APPLICATION NOTE

DRIVE CIRCUITS FOR POWER MOSFETs AND IGBTs

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1. INTRODUCTION

Unlike the bipolar transistor, which is current driven, Power MOSFETs, with their insulated gates, are voltage driven. A basic knowledge of the principles of driving the gates of these devices will allow the designer to speed up or slow down the switching speeds according to the requirements of the application.

It is often helpful to consider the gate as a simple capacitor when discussing drive circuits.

2. IGBT / MOSFET DRIVE BASICS

2.1 Gate vs Base

Power MOSFETs and IGBTs are simply voltage driven switches, because their insulated gate behaves like a capacitor. Conversely, switches such as triacs, thyristors and bipolar transistors are "current" controlled, in the same way as a PN diode.

2.2 Driving a gate

As shown in figure 2, driving a gate consists of applying different voltages: 15V to turn on the device through S1, and 0V to turn off the device through S2. A remarkable effect can be seen in both the turn-on and turn-off switching waveforms; the gate voltage exhibits a "step", remaining at a constant level while the drain voltage rises or falls during switching. The voltage at which the gate voltage remains during switching is known as the Miller voltage, V_{gm}. In most applications, this voltage is around 4 to 6V, depending on the level of current being switched. This feature can be used to control the switching waveforms from the gate drive.

2.3 MOSFET and IGBT turn-on / turn-off.

When turned on under the same conditions, IGBTs and MOSFETs behave in exactly the same way, and have very similar current rise and voltage fall times - see figure 3.

However, at turn-off, the waveforms of the switched current are different, as shown in figure 4. At the end of the switching event, the IGBT has a "tail current" which does not exist for the MOSFET.

This tail is caused by minority carriers trapped in the "base" of the bipolar output section of the IGBT causing the device to remain turned on. Unlike a

Figure 1. Nature of power semiconductor inputs

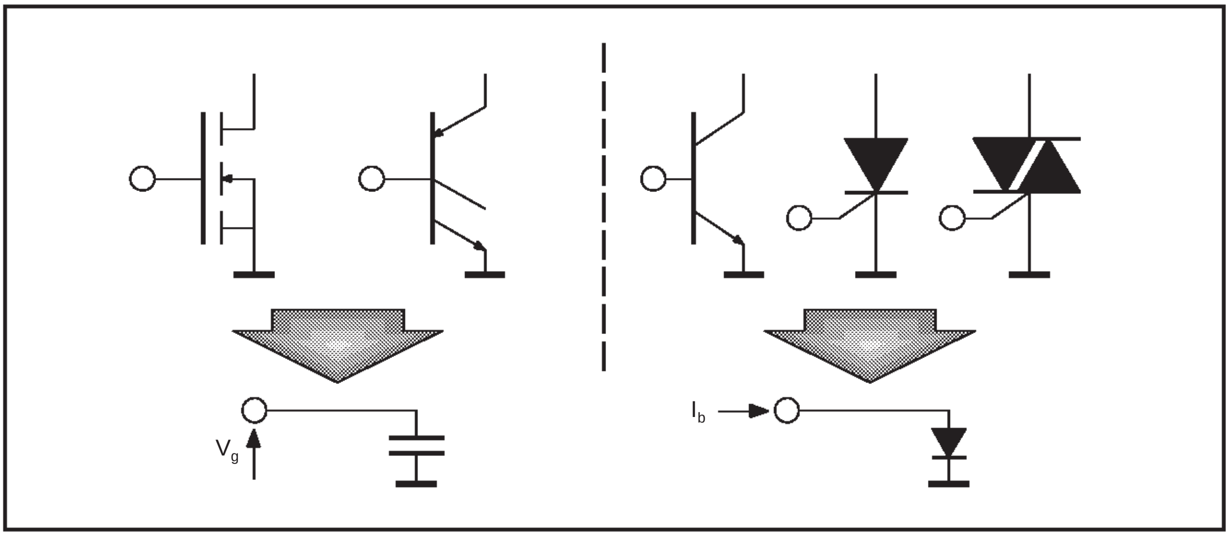


Figure 2. Driving MOSFET / IGBT gates

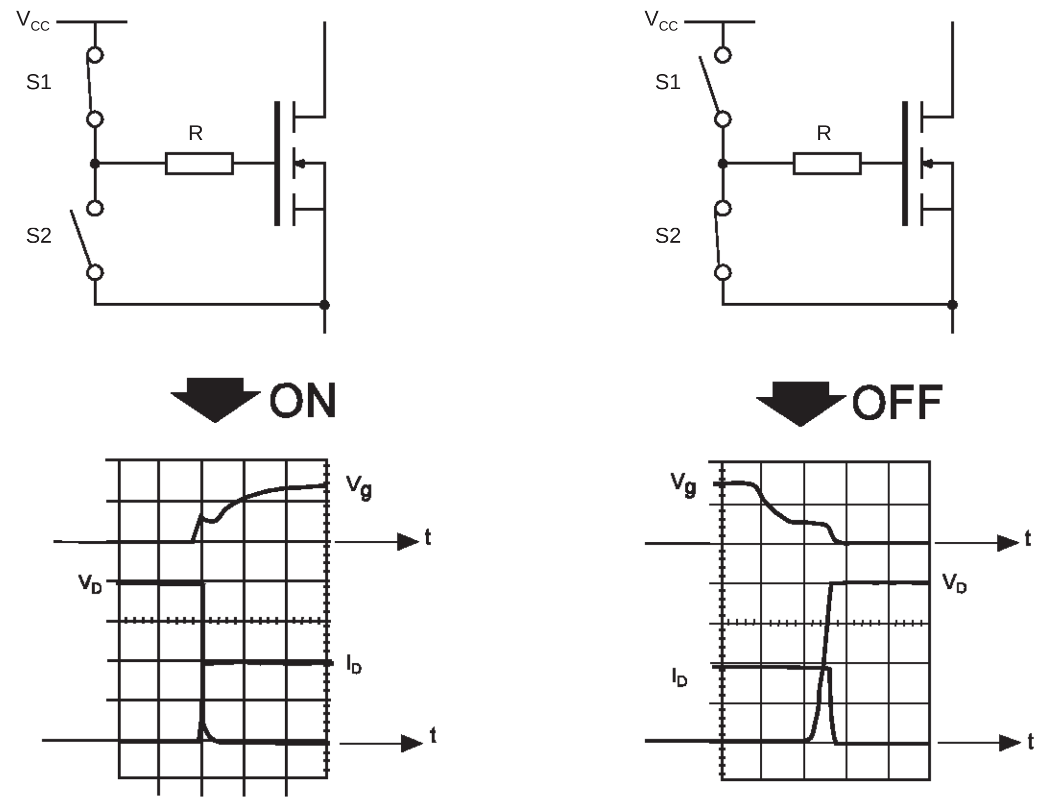
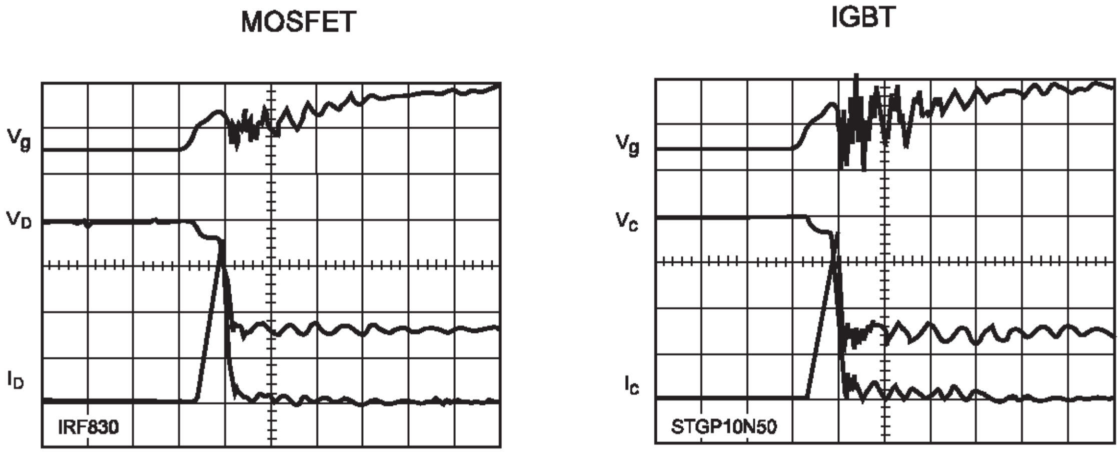
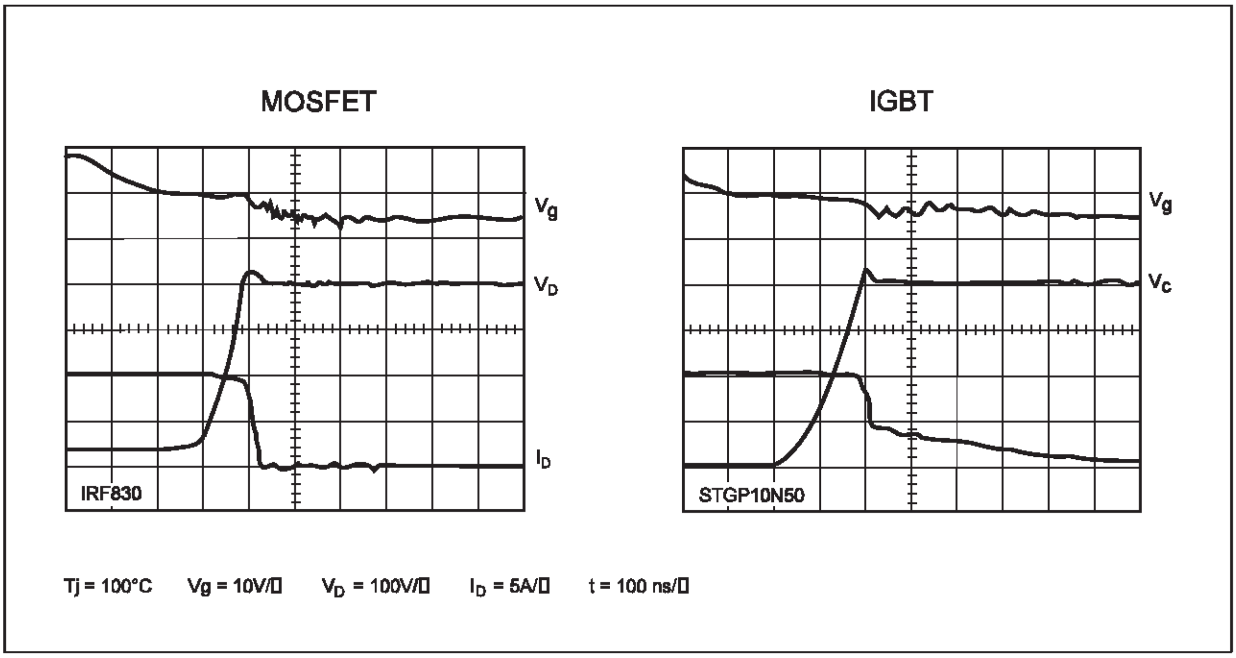


Figure 3. MOSFET / IGBT turn-on



T_j = 100°C V_g = 10V/□ V_D = 100V/□ I_D = 5A/□ t = 100 ns/□

Figure 4. MOSFET / IGBT turn-of



bipolar transistor, it is not possible to extract these carriers to speed up switching, as there is no external connection to the base section, and so the device remains turned on until the carriers recombine naturally. Hence the gate drive circuit has no effect on the tail current level and profile. The tail current does however increase significantly with temperature.

2.4 IGBT turn-off losses

The turn-off of an IGBT can be separated into two distinct periods, as shown in figure 5. In the first period, its behaviour is similar to that of a MOSFET. The increase in drain voltage (dV/dt) is followed by a very fast fall of the switched current. Losses in this “dV/dt” period depend mainly on the speed of the voltage increase, which can be controlled by a gate drive resistor.

The second “tail current” period is specific to the IGBT. As this period occurs while there is already a large voltage across the device, it causes losses at each turn-off.

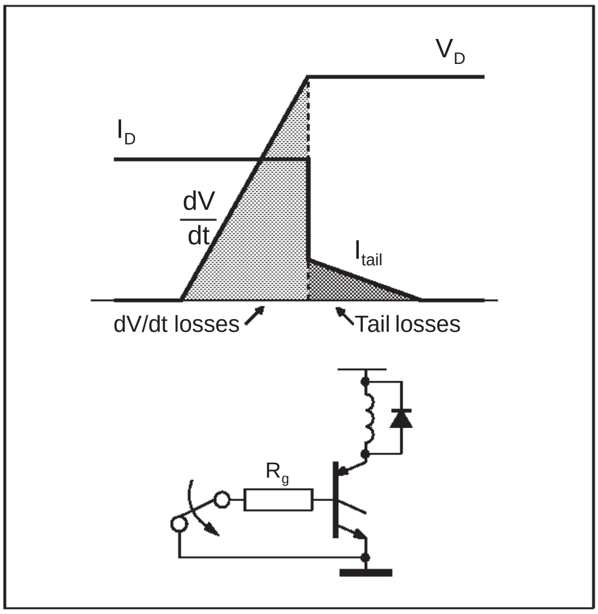
The total turn-off losses are shown in figure 5 by the shaded area.

3. FROM GATE DRIVE TO SWITCHING

3.1 Speeding up turn-off

The power involved in these two types of switching losses is linked to the switching frequency. Turn-off losses become critical when operating at high frequencies. In this case, the dV/dt can be increased (and hence losses reduced) by decreasing the size of the gate drive resistor R_g, which will allow the gate to charge more quickly. The turn-off losses are proportional to the size of the gate resistor - for example decreasing the gate resistor from 100 to 10

Figure 5. IGBT turn-off losses



will reduce the dV/dt losses by a factor of 10 - see figure 6.

However, it should be remembered that IGBT tail current losses are completely independent of the value of the gate resistor.

It can be noted that in figure 6 the dV/dt and tail current losses are around the same with a gate resistance of 47Ω.

Even though the tail current is constant, the losses in a system are often predominantly due to dV/dt, because the value of the gate resistance is often too high. In the example of figure 7, the total losses per cycle are reduced from 13mJ to 4mJ by decreasing the gate resistance from 100Ω to 10Ω.

3.2 Reducing dV/dt at turn-off

Conversely, in low frequency applications, fast switching waveforms can cause problems in the form of EMI. A gate driven switch can be used to reduce the amount of EMI, by slowing down the switching speed. This is particularly useful in applications where the mains phase angle is controlled.

The dV/dt can be expressed as:

$$\frac{dV}{dt} = \frac{V_{gm}}{(R_g \, . \, C_{iss})}$$

where V_{gm} (the Miller gate voltage) is around 6V, C_{rss} is the equivalent gate-drain capacitance and R_g is the value of the gate resistor at turn-off. One method of slowing down the switching is thus to slow the rate at which the gate capacitor is charged - see figure 8. This can be achieved using a large gate resistor to make the gate charge more slowly and hence increase the dV/dt time. Throughout the dV/dt period, the voltage across the gate resistor is equal to the Miller voltage (V_{gm}), and for a short time the power switch operates in linear mode. In this example, with a STGP10N50 IGBT ($C_{rss} \approx$ 40pF) the dV/dt will be around 7.5V/µs.

Alternatively, a capacitor can be connected between the gate and collector / source of the device, which increases the capacitance which must be discharged through the gate resistance at turn-off.

Figure 6. Speeding up turn-off

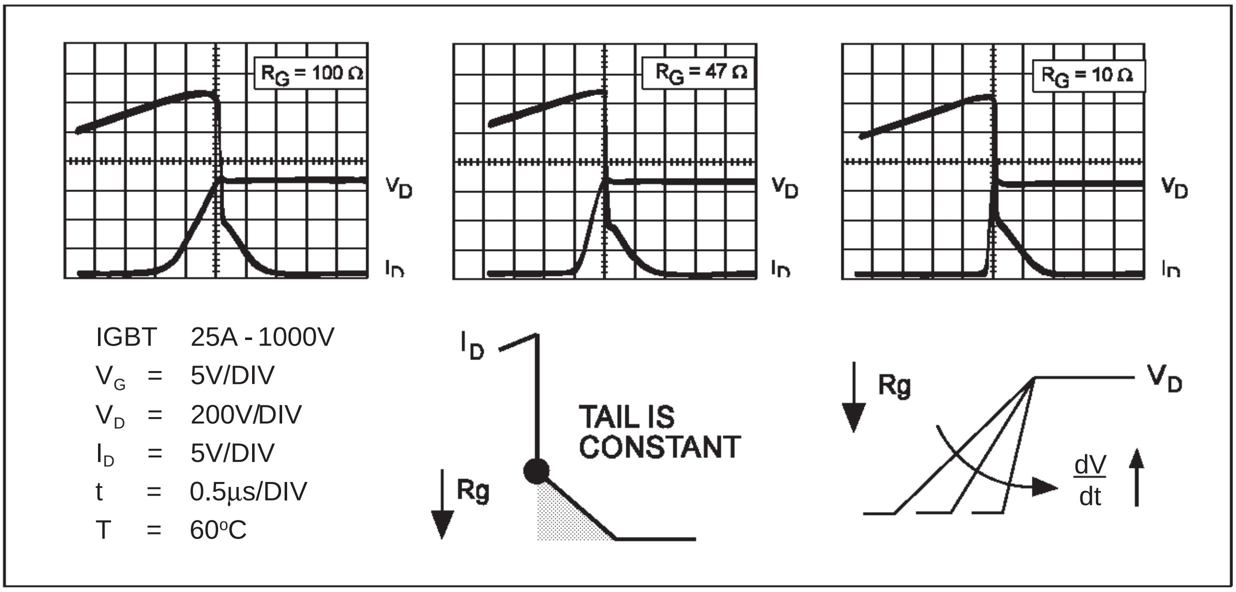


Figure 7. Variation of turn-off losses with gate resistance

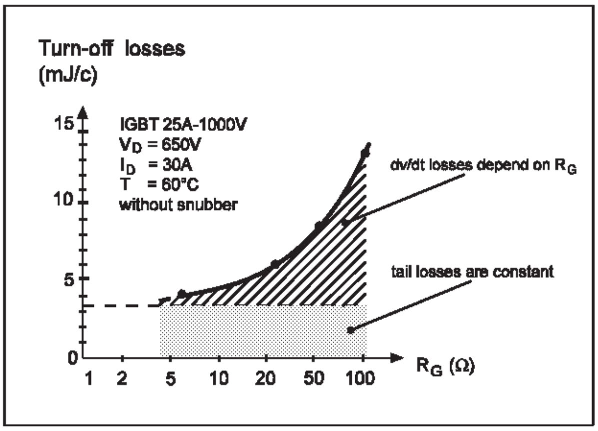
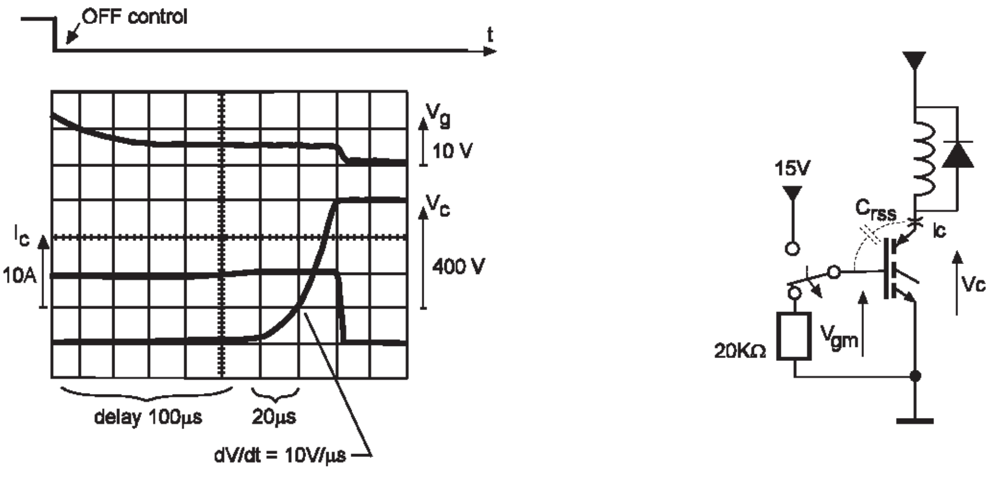


Figure 8. Slowing down turn-off using a gate resistor



3.3 Reducing dI/dt at turn-off and turn-on

A technique which slows both turn-on and turn-off uses a small inductor l_E placed in the emitter/source lead of the device, as shown in figure 9. The voltage e developed across the inductor during switching, given by:

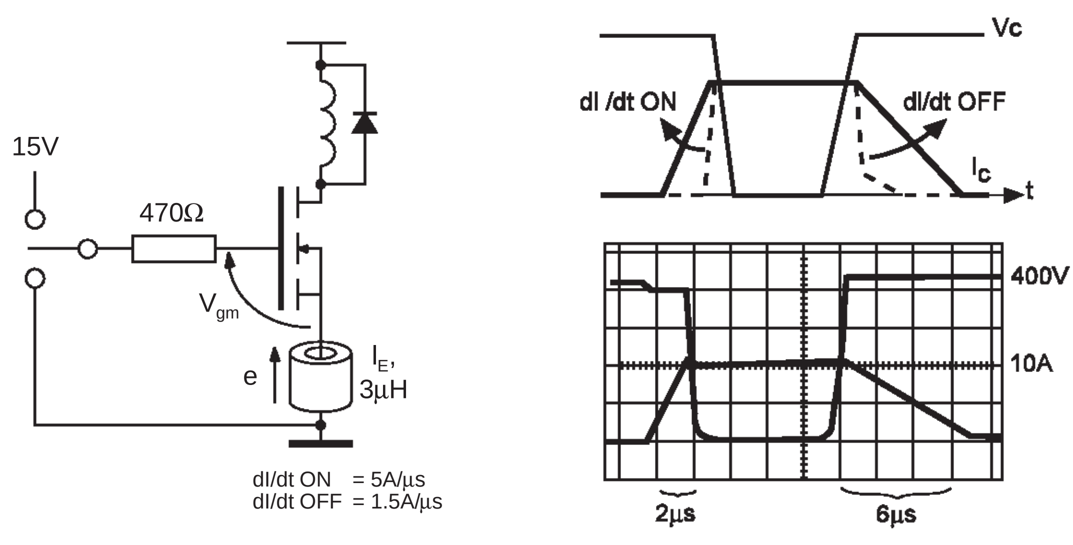
$$e = l_E \cdot \frac{dI}{dt}$$

must be equal to the difference between the gate drive voltage and the Miller gate voltage (V_{gm}, around 6V). The value of dI/dt can thus be calculated as:

$$\frac{dI}{dt} = \frac{(V_g - V_{gm})}{l_E}$$

For example, in the 4kW example shown in figure 9, at turn-off (V_g = 0V) dI/dt = -6V / 3µH = -2A/µs. To give an idea, in the circuit used in this example the switching losses are only around 0.8W.

Figure 9. Slowing down the switching of the current using a feedback inductor



4. THE GATE AS A CAPACITOR

4.1 Gate as memory

The capacitive nature of the gate input can be exploited in many different ways, for example as a memory.

In the circuit of figure 10 a single voltage pulse applied to the gate through diode D1 is sufficient to charge the input capacitance C_{in} and turn on the switch T1. When the pulse has finished, D1 prevents the gate discharging, and so the device remains on: the gate is behaving as a memory of the on-state of the switch. To "erase" the gate memory and turn off the switch, a pulse is applied to the diode D2 which turns on T2, which in turn discharges the gate of T1 and turns the device off. As T2 remains on, T1 cannot be accidentally turned on due to dV/dt effects, and so the gate of T2 is now behaving as a memory of the off state of T1.

As the pulse duration times required to turn the devices on and off are very small, this principle can be adapted to suit a wide variety of switching frequencies: from almost continuous operation up to 1MHz.

In low frequency applications, refresh pulses can be used to prevent the gate capacitor discharging due to leakage currents.

The major benefit of this technique lies in the very small size of the pulse transformer required for a wide range of switching frequencies.

For further information on this subject, see reference 1.

4.2 Using the gate in resonant circuits

The gate capacitor can also be used as part of a resonant LC network - see figure 11. With the same peak current value, the capacitor is charged around twice as fast with an inductor compared to a resistor. If the resistor is replaced with an inductor, losses in the gate drive resulting from the charge and discharge current of the gate capacitor become negligible. This solution is particularly efficient in very high frequency applications where gate drive losses become more critical.

An additional benefit is that a resonant circuit has an inherent voltage step-up ability, which means that the 15V required to drive the gate can be generated from a much lower voltage.

Figure 12 shows an example of the gate capacitance being used as part of a resonant circuit.

This type of solution is mainly of use in drive circuits of high power MOSFETs which interface directly with standard 5V CMOS microcontrollers.

Figure 10. Using the gate as a state memory

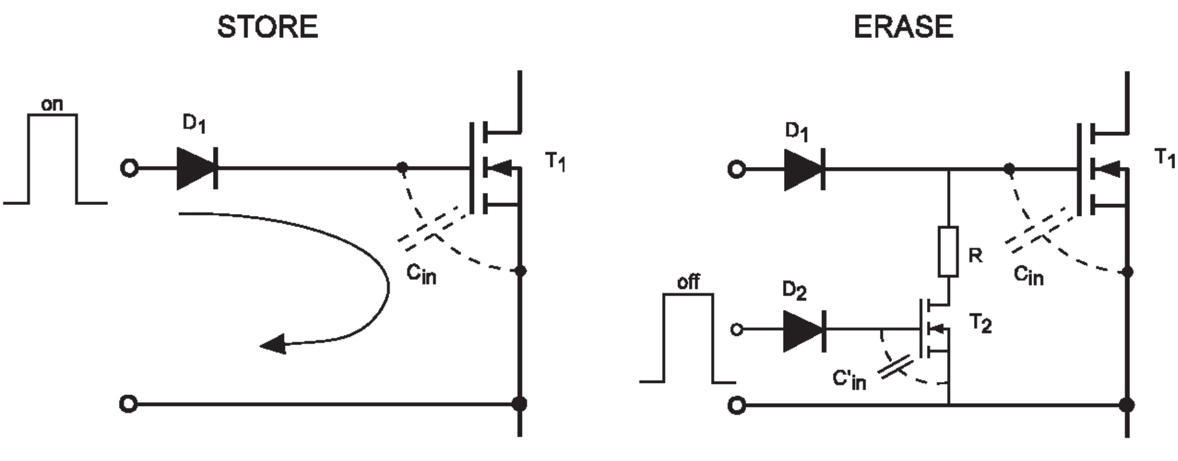


Figure 11. Using the gate capacitance in a resonant circuit

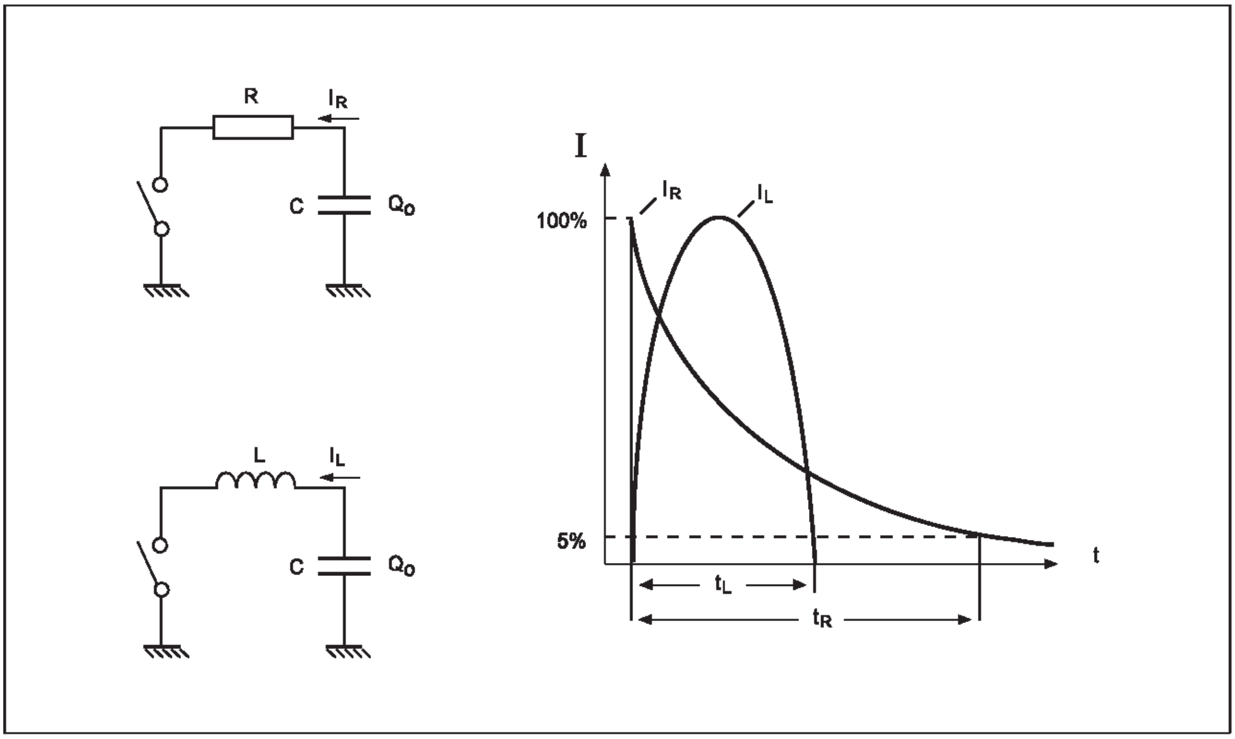
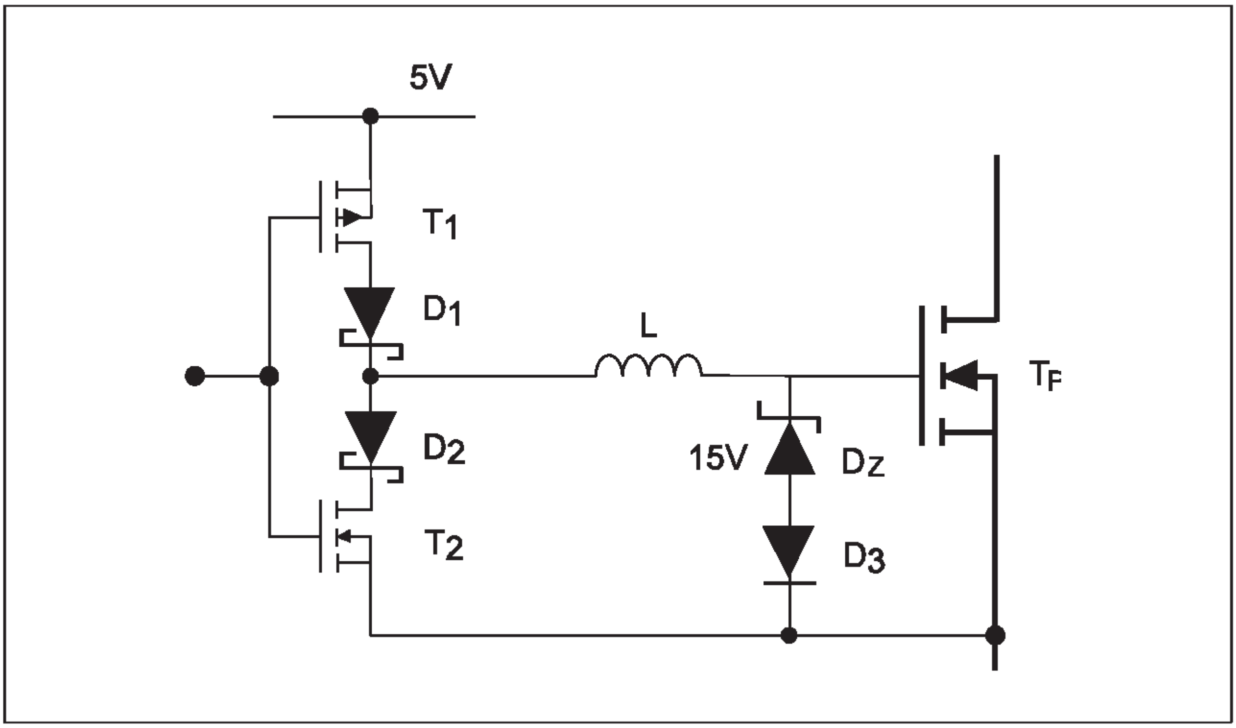


Figure 12. Resonant gate drive circuit



4.3 The gate as an EMI reducer

As mentioned above, the switching waveforms of Power MOSFETs and IGBTs can easily be slowed by adjusting the value of the gate resistor. This feature can be used as an EMI reducer in applications where the mains phase angle is switched (figure 13), for example light dimmer circuits.

Conventional dimming circuits are controlled by TRIACs. Turning a TRIAC on or off generates voltage spikes and uncontrolled dV/dt. In most cases a TRIAC requires a series inductor for EMI filtering.

When the power is controlled by an IGBT, the switching behaviour can be softened at both turn-on and turn-off so that the inductor is no longer required. The switching losses incurred by slowing down the turn-off of the IGBT are not critical at mains frequency.

The soft light dimmer shown in figure 14 and discussed in reference 2 is based on the use of an IGBT as a switch whose turn-off may be controlled. Such a circuit allows the current switching slopes to be controlled, removing the need for an EMI filter, reducing costs and eliminating the associated acoustic noise. Short circuit protection can also be built in, which means that a fuse is no longer required.

Figure 13. EMI reduction

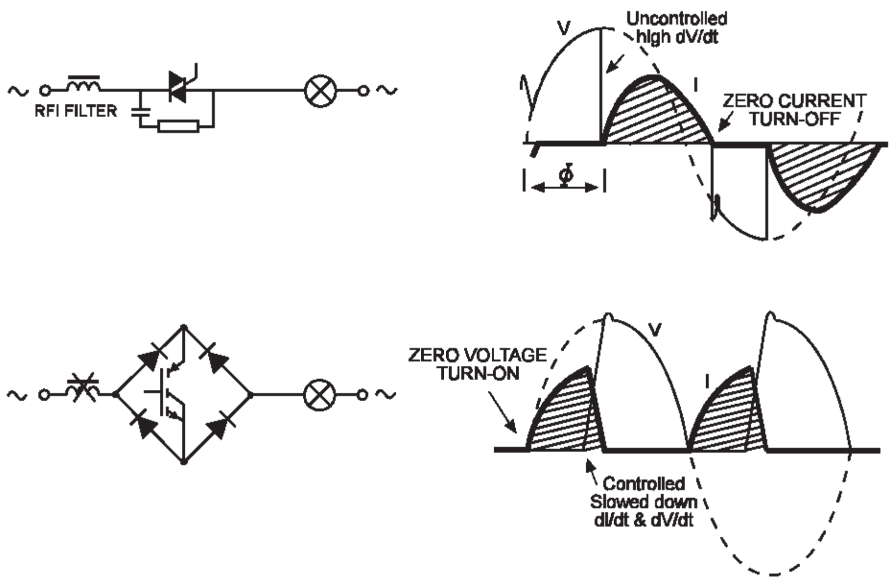
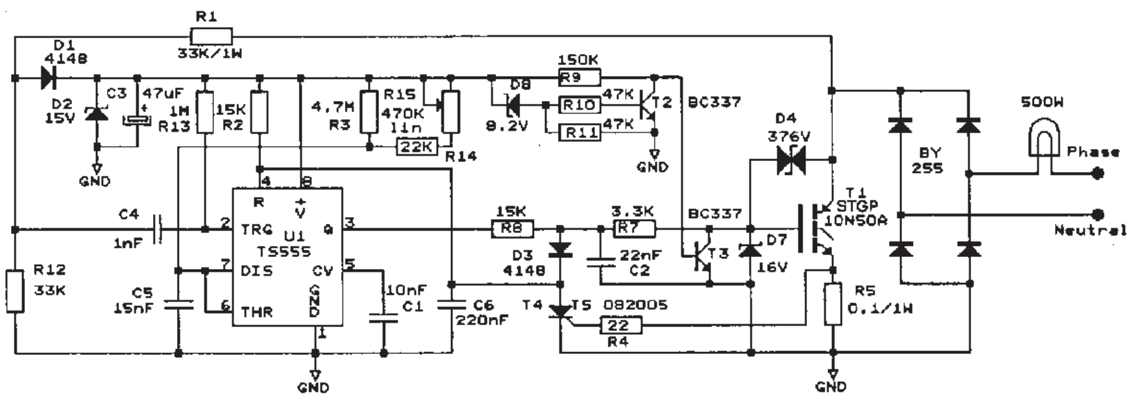


Figure 14. Soft light dimmer circuit



4.4 Automatic floating gate drive

Another useful feature resulting from the small size of the gate capacitor is the low drive energy required to switch high current levels. This characteristic has been used for automatic floating gate drives in asymmetrical half bridges - see reference 3.

Because the drain/emitter voltage of the high side switch in an asymmetrical half bridge floats, most applications require an additional pulse transformer to drive it. In most cases this pulse transformer provides the isolation required to interface the high side switch with the ground-connected PWM control circuit.

However, in the circuit shown in figure 15 an auxiliary winding of the power transformer is used to drive the high side switch as a synchronized slave of the grounded low side switch; when the low side switch turns on or off, the high side switch is automatically turned off or on.

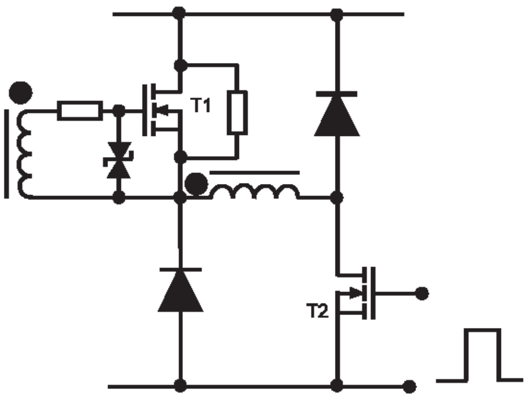
This circuit removes the need for a pulse transformer, and works with very few external components.

4.5 Using multiple drive voltages

The drive circuit shown in figure 16 takes advantage of the voltage driven nature of the gate. In normal operation, 15V is applied to drive the gate fully on, but if an overcurrent is detected, the gate voltage is clamped at 6V (the Zener diode voltage of Z2), limiting the collector current.

Overcurrent is detected by monitoring the collector-emitter voltage of the IGBT - in normal operation the V_{CE} voltage drop will typically be around 2 - 3V, but this increases with increasing collector current. The Zener diode Z1 is selected to set the V_{CE} level at which the protection will operate.

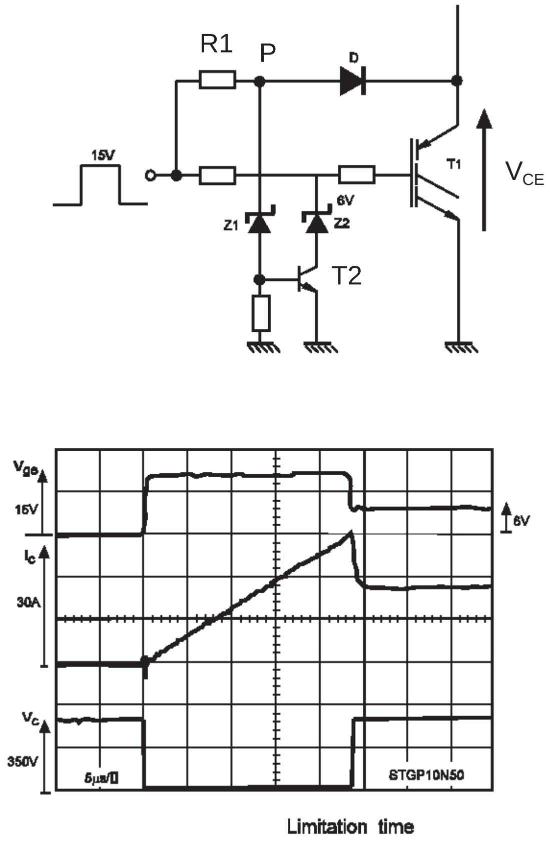
Figure 15. Automatic floating gate drive



Consequently, in the normal mode of operation, 15V is applied to the input to turn the transistor fully on, which also causes the diode D to be forward biassed through resistor R1. The voltage at point P is thus equal to the V_{CE} voltage drop across the IGBT, plus the voltage drop across D. The rating of Z1 is chosen such that in these conditions it remains blocked.

However, if an overcurrent causes the V_{CE} of the IGBT to increase, when the voltage at point P reaches the rating of the Zener Z1, Z1 begins to conduct, turning on T2, and clamping the voltage at point P, causing D to become reverse biassed. Turning on T2 causes Zener Z2 to clamp the IGBT gate voltage at 6V, limiting the collector current to a lower level.

Figure 16. Current limitation using multiple drive voltages



5. TRENDS

Although insulated gate devices are widely used and well understood, it remains interesting to reconsider the gate operating as a simple capacitor. A useful feature of insulated gate switches is their ability to soften switching waveforms easily. IGBTs used in this way, as EMI reduction / turn-off controllable switches, are a very attractive alternative to TRIACs in lamp dimming circuits.

Additionally, the ability of insulated gate switches to be driven with a small amount of energy has lowered the power level at which half bridge topologies can effectively be used. This trend of the last decade is highlighted demonstrated by the advent of integrated high side driver circuits. For this reason, equipment designers will no longer hesitate to drive high side floating Power MOSFETs and IGBTs, even in the 100W power range.

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