Abstract
A market-wide trend in industrial motor drives is an increasing demand for higher efficiency coupled with increased reliability and robustness. Power semiconductor device manufacturers are continually pushing the boundaries of conduction loss and switching time improvements. Some of the trade-offs in enhancing insulated gate bipolar transistor (IGBT) conduction loss are increased short-circuit current levels, smaller die size, and reduced thermal capacity and short-circuit withstand time. This accentuates the importance of the gate driver circuit and its overcurrent detection and protection features. This article will discuss the issues involved in successful and reliable short-circuit protection in modern industrial motor drives, with experimental examples from an isolated gate driver in a 3-phase motor control application.

IGBT Short-Circuit Capability
The short-circuit withstand time of an IGBT is related to its transconductance or gain and the thermal capacity of the IGBT die. Higher gain leads to higher short-circuit current levels within the IGBT, so clearly lower gain IGBTs will have lower short-circuit levels. However, higher gain also results in lower on-state conduction losses, and so a trade-off must be made. Advances in IGBT technology are resulting in the trend of increased short-circuit current levels and consequently reduced short-circuit withstand times. In addition, the improvements in technology allow for the use of smaller die, reducing module size but lowering thermal capacity, which further reduces the withstand time. There is also a strong dependency on the IGBT collector-emitter voltage, so the parallel trend toward higher dc bus voltage levels in industrial drives results in further reduction in short-circuit withstand times. Historically these have been in the 10 μs range, but in recent years they are trending toward 5 μs and down to 1 μs in some conditions. Moreover, the short-circuit withstand time can vary widely from device to device, so it is usually recommended to build in additional margin beyond the specified short-circuit withstand time, in IGBT protection circuits.

IGBT Overcurrent Protection
IGBT protection from overcurrent conditions is a critical part of system reliability, both in terms of asset destruction and indeed safety. IGBTs are not regarded as a fail-safe component and their failure can result in a dc bus capacitor explosion and complete drive failure. Overcurrent protection is typically implemented by means of current measurement or desaturation detection. These techniques are illustrated in Figure 2. For current measurement, measurement devices such as shunt resistors...
are required in both the inverter leg and phase output to cover shoot-through faults and motor winding faults. Fast acting trip circuitry in the controller and/or gate drivers must then shut down the IGBTs in a timely manner in order to prevent the short-circuit withstand time from being exceeded. The main disadvantage of this method is the requirement to include two measurement devices in each inverter leg, along with any associated signal conditioning and isolation circuitry. This can be alleviated by only adding shunt resistors in the positive and negative dc bus lines. However, in many cases, either a leg shunt resistor or a phase shunt resistor will be present in the drive architecture for the purposes of the current control loop and motor overcurrent protection, and these can also be potentially utilized for IGBT overcurrent protection—provided that the response time of the signal conditioning is fast enough to protect the IGBT within the required short-circuit withstand time.

Apart from short circuits occurring as the result of faults within the system, momentary inverter shoot-through can also occur in normal operation. In normal operating conditions, IGBT turn-on requires that the IGBT be driven into the saturation region where the conduction losses will be minimized. This typically implies gate-emitter voltages of >12 V during the on state. IGBT turn-off requires that the IGBT be driven to the cutoff region of operation so that it can successfully block the reverse high voltage across it once the high-side IGBT has turned on. In principle this can be achieved by reducing the IGBT gate-emitter voltage to 0 V. However, a secondary effect must be taken into account when the transistor on the low-side of the inverter leg is turning on. The rapid transition of the switch node voltage on turn-on causes a capacitively induced current to flow in the low-side IGBT parasitic Miller gate-collector capacitance (C_{GC} in Figure 3). This current flows through the turn-off impedance of the low-side gate driver (Z_{DRIVER} in Figure 3), creating a transient voltage increase at the low-side IGBT gate-emitter terminals, as shown. If this voltage rises above the IGBT threshold voltage, V_TH, it can cause a brief turn-on of the low-side IGBT, resulting in a momentary inverter leg shoot-through since both IGBTs are turned on for a brief period. This will not generally result in IGBT destruction, but it does increase power dissipation and compromises reliability.

Experimental Example
The experimental setup utilizes a 3-phase inverter powered from the ac mains through a half wave rectifier. In this case this results in a dc bus voltage of 320 V, although the system can be also used up to dc bus voltage levels of 800 V. A 0.5 HP induction motor is driven under open loop V/Hz control in normal operation. The IGBTs are 1200 V, 30 A IRG7PH46UDPBF from International Rectifier. The controller is an ADSP-CM408F Cortex®-M4F mixed signal processor from Analog Devices (ADI). Phase current measurement is carried out using isolated Σ-Δ AD74203 modulators and isolated gate drive is implemented using the ADuM4135, a magnetically isolated gate driver with integrated desaturation detection, a Miller clamp, and other IGBT protection features. Short-circuit testing is
carried out by manually switching a short-circuit between motor phases or between a motor phase and dc bus negative. The short-circuit to earth is not tested in this example.

The controller and power boards are shown in Figure 5. These are the ADSP-CM408F EZ-kit® and the EV-MCS-ISOINVEP-Z isolated inverter platform, both available from Analog Devices.

IGBT overcurrent and short-circuit protection are implemented using a range of methods in the experimental hardware. These are:

- DC bus current sensing (inverter shoot-through fault)
- Motor phase current sensing (motor winding faults)
- Gate driver desaturation detection (all faults)

For the dc bus current sensing circuit, a small filter must be added in order to avoid false tripping, since the dc bus current is discontinuous with potentially high noise content. An RC filter with 3 μs time constant is utilized. Having detected the overcurrent, the remaining delays to IGBT shutdown are delays through the op amp, comparator, signal isolator, trip response time in ADSP-CM408F, and gate driver propagation delay. These amount to an additional 0.4 μs—well within the short-circuit time constant of many IGBTs. Similar timing applies to motor phase current sensing using the AD7403 in conjunction with the integrated overload detection sinc filters on the ADSP-CM408F processor. These operate well with a sinc filter time constant of around 3 μs. The remaining system delays in this case are only due to the internal routing of the trip signal to the PWM unit and the gate driver propagation delay, since the overload sinc filters are internal to the processor. Along with the reaction time of the current sense circuitry or digital fast filters, the very short propagation delay of the ADuM4135 in both instances is critical to achieving viable fast overcurrent protection using either of these methods. In Figure 6, the delay between the hardware trip signal, the PWM output signal, and the actual gate-emitter waveform of the upper IGBT in one of the inverter legs is shown. The total delay to commencement of IGBT turn-off is seen to be around 100 ns.
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The initial increase in the desaturation voltage during turn-on is an example of the potential for spurious desaturation detection due to the transient state of the collector-emitter voltage. This can be eliminated by increasing the desaturation filter time constant to add additional blanking time.

Figure 8 shows the collector-emitter voltage across the IGBT. There is an initial controlled overshoot of about 80 V above the 320 V bus voltage due to the higher impedance in the turn-off during desaturation protection. The circulating of the current in the lower antiparallel diode and the circuit parasitic actually results in a slightly higher voltage overshoot up to about 420 V.

The value of Miller clamping in preventing inverter shoot-through in normal operation is illustrated in Figure 9.

Summary

Overcurrent and short-circuit detection and turn-off in a very short time period are becoming ever more important as the short-circuit withstand time of IGBT decreases down to 1 μs levels. Industrial motor drive reliability is strongly linked to the IGBT protection circuits. This article has outlined some approaches to handling this issue, and has presented experimental results that underline the value of robust isolated gate driver ICs such as the ADuM4135 from Analog Devices.
References

3. IRGP4266PbF Data Sheet. International Rectifier.
5. “High Speed HSJ.” Mersen.

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