Intelligent interfaces between power and control: Gate drivers for IGBTs

The furious pace of development in modern power semiconductors and packaging has made IGBT modules more compact and easier to use than ever. Another upshot of this trend is that modules are now available for even higher voltages and currents. These new power components in conjunction with new, LSI controller chips greatly simplify product design. The gate driver, which forms the interface between the controller and power stage, has a major impact on the performance and reliability of the overall system.

Within just a few years, IGBTs (insulated gate bipolar transistors) have virtually ousted other switching technologies in power electronics in the range above 300 V and at switching frequencies up to 20 kHz. The technical advantages of IGBTs - high dielectric strength, relatively high current density, ease of driving and good short-circuit protection - and their steadily falling prices have promptly made these power semiconductors standard components for every power stage rated at 1 kW or more (Fig. 1).

Sixpacks containing all the power semiconductors for a three-phase motor drive converter in a single module are now available for currents of 100 A per phase. High-power IGBT modules for reverse voltages of 1700 to 3300 V and currents up to 1200 A per module can also be supplied. IGBTs are used on a large scale for traction motors in public transportation vehicles such as streetcars, subways, metrotsains and trolley buses.

Power MOSFETs predominate only in the lower power range up to several hundred watts, at lower operating voltages and at very high clock frequencies in particular.

Innovative drivers protect power stages

The function of the IGBT driver is to process the gate driver pulses generated by the control electronics so that the power semiconductors are optimally driven. In bridge circuits, which are basic to most IGBT applications, very fast surges in potential occur at the moment of switching in the presence of large potential differences between the upper driver of the half-bridge and the control electronics.

As a typical IGBT power stage operates on several hundred volts or even several kilovolts, electrical isolation is required between the control electronics and the power stage, if only on grounds of safety. A preference is emerging for designs in which built-in protective functions in the driver protect the power semiconductors against short circuits and other dangers.
Of the various solutions conceivable, the concept of the intelligent driver is catching on in the market. This is an IGBT driver which has integrated protection functions and is connected directly to the power semiconductor. Isolation between the control electronics and power stage is located right in front of the driver.

Preventing short circuits

An IGBT is turned on when a positive voltage of typically 15 V with respect to the emitter potential is applied to its gate. It is turned off when the gate receives a negative voltage, also referred to the emitter. Although an IGBT is also blocked when there is no potential difference between gate and emitter in static operation, this mode of operation is not advisable in bridge circuits, because when one IGBT in the half-bridge is turned on, the collector-emitter voltage at the second IGBT, with which the first is connected in series, rises suddenly. The reverse transfer capacitance (also known as the Miller capacitance) now couples part of the collector voltage to the gate. The gate voltage then rises by a few volts before it is discharged again by the gate resistor after commutation is terminated. If the gate voltage is about 0 V prior to commutation, the gate threshold voltage is reached or exceeded, the IGBT is turned on and the result is a temporary short circuit through the half-bridge. At best, this short circuit leads only to a massive increase in commutation losses. But depending on type and on the design and operation of the power stage, the IGBTs can be destroyed. However, if the gate is biased with approximately –7 to –15 V with respect to the emitter when the IGBT is turned off, the temporary increase in the gate voltage cannot reach the gate threshold voltage, so the undesired temporary short circuit is safely avoided.

Whereas it is relatively easy to drive an IGBT whose emitter is connected to ground or to the minus side of the link voltage (the low side), high-side switches are more complicated. The high side refers to the upper transistor in the half-bridge circuit. The main problem in implementing drivers is found here: the mid-point of the bridge and thus the emitter potential of the high-side switch jumps back and forth at a high switching speed between the positive and negative potentials of the supply voltage. Switching speeds of 10 to 25 kV/μs are normal in PWM bridges equipped with IGBTs. The component used for electrically isolated signal transmission must transmit the drive information as quickly as possible, but this process must not be disturbed by the high dv/dt values and high potentials.

A driver must be able to recharge the gate capacitors of the IGBT quickly. Depending on the IGBT and the desired switching speed, this process requires currents of several amperes.

To provide the drive energy, every driver must have a suitable power supply with a floating voltage, at least for the high-side switches. The drive power required for smaller IGBTs is several hundred milliwatts, while larger IGBT modules can consume several watts.

How an intelligent driver protects

One of the basic functions of intelligent drivers is to ensure reliable protection of the power transistors against current surges and short circuits. In the latter case, the short-circuit characteristic of the IGBT as specified by the semiconductor manufacturer is used. These components can be operated at full collector-emitter voltage for several microseconds under short-circuit conditions. Depending on the gate voltage, the collector current is then a multiple of the rated current. When the short-circuit current is attained, the IGBT is desaturated. This means that the collector-emitter voltage then rises to the level of the operating voltage and the short-circuit current no longer increases. The current measurement is usually based on the collector-emitter voltage at the turned-on transistor. After it exceeds a defined threshold, the power transistor is turned off and remains blocked in this state for a defined minimum period.

The supply voltage of each driver must continue to be monitored, and the drive information should not be released until the correct supply voltage is present. This prevents uncontrolled or “half-way” switching of the IGBT.

This very simple protection concept allows IGBT half-bridges, full bridges and three-phase modules to be protected effectively and reliably. A typical module is shown in Fig. 2.

Smart driver design

The requirements described above can be met in various ways. The actual driver electronics with protective functions may be of discrete or integrated design. The following three components represent the most common approaches to electrically isolated transmission of the drive information:
- transformers,
- optocouplers, and
- optical fiber waveguides.

The transformer solution has the following advantages: extremely short transit times in the nanosecond region, no aging effects and maximum expected service life. Difficulties arise in developing a solution which is suitable on the one hand for the most disparate clock frequencies and any clock ratios, and is immune to high dv/dt values between the input and output on the other. If these difficulties are mastered, transformers can be used to implement drivers of the highest reliability for the most rigorous requirements.

The optocoupler solution is attractive because of its simplicity. Optocouplers can handle any clock ratio. The main difficulty is to find a way of transferring the drive information quickly while ensuring adequate dv/dt stability. Only a few optocouplers can satisfy these requirements – and carry a
matching price tag. Optocouplers are also in principle slower than transformers. Aging can still be a problem, and the mean time between failures (MTBF) of optocouplers is shorter than that of properly designed pulse transformers.

Optical waveguides offer an impressive variety of benefits: no capacitative coupling between input and output, no dv/dt sensitivity, high bandwidths (with fast fibers), long drive lines without coupling interference, isolation of any voltages, and ease of application. Their disadvantages are aging, jitter, longer delays and shorter MTBFs than transformers, sensitivity to moisture, and relatively high costs. For these reasons, optical waveguides are used wherever the advantages outweigh the drawbacks and costs are reasonable, i.e. at very high operating and isolation voltages, at very high powers and where longer lines are required between the control and power output stages.

Fig. 3 shows the block diagram of a half-bridge driver. This industrial product is offered as a driver module (Fig. 2). The drive information is transferred via transformers. The delay between the drive signals on the control side and at the potential of the power output stage is about 100 ns. A DC/DC converter is integrated to supply both driver channels with full isolation. Optocouplers are used to feed back any errors in the power output stage to the control system.

Half-bridge drivers are available in different versions to match the various voltage and power classes of the IGBT modules. At present, CT-Concept Technologie offers what is probably the largest range of IGBT drivers on the market. Every driver can be supplied for the commercial temperature range from 0 to 70 °C and for the industrial range from –40 to +85 °C. The product range is being continuously extended.

Smart power products and level shifters will not be dealt with in detail here. Their low costs and lack of electrical isolation make them suitable for low-power applications.

Intelligent power modules

A host of intelligent power modules (IPMs) are now being offered by Asian manufacturers in particular. All these IPMs feature gate driver ICs with built-in protective functions. But most of them do not offer electrical isolation of the drive information and feedback signals, or the voltage supply. They are not self-contained solutions because the user still needs numerous external components. In addition, the designer can no longer influence the switching characteristics of the modules or access the gate terminals, even for measurement purposes.

Dynamic gate controllers for high-power IGBTs

High-power IGBT modules have been available for about two years from eupec, a joint venture by Siemens and Daimler-Benz. They range from half-bridges for 600 A to single modules for 800, 1200 and 1800 A. These modules cover the 1200 and 1700 V ranges. The eupec model with the highest power density has limit data of 3300 V/1200 A.

These new high-power IGBT modules are moving into applications which used to be the uncontested domain of thyristor and GTO technology. But these IGBT converters can also be run at even higher clock rates than systems based on power semiconductors of the preceding generation. Higher clock frequencies require fast switching of power semiconductors to achieve good
system efficiency. But the line inductances and the properties of the diodes in modules with high reverse voltages significantly limit the switching speeds possible with the IGBTs and produce a distinct increase in commutation losses.

The dynamic gate controller (DGC) from CT-Concept Technologie is an innovative solution developed to drive high-power IGBTs. In this new driver concept, the turn-on and turn-off processes are regulated, irrespective of the type of load and operating mode of the converter. Fig. 4 shows the block diagram. The DGC concept permits greater utilization of high-power IGBTs in both the voltage and current ranges, even at high clock frequencies and without snubber networks in the power circuit. In addition to lower switching losses, electromagnetic interference by the converter is also reduced. An integrated IGBT status and diagnostic system ensures perfect protection of the power semiconductors under all operating conditions and also provides a straightforward user interface to higher-level control electronics. Although these functions are too complex to be described in detail here, the application benefits of DGCs will be seen from the following three examples.

Fig. 5 compares the turn-off characteristics of a eupec 1600 V/800 A IGBT operated at twice the rated current with a standard driver and a DGC. It can be clearly seen that the DGC-driven IGBT has about only half the delay and half the voltage overshoot when turned off.

Fig. 6 compares the different voltage overshoots of a 1600 V/800 A IGBT module from eupec with standard and DGC drivers when turned off at a short-circuit current of about 6000 A. Even greater differences in the voltage overshoots can be seen in this case than in normal operation. The turn-off overshoot produced with a DGC is almost three times smaller than that obtained with a standard driver.

Fig. 7 illustrates the differences in turn-on behavior. The turn-on delay of the high-power IGBT driven by a DGC is only half as long. The dI/dt regulator was set in such a way that the current is commutated with the same speed as obtained with a standard driver and the turn-on gate resistance specified by the manufacturer. After the IGBT has overcome the reverse current peak of the free-wheeling diode, the DGC-driven IGBT can switch more quickly. This feature alone reduces the turn-on losses at identical current commuting speed by about 27% in comparison with a conventional driver.

Prospects

The evolution of IGBTs in general, and of intelligent drivers and IPMs in particular, is still far from complete. IGBT chips will benefit from further advances in current-carrying capacity, current density, switching characteristics, and reduced switching and conduction losses. IGBT modules will become even more compact and technically enhanced (e.g. with load alternation stability), have higher power densities and a lower price. Integration will also surge ahead on the driver side, bringing further improvements in terms of volume, component count, cost and reliability. The innovative concept of the dynamic gate controller represents a new and unconventional approach to driving power conductors.

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