ICs Protect IGBTs and Sense Currents in Motor Drives

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In industrial and appliance motor-drive applications, high-voltage ICs can provide full IGBT protection in the inverters and sensorless measurement of motor currents at low cost.

New industrial and appliance motor drives have become more advanced in performance and more compact in size. This is largely due to advancement in power silicon technology, such as IGBTs and high-voltage integrated circuits (HVICs). This trend is particularly accelerated in low-power industrial or servo drives that are less than 5 kW and in inverter drives for energy-saving appliances, such as air conditioners, washers and refrigerators.

IGBT protection is one enabler of these performance advancements. Today’s state-of-the-art small inverters are equipped with full IGBT protection, including ground-fault protection that was once required only in high-end drive systems. These inverters require additional complexity in the detection circuit as well as sensors. Therefore, the cost associated with the implementation could be prohibitive for the low-end industrial or servo drive and especially in ultra cost-competitive appliance drives.

Another performance enhancement is the ability to sense motor current to provide high bandwidth and accurate feedback to the torque control loop. As the drive performance advances toward adoption of sensorless field-oriented control (FOC), a low-cost method to sense motor current is required.

HVIC technology is uniquely able to integrate advanced circuit functions while permitting operation in the high-voltage and noisy environment of motor-drive circuits. As a result, HVICs are changing the landscape of motor-drive design, providing high-performance yet low-cost IGBT protection and current-sensing features.

Methods of IGBT Protection

An overcurrent condition is one of the fatal drive faults that could destroy IGBT devices in a motor-drive system. IGBT overcurrent conditions basically fall into three categories—line-to-line short, ground fault and shoot-through. Table 1 lists overcurrent conditions and their potential causes.

When considering an IGBT overcurrent protection scheme, two important factors must be evaluated. The first factor is what type of overcurrent protection the system should provide and how the system can be shut down. The second factor is the control architecture. Control architecture significantly influences the method and implementation of the overcurrent protection.

Protection of IGBT devices is normally implemented in the hardware circuit. However, the circuit implementation and the type of overcurrent-sensing device varies depending on which overcurrent condition is being addressed. That reflects the different path and flow of the current in each condition (Fig. 1).

The short-circuit current in both the shoot-through and the line-to-line short condition always flows from/to the dc bus capacitor(s). However, the ground-fault current normally flows from the ac line input through the positive dc bus and a high-side IGBT to the earth ground where the failure occurs. There is no current flow across dc bus capacitor(s).

The protection scheme also depends on the control architecture. For protection against line-to-line short and

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<th>Overcurrent Condition</th>
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<td>Line-to-line short</td>
<td>Miswiring, motor leads short, motor phase-to-phase insulation breakdown</td>
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<tr>
<td>Ground fault</td>
<td>Motor insulation breakdown to ground</td>
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<tr>
<td>Shoot-through</td>
<td>False IGBT turn-on</td>
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Table 1. Overcurrent conditions and their likely causes.
shoot-through, either a Hall-effect sensor or linear opto-isolation device across the shunt resistor, inserted in series with the negative dc bus line, detects the overcurrent condition. If the system needs ground-fault protection too, an additional Hall-effect leakage current sensor can be placed on the ac line input or the positive dc bus. Protection circuitry can be implemented using fast comparators.

Two comparators are used for each Hall-effect sensor if the sensors are located in the motor-phase output. That’s because both positive and negative polarity of current flow exists in the event of the line-to-line short condition. Total propagation delay of shutdown also is important. The delay time associated with the optical isolation device in the gate drive and Hall-effect sensor is typically more than 2 µs. Therefore, no matter how the protection circuit is implemented, this delay time should be added to the circuit delay to meet the IGBT short-circuit duration time.

The circuit requires two Hall-effect sensors and/or linear opto-isolation devices and an additional protection circuit. The protection circuit contains two comparators, voltage references, capacitors and resistors. Additionally, each Hall-effect sensor would require its own separate isolated power supply.

An IGBT desaturation circuit is the alternative way to protect the IGBTs. The discrete circuit can be constructed in the secondary side of the opto gate driver or the opto-isolated device that has a desaturation circuit. The circuit detects voltage buildup across the collector and emitter while the device is fully on. If the voltage exceeds a certain limit, the desaturation circuit shuts off the associated gate signal. When implemented as a discrete circuit, the required components are a comparator with voltage reference, a high-voltage diode, and resistors and capacitors.

When an overcurrent condition is detected, the method of IGBT turn-off becomes important. It is sometimes preferable to add softness to the turn-off. This will help reduce the high-voltage spike that appears across the collector and the emitter of the IGBT. This spike is associated with the parasitic inductance in the circuit.

Creating a soft turn-off provides more safety margin in the reverse-biased safe operating area (RBSOA) limit given a short-circuit condition. If successfully implemented, the snubber circuit can be significantly minimized or eliminated. For each IGBT gate-drive circuit, an additional fast opto-isolation device and circuit with weak turn-off capability and dedicated totem-pole buffer transistors are required.

When choosing between a snubber circuit and a discrete soft shutdown circuit, there are tradeoffs. In a conventional inverter system, the snubber circuit may be favored because of its lower complexity and cost. In

Fig. 1. IGBT overcurrent conditions can occur as a line-to-line short (a), a ground fault (b) or as shoot-through (c).
In particular, for small drives the snubber circuit can be implemented using a high-frequency capacitor across the dc bus near the IGBTs.

In contrast, Hall-effect sensors and opto isolators are relatively large and bulky, thus requiring a large space when compared with other components, such as a monolithic IC. In addition, if the system requires a soft shutdown function, then an additional six opto isolators and six buffer circuits with the provision of weak turn-off capability are required.

The discrete shutdown circuit solution does not promise simplicity or further integration of the gate drive and protection circuit. This can be problematic given today’s demands for smaller size and robustness in IGBT protection in low-power industrial or appliance drives. The total cost of the discrete circuit, including the assembly cost of the inverter system, is high because the solution requires many discrete and bulky components. Moreover, some components such as Hall-effect sensors are still subject to manual assembly.

**Methods of Motor Current Sensing**

Perhaps the most difficult function in the drive design is sensing currents in the inverter stage and motor phases. The current signals are used for current-mode control, which require high precision and linearity, as well as for overcurrent protection, which requires fast response.

Different circuit techniques have to be used to process the current signals depending on where in the inverter stage the current signals are sampled. Precision, low ohm value, sensing resistors are typically used in the current path to generate a sensing voltage signal with a maximum range of ±300 mV to minimize power dissipation. Alternatively, Hall-effect sensors are used. They are generally bulkier and more expensive than sense resistors, but they have the advantages of lossless sensing.

In practice, the current signals can be sampled in series with +dc bus, –dc bus, individual IGBT phase leg or motor phase lead (Fig. 2). Current signals sampled in the +dc or –dc bus are the vector sum of all the IGBT phase leg currents. Also, the signal content is the pulse-width-modulated envelope at fixed carrier frequency of the fundamental variable frequency motor current. Therefore, rather complicated sample-and-hold plus digital signal processing circuits have to be used to extract useful current information with good linearity and accuracy.

Individual IGBT phase leg current is somewhat easier to process, but cannot escape from dealing with carrier frequency sampling. By far, the simplest current signal available is from the motor phase lead. The signal content is only the fundamental variable frequency motor current. However, the one significant complication is that the small differential signal in the millivolt range is floating on top of a 600-V to 1200-V common-mode voltage. In addition, the common-mode voltage is swinging from –dc to +dc at a dV/dt rate of up to 10 V/ns.

**HVIC Technology**

IGBT protection and motor current-sensing circuits can be simplified substantially by the monolithic integration of the gate drive, protection and sensing functions. This integration has been implemented in HVIC technology. The structure used in this HVIC supports a versatile set of devices and circuits as well as the unique capability of integrating high-voltage level shifting and floating CMOS in a single piece of silicon.

In this HVIC, 600-V or 1200-V n-channel and p-channel LDMOS silicon are used for level-shifting functions from low-voltage to high-voltage and vice versa. The CMOS circuits can be referenced to a high-voltage floating supply level for high-side gate-drive and signal-processing circuits. This floating capability allows differential-mode signal processing on top of a 600-V or 1200-V common-mode voltage. Other uses for the high-voltage devices include start-

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<th>HVIC Solution</th>
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<td>3-phase gate drive</td>
<td>Six fast optical isolators</td>
<td>Single chip</td>
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<tr>
<td>IGBT protection</td>
<td>Two Hall-effect sensors and two comparators</td>
<td>Integrated on-chip</td>
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<td>Additional circuits</td>
<td>Four floating power supplies</td>
<td>Eliminated (bootstrap power)</td>
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<td></td>
<td>Snubber circuit or discrete soft shutdown circuits</td>
<td>Eliminated by integrated soft shutdown function</td>
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<tr>
<td></td>
<td>Brake IGBT drive circuit with an optical isolator</td>
<td>Eliminated by integrated brake IGBT driver circuit</td>
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Table 2. Solution comparison of gate drive and IGBT protection.
up bias supply and synchronous bootstrapping supply.

Gate-drive circuits are implemented in enhanced voltage CMOS with supply rail up to 25 V and provide necessary gate-drive voltage to the IGBT. Analog and digital circuit blocks are implemented in BiCMOS. The circuit library includes pulse-width modulator (PWM), voltage control oscillator, precision sense amplifier, fast fault comparator and other power conversion control functions.

Another HVIC design provides a monolithic solution for all six IGBT gate drivers with full IGBT protection with soft shutdown. Table 2 shows a comparison of this device with a discrete solution.

An application circuit for this HVIC, which combines 3-phase gate drive with IGBT desaturation protection in each high-side and low-side output, is shown in Fig. 3a. The chip's internal circuitry for desaturation detection (DSD) is shown in Fig. 3b. Maximum floating high-side voltage can be as much as 600 V to 1200 V. Overcurrent is detected sensing the collector-emitter voltage of IGBT at the on-condition through an external diode, then the V_{CE} is compared with a fixed 8-V threshold; afterward, the resulting signal is filtered for 1 µs. A blanking filter of 3 µs is used to ignore the effect of the tail at the turn-on of the IGBT.

Once desaturation is detected, the output stage goes immediately into a high-impedance state and the SSD driver is activated, turning off the IGBT through the SSDH/L pin with the proper impedance. SSD events holds for 7 µs to achieve smooth IGBT gate discharge at high collector current level. An external resistor can control discharge impedance through the dedicated SSD pin on top of a minimum 75-Ω resistor internally provided.

The short-circuit detection information is shared with the other high-or low-side drivers through the SY_FLT I/O pin. In this way, the main driver—the one detecting the short circuit—communicates with the other drivers in the local network. Once active, this signal freezes all the other drivers' status on the output, regardless of the status on the inputs. The main driver itself freezes its status until the SSD takes place.

When the soft shutdown is over, SY_FLT signal is disabled and diagnostic information is sent by FAULT/SD pin to microcontroller. Then, the main driver pulls down the FAULT/SD line, forcing a hard shutdown. By means of the FAULT/SD pin, all of the other drivers in the local network are switched off and the faulty condition is reported to the main controller for diagnostic purposes.

To sense IGBT desaturation, the collector voltage is read by an external high-voltage diode. The diode is normally biased by an internal pull-up resistor connected to the lo-
Fig. 4. The IR2277 linear motor-phase current-sensing HVIC combines the current-sensing function with filtering, PWM synchronization and circuitry for generating analog or PWM output. This application circuit shows the shunt resistor (CSR) used to sense current in the motor phase lead along with the waveform that appears across CSR.

Fig. 3a. An application circuit for the IR22381Q HVIC depicts the external circuitry required for desaturation detection on each high-side and low-side output.

Fig. 3b. To detect desaturation, circuitry within the IR22381Q HVIC reads the collector voltage on the IGBT via a high-voltage diode (labeled DSD).

cal supply line (VB or VCC). When the transistor is “on,” the diode is conducting and the amount of current flowing in the circuit is determined by the internal pull-up resistor value.

In the high-side circuit, the desaturation biasing current might become relevant for dimensioning the bootstrap capacitor. In fact, using too low of a value for the pull-up resistor may result in high current significantly discharging the bootstrap capacitor. For that reason, typical pull-up resistors are in the range of 100 kΩ. This is the value of the internal pull up.

While the impedance of DSH/DSL pins is very low when the transistor is on (low impedance path through the external diode down to the IGBT), the impedance is only controlled by the pull-up resistor when the IGBT is off. In that case, relevant dv/dt applied by the IGBT during the commutation at the output results in a considerable current injected through the stray capacitance of the diode into the desaturation detection pin (DSH/L). This coupled noise may be easily reduced using an active bias for the sensing diode.

An active bias structure is available at DSH/L pin. The DSH/L pins present an active pull-up, respectively, to VB/VCC and a pull-down, respectively, to VS/COM. The dedicated biasing circuit reduces the impedance on the DSH/L pin when the voltage exceeds the VDESAT threshold. This low impedance helps in rejecting the noise providing the current inject by the parasitic capacitance. When the IGBT is fully on, the sensing diode gets forward biased and the voltage at the DSH/L pin decreases. At this point, the biasing circuit deactivates in order to reduce the bias current of the diode.

Fig. 4 shows an example of an HVIC that integrates the motor-phase current-sensing function with advanced filtering, PWM synchronization and either analog or PWM output. The current signal is sensed using an external shunt resistor in the path of the motor-phase current such that only fundamental variable frequency motor current is processed. The HVIC converts the small differential voltage—±250 mV—into a time interval through a precise circuit that also performs very good ripple rejection showing small
The time interval is level shifted and fed to the output. An analog output voltage also is provided. The voltage is proportional to the measured current and is ratio metric with respect to an externally provided voltage reference. The max throughput is 40 ksamples/s suitable for up to 20-kHz asymmetrical PWM modulation and the max delay is less than 7.5 µs at 20 kHz. Also, a fast overcurrent signal is provided for IGBT protection.

One of the particularly difficult challenges is the ability of the HVIC to sense small differential voltage floating on top of large common-mode voltage (600 V to 1200 V max) that also switches at very fast transient from the action of the IGBT inverter phase. A noise immune bidirectional level-shifting circuit is used to avoid false common-mode dV/dt noise up to 50 V/µs.

In theory, the current sensed in the motor phase lead should be purely sinusoidal, as shown in Fig. 2. But in reality, a triangular wave (an artifact of the PWM signal) is superimposed on that current-sense signal, creating the jagged waveform drawn in Fig. 4. That superimposed triangular wave must be filtered out for accurate current sensing. However, doing so with simple capacitive filtering adds phase delay.

To avoid this problem, the HVIC in Fig. 4 integrates an advanced filtering stage with PWM synchronization. The signal path consists of four stages in series (Fig. 5). The first two stages perform the filtering action. The third and fourth stages generate a PWM output signal and analog reconstruction to interface with the torque control loop of the MCU or DSP.

The input filter stage is a self-adaptive resettable integrator that passes the PWM fundamental frequency, but cancels its even harmonics (a). Simulation of the input filter’s amplitude response reveals that high-frequency noise in the megahertz range is greatly attenuated (b).

The baseband signal is left unchanged, the triangular carrier edges (SYNC2). A phase voltage and simplified phase current of a motor drive are shown together with the triangular wave in Fig. 7. The trend toward using high-voltage IC technology is accelerating as new industrial and appliance motor drives have become more advanced in performance and more compact in size. These HVICs are uniquely capable of integrating advanced circuit functions while operating in the high-voltage, noisy environment of motor-drive circuits.