Hence, the average total power dissipation, $P_{T(AV)}$, dissipated in an integrated switch with multiple output sections is:

$$P_{T(AV)} = (P_{OFF} + P_{ON}) \times n + P_Q \quad (9)$$

where:

P_{OFF} is the off-time power dissipation in each switch,

P_{ON} is the on-time power dissipation each switch,

n is the number of output switches operating, and

P_Q is the interface device bias power dissipation.

This is the average power dissipation for multiple sections whose duty cycles have a fixed time relationship to each other. For multiple outputs with variable duty cycles, the power calculation becomes more difficult.

Thermal Consideration for Power Switches

With the device total power dissipation calculated, a thermal evaluation can proceed. The objective is to determine if external heat sinking will be required.

The requirement for external heat sinking is calculated based on the device total average power dissipation, maximum junction temperature, and ambient operating temperature. The maximum power which can be dissipated in a device, P_D , can be determined as follows:

$$P_D = \frac{T_J - T_A}{R_{\theta JA}} \quad (10)$$

where:

T_J is the maximum device junction operating temperature,

T_A is the maximum ambient operating temperature, and

$R_{\theta JA}$ is the junction-to-ambient thermal resistance, in $^{\circ}\text{C}/\text{W}$.

T_J and $R_{\theta JA}$ are taken from the device specification and T_A is determined by the application environment.

If the total power dissipated in the device, P_T , exceeds the maximum power dissipation, P_D , then either a heat sink must be used or a different device must be selected. Heat sink size can be determined by first calculating the required heat sink to ambient thermal resistance, $R_{\theta SA}$, as follows:

$$R_{\theta SA} = \frac{T_J - T_A}{P_{T(AV)}} - R_{\theta JC} + R_{\theta CS} \quad (11)$$

where $R_{\theta JC}$ is the device junction-to-case thermal impedance, and $R_{\theta CS}$ is the device case-to-heat sink thermal impedance.

The $R_{\theta SA}$ required can now be compared to heat sink design specifications to determine the design type and size required.

The preceding thermal calculations are based on the assumption that the device average power was duty-cycle dependent. This is true if the pulse widths are short in relation to the device thermal time constant. An example for which this assumption would not apply is a switch that is on for one hour in every twenty-four hours. Although the actual duty cycle is low, the system must be designed to accommodate 100% on-time for the switch.

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