2.7 Reverse Transistor Action and dv/dt Turn-on

A problem that occurs with the half-bridge circuit configuration fed by a voltage source, especially in pulse width modulated inverters with inductive loads, is that of reverse transistor action. This is a condition where the transistor actually conducts in the reverse direction due to a reverse voltage applied across the transistor.

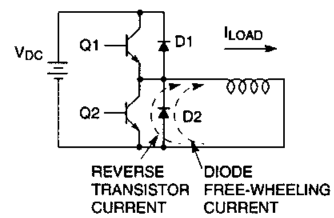
A typical half-bridge circuit driving an inductive load is shown in Figure 2.18. This circuit is a basic building block in power electronics.

Transistor Q1 turns on to establish current in the inductive load. When Q1 is turned off, the load inductance produces a voltage kick such that the load current is maintained through D2. The forward voltage drop across D2 creates a reverse voltage across Q2 in the range of 1-2 volts causing reverse current to flow through the transistor from emitter to collector. The magnitude of this current is controlled by the reverse gain of the transistor. Reverse gain is usually only a fraction of the forward gain of the transistor, and occurs due to the symmetry of the NPN construction that allows the collector and emitter to exchange their functions. That is, the collector acts as an emitter and the emitter acts as the collector. The transistor will not be as efficient as it is when used correctly, but it will in fact, operate backward.

The major problem occurs when transistor Q1 is again turned on after or when Q2 is carrying reverse current. The collector-base junction capacitance of Q2 has a charge that must be removed before it can block voltage. The high dv/dt applied to Q2 by the turn on of Q1 causes a large current to flow through the collector-base junction capacitance of Q2 which continues until this charge is removed. This recovery current of Q2 is in addition to, and can be significantly greater in duration and magnitude than, the reverse recovery current spike of the free-wheeling diode D2. The uninitiated often mistake a dv/dt current spike problem for a poor free-wheeling diode reverse recovery performance. This dv/dt current spike can easily take the transistor load line outside of the device FBSOA curve leading to catastrophic device failure at turn-on. At best, the dv/dt current spike will significantly increase turn on switching losses. The dv/dt problem is particularly acute with Darlingtons because even a small base current generated by capacitive dv/dt current is amplified by the input and output stages of the Darlington.

There are several methods for eliminating the reverse transistor action and its resultant dv/dt switching spike, including blocking diodes in the collector or emitter circuits, Schottky blocking diodes in series with the base-emitter

Figure 2.18 Half-bridge Darlington Transistor Circuit with Inductive Load



resistance, turn-on snubber consisting of an inductor and diode in the collector circuit, and reverse bias base-to-emitter on the transistor.

Most of these solutions cannot be physically realized when using power modules due to inaccessibility of internal connection points. The only foolproof solution is the use of a maintained reverse bias base-to-emitter on the transistor during its off period. In applications where a maintained reverse bias cannot be provided it is possible to use reverse bias only during defined periods. That is, during turn-off to improve switching and during turn-on of the opposite half-bridge pair to avoid dv/dt turn-on.

Figure 2.19 illustrates the effect of base emitter reverse bias on the dv/dt induced current spike.

2.8 Shoot-through Protection

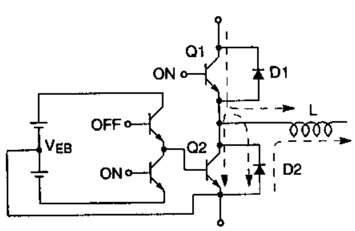
Power switching applications utilizing the half-bridge configuration in voltage fed inverters are prone to shoot-through failures. A shoot-through condition exists when both the upper and lower transistors in the half-bridge configuration are on, creating a short circuit across the DC supply. A properly designed inverter must include a lock-out circuit to prevent the upper and lower transistors from being turned on at the same time.

This lock-out logic must also function properly as bias and main power cycles on and off. Since, due to storage time, transistors take longer to turn-off than to turn-on, the lock out logic must provide a fixed delay time between turn off of one transistor and turn on of the other half-bridge transistor leg. This delay time must be greater than the longest possible storage time determined from the worse case application base drive, load and temperature conditions. The delay time for Darlington power modules is typically in the tens of microseconds.

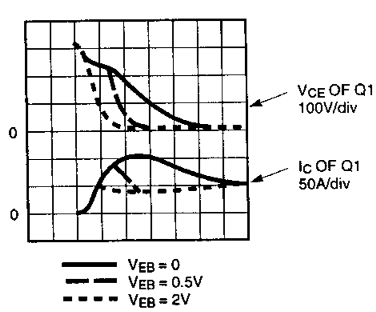
2.9 Turn-off Snubbers

Turn-off of high currents can produce large L • di/dt surge voltages across a transistor due to parasitic wiring inductances. To keep the transistor within its RBSOA rating some form of turn-off voltage snubber will be required.

Figure 2.19 Elimination of dV/dt Induced Turn-on Spike with Base-to-emitter Reverse Bias



(A) EXPLANATION OF dv/dt CURRENT FLOW



(B) RELATION BETWEEN VEB AND TURN-ON WAVEFORMS

Figure 2.20 Shoot-through Protection with Lock Out Logic

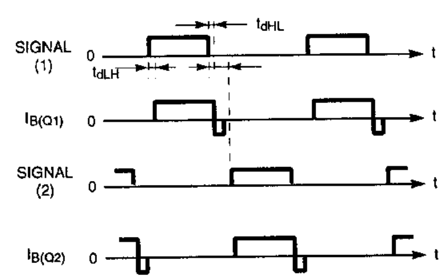


Figure 2.21 Turn-off Voltage Snubbers

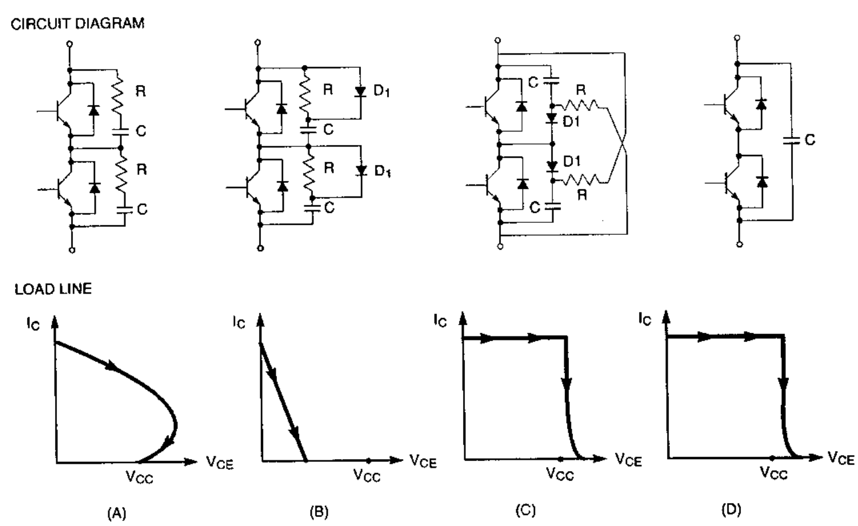


Figure 2.22 Basic Design Equations for R-C-D Turn-off Snubber

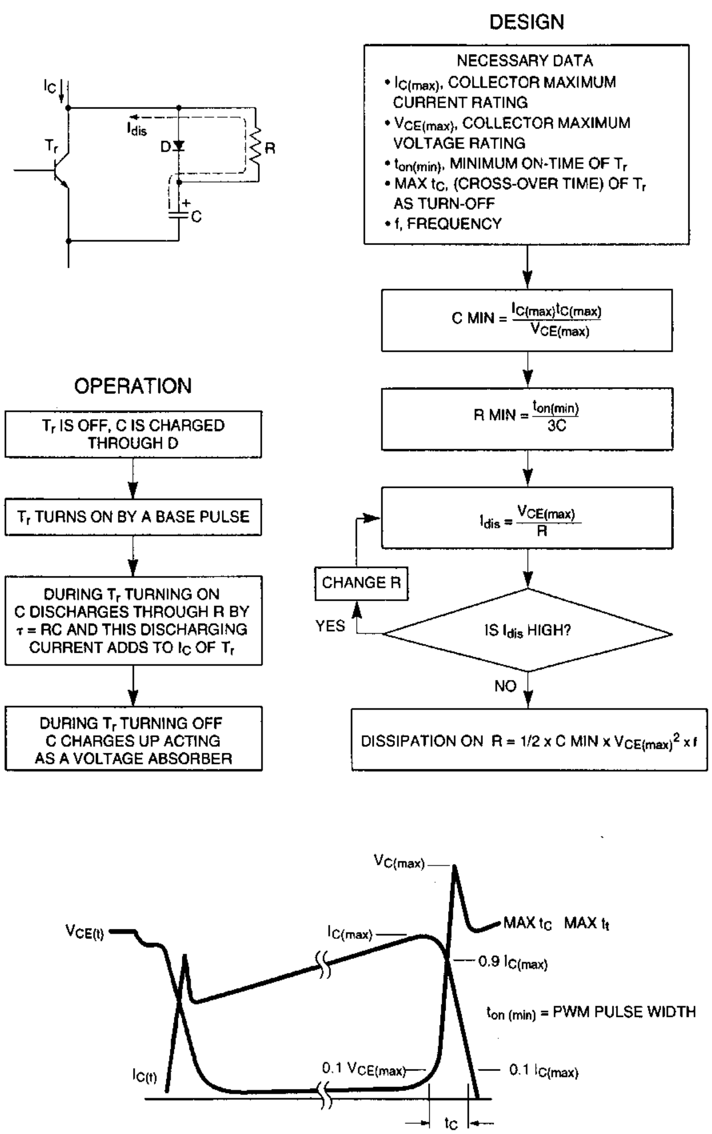


Figure 2.21 provides examples of typical voltage snubbers and illustrates the load line shaping each provides. Circuits 2.21 (C) and (D) are voltage clamps which only act to clip voltage spikes. The simple capacitor across the DC rail of Figure 2.21 (D) can oscillate with the main voltage source and the parasitic line inductance of the DC rail. The circuit of Figure 2.21 (C) adds resistance to avoid the oscillation while still providing voltage clamping. Circuits 2.21 (A) and (B) provide dv/dt control and can significantly reduce turn-off losses in the transistor.

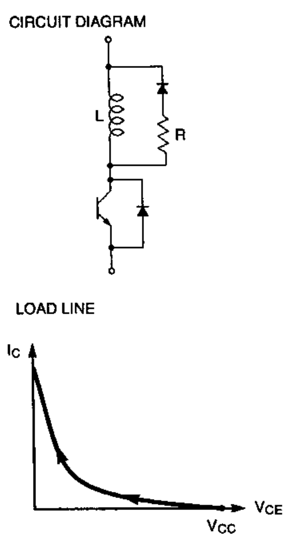
The R-C-D snubber circuit of Figure 2.21 (B) is by far the most effective turn-off snubber and details of its design are provided in Figure 2.22. The R-C-D snubber imposes a minimum on-time to the transistor of three times the RC time constant to insure that the snubber capacitor is fully discharged prior to transistor turn off for effective snubbing. R-C-D snubbers can create problems in bridge circuits because when all transistors are off the snubber capacitors charge to intermediate voltages. When a transistor is then turned on a high spike is created due to the charge of the snubber capacitor in the opposite leg of the half-bridge.

In all cases, a turn-off snubber is only effective if the snubber components are located in close physical proximity to the power module they are meant to protect. Capacitors should be of the high frequency type with good RMS ripple current capability, low ESR and ESI. Often a number of smaller capacitors in parallel will provide better performance than a single large capacitor. Diodes should be fast recovery types and resistors should be non-inductive types, specifically not wirewound resistors. Properly designed snubbers are also sized based upon the worse case fault current the transistor will have to turn off.

2.10 Turn-on Snubber

The turn-on snubber shown in Figure 2.23 may be used to keep a transistor within its FBSOA limit at turn-on. The turn-on snubber limits the rate of rise of collector current, (di/dt), and significantly

Figure 2.23 Turn-on Current Snubber



reduces transistor turn-on losses. The energy stored in the inductor during transistor turn-on must be dissipated in the resistor when the transistor is turned off. This sets a minimum off-time requirement on the transistor of three times the L/R time constant to insure that the inductor energy is dissipated before the transistor is again turned on. The energy storage in the inductor can be minimized by using a saturable inductor.

2.11 Short Circuit Endurance

When the load is suddenly shorted in a transistor circuit, the full DC rail voltage appears across the transistor and the current is limited by the transistor gain. Since power dissipation under these conditions is many times the device rated power, the transistor will fail catastrophically unless reverse base drive is quickly applied to turn-off the device.
The gain of a Darlington transistor

Figure 2.24 Collector Current vs. Collector-to-emitter Voltage for Various Base Drives and Temperatures

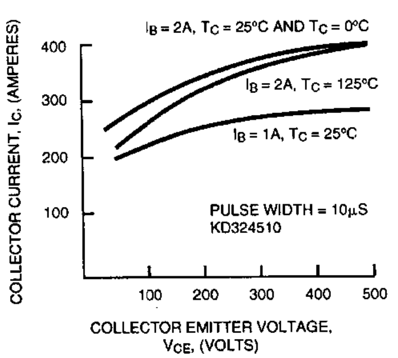
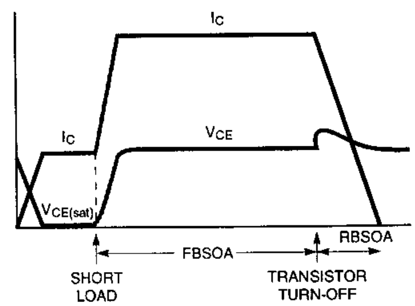


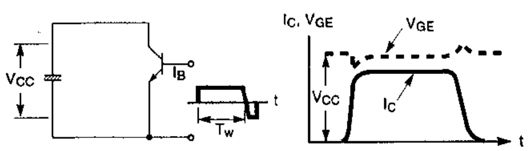
Figure 2.25 V_{CE} and I_C During Shorted Load



increases substantially as the collector to emitter voltage increases, as shown in Figure 2.24. At the high current levels associated with overload operation the gain decreases with increasing temperatures. This gain reduction with temperature is more significant in high voltage Darlingtons, 1000 volt and above, which utilize the triple Darlington configuration. The gain curves at 25°C and 125°C of the standard two stage Darlington, typical of 600 volts and below, tend to merge at high voltages.

Figure 2.25 shows the waveforms prior to and during overload operation. At the time the load is shorted, the transistor quickly comes out of saturation and the collector-to-emitter voltage rises to the rail voltage less the small voltage drops in the connecting wires. The collector current rises to a value that is dependent on the base drive and the gain of the transistor. Even at recommended forward base drive levels, selected to achieve reasonable saturation voltages, the resulting gain limited short circuit current can reach destructively high levels. During this period the transistor is

Figure 2.26 Typical Short Circuit Endurance Curve and Test Circuit



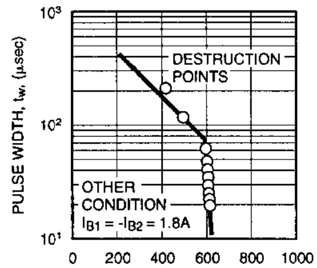
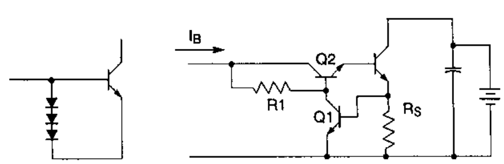


Table 2.2 Short Circuit Withstand of Powerex Darlingtons (100 Pulses, T_{CASE} = 100°C)

Transistor Type	Max. I_{B1}	Max. V_{CC}	Max. T_W	Approx. $I_{C(sat)}$	Emitter Wire I^2_t
KD224503	0.6A	400V	50µs	100A	0.7 • 10³
KD224505	0.6A	400V	50µs	160A	1.5 • 10³
KD224575	1.0A	400V	50µs	230A	2.0 • 10³
KD224510	1.5A	400V	50µs	300A	3.5 • 10³
KD224515	1.8A	400V	50µs	450A	4.0 • 10³
KS324520	2.5A	400V	50µs	550A	6.0 • 10³
KS624530	3.5A	400V	50µs	800A	8.0 • 10³
KD221K03	0.6A	580V	30µs	100A	1.5 • 10³
KD221K05	0.6A	580V	30µs	175A	2.1 • 10³
KD221K75	1.0A	580V	30µs	250A	3.4 • 10³
KD421K10	1.5A	580V	30µs	350A	4.2 • 10³
KD421K15	1.8A	580V	30µs	500A	6.5 • 10³
KS621K20	2.5A	580V	30µs	700A	8.0 • 10³
KS621K30	3.5A	580V	30µs	1000A	13.0 • 10³

Figure 2.27 V_{BE} Clamp and Active Base Control Overload Protection



operating in an FBSOA condition. It must be turned off before it exceeds the FBSOA boundaries.

When the transistor is turned off, the RBSOA curves must be observed. Note that the voltage of the RBSOA curve must never be exceeded, but the current in both the FBSOA and the RBSOA operating areas can be exceeded, provided that the maximum junction temperature is not exceeded. This maximum junction temperature is 150°C for repetitive pulses. For pulse operation, similar to surge in a diode, the transistor can be pulsed to 250°C or even greater than 300°C for a limited number of pulses.

Figure 2.26 illustrates typical short circuit endurance capabilities and the test conditions for Powerex Darlington transistors. There are two important points to note from this data. First, the short circuit current must be minimized by limiting base current. This insures that the transistor power dissipation is kept within bound. Second, there is a critical voltage level above which the transistor has no short circuit endurance capability. At this critical voltage level device destruction occurs just at the instant when I_C reaches its peak value. This failure mechanism is different than the pulse width limited thermal dissipation failure mechanism. Thus, one needs to consider the absolute voltage level in determining short circuit endurance of a given application.

Table 2.2 provides additional data on short circuit endurance capabilities of Powerex Darlington transistors. Any protection scheme should be designed to sense a short circuit and turn the device off in a period less than that of the transistor short circuit withstand capability. The best short circuit protection scheme adds an inductor in series with the transistor that acts to control the rate-of-rise of current and support voltage during the load short circuit. Of course, this inductor must be properly clamped to prevent it from creating damaging voltage spikes. V_{BE} limiting clamps and active base drive limiting, illustrated in Figure 2.27, are two solutions that may provide limiting of collector current during overload without a limiting inductor.

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When a short appears across an interphase load as shown in Figure 2.28, the total rail voltage is impressed across both transistors. If Q1 and Q4 are on during a short, the rail voltage does not divide equally across the transistors but the division of the voltage depends on the gains of the transistors. The worse case voltage division must be applied to the short circuit withstand investigation.

2.12 Typical Applications

Powerex Darlington transistor modules are provided in a number of different circuit configurations. Figure 2.29 illustrates typical applications for some of the different module configurations.

Figure 2.28 Interphase Short and Resulting Rail Voltage Division

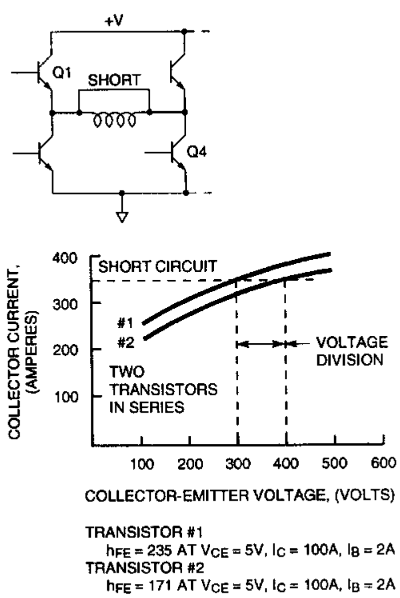

Figure 2.29 Typical Applications for Darlington Modules