Chapter 11

State-of-the-Art Intelligent Gate Drivers for IGBT Power Modules

–Monitoring, Control and Management at the Heart of Power Converters

Bing Ji¹, Wenping Cao^{2,3}, Volker Pickert⁴

- 1 Department of Engineering, University of Leicester, U.K., bing.ji@le.ac.uk
- 2 School of Electronics, Electrical Engineering and Computer Science, Queen's University Belfast, U.K., w.cao@qub.ac.uk
- 3 Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, MA, U.S.A., wencao@mit.edu
- 4 School of Electrical and Electronic Engineering, Newcastle University, U.K., volker.pickert@ncl.ac.uk

11.1 Introduction to Gate Drivers

Power semiconductors are the most important and enabling components in power converters, similar to the “muscle” in a living body. However, they are controlled by the central control unit, which is similar to the “brain” in a living body. Power semiconductors in power electronic systems process and control power flow. Largely different from their electronic counterpart used in signal processing, power semiconductor devices handle much higher voltages and currents for power flow control. In order to improve the system efficiency, power semiconductor devices are operated in a switching mode (On/Off).

As the power semiconductor devices are continuously developed for electrical power applications, their performance is gradually approaching ideal switches manifesting the following aspects:

- High current (DC, pulse, rms, average, peak, surge)
- High blocking voltage
- Fast switching (short on/off delays, short rise/fall times, short turn-on/turn-off times)
- High efficiency (low on/off conduction losses, low on/off switching losses, low control losses)
- Ease of use (low cooling effort, low control power, simple gate driver control or protection)
- High reliability (low random failure, long lifespan and robustness)

Since the characteristics of power semiconductors are getting closer to their physical limits, further improvements in performance and reliability pose a particular challenge whilst gate driver unit (GDU) technologies have been well developed to fit the bill. The GDU is an integral part of a power electronics system, as an extension of the “brain”. It provides essential control and many functions to deliver the required specifications for power semiconductor devices/modules and power electronics systems.

Various types of power semiconductors have been developed and used for a wide range of applications. Because of their different gate characteristics and control requirements, tailored designs dedicated to specific types of devices and operational conditions are gaining in popularity in industry. Among these, Insulated gate bipolar transistors (IGBTs) have shown their superior performance and are thus widely used in applications such as energy conversion, transportation, industrial and home appliances. Their gate drivers are the focus of this chapter.

11.1.1. Power Electronic Systems, IGBTs and Gate Driver Units

Power electronic systems consist of a variety of elements to deal with electrical energy conversion. A block diagram of a typical power converter is shown in Figure 11.1. It includes three parts: the power circuit formed by the power semiconductor devices and passive components, a centralized control unit providing functions such as communication (input/output), data storage, signal/data processing, control algorithm and command, and an interface formed by gate drivers and sensing units. The control unit operates at much lower

voltage and power levels. An interface is therefore required for the control unit to receive sensor signals and issue control commands to gate drivers.

Figure 11.1 Block diagram of a power converter.

IGBTs are packaged for various purposes (power rating, cost, footprint, etc). Some commonly used packaging types include “Transistor Outline” (TO) packages, “Single In-Line” (SIL) packages, “Dual In-Line” packages (DIL/DIP), standard power modules, and press-pack modules (also called capsules). Figure 11.2(a) shows various existing technologies for different applications and power ratings. Discrete packages are dominant in low power applications. Standard power modules are adopted in vast majority of medium and high power markets due to their easiness and flexibility in manufacturing, assembly, function integration and power scaling. The press-pack IGBTs (PPIs) has also become a mature technology to manipulate very high power ratings (several MW) and is frequently found in use as series connection for power transmission and distribution applications. IGBT module packages normally contain IGBTs and freewheeling diodes (FWDs) with a defined IGBT/FWD ratio for an inductive load and their circuit symbols are shown in Figure 11.2(b).

(a)

IGBT	Freewheeling diode(FWD)	IGBT + FWD
Collector Gate Emitter	Cathode Anode	

(b)

Figure 11.2 Commercially available IGBTs. (a) Different packaging techniques. (b) Circuit symbols.

The GDU is an integral interface between the high-voltage power stage (IGBT devices/modules) and the low voltage control unit of the power converter which provides essential control and protection functions. A typical IGBT GDU comprises a low-voltage side (interfacing the control unit) and a high-voltage side (interfacing the IGBT). The former consists of a low voltage logic device, or a logic-to-driver interface (LDI) and auxiliary components such op-amps and comparators. It generates the control signals (On/Off), processes the feedback signals and communicates with the master controller. The latter is the output stage that controls and interfaces the high-voltage power semiconductor devices. The output stage power circuit is tailored to match to the individual IGBT device/module for specific applications. Figure 11.3 shows a commercial GDU and an in-house made GDU.

Figure 11.3 Standard gate driver for IGBT modules. (a) A commercial GDU. (b) An in-house made GDU.

In general, the high-voltage side of conventional GDUs provides five basic functions (rectangular boxes in Figure 11.4) and other features have evolved for that of the innovative GDUs (hexagon boxes in Figure 11.4). Firstly, the high-voltage side is an amplifier or a booster. Since a high driving power is required for IGBT gate capacitance charging/discharging during On/Off switching transients, the instantaneous gate current can reach up to tens of amps and volts. In addition, isolation and/or level shifting is required for both signal and power transmissions. The control signal is transmitted through communication channels so that the switching patterns is mapped from the low-voltage side to the high-voltage power converters while the high-voltage side feedback signal (status or sensor information) is also sent back. An isolated power supply is also normally required for the output stage in most converter topologies. For instance, the collector of the top (high-side) IGBT in a half bridge is connected to DC+ bus. The emitter of that IGBT floats with respect to DC- to follow IGBT's output characteristics. This in turn requires the use of an isolated gate driver in order to isolate the low-voltage inputs/outputs of the control unit from the high voltages of the IGBTs. The isolated gate-drivers are also used for the bottom (low-side) IGBTs' control. Common signal transmission methods use transformers, coreless transformers, optocouplers, optic fibers, capacitive barriers and giant magnetoresistive

(GMR) isolators. Some examples of the voltage supply methods can be found in Table 11.1. The high-voltage side electronics employ the sensing and monitoring mechanisms (e.g. voltage, current or temperature monitoring) to protect IGBTs from hazards during critical destructive operations (e.g. shoot-through faults). A post-fault protection scheme is activated under fault detection and the alarm is generated to prevent failure propagation.

Figure 11.4 Examples of basic (rectangular) and extensive (hexagon) functions in a gate driver unit.

Table 11.1 GDU voltage supply

Supply and Functional diagram	Key features
<p style="text-align: center;">Bootstrap</p>	<p>Cost effectiveness. No isolation. Duty cycle and on time are both constrained to recharge and discharge the bootstrap capacitor. The bootstrap capacitor voltage decreases until a new charging state due to both the gate leakage current and charging energy. Only unipolar dc source is available. Start-up scheme required.</p> <p>.</p>

<p style="text-align: center;">Isolated DC-DC converter</p>	<p>Isolated supply voltage. Constant driving voltage is available for very low frequency applications. The unwanted displacement current is induced by the high dv/dt acting on the coupling capacitance of the converter isolation barrier.</p>
<p style="text-align: center;">Self-powering</p>	<p>Self-power supply based on linear regulation. The efficiency of the linear regulator should be noted. Good compatibility with the main power semiconductors. Storage capacitor voltage decreases until a new charging state due to both the gate leakage current and charging energy. Only unipolar dc source is available.</p>
<p style="text-align: center;">Wireless power and energy storage</p>	<p>Coreless inductive power transmission for harsh environments. Safe solution for isolated measurements with respect to high and / or transient reference voltages. Supply efficiency is largely reduced with increased power transmit distance and reduced alignment</p>

11.1.2. Sensing and Control Systems

Typical power electronic converters are equipped with a number of sensors and instrumentation electronics in order to deliver the expected system performance. Figure 11.5 shows a typical block diagram of a full bridge power inverter in an AC motor drive system.

Figure 11.5 Block diagram of a typical full-bridge power inverter in an AC motor drive.

It consists of a rectifier, an inverter, DC bus, sensor network and CPU (e.g. microcontroller, microprocessor). Typical sensors and their measurement points in a power inverter system are presented in Table 11.2. Voltage, current and temperature readings are collected and transmitted through signal conditioning electronics to the control unit for signal processing and control algorithm execution. It then outputs appropriate switching signals to provide control and fault management at the system level. A combination of different sensors can be selected to achieve the control targets associated with the specific system profile.

Table 11.2 Typical sensors and their measurement points in power converters

Measurement	Symbol	Measurement point	Features
Current	A1	DC+ bus	Short circuit faults (line-to-line, ground and shoot through) can be monitored. Isolation is required.
	A2	Ground reference	Measurement is taken at ground reference and isolation is not required. Ground fault can not be monitored.
	A3	emitter side cable of bottom IGBTs	Measurement is taken at ground reference and isolation is not required. Ground fault can not be monitored.
	A4	inverter output phases	Typical measurement for high-end motor drive. The third phase current sensor can be omitted in normal operation.
	A5	emitter/auxiliary emitter of six IGBTs	Current sense IGBTs or emitter inductance integrator is required. Integrated in GDUs.
Voltage	B1	collector-emitter of six IGBTs	Desaturation monitoring feeding the integrated comparator to prevent short circuit faults. Integrated in GDUs.
	B2	DC+ bus	Measured at both capacitor pre-charge and normal operation phases. Resistive divider with or without isolation is used to match the DC bus with the read-out electronics.
Temperature	C1	six IGBT dies	IGBT temperature is measured by the integrated temperature sense pn-diode but not for freewheeling diodes. Integrated in GDUs.

	C2	Heat sink or baseplate	Temperature reference measured by contact sensors such as thermistor (e.g. NTC/PTC) and resistance temperature detector (RTD, e.g. Pt100)
	C3	Motor	Temperature reference for motors

11.2 Innovative Gate Driver and System Architecture

Recently, the power electronics market has moved towards innovative gate driver features and optimized solutions. Extension of the GDU performance and functions is necessary and this is largely associated with product-driven performance requirements. It is already known for the low power consumer market, the cost and robustness of GDUs are critically important while in the high end market (mainly for medium/high power applications), their performance and controllability are of major concerns. High-temperature performance is sometimes intended for harsh environments and extended lifetime. With the advances in materials (SiC, GaN, etc.) and design/fabrication/packaging techniques, some high-temperature power semiconductors are now commercially available, pushing the operational temperature over 200°C.

11.2.1 System Integration

Integration of elements and functions is a current trend in power electronic systems. It helps achieve system miniaturization (footprint, volume and weight), reduced interconnection, reduced assembly effort and increased power density. Intelligent power modules (IPMs) have been well developed mainly for low- and medium-power applications. They are normally comprised of power semiconductors in a certain circuit topology, associated gate drivers integrating various functions, interconnections (wires, copper tracks, etc.) and terminal leads interfacing the power circuit and the control unit.

The existing gate driver integration technologies are developed at different levels. Due to the well-developed silicon-on-insulator (SOI) technology with high voltage blocking capability, the monolithic gate driver can be directly integrated on the direct copper bonded (DCB) substrate of power modules [1], as shown in Figure 11.6(a). A key advantage of this technology is the good thermal conductivity to assist cooling for both the power semiconductors and the gate drivers. However, the asymmetric propagation delay of driving signals arising from the restricted copper track layouts should be considered. Alternatively, the monolithic gate driver can be integrated in the printed circuit board (PCB) inside the IPM as in Figure 11.6(b). This is compatible with the current gate driver integrated circuit (IC) design. In Figure 11.6(c), a combination of power semiconductors and a discrete gate driver IC with peripheral components (capacitors and resistors) are integrated into a module package. A “thick film” technology is used for the integration, where different layers of conducting and isolating materials are printed on a ceramic sheet, similar to PCBs for tracks, pads, ICs, capacitors and resistors.

Figure 11.6 Different IPMs with integrated gate drivers. Courtesy of (a) SEMIKRON International GmbH. (b) Fuji Electric. (c) Vincotech GmbH.

Since the embedded passive integrated circuit (emPIC) techniques are still under development, realization of isolation inside the module package results in complexity with increased manufacturing effort. The integrated voltage supply for IPM gate drivers are mainly powered by the bootstrap circuits, resulting in a limited blocking voltage (up to 1200 V). To properly operate the IPM under all specified conditions, an external power supply is needed. Therefore, gate drivers integrated with galvanically separated power supplies sufficient for higher voltages are to be developed in the future.

11.2.2 High Temperature Operation

Silicon (Si) is by far the most commonly used semiconductor material and the operating temperature of traditional silicon-based devices range from -40°C to 150°C . Higher temperature may be desired for specific applications. Currently, high-temperature IGBTs show good robustness at a junction temperature of 200°C . Wide band-gap (WBG) devices such as SiC and GaN have intrinsic temperature capabilities and push the operating temperature to the range of $200\text{--}300^{\circ}\text{C}$. The advances in packaging materials and WBG devices (e.g. diamond) promise further improvement over operating temperature of $300\text{--}500^{\circ}\text{C}$. As a potential disruptive technology, high-temperature power semiconductors have

received much attention in harsh-environment and power-dense applications, including automotive, aerospace, down-hole drills and nuclear. For instance, there is a trend for more electric aircraft (MEA) to replace conventional hydraulic systems with electric actuators, which promises reduced weight and improved reliability. However, other associated high temperature components and control electronics are still challenging. The gate driver unit is within the most closed vicinity of power devices (heat source) and is therefore required to sustain high temperature operation.

The evolution of high-temperature IGBTs has led to the development of high temperature gate driver ICs and gate driver units. A SOI-based gate driver is proposed in [2] and its driving capability is demonstrated for SiC MOSFET (1200V/100A) at the ambient temperature of 200°C and the junction temperature of 250°C. The high temperature integrated SOI gate drive chip provides a multitude of functions including logic control, output stage, on-chip power supply and protection, as shown in Figure 11.7(a). An on-chip temperature supervisory circuit can also be integrated for over temperature protection. Another high temperature gate driver solution using hermetic chipset (see Figure 11.7(b)) is commercially available for a chip junction temperature of 225°C. These innovations offer generous freedom to lay gate drivers next to the power transistors to minimize the parasitic components and maximize the switching speed. They can also be integrated into IPMs based on high-temperature semiconductors to further exploit their high-temperature and high-speed capability.

(a)

(b)

Figure 11.7 High-temperature gate driver unit. (a) SOI gate driver chipsets (Courtesy of Oak Ridge National Laboratory). (b) HADES® chipsets (Courtesy of CISSOID S.A.).

11.3 Integrated Data Acquisition Methods

The centralized control architecture with the sensing elements and GDUs is widely used for conventional power electronics converter systems to provide system level control and protection. For the interest of high performance IGBT modules and their intelligent gate drivers, innovative data acquisition functions are incorporated to enhance condition monitoring and control optimisation. In addition to treating the whole converter system as a control target, the performance of individual power semiconductor switches and their controllability also attract much attention. Conventional sensing and instrumentation technologies for power converter control might not be capable of meeting the new data acquisition requirement and require further considerations. Before identifying the appropriate sensing techniques for various parametric measurements such as current, voltage, temperature, power semiconductor characteristics in an operating converter are needed to understand. As shown in Figure 11.8, IGBT devices in power converters are characterized with dramatic change in magnitude and frequency, especially within their switching transients.

Figure 11.8 A typical PWM chopped sinusoidal waveform for IGBT switches.

Typical voltage and current waveforms of an IGBT switch from a PWM chopped sinusoidal waveform are shown in Figure 11.8. For a high fidelity measurement, both DC and high bandwidth parametric measurement are required. In the static states of (2) and (4), current varies between nil and its peak ratings while voltage magnitude varies to the order of 2 or 3. During the dynamic transients of (1) and (3), current and voltage are traversing a large magnitude within a few ns to us resulting high di/dt and dv/dt up to tens or hundreds of A/ns and V/ns, respectively. A dedicated measurement technique is therefore required to cope with the challenging conditions including EMI, distortion and noise. Moreover, it should cause neither damage nor intrusion (performance, control strategy, etc.) to operating power converters. For example, the measurement circuit design should take into account of design challenges such as insulation, short fault in the switching operation and should avoid induced anomalies to the gate drives and converter systems.

11.3.1 Voltage Measurement

The IGBT collector-emitter voltage is a commonly monitored performance parameter. An IGBT is used as a power switch and it traverses from several volts to hundreds or thousands of volts for on-state and off-state with a dynamic dv/dt up to a few hundreds V/ns . To accurately quantify its performance characteristic, high-fidelity voltage measurement has to be made on both the switching transients and the on-state conditions.

In order to acquire the transient behaviour, oscilloscopes with high bandwidth (in MHz) voltage probes are normally used. To precisely obtain the IGBT transient voltage characteristics is challenging. Recently, some field programmable devices (e.g. FPGA, CPLD, etc.) with front-end high-speed electronics have been integrated into gate drivers to provide in-situ measurement [3][4]. The data-acquisition subsystem can be used in a burst mode to adapt the periodic transient characterization, where higher sample rates only apply for shorter periods to reduce the throughput demands. However, it is still extravagant to achieve a high-fidelity switching transient measurement. An alternative method is to prolong the switching transient period (e.g. by increasing the gate resistance) but this seriously impact the IGBT performance and generates more switching losses as well [5]. Yet others obtain transient characteristics with cost-effective solutions by sacrificing the signal integrity. Commonly used measurement techniques include reduced sampling rate and event-triggered measurement. However, the critical information in the high frequency contents of the **analogue** signal may be lost. For example, peak detectors screen and pinpoint the specific features in IGBT switching waveforms [6].

For IGBT on-state voltage measurement with their intermittent exposure to high blocking voltage at off-states, read-out electronics can be provided with voltage dividers or scaling functions to avoid overdrive. To detect the comparatively small on-state voltage changes in a very large overall voltage (voltage surges, off-state voltage, turn-off voltage transients, etc), the sensitivity might be insufficiently low.

$$Sensitivity = \frac{Full\ Scale}{2^{ADC/s\ resolution\ in\ bits}} \quad (1)$$

For instance, a 400-V DC-link voltage is assumed as the full scale measurement voltage and a 10-bit ADC provides a sensitivity of $400/2^{10} \approx 0.39\ V$.

In order to achieve high accuracy measurement (in the level of a few millivolts) in a kilovolt range, a practical way is to block or clamp the high voltage in order to maximize the effective full scale. As for the previous example when the maximum scale set to 5V the new sensitivity is $5V/2^{10} \approx 4.9\ mV$.

There have been some practical solutions proposed in the literature, as demonstrated in Figure 11.9. The first possible approach is to apply a decoupling diode to block the high voltage as shown in Figure 11.9(a). It is a simple and cheap solution with high bandwidth, but the voltage across the diode is included in the output and an external voltage reference (V_r) is required. The second category introduces a series connection of a diode and a Zener diode after a limiting resistor as displayed in Figure 11.9(b). The output voltage is clamped by the Zener diode when the power module is turned off [7]. This is still a simple and economic solution but the bandwidth is limited by the current limiting resistor and performance of the diodes. In [8], the JFET (N-channel) current generators cells are used instead of the current

limiting resistors, which could make the voltage clamping up to 100 kHz. The third category is employing a relay or an active switch to connect and disconnect the measuring circuit, as shown in Figure 11.9(c). Potential problems with this circuit are the limited bandwidth due to the dead time and the need for additional gate signals for the control switch.

Figure 11.9 $V_{ce(on)}$ measurement circuit. (a) Decoupling diode. (b) Zener clamp. (c) Control switch.

11.3.2 Current Measurement

Current measurements in conventional power electronics converters are taken for two purposes, achieving the converter control target and protecting the power semiconductor devices from fault (e.g. short fault, overcurrent, etc.). A number of current measurement methods with different performance index can be determined depending on the measurement goals. For instance, system level dynamic control requires a sampling rate of PWM frequency (normally varies from DC to tens of kHz) and accuracy of approximately 2~5%. However, for the purpose of IGBT characterization especially during switching transients, most specific requirement in current measurement should be noted:

- i) The bandwidth of the sensor should be high enough to accurately track the rising and falling transients as rapid as tens of nanoseconds.
- ii) The sensor dynamic range should match the peak amplitude of the measured signal while maintaining sufficient sensitivity at small current and out of saturation at peak current.
- iii) For the invasive approaches, the interference due to the added impedance should be minimized.

Current sensing techniques can be divided into two main categories: the non-isolated and the isolated. The former embraces the two-wire shunt, four-wire shunt (including coaxial shunts or pseudo four-wire), and current sense IGBT using split cells. In particular, subsequent read-out electronics is also integrated to provide analogue-digital converter (ADC) and isolation. They are illustrated in Figure 11.10. The current shunt based sensing technology is known to achieve high bandwidth. However, the parasitic effects due to internal inductance need to be minimized or compensated for accurate measurement. Moreover, their power losses and thermal issues in high current applications should be addressed. In particular, the split-cells in IGBTs are fabricated by some manufactures to reduce the shunt power losses. In order to make shunt sensing signal available for control units while minimizing distortions, digitalized isolation techniques such as optocouplers or pulse transformers are used. For instance, some sense IGBTs employ the Sigma/Delta-ADC technique with the built-in integrator and comparator for shunt front-end measurement, which allows for significant compromise to be introduced between the effective sampling rate and signal resolution. The V_{CEsat} monitoring technique is commonly found in gate drivers and

makes use of the IGBT itself as a shunt. The collector-emitter voltage is monitored based on the IGBT output characteristics for short protections and a fault warning is issued when the IGBT runs into desaturation, i.e. a surge of effective IGBT resistance occurs. For short protection typical shunts feature cost effectiveness and design simplicity, they may suffer from a demanding surge for accurate measurement during rapid switching transients where ultra-low inductance shunts and high performance read-out electronics (e.g. compensation and isolation features) are required.

Figure 11.10 Typical non-isolated current measurement circuits. (a) Two-wire shunt. (b) Four-wire shunt. (c) Current split cell. (d) Integrated Sigma/Delta-ADC.

The latter isolated technologies are more expensive than current shunts. Hall Effect based current transducers categorized as both open-loop and closed-loop types are widely used for converter control but their comparatively low bandwidth may hinder their applications in dynamic current transients. In case of the short-current fast protection (e.g. normally within 10 μ s), gate drivers with shunt or V_{CE} measurement are required. Current Transformer (CT) is used for pulse and frequency alternating current applications. Present products can measure the current up to 250 MHz with hundreds of amps by applying advanced material and techniques. However, its comparatively large footprint makes it hard to be implemented in practical applications. Moreover, the DC and low frequency components of the measured current may cause core magnetic saturation [9]. A Rogowski coil also measures pulse and frequency alternating current by using an air toroid with an additional integrator. Its small footprint leads to an easy circuit integration. The iron coreless design results in a wider current measuring range compared to the CT, however, signal bandwidth is largely limited by their self-inductance and the capacitive effect in windings and integration electronics. In [10], the experimental results of comparison between Ultra Mini Rogowski and Pearson current monitor (a commercial CT) show that the latter has better performance for high dynamic switching current measurement (e.g. fast transient response, less harmonic). Since both methods stated above can only be employed in the AC measurement, authors in [11] present a highly dynamic current measuring method by applying the inductive current sensor for high-frequency component measurement and low dynamic DC-current probe for calibration. In order to get the accurate results for the current flow of extremely fast switching semiconductors, the Q-algorithm method is utilized to calculate the final current waveform after offset correction and calibration. Direct-Current Current Transformers (DCCTs) are

capable of measuring DC and AC currents over the magnetic coupled device by incorporating novel principles of operation and technology [12]. However, due to the magnetic modulator principle applied in DCCTs, an accurate measurement of current is ranging from DC to a few hundred kHz, which becomes one of its limitations. Magnetoresistance (MR) current sensors, based on magneto-resistance effect or giant magnetoresistance where constructive material resistance changes with applied magnetic field, are developed for power converter applications to meet high bandwidth, accuracy and insulation performances but have limited bandwidth for switching transients. It is exempt from iron core and achieves high linearity and accuracy [13]. Magnetoimpedance (MI) current sensors also emerge, showing more potential advantages than MR sensors in terms of cost, flexibility, size, sensitivity and bandwidth [14]. Fiber-optic current sensors, based on Faraday magneto-optic effect, perfectly integrate the magnetic field along the sensing fiber and directly measure the current [15]. Its measurement range is up to several hundred kA but bandwidth is still limited as shown in Figure 11.11. An overview of current sensing technologies that are suitable for packaging into integrated power electronics modules is presented in [16]. The integrated planar shunts and planar embedded Rogowski coils technologies [17] are proposed as two candidates for fully integrated current sensors in power modules.

Figure 11.11 Bandwidth and measurement range of typical current sensors.

The popular WBG power semiconductors and their higher switching speed are leading the way to high bandwidth current sensors especially for the switching current measurement. The appropriate current sensors (together with their read-out electronics) must be selected to avoid the tremendous interference to the semiconductor characteristics. Most conventional current sensors may have their own limit for this specific application. Different characteristics of these sensors should be taken into account in terms of sensing elements, operating frequency range, accuracy, high current measuring capacity, temperature sensibility, power consumption, relative cost, integratability and current type.

11.3.3 Temperature Measurement

The semiconductor chip junction temperature (T_j) is an important parameter for the thermal and electrical characterization and it is generally used for advanced condition monitoring and control. Traditionally, three different methods can be used for in-situ measurement, namely optical instrumentation, physical contacts and temperature sensitive electrical parameters (TSEPs). TSEP provides a global value for the entire chip, so called “virtual” junction temperature, without a significant intrusion to the conventional power modules. It can generally be divided into two groups in terms of device operational conditions: static and dynamic parameters. Although the dynamic TSEPs have potential ability to be utilized for normal operational drives, they have a demanding requirement to readout electronics and signal conditioning circuits. Their accuracy and resolution can hardly meet the health monitoring purpose without rigorous examinations. A number of static TSEPs are considered and their pros and cons are briefly discussed in [18]. It should also be noted that “virtual” junction temperature only provides a medium temperature while the temperature distribution occurring in the monolithic chip and multiple parallel connected chips can hardly be derived.

11.4 Intelligent Control

Power electronic systems advance with the development of power semiconductor components, signal processing units and control algorithms. With the trends of integration and intelligence of power control, high performance of gate drivers, which takes a central place in an inverter to interface between the control unit and the power semiconductor devices, will inevitably demand. Apart from the typical control, protection and communication functions, novel GDUs incorporated digital technology with new features developed such as data acquisition, data logger, signal processing and in-system configuration, etc. The digitalized gate drive provides more functionality, flexibility and controllability. Figure 11.12 shows the schematic diagram of innovative GDUs integrated with main intelligent control features.

Figure 11.12 Schematic diagram of the innovative digitalized GDUs.

11.4.1 Condition Monitoring

With the extensive development of microelectronics (analogue and digital electronics), signal conditioning and processing techniques, protection and condition monitoring functions have been achieved and improved by integrating a multitude of advanced sensing, data-processing and control functionality into GDUs. The localized sensing, computing and control are completed within the vicinity of IGBTs in the gate drivers, which can relieve the monolithic core of the master control unit, reduce signal propagation delay and simplify communication demands over long distance. Advanced GDUs allow the IGBT and power converter parameters in-situ monitored and logged, which can then be post-processed for diagnostic and prognostic purposes.

Since IGBTs are subject to significant stresses in line with their load and environmental conditions, both abrupt and degraded failure modes can occur. To improve reliability, in-situ condition monitoring techniques have been integrated into gate drivers to provide insights into performance and health conditions. The integrated condition monitoring and health management techniques enable in-service root failure reasoning, early warnings of incipient failures, preventative maintenance scheduling and adaptive health management. Some common precursor parameters in respect of degradation failure modes include forward voltage, $V_{CE(sat)}$, threshold voltage, V_{TH} thermal resistance, R_{th} , etc.

11.4.2 Control of Switching Characteristics

With the advanced in-system monitoring electronics and complex digital control unit, the output stage of the intelligent GDUs can be adaptively configured or controlled. This helps to achieve optimal IGBT performance under both normal and fault operating conditions and the

operational tradeoff (e.g. delay time, Miller plateau duration, electrical stresses, losses, temperature). Since the switching transients (turn-on and turn-off) are the key states for operating IGBTs and their characteristics are interrelated with their switching losses, safe operating area (SOA), electromagnetic interference (EMI), commutation behavior, etc., they are among the most attractive control targets for intelligent GDUs.

The output stage power source can be actively controlled during IGBT switching transients to modify the switching waveforms. In particular, the derivatives of the IGBT collector-emitter voltage and collector current can be adjusted with control parameters and some common ways to achieve this are shown in Figure 11.13. Figure 11.13(a) shows an example of output stage with different gate resistors. The source follower receives the logic signal to activate/deactivate the gate charging. The additional current injection can be switched in or out at certain stages to minimize the turn-on delay time and switching losses. Gate discharge during turn-off transients can be regulated by current removal electronics in the same manner and omitted for clarity. Figure 11.13(b) shows an output stage with a gate current booster. It comprises an extra voltage source with higher amplitude and a digitally controlled switch. Figure 11.13(c) shows a voltage-controlled current source (VCCS) to adjust the gate current based on a digital to analogue converter (DAC) output signal. The DAC outputs a gate current command within ± 10 V, which is determined by control unit at individual subdivided stages of a switching period. Figure 11.13(d) shows the use of an external gate-emitter capacitor, which is normally used to reduce the IGBT parasitic turn-on and optimize the switching characteristics. A zener diode with its internal resistance is used for damping the possible resonance and counteracts the slow turn-off. All the output stage topologies can follow a predefined control profile or be based on an event feedback. By subdividing the switching transients into different intervals, the switching performance at each stage can be to a large extent individually tuned, which includes delay, voltage and current derivatives, voltage and current overshoots, etc.

(a)

(b)

Figure 11.13 Circuit diagrams of the IGBT gate driver active control. (a) Selectable gate resistor. (b) Gate current booster. (c) Voltage-controlled current source. (d) External gate-emitter capacitor.

An active gate drive that influences the switching behaviour of an IGBT by adjusting the gate current profiles is presented in [3]. The desired gate current is provided by a VCCS that follows the voltage command ($v_{\text{actuating}}$) at different switching stages. The current slope dI_C/dt during turn-on and voltage slope dV_{CE}/dt during turn-off in respect of various gate currents are influenced as shown in Figure 11.14. The current slope dI_C/dt and the voltage slope dV_{CE}/dt increase in line with the amplitude of the gate current. The turn-on and turn-off times are reduced and same for the switching losses.

Since the IGBT characteristics and performance are largely determined by the device itself as well as being subject to the operating point (V , I , T) and conditions (load, filter, snubber, parasitic aspects, etc.), the GDU control parameters should be adaptively determined to optimize the IGBT performance. Several adaptive strategies have been compared and discussed in [3] in order to determine the optimal switching transients at individual operating point (i.e. load conditions, temperature, variations of circuit topology). The closed-loop concept has applied to achieve optimized control based on reference and feedback signals. However, the GDU complexity and cost are increased accordingly. One should note that the system stability should be justified before in-field implementation.

Figure 11.14 Switching waveforms in respect of various gate currents. (a) Turn-on. (b) Turn-off.
©2014 IEEE. Reprinted with permission from [3].

11.4.3 Series Connection

High voltage (HV) IGBT modules with voltage blocking capability of up to 6.5 kV are used in many high power applications. For higher blocking voltages, a common way is to employ circuits with cascaded or multilevel structures where the voltage rating of individual semiconductors is not critical. Alternatively, power switches may be constituted by IGBT power modules in series connections. For instance, to form a 13kV switch for the rail traction drive, a number of HV-IGBT modules can be connected in series (e.g. $3 \times 4.5\text{kV}$ or $2 \times 6.5\text{kV}$ HV-IGBTs are connected in series). Voltage unbalance between individual IGBT modules might occur during both static and dynamic states, which necessitates the de-rating and even results in power switch breakdown. This is because of the production tolerances of the IGBT chips and packages that lead to the dispersions between the characteristics of the different IGBT devices/modules. This can also be attributed to the uneven module temperature as well as characteristic differences of the associated gate drivers. Mismatches of main circuit (e.g. layout) and parasitic components (e.g. inductance, capacitance) can also influence.

For static state voltage balancing when the switch is turned off, balancing resistors in parallel with the IGBT devices are used (see Figure 11.15(a)). The leakage (or cut-off) current I_{CES} in the blocking IGBT module, i.e. the sum of collector-emitter blocking current of the IGBT and the reverse blocking current of the diode, is compensated by the parallel connected balancing resistors. By rating the resistor current 3~5 times of I_{CES} , the symmetry of effective blocking resistance and thus the static voltage balancing can be achieved. The voltage balancing during dynamic states is achieved with power switch layout/structure optimization, snubber circuits and advanced gate control. In order to minimize the negative effects of parasitic capacitances within gate drivers and the main power circuit, a self-powered gate

driver with a vertical structure for IGBT strings is reported in [19], as compared to the ground-referenced isolated power supply with a horizontal structure.

Passive snubber networks (either RC or RCD) in parallel with power devices to slow down the switching are used (see Figure 11.15(b)). However, their performance is very much related to the operating point and it also **causes** losses and reliability concerns. A quasi-active gate control circuit is implemented in Figure 11.15(c) that is consisting of only passive components with a master-slave structure. It provides dynamic and static voltage sharing by using a simple RC balancing network. Only the bottom switch (master) receives pulse control and the RC balancing network induces the switching operation of the top switch (slave). The zener diodes Z_1 and Z_2 are used to protect the gate from over-voltage while Z_3 prevents the gate circuit to flow the collector circuit during static conduction [20]. Some active control techniques are also carried out for series-connected IGBTs to eliminate the snubber networks. The delay times t_{don} and t_{doff} for turn-on and turn-off are set relative to one another by a dynamic balancing controller as shown in Figure 11.15(d). A compensation time can be generated according to the status feedback, which interprets the voltage unbalance between individual IGBTs [21]. Figure 11.15(e) shows the dV_{CE}/dt control during dynamic voltage transition. Both turn-on and turn-off transitions are controlled to follow a predetermined dV_{CE}/dt . The IGBT switch trajectory can be regulated by a tailored voltage reference, V_{ref} , via the feedback loop [22]. A number of compensated control signals is generated by the feedback circuit integrating scaling and limiting circuits and these switching parameters generally includes V_{CE} , i_C , V_{GE} , dV_{CE}/dt , di_C/dt or their combinations.

Figure 11.15 Diagram of the voltage balancing methods. (a) Balancing resistors. (b) RC and RCD Snubbers. (c) Master-slave quasi-active control. (d) Delay time control. (e) dV_{CE}/dt control.

(c) © 2014 IEEE. Reproduced with permission from [20].

11.4.4 Parallel Connection

The maximum current density and chip size of IGBTs are limited by thermal and manufacturing capacity. The current density of commercially available IGBT chips ranges from 100 to 200 A·cm⁻². The chip size extends to 3 cm² since concerns associated with both the yield rate (resulted by single cell defect for high cell densities) and isothermal chip conditions manifest. To achieve the high power and current ratings, parallel arrangement is consequently implemented at various levels. Power modules (up to a few MW) possessing multiple semiconductor chips in parallel are manufactured in large quantities for emerging market sectors such as renewable energy and electric vehicles. The switching cells making use of standard power modules in parallel connections are used at the highest power levels up to several gigawatts.

In order to maximize the overall power capability and ensure the safe operation of the shunt-connected switches, the current balancing between IGBT modules should be taken care of under both static (i.e. conduction state) and dynamic conditions. The reasons for unbalancing current distribution are due to the differences either in the control input or in the power circuit loop. More specifically, it is because of tolerances in the IGBT modules (transfer characteristics, gate threshold voltage, etc.), switching cells (asymmetry of current paths and parasitic elements), or the commutation circuits (including bus-bar, FWDs, conductors and cables). This can also be attributed to the gate driver circuitry differences (signal propagation times, voltage supply tolerances). The secondary effects of the inhomogeneous temperature also cause the uneven drift of IGBT/FWD electrical properties.

Although with optimal selection and system layout, tolerances of IGBT modules as well as their gate drivers and cooling circuit performance, a minimum derating of 10% is normally required for power modules of parallel connections and it can be even higher in asymmetric layouts/arrangements.

For static current balancing in parallel connections, IGBT modules with low tolerances of I-V characteristics are generally selected. The current asymmetry can also be mitigated with the positive temperature coefficient property of the on-state voltage over majority current range.

For dynamic current balancing, some active gate control techniques are implemented. Based on the parameters monitored from the gate driver, IGBTs and the system, the driver output stage can be adaptively reconfigured and controlled for optimal balancing. The collector currents i_C as well as its rising and falling edges between the directly parallel-connected IGBTs were measured through a printed circuit board (PCB) Rogowski coil and the delay time is determined on the detection of a predefined current trigger, as shown in Figure 11.16(a) [23]. The resulting delay time and current signals feed a control unit (FPGA/DSP), which adjusts both the amplitude and the firing edges of different gate drivers to in order to achieve balanced collector currents i_C , as shown in Figure 11.16(b). Based on the detected current edge from the feedback loop of Figure 11.16(c), the on/off pulse edges are shifted

accordingly for the consequent pulses. In another example, a delay time compensator is implemented for the current balancing of the parallel connected IGBTs. The measurement of emitter-to-auxiliary emitter voltage enables feature extraction and the consequent delay time compensation. It also allows removing the high bandwidth dynamic current measurement and is less demanding for the control unit [24].

Figure 11.16 Example illustration of current balancing of parallel-connected IGBTs. (a) Without active gate control. (b) With amplitude and the firing edge control, and (c) Simplified control loop block diagram. (a) and (b) © 2014 IEEE. Reprinted with permission from [23].

11.5 Summary

In this chapter, the current and future developments of gate driver techniques have been presented and extensively discussed. The focus is placed on the technical advances in data-acquisition and control functions adapted for gate drivers. The direction of technology development of power electronics is towards higher power density, higher efficiency, higher reliability, more informatics at lower cost. For the low power applications, the integration of both electronics and power electronics is the trend. The optimization and system integration of different elements (e.g. gate resistance, temperature measurement, driver, monitoring and protective functions) are under development.

In the realm of medium to high power applications, the performance of power modules and their gate driver units play an important role and their reliability is a key issue. The

application of embedded digital control to the distributed gate driver allows in-situ measurement of the gate driver and IGBT parameters. These parameters provide insights into the performance of the gate drivers, IGBT power modules and the power electronics system. Extended solutions dedicated to specific issues are available with innovative intelligent monitoring and adaptive control capability of the intelligent gate drivers.

11.6 Acknowledgements

The authors would like to thank the researchers who supported this work with helpful comments and discussions. Special thanks go to Haimeng Wu, Dave Atkinson, and Chen Wang from Newcastle University.

11.7 References

- [1] B. Vogler, M. Rossberg, R. Herzer, L. Reusser, "Integration of 1200V SOI gate driver ICs into a medium power IGBT module package," *22nd International Symposium on Power Semiconductor Devices & IC's (ISPSD)*, pp. 97-100, 6-10 June 2010.
- [2] Z. Wang, X. Shi, L. M. Tolbert, F. F. Wang, Z. Liang, D. Costinett, B. J. Blalock, "A high temperature silicon carbide mosfet power module with integrated silicon-on-insulator-based gate drive," *IEEE Trans. Power Electronics*, Vol.30, No. 3, pp.1432-1445, March 2015.
- [3] L. Dang, H. Kuhn, A. Mertens, "Digital adaptive driving strategies for high-voltage IGBTs," *IEEE Trans. Industry Applications*, Vol. 49, No. 4, pp.1628-1636, July-Aug. 2013.
- [4] M. Shahbazi, P. Poure, S Saadate, and M. R. Zolghadri, "FPGA based fast detection with reduced sensor count for a fault-tolerant three-phase converter," *IEEE Trans. Ind. Inf.*, Vol. 9, No. 3, pp. 1343-1350, Aug. 2013.
- [5] H. Chen, B. Ji, V. Pickert, W. Cao, "Real-time temperature estimation for power MOSFET considering thermal ageing effects," *IEEE Trans. Device and Materials Reliability*, Vol. 14, Issue 1, pp. 220-228, Mar. 2014.
- [6] V. K. Sundaramoorthy, E. Bianda, R. Bloch, F. Zurfluh, "Simultaneous online estimation of junction temperature and current of IGBTs using emitter-auxiliary emitter parasitic inductance," *International Exhibition and Conference for Power Electronics, Intelligent Motion (PCIM Europe'14), Renewable Energy and Energy Management*; 20-22 May 2014.
- [7] B. Ji, V. Pickert, W. Cao, B. Zahawi, "In situ diagnostics and prognostics of wire bonding faults in IGBT modules for electric vehicle drives," *IEEE Trans. Power Electronics*, Vol. 28, Issue 12, pp. 5568-5577, Dec. 2013.
- [8] A. Calmels "VDS(on), VCE(sat) measurement in a high voltage, high frequency system," *Application note Advanced Power Technology*, 2004.
- [9] M. Hartmann, J. Biela, H. Ertl, J. W. Kolar, "Wideband current transducer for measuring AC signals with limited DC offset," *IEEE Trans. Power Electronics*, Vol. 24, Issue 7, pp. 1776-1787, 2009.
- [10] H. Li, M. N. Stig, "Challenges in switching SiC MOSFET without ringing," *the International Exhibition and Conference for Power Electronics, Intelligent Motion (PCIM Europe'14), Renewable Energy and Energy Management*, pp. 1-6, 2014.

- [11] S. Hain, M. M. Bakran, "Highly dynamic current measurements with inductive current sensors - a numerical recipe," *the International Exhibition and Conference for Power Electronics (PCIM Europe'14)*, Intelligent Motion, Renewable Energy and Energy Management; pp. 1-8, 2014.
- [12] G. Hudson, K. Bouwknecht, "4-13 kA DC current transducers enabling accurate in-situ calibration for a new particle accelerator project, LHC," *2005 European Conference on Power Electronics and Applications*, pp. 1- 8, 2005.
- [13] S. Scherner, R. Slatter, "New applications in power electronics for highly integrated high-speed magnetoresistive current sensors," *the 8th International Conference on Integrated Power Systems (CIPS)*, pp. 1-7, 2014.
- [14] A. Asfour, M. Zidi, J. Yonnet, "High frequency amplitude detector for GMI magnetic sensors," *Sensors*, 2014.
- [15] P. Dreler, P. Fiala, "Utilization of Faraday mirror in fiber optic current sensors," *Radioengineering*, Vol. 17, No. 4, 2008.
- [16] C. Xiao, L. Zhao, T. Asada, W. G. Odendaal, J. D. van Wyk, "An overview of integratable current sensor technologies," *the 38th IAS Annual Meeting. Conference Record of Industry Applications Conference*, Vol. 2, pp. 1251-1258, 2003.
- [17] A. Ahmed, L. Coulbeck, A. Castellazzi, C. M. Johnson, "Design and test of a PCB Rogowski coil for very high di/dt detection," *15th International Power Electronics and Motion Control Conference (EPE/PEMC)*, pp. DS1a.2-1- DS1a.2-4, 2012.
- [18] B. Ji, X. Song, H. Wu, V. Pickert, W. Cao, "Integrated condition monitoring for vehicle-ready power modules," *the IEEE Transportation Electrification Conference and Expo (ITEC) Asia-Pacific*, Beijing, Aug. 2014.
- [19] N. Van, P. Jeannin, E. Vagnon, D. Frey, J. C. Crebier, "Series connection of IGBTs with self-powering technique and 3-D topology," *IEEE Trans. Industry Applications*, Vol. 47, No. 4, pp. 1844-1852, July-Aug. 2011.
- [20] N. Teerakawanich, C. M. Johnson, "Design optimization of quasi-active gate control for series-connected power devices," *IEEE Trans. Power Electronics*, Vol. 29, No. 6, pp. 2705-2714, June 2014.
- [21] S. Ji, T. Lu, Z. Zhao, H. Yu, L. Yuan, "Series-connected HV-IGBTs using active voltage balancing control with status feedback circuit," *IEEE Trans. Power Electronics*, vol.30, no.8, pp.4165-4174, Aug. 2015
- [22] T. C. Lim, B. W. Williams, S. J. Finney, P. R. Palmer, "Series-connected IGBTs using active voltage control technique," *IEEE Trans. Power Electronics*, vol.28, no.8, pp.4083-4103, Aug. 2013
- [23] D. Bortis, J. Biela, and J. Kolar, "Active gate control for current balancing of parallel-connected IGBT modules in solid-state modulators," *IEEE Trans. Plasma Sci.*, Vol. 36, pt. 3, No. 5, pp. 2632-2637, Oct. 2008.
- [24] N. Idir, R. Bausiere, J.J. Franchaud, "Active gate voltage control of turn-on di/dt and turn-off dv/dt in insulated gate transistors," *IEEE Trans. Power Electronics*, vol.21, No.4, pp.849-855, July 2006.