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APPLICATION NOTES

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Protecting IGBTs Against Short Circuit

(HEXFET is a trademark of International Rectifier)

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Summary

Insulated Gate Bipolar Transistors (IGBTs) with the most rugged intrinsic short circuit performance generally have high saturation voltage and high operating losses, and vice versa.

This application note demonstrates that IGBTs with even modest intrinsic short-circuit capability can be fully protected against short circuit, allowing the most efficient, cost effective IGBTs to be used, without compromising ruggedness of the overall system.

Introduction

IGBTs are set to displace bipolar transistors and Darlingtons in applications such as variable speed motor controllers, uninterruptible power supplies, and high frequency welders. They generally offer comparable or lower power dissipation, higher operating frequency, and simplification of drive circuitry.

Systems using IGBTs offer greater compactness, greater efficiency, and superior dynamic performance than those with bipolar transistors.

The properties of the IGBT that make these advantages possible bring with them a new design consideration. An IGBT designed to maximize efficiency has a relatively high gain and this means a short-circuit current that is significantly greater than that obtained with a bipolar. The power density in the IGBT with an applied short circuit can therefore be much higher than that in a bipolar transistor.

An IGBT designed to minimize power dissipation under normal load conditions is unable to handle an unabated short circuit for as long as a bipolar transistor. The IGBT is not, therefore, as intrinsically fault-tolerant and will require a more "alert" protective circuit.

The purpose of this application note is to show how such a protective system can be implemented and to demonstrate that it can provide full short circuit protection, even for the most efficient high gain IGBT.

IGBT Short Circuit Characteristics

A test circuit for characterizing the short circuit capability of an IGBT is shown in Figure 1.

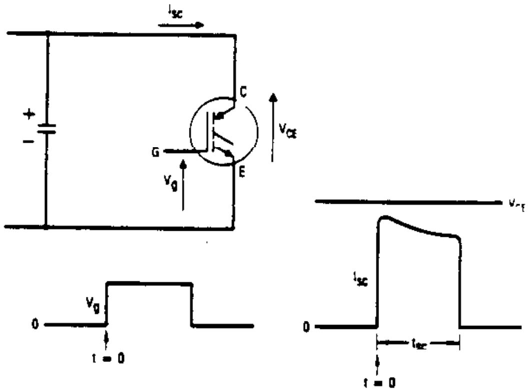

Figure 1. Typical short-circuit test for IGBT

A "stiff" voltage is applied from the reservoir capacitor, directly across the collector-emitter terminals of the device under test.

A pulse of voltage is applied to the gate (at a low repetition rate), and a pulse of "short-circuit" current flows. The short circuit time, t_{SC}, is gradually increased, until device failure occurs. The permissible short circuit time, for given values of collector-emitter voltage, gate voltage and starting temperature, can thus be determined.

This simple test circuit is useful for obtaining a first order assessment of the short circuit capability of an IGBT. It does not completely represent an actual application short-circuit condition because it does not apply dynamic dv/dt, which could induce the IGBT to latch-up. A more application-representative test circuit is described later.

This short circuit test will yield different results for IGBTs from the various manufacturers and different types. Generally, the higher the saturation voltage, $V_{CE(SAT)}$, of the IGBT the longer will be the permissible short circuit time.

Typical permissible short-circuit times, for different types of IGBTs, are shown in Figure 2. This data assumes that sufficient voltage is applied to the gate to keep the normal saturation voltage close to a practical minimum, and that this same gate drive voltage is maintained during the fault.

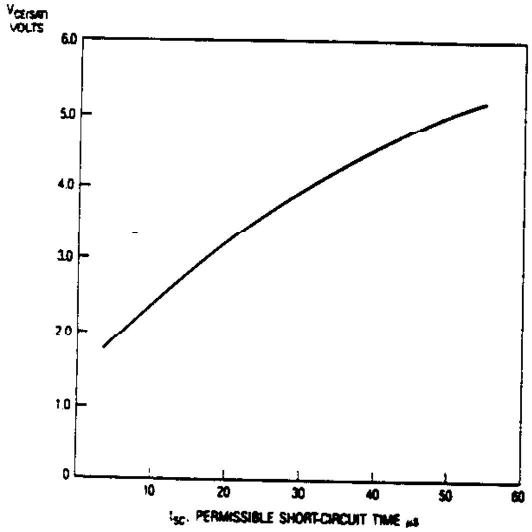

Figure 2. Typical IGBT short circuit time versus saturation voltage drop, $V_{CE(SAT)}$

Figure 2 indicates that an IGBT with a saturation voltage less than 2V typically has a permissible short circuit time of 5µS or less. An IGBT with a saturation voltage of 4 to 5V can have a short circuit time in the range of 30µS. (This is of the same order as for a typical bipolar transistor. But the saturation voltage is now higher than that of a bipolar).

Protecting Against Overcurrent – System Considerations

Different types of overcurrent condition will exist in a typical application. The most common type of overload is due to motor start-up, filter inrush current, step changes of load, and so on.

It is usually not feasible for the transistor (whatever type it is) to ride "brute force" through this type of situation, relying only upon its intrinsic short-circuit capability to carry it through. This type of overload typically lasts much longer than the transistor's intrinsic short-circuit time. The overload must be brought under proper control by other means.

A closed loop control is normally used that acts on the drive pulse timing signals to modify the switching instants and "hold back" the output current to a set level. The response of this control loop only has to keep pace with the rate of change of current that is naturally limited by motor or filter inductance.

This type of overload, when controlled as above, is not a threat to the integrity of the IGBT.

A second, more severe and more sudden type of overload is due to "mishaps," such as ground faults, or inadvertent terminal-to-terminal short circuits. Fault current now bypasses motor or filter inductance, and rises very rapidly in the transistor.

The regular PWM loop is powerless to protect against this type of fault. Protection must rely, in the first instance, upon the intrinsic short-circuit capability of the transistor, followed by rapid sensing of the fault and removal of the drive voltage, if the fault persists beyond the permitted short circuit period.

If the "fault" is a transient that clears itself before the permitted short-circuit period has expired, then the transistor should remain in conduction; turning it off would only constitute an unnecessary "nuisance" trip.

Diode reverse recovery current is an example of the type of transient overcurrent which should be ignored.

Referring to the characteristics of the IGBTs illustrated in Figure 2, the circuit designer's job is to provide an iron-clad protection circuit for an IGBT with the lowest $V_{CE(SAT)}$, and hence lowest t_{SC}, (but highest efficiency).

This circuit must provide reliable protection against real faults, yet be insensitive to spikes and "false alarms."

Stretching the IGBT's Short Circuit Time

The most-efficient IGBT, with the lowest saturation voltage drop, will typically have a short circuit time of less than 5μS. Allowing a suitable safety margin, the protection circuitry should react within 1 or 2μS maximum. One possibility is to remove the gate drive completely after 2μS, as represented by the waveforms in Figure 3(a). This would protect the IGBT, but a period of 1 or 2μS may generally be too short to distinguish properly between a real fault and a "false alarm." Nuisance trips could result as illustrated in Figure 3(b).

Possible Ways of Protecting the IGBT (Method 1)

- "Full" gate drive voltage for normal conduction
- Gate drive voltage rapidly removed in event of fault

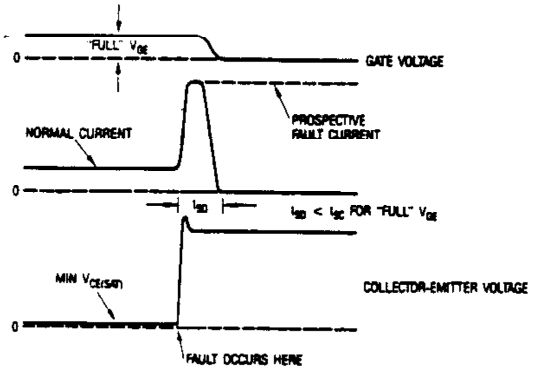

Figure 3a. Normal conduction losses minimized. Rapid fault shut-down.

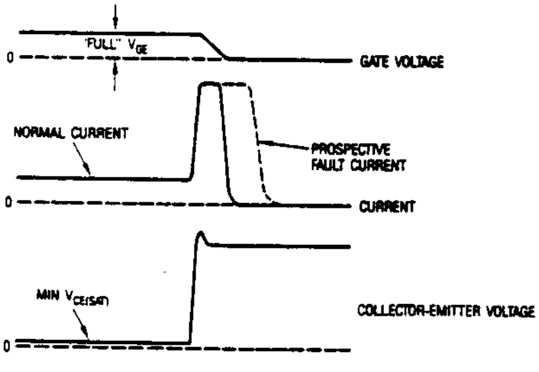

Figure 3b. Nuisance shut-down can occur under transient fault

The short circuit time can be stretched significantly by the simple expedient of reducing the gate voltage. Figure 4 illustrates that with reduced gate voltage, short circuit current is significantly reduced, and short circuit time is correspondingly increased.

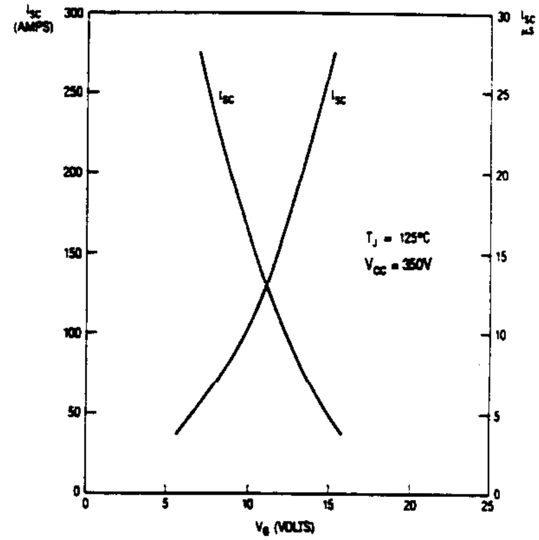

Figure 4. Typical relationships between gate voltage, V_G, short circuit current, I_{SC}, and permissible short-circuit time (IRGPC40F).

Reduction of the gate drive voltage, of course, increases $V_{CE(SAT)}$ which cannot be permitted for normal conduction.

The object is to reduce the gate drive voltage only when the "short circuit" occurs. This is illustrated by the operating waveforms in Figure 5(a, b). The short circuit period is now "stretched," prolonging the "fault inspection" period, at the end of which the IGBT must be turned off if the fault is still present.

The IGBT represented in Figure 3 has a short circuit time of about 5μS with full gate drive voltage of 15V, and about 15μS with gate drive voltage of 10V. Thus, if the gate voltage is reduced to 10V as soon as a fault is detected, the "fault inspection" period can be stretched to about 10μS (permitting a safety margin of about 5μS), allowing ample time for "rejection" of transient faults and false alarms. Operation is illustrated by the waveforms of Figure 5.

If the fault still persists after 10μS, the IGBT is turned off. If the fault disappears before that, full gate voltage is restored, and operation proceeds almost as if nothing had happened.

Possible Ways of Protecting the IGBT *(Method 2)*

- "Full" gate drive voltage for normal conduction
- Gate drive voltage rapidly reduced in event of fault
- Gate drive voltage removed after delay, if fault persists

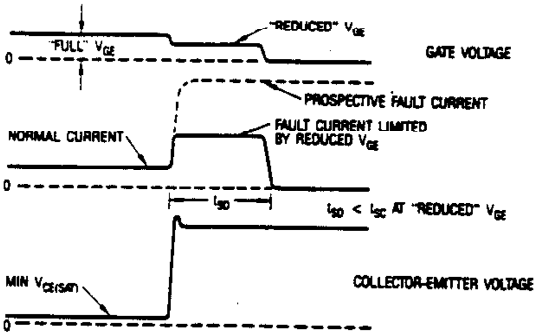

Figure 5a. Normal conduction losses minimized. Fault current reduced. Delayed fault shut-down.

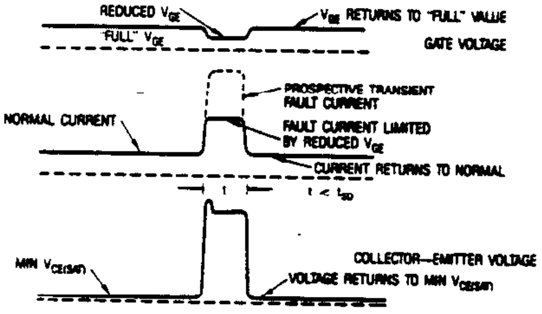

Figure 5b. Nuisance shut down avoided under transient fault

Protection Circuit Implementation

A functional schematic of a protection circuit is illustrated in Figure 6.

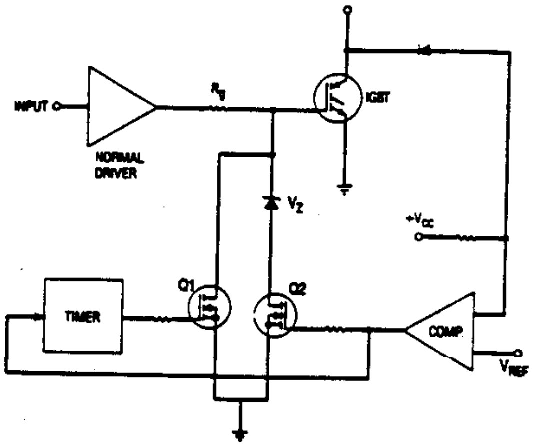

Figure 6. IGBT short circuit protection drive circuit schematic

During normal conduction, the saturation voltage of the IGBT is less than V_{ref}. The output of the comparator is low, and the small MOSFETs Q1 and Q2 are OFF. The IGBT's gate drive voltage is unmodified.

When an overload occurs, the collector-emitter voltage of the IGBT increases above V_{ref}, and the output of the comparator goes high. This initiates the timer; simultaneously Q2 is turned ON, reducing the IGBT's gate voltage to the zener voltage, V_Z.

If the fault disappears before the end of the timer period, the output of the comparator goes low, Q2 switches OFF, full gate drive voltage is restored, and normal operation proceeds.

If the fault is still present at the end of the timer period, the timer output goes high, Q1 switches ON and the IGBT's gate voltage is removed, turning it OFF.

Performance of Protection Circuit

Test circuit

The protection circuit shown in Figure 6 was tested in combination with International Rectifier's IGBT type IRFPC40F. This IGBT has a maximum permissible short circuit time, at $V_{CC} = 350V$ and $V_{GE} = 15V$, of about 5μS, as illustrated in Figure 3.

Figure 10 shows the "prospective" short circuit current. This is the fault current through the IGBT when the protection circuit is disabled and 15V gate voltage is maintained during the fault.

The peak short circuit current is about 280A. Note that the time for which the short-circuit is applied has been reduced to about 5μS, so as not to exceed the capability of the IGBT with 15V gate voltage.

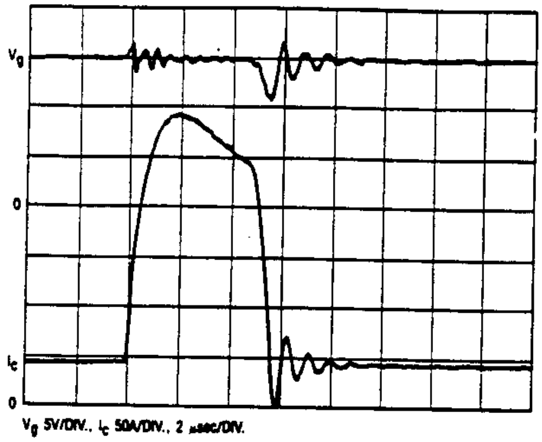

Figure 10. Prospective short-circuit current (i.e., without gate voltage reduction) under transient short circuit. (IRGPC40F)

Figure 11 shows the gate voltage and the collector current on an expanded time scale for approximately the same conditions as for Figures 8 and 9. Note the very effective current limiting action of the protection circuit relative to the prospective short circuit current.

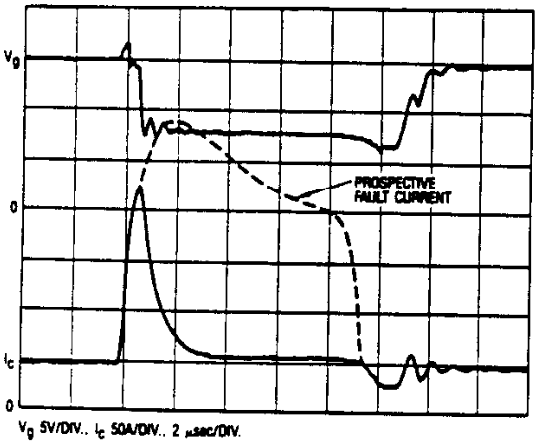

Figure 11. Actual fault current with gate voltage reduction from 15V to 8V under transient short-circuit, and superimposed prospective fault current with no gate voltage reduction. (IRGPC40F)

Figure 12 shows waveforms for a similar fault as for Figure 11, but with the gate voltage reduced to 10V during the fault.

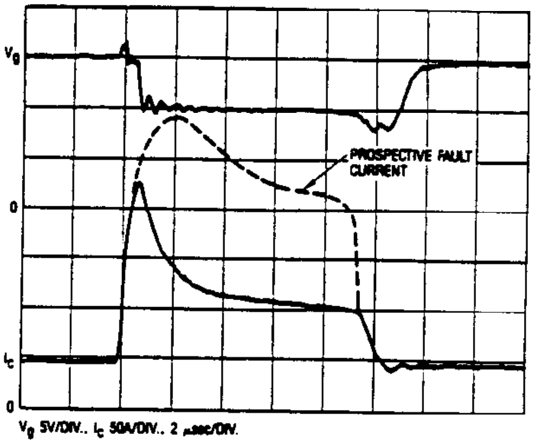

Figure 12. Actual fault current with gate voltage reduction from 15V to 10V under transient short circuit, and superimposed prospective fault current with no gate voltage reduction. (IRGPC40F).

Figure 13 shows the operation of the protection circuit when the duration of the short circuit exceeds the time-out period of the protection circuit. The gate voltage is removed at the end of the time-out period.

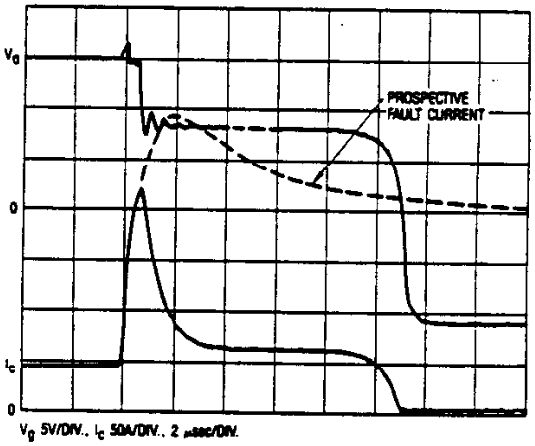

Figure 13. Actual fault current with gate voltage reduced from 15V to 8V under short-circuit, and superimposed prospective fault current with no gate voltage reduction. Short-circuit is permanent, and driver switches off after 10 μS (IRGPC40F).

The overall test circuit shown in Figure 7 was used to evaluate the operation of the protection circuit.

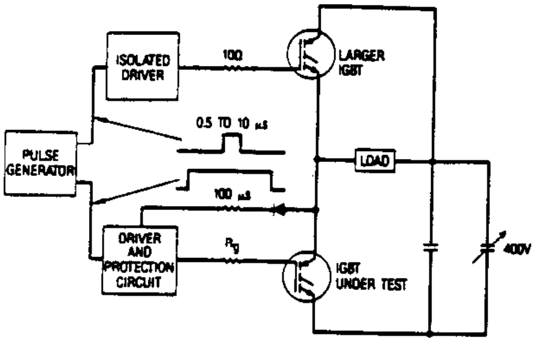

Figure 7. IGBT short-circuit test circuit

With reference to Figure 7, an input ON pulse of about 100µS. is applied to the driver/protection circuit of the IGBT under test. About midway through this ON pulse, a drive pulse is applied to the larger IGBT, which short-circuits the load for a controlled period.

When this happens, it is the job of the protection circuit to immediately react by reducing the gate voltage of the device under test. It subsequently restores the full gate voltage, if the fault disappears before the end of the time-out period, or it removes the gate voltage at the end of the time-out period, if the fault still exists.

Test Results

The waveforms of Figures 8 through 13 illustrate the performance of the protection circuit.

Figure 8 shows a pulse of normal current of about 40A, with 110µS duration, and a superimposed short circuit of about 10µS duration occurring midway through the conduction period. The short circuit current initially rises to about 220A, but is quickly pulled back to about 60A by the action of the protection circuit. In this case, the gate voltage is pulled down to about 8V. After about 10µS, the short circuit is removed, the current returns to the normal load value, and full gate voltage is restored to the IGBT under test.

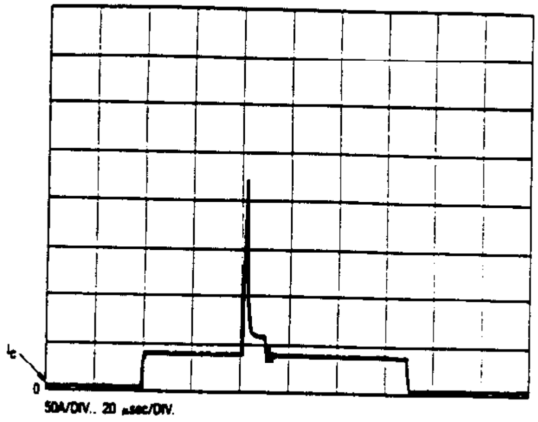

Figure 8. Load current with superimposed transient fault current. (IRFPC40F).

Figure 9 shows the collector-emitter voltage corresponding to the current waveform in Figure 8. The supply voltage is about 370V.

When the short circuit occurs, the voltage across the IGBT rises to the full supply voltage. When the fault is removed, the IGBT voltage falls back to the normal conduction voltage.

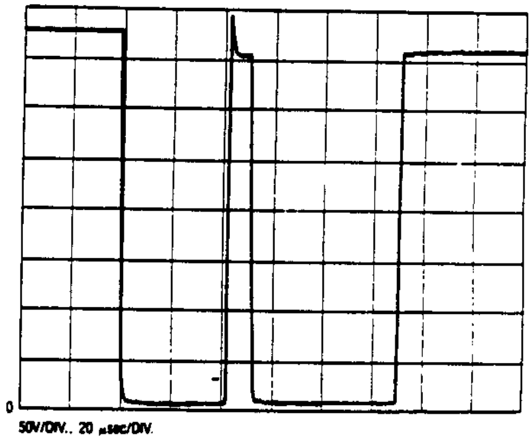

Figure 9. Collector-emitter voltage across device under test (IRGPC40F) with superimposed transient short-circuit.

Soft Turn-On

Peak diode reverse recovery current when turning on the IGBT into a diode-clamped inductive load can be limited by limiting the IGBT's gate drive voltage at turn-on.

This may sometimes be desirable, though use of this technique inevitably increases the total turn-on energy.

A test circuit for demonstrating the effect is shown in Figure 14. The gate drive circuit for the IGBT has the facility for limiting the drive voltage for the first 1 or 2μS at turn-on, prior to stepping up to full drive voltage.

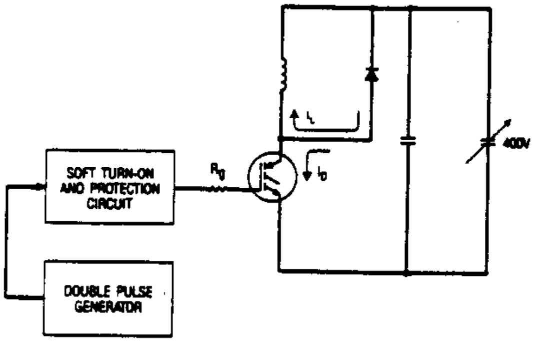

Figure 14. Soft turn-on test circuit.

Figure 15 shows oscillograms of IGBT voltage and current at turn-on, with 15V drive applied to the gate. The peak reverse recovery current of the diode is about 100A, and the total turn-on energy dissipated in the IGBT is about 22 mJ.

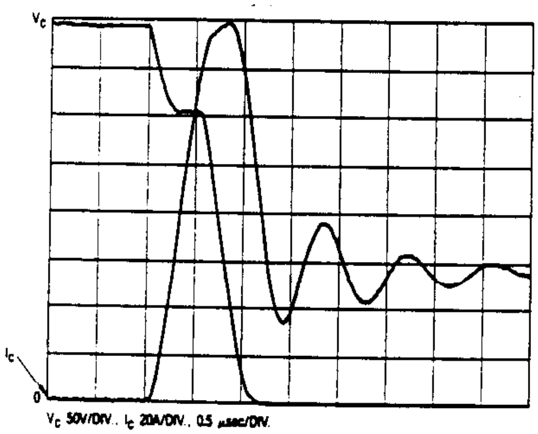

Figure 15. Collector voltage and current at turn-on with $V_{g(on)}$ = 15V. (IRGPC40F).

Figure 16 shows equivalent waveforms when the IGBT's gate drive voltage is held to 10V for the first 2μS before being stepped up to 15V. The peak reverse recovery current of the diode is reduced to about 30A. The total turn-on energy, however, increases more than twice, to about 52 mJ.

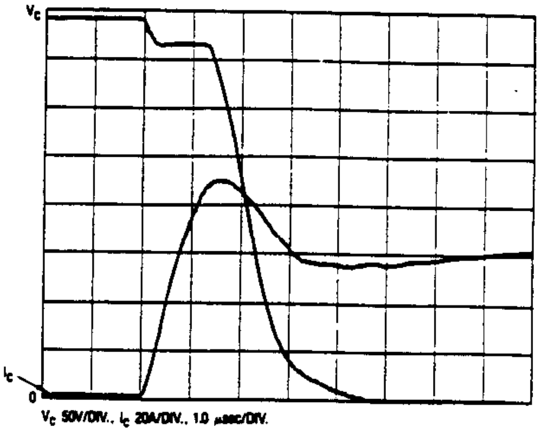

Figure 16. Collector voltage and current at turn-on with $V_{g(on)}$ = 10V. (IRGPC40F).

Conclusion

This application note demonstrates that it is possible to provide reliable short-circuit protection of an IGBT with modest intrinsic short-circuit capability, and correspondingly with low saturation voltage drop and high efficiency.

Thus the user is able to capitalize on the most efficient IGBTs without having to compromise overall system ruggedness. ☐