

Powering IGBT Gate Drives with DC-DC converters

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Word count: 2573, Figures: 6

May 2014

ABSTRACT

IGBTs are commonly used in high power inverter and converter circuits and can require significant isolated gate drive power to switch optimally. This paper describes how small isolated DC-DC converters can provide that power, what performance characteristics they need and how they confer advantages over alternative methods. The same considerations apply in principal to gate drives for silicon, silicon carbide and gallium nitride MOSFETs.

PAPER

When the Insulated Gate Bipolar Transistor (IGBT) was invented by Professor Jayant Baliga in 1980, it was seen as an ideal combination of the low on-state saturation voltage of a bipolar transistor and ease of gate drive of a MOSFET. IGBTs now find their natural home in applications at high power using devices with effective gate capacitances measured in hundreds of nanofarads. Although this capacitance has simply to be charged and discharged to turn the IGBT on and off, the circulating current to do so causes significant power dissipation in voltage drops in the gate driver circuit and within the IGBT. When IGBTs are paralleled, the gate drive power required is higher still.

At high power, inverters or converters typically use ‘bridge’ configurations to generate line-frequency AC or to provide bi-directional PWM drive to motors, transformers or other loads. Bridge circuits include IGBTs whose emitters are switching nodes at high voltage and high frequency so the gate drive PWM signal and associated drive power rails, which use the emitter as a reference, have to be ‘floating’ with respect to system ground, so called ‘high side’ drives. Additional requirements are that the drive circuit should be immune to the

high ' dV/dt ' of the switch node and have a very low coupling capacitance. In many instances, the bridge circuit requires safety agency-rated isolation from the control circuitry and therefore the barrier must be robust and show no significant degradation over the design life time due to partial discharge effects.

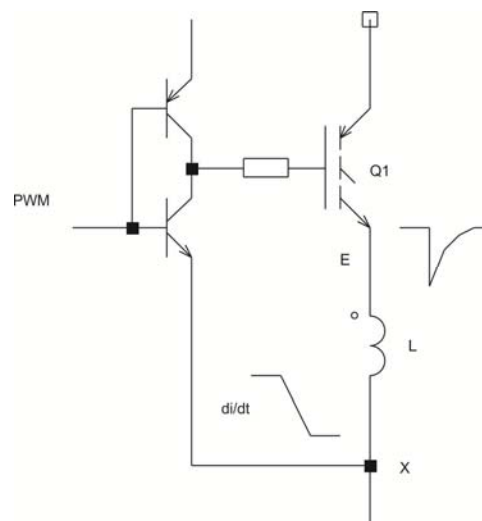
We will now consider how DC-DC converters can provide optimum power rails for these 'floating' drive circuits using a typical IGBT from Infineon as an example, type FZ400R12KE4.

On and off drive voltages

An initial consideration is to set the on and off-state gate voltages. While part FZ400R12KE4 has a minimum turn-on threshold of 5.2 V at 25 Celsius, in practice to ensure full saturation and rated collector current of 400 A, at least 10 V must be applied. The part has a maximum gate voltage of ± 20 V so +15 V is a good value with some margin. Higher values produce unnecessary dissipation in the gate drive circuit.

For the off-state, 0 V on the gate can be adequate. However, a negative voltage typically between -5 and -10 V enables rapid switching controlled by a gate resistor. A consideration also is that any emitter inductance between the IGBT and the driver reference, (point x in Figure 1), causes an opposing gate-emitter voltage when the IGBT is turning off. While the inductance may be small, just 5 nH would produce 5 V at a di/dt of 1000 A/ μ s which is not unusual. 5 nH is just a few millimetres of wired connection (the FZ400R12KE4 has a stray package inductance of 16 nH). An appropriate negative drive ensures that the gate-emitter off-voltage is always zero or less.

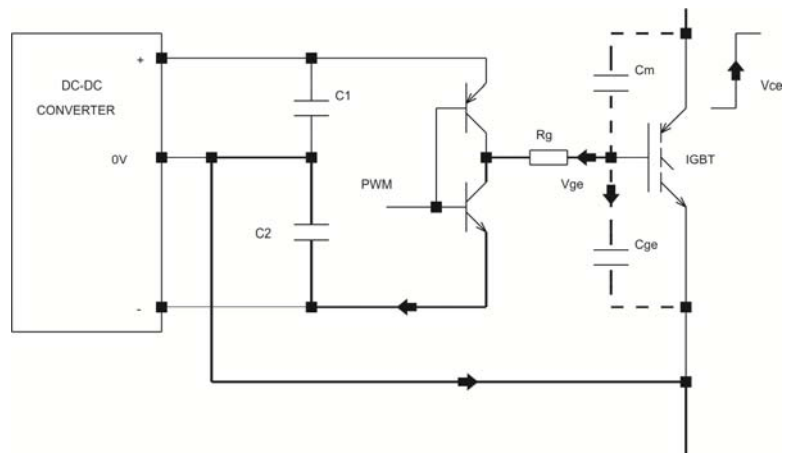
Figure 1. On switch-off with stray inductance L, negative di/dt produces a negative voltage on the emitter, opposing the turn-off voltage.



A negative gate drive also helps to overcome the effect of collector-gate ‘Miller’ capacitance on device turn-off which works to inject current into the gate drive circuit. When an IGBT is driven off, the collector-gate voltage rises and current flows through the Miller capacitance of value C_m . dV_{ce}/dt into the gate emitter capacitance C_{ge} and through the gate resistor to the driver circuit, see Figure 2. The resulting voltage V_{ge} on the gate can be sufficient to turn the IGBT on again with possible shoot-through and damage. Driving the gate to a negative voltage mitigates this effect.

A DC-DC converter with +15/-9V outputs conveniently provides the optimum voltages for the gate driver.

Figure 2. Current through ‘Miller’ capacitance C_m works to turn on the IGBT.



Gate power requirements

The gate of an IGBT must be charged and discharged through R_g in each switching cycle. If the IGBT data sheet provides a gate charge curve then the relationship is:

$$P = Q_g \cdot F \cdot V_s$$

Where P is gate drive power, Q_g is data sheet charge for a chosen gate voltage swing, positive to negative, of value V_s .

If the data sheet does not provide a charge curve but just a Qg value at specific gate voltages, the value of Qg at other gate voltage swings can be approximated by multiplying by the ratio of the actual versus data sheet voltage swings. For example the FZ400R12KE4 has a Qg value of 3.7 µC with ±15 V gate voltage swing (30 V total). For a swing of +15/-9 V (24 V total) gate charge approximates to:

$$Qg = 3.7e^{-6} \cdot 24/30 \approx 3 \mu C$$

At 10 kHz this requires gate drive power of:

$$Pg = 3e^{-6} \cdot 10e^3 \cdot 24 \approx 0.72 W$$

With derating and allowing for other incidental losses, a 2 W DC-DC converter would be suitable.

Average current requirements

In our example, with 24 V total gate voltage swing, the charge and discharge energy must be the same in each cycle, so the average charge and discharge current must be the same, at 30 mA given by Pg/Vs.

Peak current requirements

The peak current I_{pk} , required to charge and discharge the gate is a function of Vs, gate resistance of the IGBT R_{int} and external resistance Rg.

$$I_{pk} = V_s / (R_{int} + R_g)$$

The FZ400R12KE4 has $R_{int} = 1.9$ ohms so with a typical external resistor of 2 ohms and a swing of 24 V, a peak current of over 6 A results. This peak current must be supplied by ‘bulk’ capacitors on the driver supply rails as the DC-DC converter is unlikely to have sufficient value of output capacitors to supply this current without significant ‘droop’. Of course the gate driver itself must be rated for these peak current values as must the gate resistors.

Bulk capacitance values

For our example, total gate drive energy E per cycle is given by:

$$E = Qg. Vs = 72 \mu J$$

The bulk capacitors on the +15 and -9 V rails supply this energy in proportion to their voltages so the +15 V rail supplies 45 μJ . If we assume that the bulk capacitor on the +15 V rail should not drop more than say 0.5 V each cycle then we can calculate minimum capacitance C by equating the energy supplied with the difference between the capacitor energies at its start and finish voltages, that is;

$$45 \mu J = \frac{1}{2} C (V_{init}^2 - V_{final}^2)$$

$$C = (45e^{-6} \cdot 2)/(15^2 - 14.5^2) \approx 6.1 \mu F$$

Although the -9 V rail supplies about a third of the energy, it requires the same capacitor value for 0.5 V drop as this is a larger percentage of the initial value.

In practice the voltage drop may be affected more by the ESR and ESL of the capacitor. For example an ESR of 0.1 ohm would drop more than 0.5 V peak at our peak current of 6 A. High performance capacitors should therefore be chosen, often necessitating large can sizes to achieve the low ESR, giving many times the minimum capacitance value.

DC-DC regulation

The absolute values of gate drive voltages are not very critical as long as they are above the minimum, comfortably below breakdown levels and dissipation is acceptable. The DC-DC converters supplying the drive power therefore may be unregulated types if the input to the DC-DCs is nominally constant. Unlike most applications for DC-DCs however, the load is quite constant when the IGBT is switching at any duty cycle. Alternatively the load is close to zero when the IGBT is not switching. Simple DC-DCs often need a minimum load otherwise their output voltages can dramatically increase, possibly up to the gate breakdown level. This high voltage is stored on the positive bulk capacitor so that when the IGBT starts to switch, it could see a gate overvoltage until the level drops under normal load. A DC-DC should be chosen therefore that has clamped output voltages or zero minimum load requirements.

DC-DC converter start-up and shutdown

IGBTs should not be actively driven by PWM signals until the drive circuit voltage rails are at correct values. However, as gate drive DC-DCs are powered up or down, a transient condition might exist where IGBTs could be driven on, even with the PWM signal inactive, leading to shoot-through and damage. The DC-DC should therefore be well behaved with short and monotonic rise and fall times. A primary referenced on-off control can enable sequencing of power-up of the DC-DCs in a bridge reducing the risk of shoot-through.

DC-DC converter coupling capacitance

DC-DCs for 'high side' IGBT drives see the switched 'DC-link' voltage across their barrier. This voltage can be kilovolts with very fast switching edges from 10 kV/μs upwards. Latest GaN devices may switch at 100 kV/μs or more. This high 'dV/dt' causes displacement current through the capacitance of the DC-DC isolation barrier of value:

$$I = C \cdot dV/dt$$

So for just 20 pF and 10 kV/μs, 200 mA is induced. This current finds an indeterminate return route through the controller circuitry back to the bridge causing voltage spikes across connection resistances and inductances potentially disrupting operation of the controller and the DC-DC converter itself. Low coupling capacitance is therefore desirable, ideally less than 15 pF.

Converter isolation

When the IGBT driver is powered by an isolated DC-DC converter, the barrier in the converter will be expected to withstand the switched voltage applied to the IGBTs which may be kilovolts at tens of kHz. Because the voltage is switched, the barrier will degrade over time faster than with just DC by electrochemical and partial discharge effects in the barrier material. The DC-DC converter must therefore have robust insulation and generous creepage and clearance distances. If the converter barrier also forms part of a safety isolation system, the relevant agency regulations apply for the level of isolation required

(basic, supplementary, reinforced), operating voltage, pollution degree, overvoltage category and altitude.

EN 62477-1:2012 is an appropriate standard to apply for 'Power Electronic Converter Systems' where IGBTs would commonly be used.

Temperature ratings

It is advisable to place the IGBT driver and its DC-DC converter as close as possible to the IGBT to minimise noise pick up and volt drops. This places the components in a potentially high temperature environment where reliability and lifetime reduces. DC-DC converters should be chosen with appropriate ratings and without internal components that suffer significantly with temperature such as electrolytic capacitors and opto-couplers. The rated maximum operating temperature for a low power DC-DC converter will normally be specified at maximum load and no forced airflow. If the average load is lower than maximum or there is guaranteed airflow, the converter manufacturer may be able to provide data showing that critical temperatures are not exceeded at higher temperatures. This will not always be the case as the simplest of converters can have much reduced efficiency at lighter loads negating any load derating benefit. If the converter is providing a safety barrier, the user should also look for any conditions of use in the data sheet imposed by the safety agency. This would typically be a maximum operating temperature less than the manufacturer's maximum for non-safety barrier applications. Consider any thermal shock conditions; a DC-DC converter may work at constant extremes of temperature happily but may fail or degrade if subjected to very high thermal shock.

Operating temperature affects any converter's failure rate. Data sheet MTTF values will typically be quoted at 25 or 40 Celsius and should be extrapolated for actual operating temperatures. The converter manufacturer should be able to do this easily. Often MIL-HBK 217 is used for reliability prediction as a most pessimistic standard but other standards are sometimes used giving dramatically different answers so comparison of data sheet values should be approached with care.

Alternatives to isolated DC-DC converters

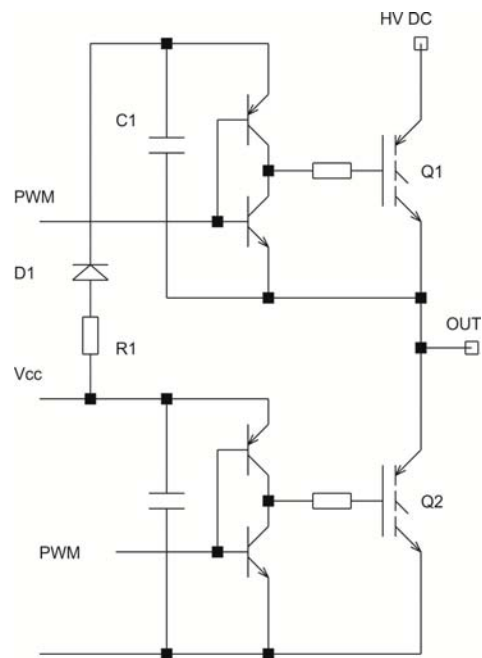
It is not always necessary to use isolated DC-DC converters to provide drive power to IGBTs. If isolation is not required then a cheap and simple charge pump can suffice as shown in Figure 3. C1 is charged through D1

and R1 when Q2 is on. When Q2 is off and Q1 switches on, D1 is reverse biased and C1 now provides a voltage referenced to the upper IGBT emitter to power its driver.

Disadvantages of this approach are:

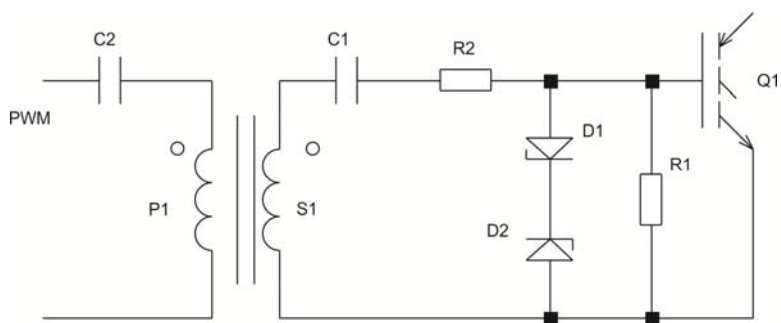
- No drive voltage available if IGBTs are not switching.
- No isolation to meet safety requirements.
- Only suitable for low power.
- Generation of positive and negative gate drive voltages is more complex.
- Not suitable for 'normally on' devices.
- Diode D1 must be high voltage and have very low reverse recovery current.
- R1 is necessary to limit high peak current into C1 but affects C1 voltage as duty cycle changes.
- No continuous power for control and monitoring (e.g. desaturation detection).

Figure 3. IGBT gate drive power provided by a charge pump.



Another alternative to an isolated DC-DC converter is to drive the gate of the IGBT directly from the PWM signal through a transformer as shown in Figure 4.

Figure 4. IGBT transformer- coupled gate drive.



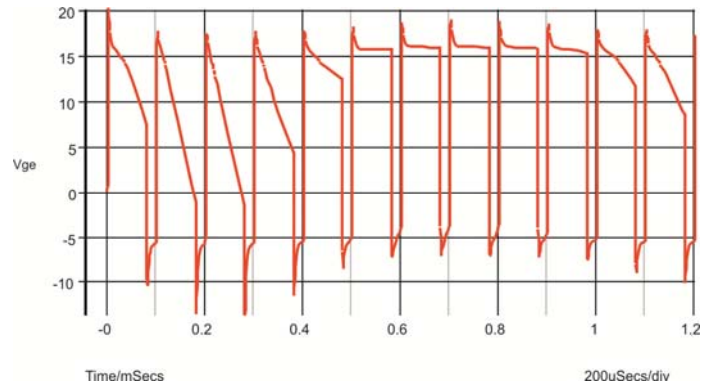
Disadvantages of this approach are:

- Drive voltages depend on duty cycle without C1, C2, D1 and D2 to provide 'DC restoration' and constant positive/negative drive voltages.
- C1, C2 have to 'settle' to DC offsets on start-up and with changes in duty cycle. See Figure 5.
- The transformer may have to deliver significant power (watts) so may be large and unsuitable for high frequencies (IGBT gate power requirement increases with frequency).
- A large transformer has high coupling capacitance giving high circulating currents from dV/dt across the transformer.
- Transformers designed for low coupling capacitance have high leakage inductance limiting PWM slew-rate.
- The transformer requires special construction to meet any safety agency standards for isolation.
- The transformer primary has to be driven by a high speed buffer for high power which is complex and costly for good bandwidth.
- Not suitable for 'normally on' devices.
- No continuous power for control and monitoring (e.g. desaturation detection).
- Transformer must 'reset' between pulses – must consider pulse width limits and reset voltage limits.

Figure 5 shows a simulation of the typical effect on the gate drive voltage of C1 and C2 resonantly settling to their final average DC offsets after switch on to 80% duty cycle. On-state drive voltages are seriously

distorted risking IGBTs being insufficiently saturated for the duration. Sudden changes in duty cycle produce the same effect during normal operation.

Figure 5. Distortion of IGBT gate drive voltage while coupling capacitors settle.



Conclusion

DC-DC converters providing gate drive power for IGBTs need specific performance characteristics but provide significant advantages over alternative techniques in obtaining optimum IGBT efficiency and security under all start-up, transient and continuous operating conditions.

Figure 6. Typical 2 W IGBT driver DC-DC converter from Murata Power Solutions with 5.2 kV test isolation voltage, 3 pF coupling capacitance, optimised output voltages, zero minimum load requirement and safety agency ratings. The product is available with a selection of inputs and bipolar outputs to suit IGBTs and MOSFETs.

