CHAPTER 5

Automotive Power Electronics

5.1 Automotive Motor Control (including selection guides)

5.2 Automotive Lamp Control (including selection guides)

5.3 The TOPFET

5.4 Automotive Ignition

Automotive Motor Control

(including selection guides)

5.1.1 Automotive Motor Control with Philips MOSFETS

The trend for comfort and convenience features in today's cars means that more electric motors are required than ever - a glance at Table 1 will show that up to 30 motors may be used in top of the range models, and the next generation of cars will require most of these features as standard in middle of the range models.

All these motors need to be activated and deactivated, usually from the dashboard; that requires a lot of copper cable in the wiring harnesses - up to 4km in overall length, weighing about 20 kg. Such a harness might contain over 1000 wires, each requiring connectors at either end and taking up to six hours to build. Not only does this represent a cost and weight penalty, it can also create major 'bottlenecks' at locations such as door hinges, where it becomes almost impossible to physically accommodate the 70-80 wires required. Now, if the motor switching, reversing or speed control were to be done at the load by semiconductor switches, these in turn can be driven via much thinner, lighter wiring thus alleviating the bottlenecks. Even greater savings - approaching the weight of a passenger - can be achieved by incorporating multiplex wiring controlled by a serial bus.

Types of motors used in automobiles

Motor design for automotive applications represents an attempt at achieving the optimum compromise between conflicting requirements. The torque/speed characteristic demanded by the application must be satisfied while taking account of the constraints of the materials, of space and of cost.

There are four main families of DC motors which are, or which have the potential to be used in automobiles.

Wound field DC Commutator Motors

Traditionally motors with wound stator fields, a rotor supply fed via brushes and a multi-segment commutator - see Fig. 1 - have been widely used. Recently, however, they have been largely replaced by permanent magnet motors. Characteristically they are found with square frames. They may be Series wound (with high torque at start up but tend to 'run away' on no-load), Shunt wound (with relatively flat speed/torque characteristics) or (rarely) Compound wound.

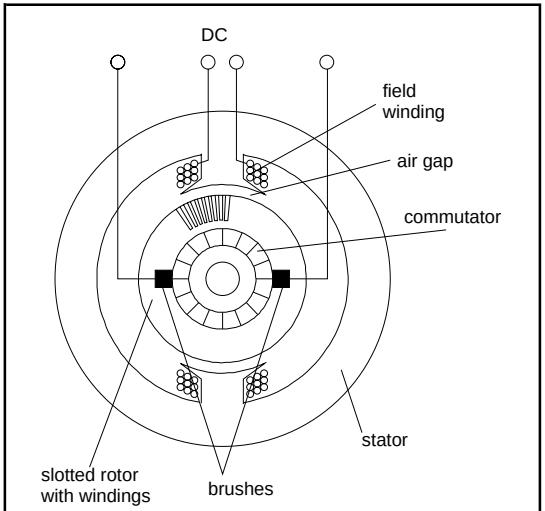
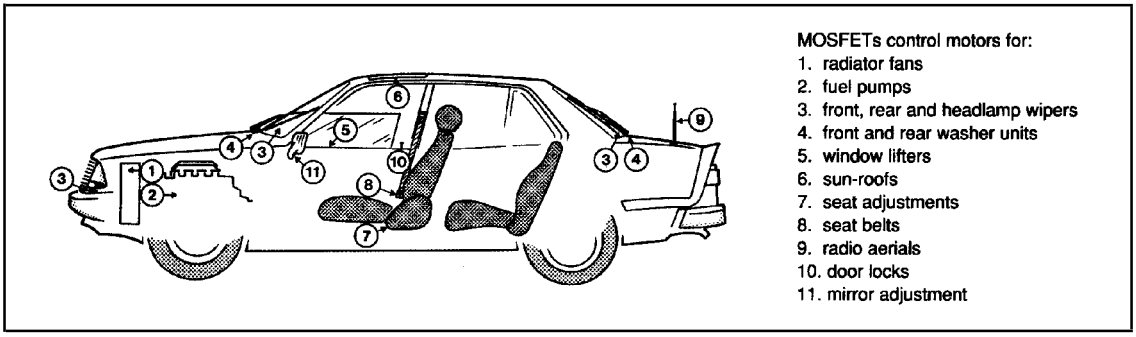


Fig. 1 Wound Field DC Commutator Motor



motor application	typical power (W)	nominal current (A)	typical number of such motors	type of drive	typical number of switches per motor	proposed standard BUK-	MOSFET * L^2FET BUK-	comments
air-conditioning	300	25	1	unidirectional, variable speed	1	456	556	Active suspension may also require such high power motors
radiator fan	120-240	10-20	1	unidirectional, variable speed	1	455	555	These motors may go brushless, requiring 3 to 6 lower rated switches
fuel pump	100	8	1	unidirectional	1	453	553	
wipers: front			1-2	unidirectional, variable speed				Reversing action is at present mechanical. This could be done electronically using 2 or 4 switches
rear	60-100	5-8	1		1	452/453	552/553	
headlamp			2					
washers: front			1-2					
	30-60	2.5-5		undirectional	1	452	552	
rear			1-2					
window lifter	25-120	2-10	2-4	reversible	4	452/455	552/555	
sun-roof	40-100	3.5-8	1	reversible	4	452/453	552/553	
seat adjustment (slide, recline, lift, lumbar)	50	4	4-16	reversible	4	453	553	
seat belt	50	4	2-4	reversible	4	453	553	
pop-up headlamp	50	4	2	reversible	4	453	553	
radio aerial	25	2	1	reversible	4	452	552	
door lock	12-36	1-3	6-9	reversible	4	451/452	551/552	
mirror adjustment	12	1	2	reversible	4	451	551	

* These are meant for guidance only. Specific applications should be checked against individual users requirements. In addition to standard and L^2FETs, FredFETs and low and high side TOPFETs might be considered. Also a variety of isolated, non-isolated and surface mount package options are available

Table 1 Typical motor and switch requirements in top of range car.

Permanent Magnet (PM) DC Commutator Motors

These are now the most commonly used motors in modern cars. The permanent magnet forms the stator, the rotor consists of slotted iron containing the copper windings - see Fig. 2. They have a lighter rotor and a smaller frame size than wound field machines. Typical weight ratios between a PM and a wound field motor are:

Copper	1:10
Magnets	1:7
Rotor	1:2.5
Case	1:1

PM motors have a linear torque/speed characteristic - see Fig. 3 for typical curves relating torque, speed, current and efficiency. (Philips 4322 010 76130). They are generally used below 5000 rpm. Their inductance (typically 100 - 500 μH) is much lower than wound field machines. New materials (e.g. neodymium iron boron compounds) offer even more powerful fields in smaller volumes.

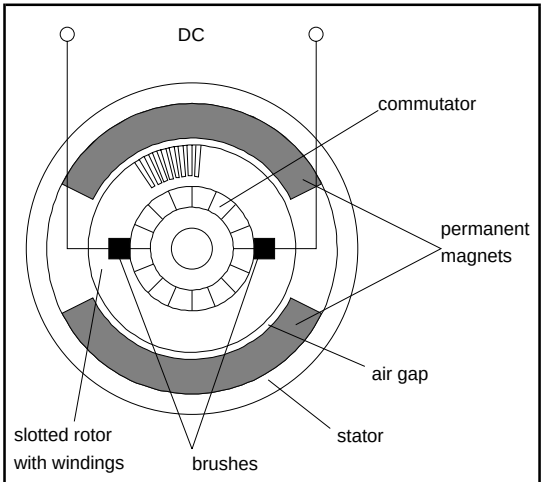


Fig. 2 Permanent Magnet Commutator Motor

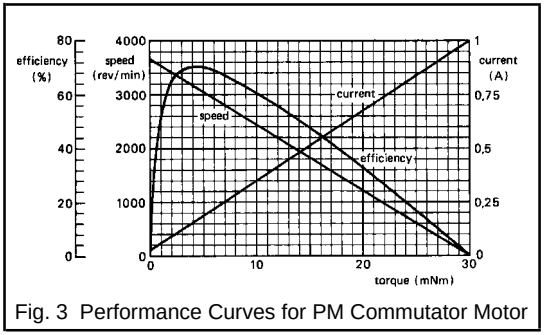


Fig. 3 Performance Curves for PM Commutator Motor

PM Brushless DC Motors

Although common in EDP systems, brushless DC motors are not yet used extensively in cars. They are under consideration for certain specialised functions, e.g. fuel pump where their 'arc free' operation makes them attractive. They have a wound stator field and a permanent magnet rotor - Fig. 4. As their name suggests they have neither mechanical commutator nor brushes, thus eliminating brush noise/wear and associated maintenance. Instead they depend on electronic commutation and they require a rotor position monitor, which may incorporate Hall effect sensors, magneto resistors or induced signals in the non energised winding. Thanks to their lightweight, low inertia rotor they offer high efficiency, high power density, high speed operation and high acceleration. They can be used as servos.

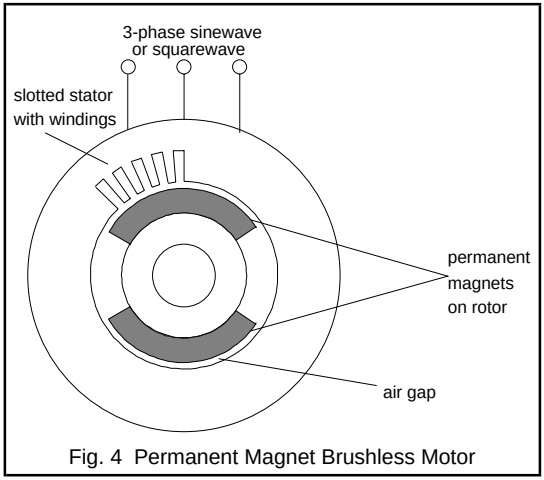


Fig. 4 Permanent Magnet Brushless Motor

Switched Reluctance Motors

These motors - see Fig. 5 - are the wound field equivalent to the PM brushless DC machine, with similar advantages and limitations. Again, not yet widely used, they have been proposed for some of the larger motor applications such as radiator and air conditioning fans, where their high power/weight ratio makes them attractive. They can also be used as stepper motors in such applications as ABS and throttle control.

Motor drive configurations

The type of motor has a considerable influence on the configuration of the drive circuit. The two families of DC motors, commutator and brushless need different drive circuits. However suitably chosen MOSFETs can be used to advantage with both.

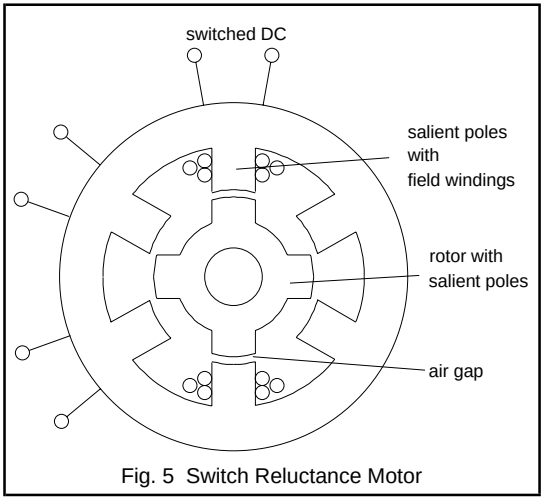


Fig. 5 Switch Reluctance Motor

Commutator Motors

Both permanent magnet and wound field commutator motors can be controlled by a switch in series with the DC supply - Fig. 6. Traditionally relays have been used, but they are not considered to be very reliable, particularly in high vibration environments. Semiconductors offer an attractive alternative, providing:

- low on-state voltage drop.
- low drive power requirements.
- immunity from vibration.

The Power MOSFET scores on all counts, offering ON resistances measured in mΩ and requiring only a few volts (at almost zero current) at the gate, to achieve this.

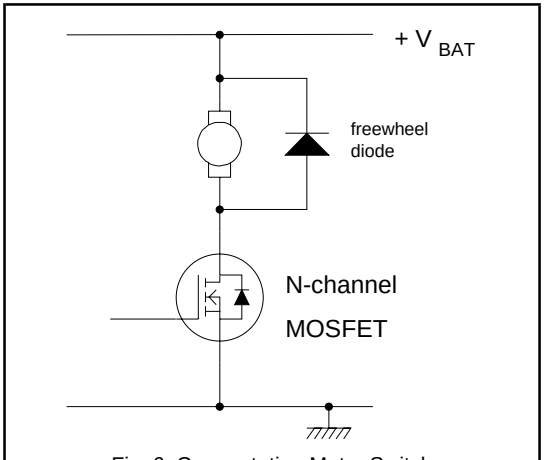


Fig. 6 Commutating Motor Switch

When a motor is switched off, it may or may not be running. If it is, then the motor acts as a voltage source and the rotating mechanical energy must be dissipated either by friction or by being transformed into electrical energy and returned to the supply via the inherent anti-parallel diode of the MOSFET. If it is not turning, then the motor appears as purely an inductance and for a low side switch the voltage transient developed will take the MOSFET into avalanche. Now, depending on the magnitude of the energy stored in the field and the avalanche capability of the MOSFETs, a diode in parallel with the motor may or may not be required.

As a first approximation, if

$$\frac{1}{2}.L_m I_m^2 < W_{DSS}$$

then a diode may not be needed.

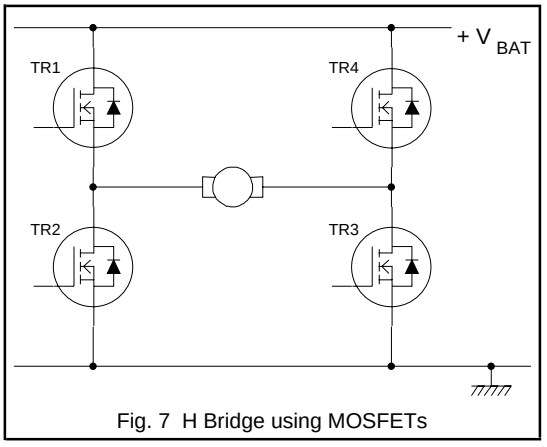


Fig. 7 H Bridge using MOSFETs

Reversing the polarity of the supply, to a commutator motor, reverses the direction of rotation. This usually requires an H bridge of semiconductors, see Fig. 7. In this case the built in diodes, inherent in MOSFETs, mean that no extra diodes are necessary. It should be noted that there are now two devices in series with the motor. So, to maintain the same low level of on-state voltage drop, each MOSFET must be doubled in area. With four devices in all, this means a reversing H bridge requires 8 x the crystal area needed by a unidirectional drive.

Chopping the supply, controls the mean voltage applied to the motor, and hence its speed. In the case of the H bridge TR1 and TR4 might be used to control direction, while a chopping signal (typically 20kHz) is applied to TR3 or TR2. When reversing the direction of rotation, it is preferable to arrange the gating logic so that the system goes through a condition where TR1, TR2, TR3 and TR4 are all off.

Switched Field Motors

PM brushless motors typically require 6 switches to generate the rotating field, see Fig. 8. Although there are motors, which operate at lower power density, which can be driven from 3 switches. The circuit in Fig. 9 shows a low side switch version of such a drive. A similar arrangement with high side switches would be possible.

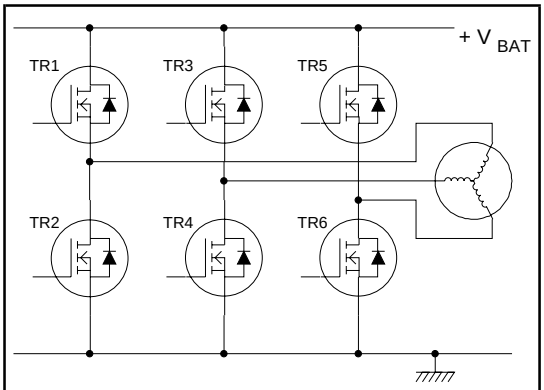


Fig. 8 MOSFET Brushless Motor Drive

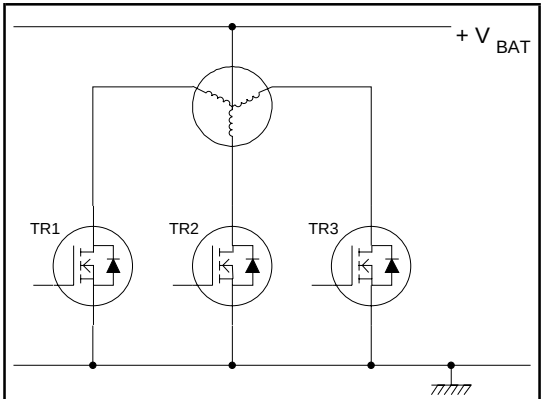


Fig. 9 3 MOSFET Brushless Motor Drive

Switched reluctance motors may use as few as 4 or as many as 12 switches to generate the rotating field, a 4 switch version is shown in Fig. 10.

The speed and direction of all switched field motors is controlled by the timing of the field pulses. In the case of brushless DC machines these timing pulses can be derived from a dedicated IC such as the Philips NE5570. Rotor position sensing is required - using, for example, magnetoresistive sensors - to determine which windings should be energised. Compared with a DC commutator motor, the power switches for a brushless motor have to be fast, because they must switch at every commutation.

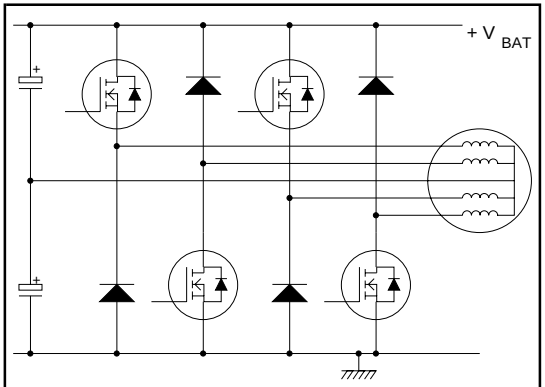


Fig. 10 4 MOSFET Switched Reluctance Motor Drive

PWM speed control pushes up the required switching speed even further. Philips MOSFETs are designed so that both switch and inbuilt diode are capable of efficient switching at the highest frequencies and voltages encountered in automotive applications.

High side drivers

Often, in automobiles, there is a requirement for the switch to be connected to the positive battery terminal with the load connected via the common chassis to negative. Negative earth reduces corrosion and low side load is safer when loads are being worked on or replaced. Also, when H bridges are considered the upper arms are of course high side switches.

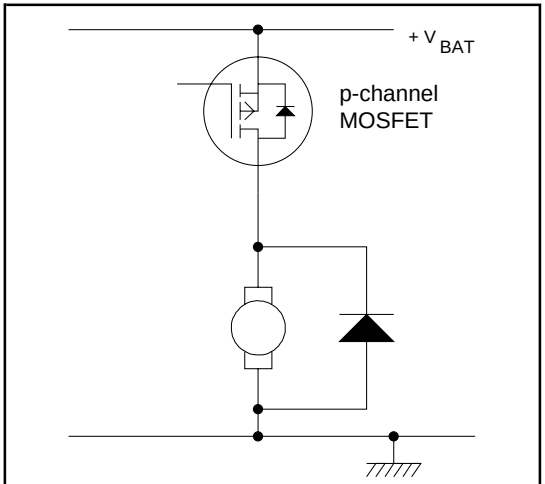


Fig. 11 P-channel high side switch

There are two MOSFET possibilities for high side switches:

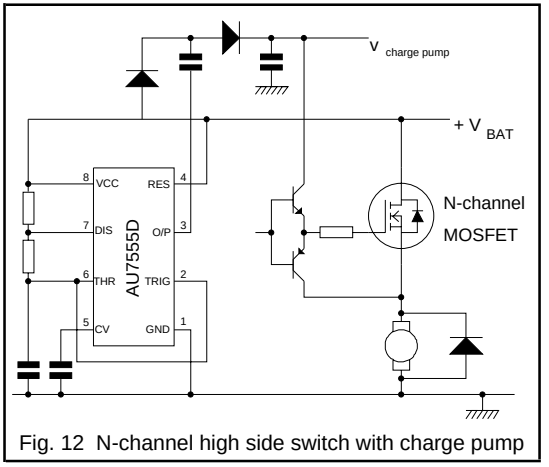


Fig. 12 N-channel high side switch with charge pump

- **P-channel switches**. These simplify the drive circuit which only needs referencing to the positive supply, see Fig. 11. Unfortunately p-channel devices require almost three times the silicon area to achieve the same on resistance as n-channel MOSFETs, which increases cost. Also P-channel devices that can be operated from logic level signals are not readily available.

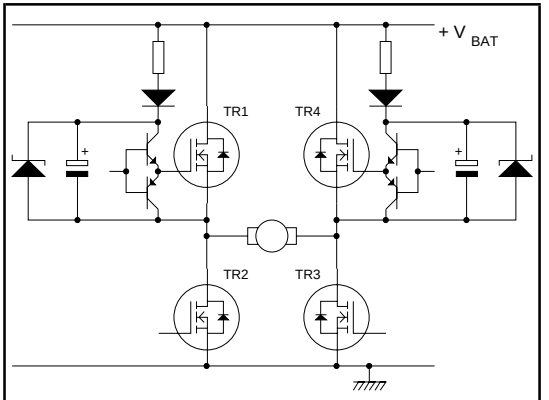


Fig. 13 Bootstrap bridge drive

- **N-channel switches.** To ensure that these are fully turned on, the gate must be driven 10 V higher than the positive supply for conventional MOSFETs or 5 V higher for Logic Level types. This higher voltage might be derived from an auxiliary supply, but the cost of 'bussing' this around the vehicle is considerable.

The additional drive can be obtained locally from a charge pump, an example in shown in Fig. 12. An oscillator (e.g Philips AU7555D) free runs to generate a rectangular 12 V waveform, typically at around 100kHz. A voltage doubler then raises this to around twice the battery voltage. This arrangement is equally suitable for 'DC' or chopper drives.

An alternative approach for H bridge choppers is to use the MOSFETs themselves to generate the drive voltage with a bootstrap circuit as shown in Fig. 13. This circuit works well over a range of mark-space ratios from 5% to 95%. Zener diodes should be used in this circuit to limit the transients that may be introduced onto the auxiliary line.

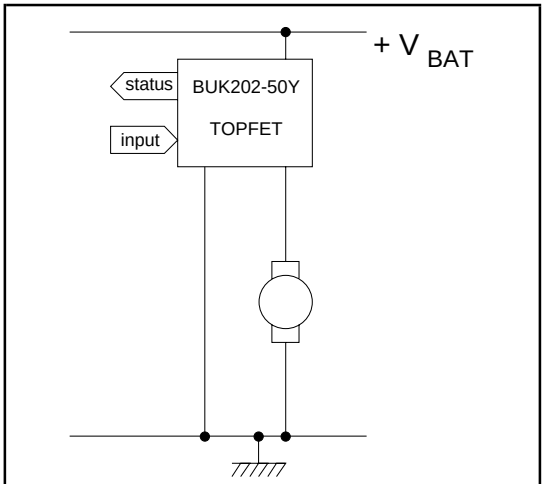


Fig. 14 High Side TOPFET

High Side TOPFET

The ideal high side switch to drive motor loads would be one which could be switched on and off by a ground referenced logic signal, is fully self-protected against short circuit motors and over temperatures and is capable of reporting on the load status to a central controller.

The Philips response to these requirements is a range of high side TOPFETs. The range contains devices with $R_{DS(ON)}$ from 38 to 220 mΩ, with and without internal ground resistors. All the devices feature on board charge pump and level shifting, short circuit and thermal protection and status reporting of such conditions as open or short circuit load. As can be seen in Fig. 14, the use of a TOPFET makes the circuit for a protected high side drive for a motor very simple.

Currents in motor circuits

There are 5 classes of current that can flow in a motor circuit:-

- **nominal** - this is the maximum steady state current that will flow when the motor is performing its function under normal conditions. It is characterised by its relatively low level and its long duration.

- **overload** - this is the current which flows when the motor is driving a load greater than it is capable of driving continuously, but is still performing its function i.e not stalled. This is not necessarily a fault condition - some applications where the motor is used infrequently and for only a short time, use a smaller motor, than would be needed for continuous operation, and over-run it. In these cases the nominal current is often the overload current. Overload currents tend to be about twice the nominal current and have a duration between 5 and 60 seconds.

- **inrush** - or starting currents are typical 5 to 8 times the nominal current and have a duration of around 100 ms, see Fig. 15. The starting torque of a motor is governed by this current so if high torque is required then the control circuit must not restrict the current. Conversely if starting torque is not critical, then current limiting techniques can be employed which will allow smaller devices to be used and permit sensitive fault thresholds to be used.

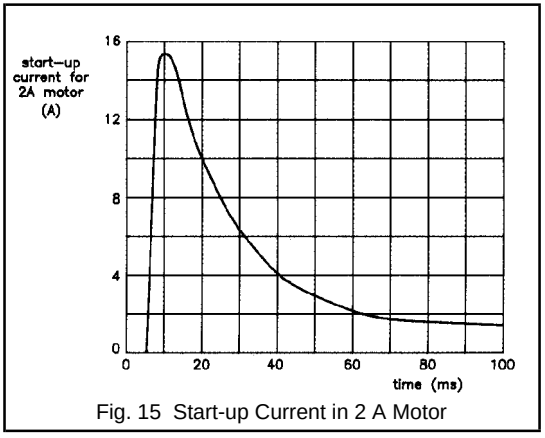


Fig. 15 Start-up Current in 2 A Motor

- **stall** - if the motor cannot turn then the current is limited only by the series resistance of the motor windings and the switch. In this case, a current of 5-8 times the running current can flow through the combination. Fig. 16 shows the current that flows through a stalled 2 A motor - the current gradually falls as the temperature, and consequently the resistance, of the motor and the MOSFET rises.

- **short circuit** - if the motor is shorted out then the current is limited only by the resistance of the switch and the wiring. The normal protection method, in this case, is a fuse. Unless other current control methods are used then it is the I^2t rating of the fuse which determines how long the current will flow.

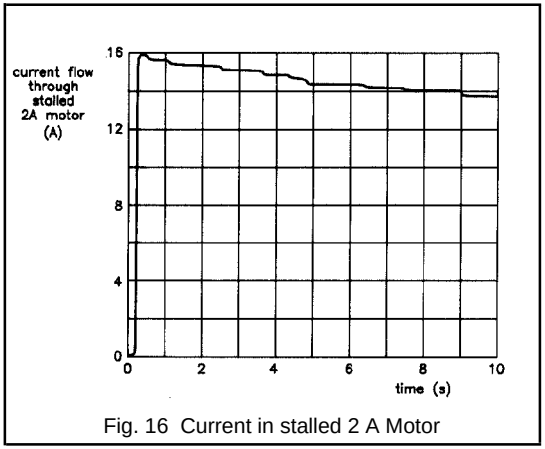


Fig. 16 Current in stalled 2 A Motor

It is important that the devices, selected for the control circuit, can operate reliably with all of these currents. With some types of switching device, it is necessary to select on the basis of the absolute maximum current alone. Often this results in a large and expensive device being used. The characteristics of MOSFETs, in particular their thermally limited SOAR (no second breakdown), allows the designer to specify a much smaller device whose performance more closely matches the needs of the circuit.

Device requirements

Voltage

The highest voltage encountered under normal operation is 16 V, under jump start this can rise to 22 V. In the case where the battery becomes disconnected with the alternator running the voltage can rise to 50 V (assuming external protection is present) or 60 V in the case of 24 V vehicles see Table 2. Thus the normal voltage requirement is 50/60v, however the power supply rail in a vehicle is particularly noisy. The switching of the numerous inductive loads generates local voltage spikes and surges of both polarities. These can occur singly or in bursts, have magnitudes of 100 V or more and durations of the order of 1ms.

It is important to chose MOSFETs capable of withstanding these stresses, either by ensuring V_{DS} exceeds the value of the transients or by selecting 50/60 V devices with sufficient avalanche energy capability to absorb the pulse. For transients in excess of these values it is necessary to provide external protection.

However, the TOPFET range of devices, both low and high side, have overvoltage protection on chip. As a consequence they are rated to withstand very much higher transient energies.

Voltage Range	Cause
>50 (60)*	coupling of spurious spikes
30 to 50	clamped load dump
22 to 30	voltage surge on cut-off of inductive loads
16 to 22 (32 to 40)*	jump start or regulator degraded
10.5 to 16 (20 to 32)*	normal operating condition
8 to 10.5	alternator degraded
6 to 8 (9 to 12)*	starting a petrol engine
0 to 6 (0 to 6)*	starting a diesel engine
negative	negative peaks or reverse connected battery
* 24 V supply	

Table 2 Conditions Affecting Abnormal Supply Voltages

Temperature

The ambient temperature requirement in the passenger compartment is -40 to +85˚C , and -40 to +125˚C under the bonnet. All Philips MOSFETs shown in Table 1 have T_{jmax} = 175˚C.

The TOPFETs have a maximum operating T_j of 150˚C because above this temperature the on chip protection circuits may react and turn the device off. This prevents the device from damage that could result from over dissipation. This protection eases the problems of the thermal design by reducing the need for large safety margins.

L^2FETs

The supply voltage in an automobile derived from the battery is only 12 V (nominal). This can vary from 10.5 V to 16 V under normal operation. It is important that the MOSFET switches be fully turned on under these conditions, not forgetting that for high side switches it may be necessary to derive the gate drive from a charge pump or bootstrap.

Whilst a gate source voltage of 6 V is usually sufficient to turn a conventional MOSFET on, to achieve the lowest on resistance, 10 V is required. Thus the margin between available and required gate drive voltage may be quite tight in automotive drive applications.

One way to ease the problem is to use Logic Level MOSFETs (L^2FET), such as the BUK553-60A or BUK555-60A, which achieve a very low on resistance state with only 5 V gate-source.

Conclusions

There is an increasing demand for low cost, reliable electronic switching of motors in automobiles. Despite the wide variety of motor types and drive configurations there is a Philips Power MOSFET solution to all of these demands. The broad range of types includes standard and logic level FETs, FredFETs, high and low side TOPFETs. The combination of low on-state resistance, ease of drive and ruggedness makes them an attractive choice in the arduous automotive environment.

Automotive Lamp Control

(including selection guides)

5.2.1 Automotive Lamp Control with Philips MOSFETS

The modern motor vehicle, with its many features, is a complex electrical system. The safe and efficient operation of this system calls for sophisticated electronic control. A significant part of any control system is the device which switches the power to the load. It is important that the right type of device is chosen for this job because it can have a major influence on the overall system cost and effectiveness. This choice should be influenced by the nature of the load. This article will discuss the features of the various types of switching device - both mechanical and solid state. These factors will be put into the context of the needs of a device for the control of resistive loads like lamps and heaters. It will be shown that solid state devices allow the designer a greater degree of control than mechanical switches and that the features of Power MOSFETs make them well suited to use in automotive applications.

Choice of switch type

Mechanical or solid-state

Designers of automotive systems now have the choice of either mechanical or solid-state switches. Although mechanical switches can prove be a cheap solution they do have their limitations. Solid-state switches overcome these limitations and provide the designer with several useful additional features.

Areas where the limitations of relays become apparent include:-

- **Reliability** - to achieve the required levels of sensitivity and efficiency means that relay coils have to be wound with many turns of very fine wire. This wire is susceptible to damage under conditions of high mechanical stress - vibration and shock.
- **Mounting** - special assembly techniques are needed when dealing with automotive relays. Their outlines are not compatible with the common methods of automated assembly like auto insertion and surface mounting.
- **Dissipation** - the power loss in the coil of a relay is not negligible - the resulting temperature rise makes it unwise to mount other components in close proximity. In some multiple relay applications it is necessary to provide cooling by ventilation.
- **Temperature** - the maximum operating temperature of relays is typically in the range 70˚C - 85˚C.
- **Corrosion** - the unsealed mechanism of relays are vulnerable in contaminating and corrosive environments.
- **Overloads** - relays can also prove to be unreliable under high transient load conditions. The arcing which occurs when switching high currents and voltages causes contact wear leading eventually to high resistance or even the contacts welding together.
- **Hazardous Materials** - to achieve the prefered switching performance, relays need to use materials like cadmium. The use of such materials is becoming restricted by legislation on health and safety grounds.
- **Noise** - the operation of a relay is not silent. This is proving to be unacceptably intrusive when relays are sited in the passenger compartment.

Solid-state switches can overcome these limitations but can also give the designer the option of introducing the following useful features:-

- **Current limiting** - a relay has two states - on or off so the current which flows depends only on the load. There is no mechanism which allows a relay to regulate the current which flows through it. The best that a relay can do is to try and turn off, when a high current is detected, but because they are so slow, very large currents may be flowing before the relay can react and damage may have already been caused. However the characteristics of solid state devices like MOSFETs and bipolar transistors allow them to control the current. This allows designers the chance to introduce systems which can handle faults in a safe and controlled manner.
- **Control of switching rate** - the lack control that a relay has over the current proves to be a limitation not only during fault conditions but also during normal switching. Without control, the rate at which current changes, dI/dt, depends only on the external circuit and extremely high rates can result. The combination of high dI/dt and the contact bounce that relays are prone to, creates an 'electrically' noisy environment for surrounding systems. The control available with solid-state switches permits the designer to restrain the current and produce 'soft' switching eliminating any possible EMC problems.

Power MOSFET or Bipolar Transistor

All solid-state switches have significant advantages over relays but there are different types of solid-state switch and their particular characteristics need to be taken into account if an optimum choice is to be made. There are two major types of solid-state switches which are suitable for use in automotive applications - power MOSFETs and bipolar transistors - and several factors need to be considered if the optimum choice is to be made.

- **Overload** - The choice of device type can be influenced by the magnitude and duration of overload currents associated with the application - for example the inrush current of lamps. This factor is particularly important because the maximum current that can be safely conducted by a bipolar transistor is independent of its duration. Whereas the safe operating area of a MOSFET allows it to handle short duration currents very much greater than its DC rating.
- **Drive power** - There can be a significant difference between the total power needed to drive bipolar and MOS transistors. A MOSFET's oxide insulation makes it a voltage controlled device whereas a bipolar needs current drive. However, most control circuits are voltage rather than current orientated and the conversion to current operation often involves the used of loss inducing resistors.
- **Reverse protection** - If the switching device is required to survive reverse conduction conditions then it is necessary to have a diode, connected in anti parallel, around it. If the device is a bipolar transistor then an extra component will be needed. However the device is a MOSFET then it has an inherent body / drain diode which will perform this function without the additional expenditure in components or board space.

Logic level and standard mosfets

The battery voltage in a car is a nominal 12 V. This can vary from 10.5 V to 16 V under normal operation and can fall as low as 6 V during starting. It is important that MOSFET switches be fully turned on at these voltages, bearing in mind that for a high-side switches it may be necessary to derive the gate voltage from a charge pump circuit. While a V_{GS} of 6 V is usually sufficient to turn a standard MOSFET on, 10 V is required to achieve the lowest on-state resistance, $R_{DS(ON)}$. Thus the margin between available and required gate drive voltage may be quite tight in automotive drive applications. One way to overcome this problem is to use L^2FETs such as the BUK553-60A or BUK555-60A, which achieve a very low $R_{DS(ON)}$ with a V_{GS} of only 5 V.

Switch configuration

A load's control circuit can be sited in either its positive or negative feeds. These are referred to as high side and low side switching respectively. Which configuration is chosen often depends on the location of the load/switch and the wiring scheme of the vehicle but other factors like safety can be overriding. The use of semiconductor switches introduces another element into the decision process because of the need to ensure that they are being driven correctly.

Low Side Switch

In this arrangement the load is permanently connected (perhaps via a fuse and the ignition switch) to the positive supply. The switching device is connected between the negative terminal of the load and the vehicle ground. This, together with the almost universal practice of referencing control signals to the vehicle ground, makes the implementation of a low side switch with MOSFETs extremely simple. The circuit shown in Fig. 1 shows a MOSFET connected as a low side switch to a lamp load. The Source terminal of the MOSFET is connected to ground so the control signal, which is also referenced to ground, can be connected to the Gate.

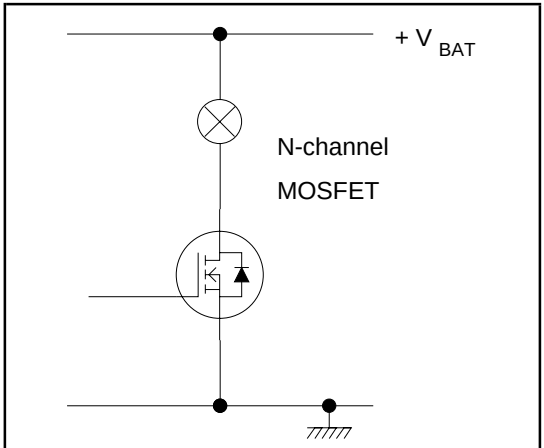


Fig. 1 Low side switch with N-channel MOSFET

High Side Drivers

Often, however, there is a requirement for the switch to be connected to the positive battery terminal with the load connected via the common chassis to the negative. This arrangement reduces electrochemical corrosion and the risk of accidentally activating the device during maintenance.

One method of creating such a high side switch is to use P-channel rather than N-channel MOSFETs. A typical arrangement is shown in Fig. 2. In this the source is connected to the +ve feed and the drain to the load. The MOSFET can be turned ON by taking the control line to zero and it will be OFF when the gate is at +ve supply voltage. Unfortunately P-channel MOSFETs require almost three times the silicon area to achieve the same low on-state resistance as N-channel types and so are much more expensive. An additional problem is the difficulty of obtaining P-channel devices with low enough gate threshold voltage to operate reliably at low battery voltages.

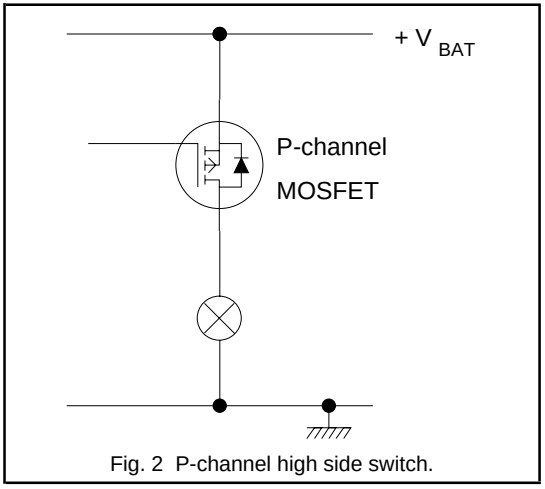


Fig. 2 P-channel high side switch.

Using N-channel devices overcomes these problems but involves a more complicated drive circuit.

To ensure that a n-channel MOSFET is fully turned on, the gate must be driven 10 V higher than its source, for conventional MOSFETs, or 5 V higher for Logic Level (L^2) FETs. With the source connected to the load and with most of the supply being dropped across the it, the gate has to taken to a voltage higher than the supply voltage. This higher voltage might be derived from an auxiliary supply, but the cost of 'bussing' this around the vehicle would be high. Figure 3 shows how this auxiliary supply could be produced locally. It consists of an oscillator - based around the Philips AU7555D - running at approximately 100 kHz which is driving a charge pump which nearly doubles the supply voltage.

An alternative approach, which can be used when the device doesn't have to be continuously ON, for example PWM lamp dimming or lamp flashing, is shown in Fig. 4. In this bootstrap arrangement capacitor C is charged to the supply voltage when the MOSFET is OFF. When the MOSFET is turned ON, its source terminal, and the negative end of C, rises to the supply voltage. The potential of the positive end of C is now higher than the +ve supply and diode D is reverse biased preventing C from being discharged. C can now act as the high voltage supply for the gate. The inevitable leakages will tend to discharge C and hence reduce the gate/source voltage, but with good components it is easy to ensure that a voltage high enough to keep the MOSFET fully ON is available for several seconds.

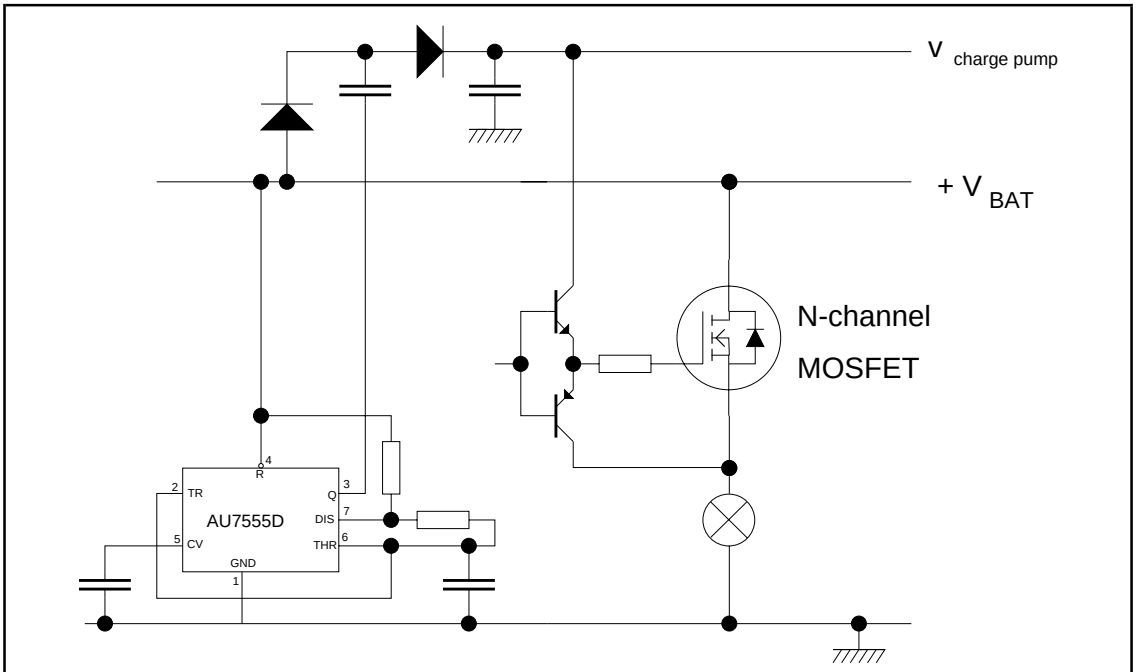


Fig. 3 N-channel High-side switch with charge pump

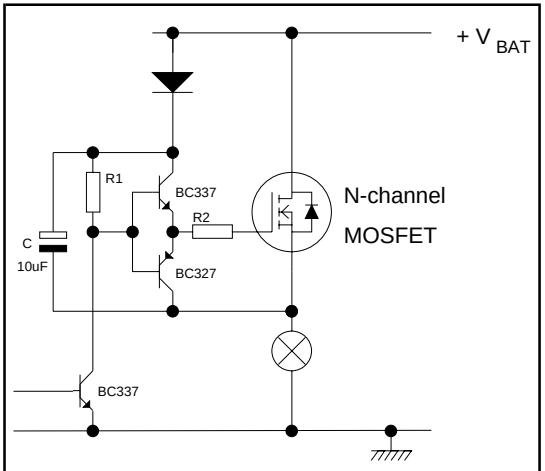


Fig. 4 Bootstrap High side driver

Inrush current

Any circuit or device which is intended to drive either a lamp or a heater must be able to handle not only the normal running current but also the inrush current at start up. All lamps and many heaters are essentially resistors made from metal conductors whose resistivity will increase with temperature.

In the case of lamps, the extremely high operating temperature (3000 K) means that the hot to cold resistance ratio is large. Typical values for a 60 W headlamp bulb are:-

	filament resistance	current
cold (-40˚C)	0.17 Ω	70 A
hot	2.4 Ω	5 A

The figures given for the currents assume that there is 12 V across the lamp, in practice wiring and switch resistance will reduce the cold current somewhat, but the ratio will still be large. The actual ratio depends upon the size and construction of the lamp but figures between 10 and 14 are common. For safety, the higher figure should be used.

The low thermal mass and the high power dissipation (850 W peak in 60W lamp) means that the lamp heats up very quickly. This means that the current falls from its peak value equally quickly. The time it takes for the current to fall back to its normal value depends on the size and construction of the lamp - the larger the lamp the longer it will take to heat up. Typically the current will have an exponentially decay with a time constant of 1 - 10 ms. The waveforms in Fig. 5 show the typical inrush current for a 60 W lamp being switched on by a MOSFET. The initial temperature of the lamp filament was 25˚C.

The normal operating temperature of a heater is not as high as that of a lamp, so the inrush current is rarely greater than twice the nominal current and often less. The duration of the 'inrush' can, however, last for many minutes and it may be this current which is used to define the 'normal' operating condition.

Being essentially resistive, lamps and heaters have very low inductance. This means that the current in the load will rise as quickly as the rest of the wiring will let it. This can lead to serious interference problems.

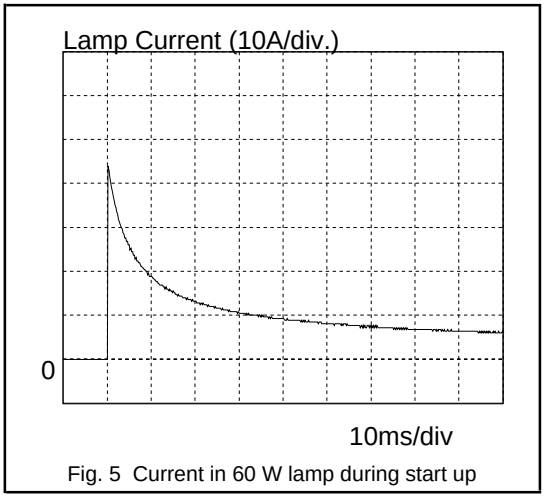


Fig. 5 Current in 60 W lamp during start up

Switch rate

The inductance associated with the supply wires in a car, is not negligible - a figure of 5µH is often quoted. This inductance, combined with the high rates of change of current associated with the switching of resistive loads and lamps, results in transient voltage appearing on the supply leads. The magnitude of the transient is given by:-

$$V_{transient} = -L.\frac{dI}{dt}$$

For example a current which rises as slowly as 2 A/µs will cause a 10 V dip in the supply to the switching circuit. This effect can be clearly seen in the waveforms of Fig. 6a. Such a perturbation can have an effect in two ways. In the first case the control circuit may be upset by having its supply reduced to only 2 V and may, if not specifically designed to cope with it, fail to function correctly. In the second case, it is easy for a transient as large as this, with its significant high frequency content, to be transmitted into adjacent conductors in the wiring loom. If some of the conductors are signal wires then false triggering of other functions could result.

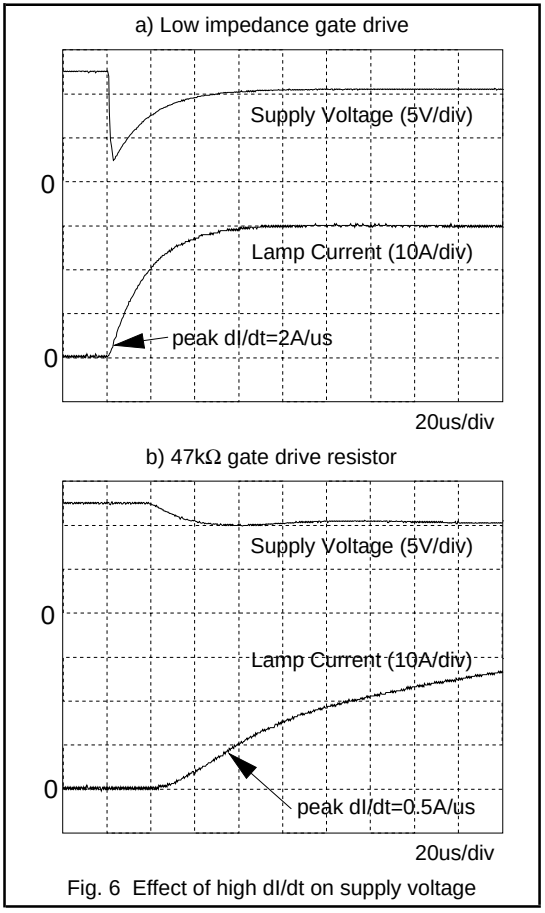


Fig. 6 Effect of high dI/dt on supply voltage

The dip will be reduced to manageable proportions if the dI/dt can be held to 0.5 A/µs. Since the loads are resistive, achieving this means reducing the rate that the voltage is applied to the load. This type of 'soft' starting is relatively easy to implement when the controlling device is a Power MOSFET. All that is needed is to put resistance in series with the gate drive.

The plots shown in Fig. 6b illustrate the effect inserting 47 kΩ in series with the gate supply of a BUK455-60A. The load for these tests was a 60W lamp being supplied from a battery via a 5 µH inductor. The dip in voltage due to dI/dt is now lost in the voltage drop from the wiring resistance.

The rate at which current falls at turn off is also important. High negative dI/dt will result in a large positive spike on the supply rails. As with the negative dip, this spike could cause interference in adjacent wires but it could also cause overvoltage damage. Unlike the turn on dip which can never be greater than 12 V, the magnitude of the turn off spike is potentially unlimited. In practice, however, it is extremely

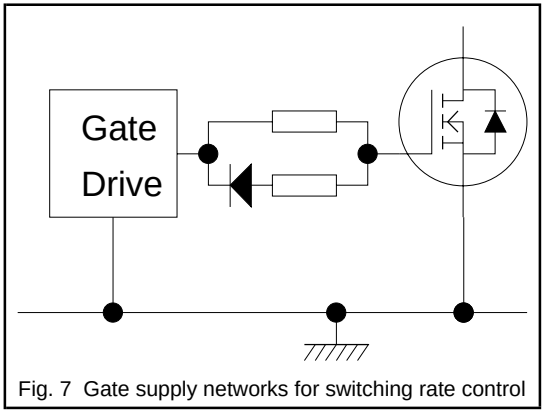


Fig. 7 Gate supply networks for switching rate control

unlikely that the voltage would exceed 30 V. Transient voltages of this magnitude are relatively common in the automotive environment and all circuits should be able to withstand them. It is still worthwhile keeping the turn off transient under control by ensuring that the dI/dt is low enough - a figure of <1 A/µs is standard.

Soft turn off, like soft turn on, is easy to implement if the controlling device is a Power MOSFET. In fact the same series resistor can be used to limit both the turn on and turn off rates. With a lamp load, however, this method will give a much slower turn off than is really necessary because of the large difference between the current at turn on and turn off. If this is a problem then an additional resistor and diode put in parallel with the first resistor - see Fig. 7 - will speed up the turn off.

MOSFET selection

The type of device chosen for a particular application depends upon the features that the control circuit needs to have. Table 3 lists the available MOSFET types and some of their features that would be useful in automotive applications.

Having chosen the type of MOSFET it becomes necessary to decided on the size of device. With MOSFETs this decision is made easier because, in its on-state, a MOSFET can be treated as a resistance and because its safe operating area (SOAR) is set by thermal considerations only (no second breakdown effects). The first stage of the selection process is to chose a device on the basis of the nominal current requirement. The next stage is to check that the inrush current, of the particular application and the drive method used, does not result in the MOSFET exceeding the transient thermal ratings. Having selected a device that is capable of switching the load the designer can then use the quoted values for the on-state resistance ($R_{DS(ON)}$) to check that any on-state voltage drop

requirements are being met. Tables 3 and 4 lists many of the different of lamps and resistive loads found in cars and suggests MOSFET types that can be used to control them.

MOSFET Type	Features
Standard	Wide range of current ratings from 5 to >100 A. Wide range of package styles Fast recovery anti-parallel diode (60 / 100 V types) Extremely fast switching.
L^2FET	as standard + Fully operational with low voltage supply
Low side TOPFET	as L^2FET + overvoltage protection overload protection over temperature protection 3 and 5 pin versions linear and switching control
High side TOPFET	Single component providing:- high side switch (on chip charge pump and level shifting) device protection load protection status reporting CMOS compatible input

TABLE 1 MOSFET Types and Features

The automotive environment

The environment that circuits and devices can be subjected to in automotive applications can prove to be extremely severe. Knowledge of the conditions that can exist is necessary to ensure that suitable devices and circuits are chosen. The two most stressful aspects of the environment are the temperature and voltage.

Temperature

The lowest temperature that is likely to be reached is -40˚C. This is related to the minimum outside temperature and may be lower under some special circumstances. The maximum temperature depends to a great extent upon the siting of circuits. The general ambient temperature in the engine compartment can be quite high and it is reasonable to assume that devices will see temperatures of 125˚C. Within the passenger area, conditions are somewhat more benign, but in areas where heat is generated and air flow is restricted, the temperature will be higher than might be expected. For this reason it is necessary to assume that the circuits and devices will have to work in an ambient temperature of 85˚C.

Voltage

It is possible to split the voltage conditions that can occur into two groups - Normal and Abnormal. 'Normal' conditions are essentially those which can be present for very long periods of time. Under such conditions it is reasonable to expect devices and circuits to be completely operational and to suffer no ill effects. 'Abnormal' conditions are characterised by their temporary nature. They are not expected to persist for long periods and during them, some loss in device / circuit performance can be expected and, in some cases, is allowable.

Normal voltages

When considering the 'Normal' environment it is important to included both the typical and extreme cases. The crucial condition for most devices and circuits is when the engine is running. At this time the supply voltage can be anywhere between 10.5 and 16 V in '12 V' systems or between 20 and 32 V in '24 V' systems.

The other significant 'normal' operating mode is when engine not running. In this state the supply voltage could be very low but voltages below some level must be considered as a fault condition. However some circuits will have to operate with voltages as low as 6 V.

Voltage Level		Cause
12 V systems	24 V systems	
40 V - 50 V	60 V - 75 V	external spikes
30 V - 40 V	50 V - 60 V	clamped load dump
22 V - 30 V	22 V - 30 V	inductive load switch off
16 V - 22 V	32 V - 40 V	jump start
16 V - 22 V	32 V - 40 V	faulty regulator
8 V - 10.5 V	12 V - 20 V	faulty alternator
6 V - 8 V	9 V - 12 V	starting a petrol engine
0 V - 6 V	0 V - 6 V	starting a diesel engine

Table 2 Abnormal Supply Voltages

Abnormal voltages

It is possible to envisage a situation in which nearly any voltage could appear on the supply wires of a vehicle. How extreme the voltages get depends to a great extent upon the protection, both deliberate and incidental, built into the system. The actual voltage that appears at the terminals of a circuit is also influenced strongly by its location and the location of the protection. Analysis of the automotive environment has produced a list of expected abnormal conditions. The values of voltage that these conditions can be expected to produce are shown in Table 2.

Load	Typical Power	Nominal Current	Peak Inrush Current	Number of lamps /car	Recommended MOSFET[1]			
					Standard FET		Logic Level FET	
					SOT186	TO220	SOT186	TO220
headlamp	60 W 55 W 45 W 40 W	5 A 4.6 A 3.8 A 3.3 A	70 A 64 A 53 A 47 A	2	BUK445-60A	BUK455-60A	BUK545-60A	BUK555-60A
spotlight	55 W	4.6 A	64 A	2	BUK445-60A	BUK455-60A	BUK545-60A	BUK555-60A
front fog light	55 W	4.6 A	64 A	2	BUK445-60A	BUK455-60A	BUK545-60A	BUK555-60A
rear fog light	21 W	1.8 A	25 A	2	BUK442-60A BUK443-60A[2]	BUK452-60A BUK453-60A[2]	BUK542-60A BUK543-60A[2]	BUK552-60A BUK553-60A[2]
front sidelight	5 W	0.4 A	6 A	2	BUK441-60A	BUK451-60A	BUK541-60A	BUK551-60A
rear sidelight	5 W 10 W	0.42 A 0.83 A	5.8 A 12 A	2 2	BUK441-60A	BUK451-60A	BUK541-60A	BUK551-60A
brake light	21 W	1.8 A	25 A	2	BUK442-60A BUK443-60A[2]	BUK452-60A BUK453-60A[2]	BUK542-60A BUK543-60A[2]	BUK552-60A BUK553-60A[2]
direction indicator light	21 W	1.8 A	25 A	4	BUK442-60A BUK443-60A[2]	BUK452-60A BUK453-60A[2]	BUK542-60A BUK543-60A[2]	BUK552-60A BUK553-60A[2]
side marker light	3 W 4 W 5 W	0.25 A 0.33 A 0.42 A	3.5 A 4.7 A 5.8 A	4 4 4	BUK441-60A	BUK451-60A	BUK541-60A	BUK551-60A
license plate light	3 W 5 W	0.25 A 0.42 A	3.5 A 5.8 A	2 1	BUK441-60A	BUK451-60A	BUK541-60A	BUK551-60A
reversing / backup light	21 W	1.8 A	25 A	2	BUK442-60A BUK443-60A[2]	BUK452-60A BUK453-60A[2]	BUK542-60A BUK543-60A[2]	BUK552-60A BUK553-60A[2]
instrument panel light	2.2 W	0.18 A	2.5 A	5	BUK441-60A	BUK451-60A	BUK541-60A	BUK551-60A
courtesy light	2.2 W	0.18 A	2.5 A	4	BUK441-60A	BUK451-60A	BUK541-60A	BUK551-60A
door light	2.2 W	0.18 A	2.5 A	4	BUK441-60A	BUK451-60A	BUK541-60A	BUK551-60A
boot / bonnet light	2.2 W	0.18 A	2.5 A	4	BUK441-60A	BUK451-60A	BUK541-60A	BUK551-60A

Notes

[1] These are meant for general guidance only. Specific applications should be checked against individual users' requirements. In addition to standard and logic level MOSFETs, high and low side TOPFETs might also be considered.

[2] This device can be used to control two bulbs simultaneously.

TABLE 3 Automotive lamps - characteristics and recommended MOSFET drivers

Load	Typical Power	Nominal Current	Number /car	Recommended MOSFET[1] TO220	SOT186(A) F-pack	Comments
screen heater	300-600 W	25-50 A	1	2 x BUK556-60H		Devices connected in parallel
seat heater	100-120 W	8-10 A	2	BUK452-60A[2]	BUK442-60A[2]	

Notes

[1] These are meant for general guidance only. Specific applications should be checked against individual users' requirements. In addition to standard MOSFETs, L^2FETs, low and high side TOPFETs might also be considered.

[2] To achieve an on-state voltage drop of <1 V the BUKxx3-60A device should be used.

TABLE 4 Automotive Resistive Loads - characteristics and recommended MOSFET drivers

The TOPFET

5.3.1 An Introduction to the 3 pin TOPFET

The TOPFET (**T**emperature and **O**verload **P**rotected MOS**FET**) concept has been developed by Philips Semiconductors and is achieved by the addition of a series of dedicated on-chip protection circuits to a low voltage power MOSFET. The resulting device has all the advantages of a conventional power MOSFET (low $R_{DS(on)}$, logic level or standard gate voltage drive) with the additional benefit of integrated protection from hazardous overstress conditions.

TOPFETs are designed for operation in low voltage power applications, particularly automotive electronic systems. The operation and protection features of the TOPFET range of devices also make them suitable for other low voltage power systems. TOPFETs can be used for all common load types currently controlled by conventional power MOSFETs.

The first generation of TOPFET devices are summarised in Table 1.

Protection strategy

A functional block diagram and the circuit symbol of the first generation 3-pin TOPFETs are shown in Fig. 1. The functional block diagram indicates that the logic and protection circuits are supplied directly from the input pin. This places a requirement on the user that the input voltage must be sufficiently high to ensure that the protection circuits are being correctly driven.

The TOPFET includes an internal resistance between the input pin and the power MOSFET gate. This is required to ensure that the protection circuits are supplied even under conditions when the circuits have been activated to turn off the power MOSFET stage. The value of this resistance has been chosen to be a suitable compromise between the requirements of switching speed and drive capability. Variants of this configuration with differing input resistor values (higher or lower) will be produced to suit different application requirements.

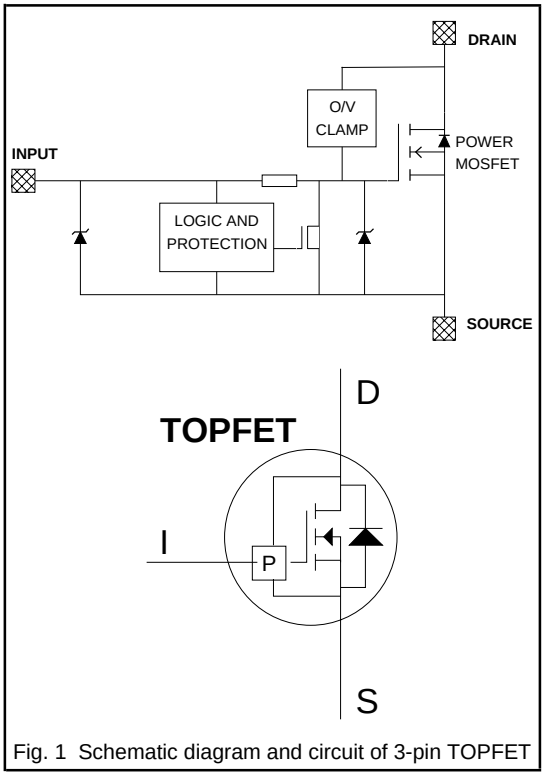


Fig. 1 Schematic diagram and circuit of 3-pin TOPFET

TOPFET	Package	V_{DS} (V)	$R_{DS(ON)}$ (mΩ)	at V_{IS} = (V)
BUK100-50GL	TO220	50	125	5
BUK100-50GS	TO220	50	100	10
BUK101-50GL	TO220	50	60	5
BUK101-50GS	TO220	50	50	10
BUK102-50GL	TO220	50	35	5
BUK102-50GS	TO220	50	28	10

Table 1. 3-pin TOPFET type range

Overtemperature protection

TOPFETs include an on-chip protection circuit which measures the absolute temperature of the device. If the chip temperature rises to a dangerous level then the overtemperature protection circuit operates to turn off the power MOSFET stage. Once tripped, the device remains protected until it is reset via the input pin. In the tripped condition the gate of the power MOSFET stage is pulled down by the control logic and so some current is drawn by the input pin of the TOPFET. If the overtemperature condition persists after the gate has been reset then the protection circuit is reactivated.

Short circuit protection

In the case of short circuit faults the rate of rise of temperature in a MOSFET switch can be very rapid. Guaranteed protection under this type of condition is best achieved using the on-chip protection strategy which is implemented in the TOPFET range of devices. The short circuit protection circuit acts rapidly to protect the device if the temperature of the TOPFET rises excessively.

The TOPFET does not limit the current in the power circuit under normal operation. This ensures that the TOPFET does not affect the operation of circuits where large inrush currents are required. As with the overtemperature protection circuit, the short circuit protection circuit turns off the power MOSFET gate via the control logic and is reset by taking the input pin low.

Overvoltage protection

Transient overvoltage protection is an additional feature of the TOPFET range. This is achieved by a combination of a rugged avalanche breakdown characteristic in the PowerMOS stage and an internal dynamic clamp circuit. Operation is guaranteed by an overvoltage clamping energy rating for the TOPFET. Overvoltage protection gives guarantees against fault conditions in the system as well as the ability for unclamped inductive load turn-off.

ESD protection

The input pin of the TOPFET is protected with an ESD protection zener. This device protects the PowerMOS gate and the TOPFET circuit from ESD transients. The energy in the ESD pulse is dissipated in the ESD source rather than in the TOPFET itself. This input zener diode cannot be used in the continuous breakdown mode and so is the determining factor in setting the maximum allowable TOPFET input voltage.

One feature of the implementation of the protection circuits used in the first generation TOPFET devices is that the input cannot be reverse biased with respect to the source. This must be adhered to at all times. When the TOPFET is in reverse conduction the protection circuits are not active.

5.3.2 An Introduction to the 5 pin TOPFET

The TOPFET (**T**emperature and **O**verload **P**rotected MOS**FET**) concept has been developed by Philips Semiconductors and is achieved by the addition of a series of dedicated on-chip protection circuits to a low voltage power MOSFET. The resulting device has the advantages of a conventional power MOSFET (low $R_{DS(on)}$, logic level gate voltage drive) with the additional benefit of integrated protection from hazardous overstress conditions.

TOPFETs are designed for operation in low voltage power applications, particularly automotive electronic systems. The operation and protection features of the TOPFET range of devices also make them suitable for other low voltage power systems. TOPFETs can be used for all common load types currently controlled by conventional power MOSFETs.

The second generation of TOPFET devices offers enhanced protection and drive capabilities making them suitable for a wide variety of applications, including those requiring fast switching (eg PWM control) or linear control. The circuit diagram for the 5-pin TOPFET types is shown in Fig. 1. The key features of these devices are:

- Overtemperature protection
- Short circuit load protection
- Overvoltage protection
- Full ESD protection
- Direct access to the gate of the Power MOSFET.
- Flag signal reporting of certain fault conditions
- Separate protection circuit supply

The 5-pin TOPFET range is summarised in Table 1.

Overtemperature protection

TOPFETs include an on-chip protection circuit which measures the absolute temperature of the device. If the chip temperature rises to a dangerous level then the overtemperature protection circuit operates to turn off the power MOSFET stage. Once tripped the device remains protected until it is reset via the protection supply pin.

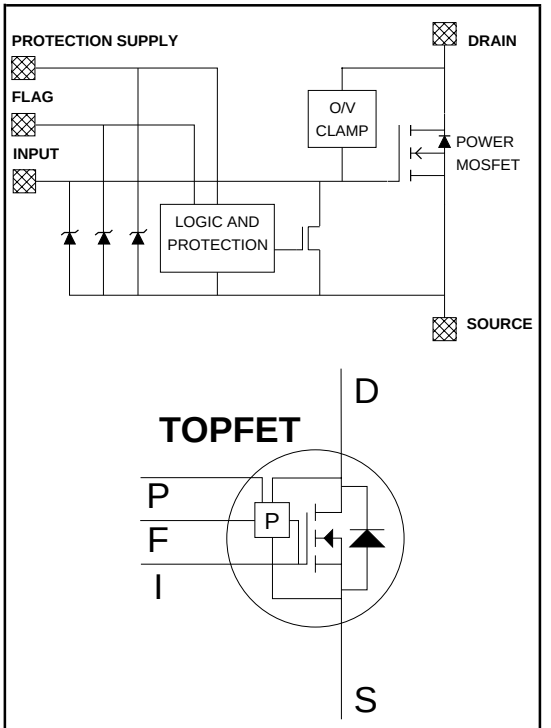


Fig. 1 Schematic diagram and circuit of 5-pin TOPFET

TOPFET	Package	V_{DS} (V)	$R_{DS(ON)}$ (mΩ)	at V_{IS} (V)	for V_{PSP} > (V)
BUK105-50L	SOT263	50	60 50	5 7	4 4.4
BUK105-50S	SOT263	50	60 50	5 7	5 5.4

Table 1. 5-pin TOPFET type range

In the tripped condition the gate of the power MOSFET stage is pulled down by the control logic and so current is drawn by the input pin of the TOPFET. A minimum value of external gate drive resistor is specified in order that the protection circuit can turn off the PowerMOS stage and thus protect the device. The flag pin gives a logic high output to indicate that a fault has occurred. If the overtemperature condition persists after the protection supply has been reset then the protection circuit is reactivated.

Short circuit protection

In the case of short circuit faults the rate of rise of temperature in a MOSFET switch can be very rapid. Guaranteed protection under this type of condition is best achieved using the on-chip protection strategy which is implemented in the TOPFET range of devices. The short circuit protection circuit acts rapidly to protect the device if the temperature of the TOPFET rises excessively.

The TOPFET does not limit the current in the power circuit under normal operation. This ensures that the TOPFET does not affect the operation of circuits where large inrush currents are required. As with the overtemperature protection circuit the short circuit protection circuit turns off the power MOSFET gate via the control logic and provides a flag signal. The TOPFET is reset by taking the protection supply pin low.

Overvoltage protection

Transient overvoltage protection is an additional feature of the TOPFET range. This is achieved by a combination of a rugged avalanche breakdown characteristic in the PowerMOS stage and an internal dynamic clamp circuit.

ESD protection

The input pin, flag pin and protection supply pins of the TOPFET are all protected with ESD protection zeners. These devices protect the PowerMOS gate and the TOPFET circuits from ESD transients. The protection devices cannot be used in continuous breakdown.

Protection supply

An error condition is recorded and the flag signal is activated if the protection supply is absent. Valid protection is only guaranteed once the protection supply is in excess of V_{PSP} (See Table 1).

One feature of the implementation of the protection circuits used in this generation of TOPFET devices is that the input, flag or protection supply pins cannot be reverse biased with respect to the source. This must be adhered to at all times. When the TOPFET is in reverse conduction the protection circuits are not active.

5.3.3 BUK101-50DL - a Microcontroller compatible TOPFET

The TOPFET version BUK101-50**DL** can be directly controlled by the port outputs of standard microcontrollers and other high impedance driver stages. This member of the TOPFET family has the same functional features as its predecessors BUK101-50**GS** and BUK101-50**GL**. All these versions are 3-pin devices for the replacement of Power MOSFETs or partially protected Power MOSFETs. They are internally protected against over temperature, short circuit load, overvoltage and electrostatic discharge. For more information concerning the basic technical concept of TOPFET see Philips Technical Publication 'TOPFET - A NEW CONCEPT IN PROTECTED MOSFET'. This section covers the special features of the BUK101-50**DL** version, criteria for driver stage design and application.

Overview on BUK101-50 versions

The GS, GL and DL versions of the BUK101-50 TOPFET each have the same functionality but differ in their input characteristics. Table 1 gives an overview on these characteristics.

Type	Nominal Input Voltage (V)	Normal Input Current (mA)	Latched Input Current (mA)	Max. Input Voltage (V)
GS	10	1.0	4.0	11
GL	5	0.35	2.0	6
DL	5	0.35	0.65	6

Table 1. Comparison of GS, GL and DL versions

Table 1 shows that the GS version (S for Standard type) is specified for 10V driver outputs while the GL and DL versions (L for Logic Level type) are specified for 5V logic level driver outputs. The two logic level types differ in the input current, I_{ISL}, which flows when the device is in its 'latched' state i.e. shutdown has occurred due to over temperature or short circuit load. The GL version is suitable for pulsed applications up to 1kHz and needs a push-pull driver stage while the DL version is optimised for high impedance drive circuits and can handle pulsed applications up to 100Hz.

Criteria for choice/design of driver stage

Figure 1 shows a simplified circuit diagram for the input of a 3-pin TOPFET. Also indicated is the high level output impedance of the driver stage R_{out}.

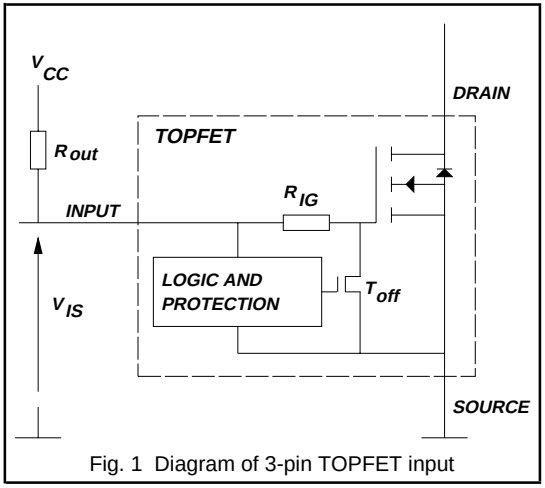


Fig. 1 Diagram of 3-pin TOPFET input

For all versions the internal circuits for over temperature and short circuit load protection are supplied from the input pin. This determines the input current I_{IS} under normal conditions, i.e. the Power MOS transistor is on and T_{off} in Fig. 1 is off. To ensure proper function of the protection circuits, a minimum input voltage $V_{IS} = 4V$ has to be applied. If, however, the device has turned off due to over temperature or short circuit load (i.e. transistor T_{off} in Fig. 1 is on), a minimum of $V_{IS} = 3.5V$ is required to keep the device in its 'latched' state. Latched means that the device will stay off even if the error condition has disappeared. Figure 1 indicates that under this condition the input current I_{ISL} will be increased due to the additional current that has to be sourced into resistor R_{IG}. R_{IG} allows the Power MOS gate to be pulled down internally while the input pin is at high level. The typical value of R_{IG} in the GL version is 4kΩ, while for the DL version this value has been increased to 30kΩ. Thus the maximum input current has been reduced to allow for high impedance driver stages such as microcontroller port outputs.

The criteria stated above result in the following requirements on the driver stage output resistance R_{out}:

$$Normal: \quad R_{out} \leq \frac{V_{cc} - 4V}{I_{IS}(V_{IS} = 4V)} \tag{1}$$

$$Latched: \quad R_{out} \leq \frac{V_{cc} - 3.5V}{I_{IS}(V_{IS} = 3.5V)} \tag{2}$$

The maximum input currents of the BUK101-50DL are specified as follows:

$I_{IS,max}$ = 270µA at V_{IS} = 4V
$I_{ISL,max}$ = 430µA at V_{IS} = 3.5V

Considering a 5V supply, equation (2) leads to a maximum output resistance $R_{out,max}$ = 3.5kΩ.

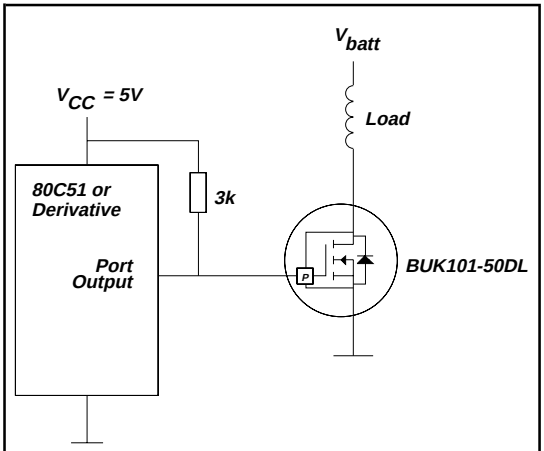


Fig. 2. Direct control by 80C51 microcontroller

Application example - 80C51 microcontroller as TOPFET driver

Figure 2 shows an application that takes advantage of the low input current of the BUK101-50DL. As has been shown above, the external pull-up resistor $R_{pull-up}$ in this circuit should have a maximum value of 3.5kΩ at V_{CC} = 5V for safe operation of the TOPFET protection circuits. An additional requirement is that the TOPFET must be off when the port output is at low level. Thus the limited sinking capability of the port output demands a minimum value for $R_{pull-up}$. For the 80C51 microcontroller family a maximum output voltage of $V_{out,low}$ = 0.45V is specified at a sink current of 1.6mA for ports 1 to 3 and 3.2mA for port 0. This voltage level is safely below the minimum turn-on threshold $V_{IS(TO)}$ = 1V of the TOPFET. Considering V_{CC} = 5V and the above specification of the port output, the minimum value for $R_{pull-up}$ is:

$$R_{pullup} \geq \frac{5V - 0.45V}{1.6mA} = 2.8k\Omega$$

Thus a value of 3kΩ meets the requirements.

Other applications for the BUK101-50DL

Logic IC as driver

Besides microcontroller port outputs the BUK101-50DL can also be driven by standard 5V logic IC families. Table 2 gives an overview on these families and states - if necessary - the minimum value for a pull-up resistor.

Family	$R_{pull-up\ min}$
TTL	300Ω
LSTTL	620Ω
STTL	240Ω
HE4000B	no $R_{pull-up}$ required
HCMOS	no $R_{pull-up}$ required
ACL	no $R_{pull-up}$ required

Table 2. 5 V logic IC families driving the BUK101-50DL

High Side driver

The low input current of the BUK101-50DL is also advantageous, when using the device as a high side switch. In this configuration the low drive requirements mean that smaller capacitors are needed in charge pump or bootstrap circuits. This subject is described more fully in section 5.3.6.

5.3.4 Protection with 5 pin TOPFETs

TOPFETs in the 5-pin SOT263 outline extend the range of application of TOPFET to circuits requiring faster switching or protected linear operation. 3-pin TOPFETs are ideal for use in DC and low frequency switching applications but the need to generate the protection supply from the input is a limitation. Providing a separate pin for the protection supply gives the designer freedom to control the input / MOSFET gate in the way he chooses.

This note will look at the organisation of the 5-pin devices and then discuss some of the more important operational considerations. Application examples will be presented in the later sections in this chapter.

Functional description

The logic and protection circuits within this device are similar to those in the 3-pin TOPFETs but the configuration has been modified (see Fig. 1) to give greater operational versatility.

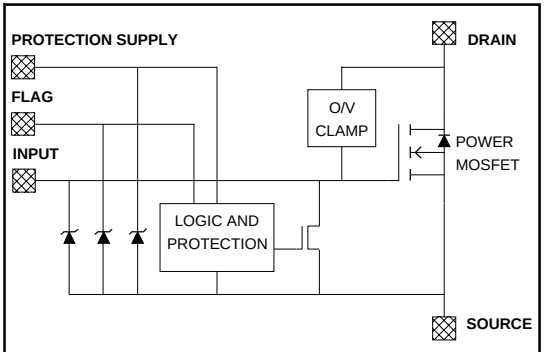


Fig. 1 Elements of a 5-pin TOPFET

These devices use pin 2 of the SOT263 as a flag and pin 4 as the supply / reset to the logic and protection circuits. Separating the protection supply from the input has allowed the internal input gate resistor to be removed. (In a 3-pin TOPFET, this resistor is needed to maintain the protection supply during latched fault conditions).

The operation of the protection circuits has not been changed. If there is an overvoltage between drain and source, the overvoltage protection circuit will still try to turn the MOSFET partially ON. In an overtemperature or overload situation the TOPFET will turn on the gate pull-down transistor and attempt to turn itself OFF.

The flag indicates when the TOPFET has been tripped by an overtemperature, overload or short circuit condition. It will also indicate if the protection supply is absent, for example during a reset. It should be pointed out that the flag low state does not mean that the protection supply is high enough, just that it is present.

The flag is the open drain of a MOS transistor which is OFF to indicate a fault. It is intended that the flag pin is connected to a 10 kΩ pull-up resistor. This arrangement gives the flag a failsafe characteristic.

Operational considerations

Supplying the protection circuits from their own pin, rather than sharing a pin with the MOSFET gate drive, has several beneficial effects. One is that it allows the MOSFET gate to be independently controlled without adversely affecting the protection features. This is particularly useful when TOPFET is being used as a linear controller.

The removal of the input gate resistor gives the designer the opportunity of selecting the most appropriate value. It is important to understand that if TOPFET is to protect itself, it needs to control its gate by overriding the external drive circuit. It can only do this if the impedance of the driver is high enough. The conditions for satisfactory operation are given in Table 1.

Protection level	Minimum driver impedance		
	ON drive		OFF drive
	5 V	10 V	input / source
Full self protection	1 kΩ	2 kΩ	100 Ω
Overvoltage protection only	0 Ω	0 Ω	100 Ω
Overtemperature, overload and short circuit protection only	1 kΩ	2 kΩ	0 Ω

Table 1. Driver impedance and protection level

The simplest way of satisfying the self protection requirements is to fit a 2 kΩ resistor between the driver and the input pin. This is simple in a linear controller but may not be feasible in a switching controller where this resistance will result in a significant turn OFF delay. An alternative may be to have an ON drive via 2 kΩ and an OFF drive via 100 Ω.

If lower turn ON drive impedance is needed then the approach would be to use the flag output to control the signal being fed to the driver circuit. It should be noted that to have overvoltage protection the turn OFF impedance must still be > 100 Ω.

The S and L versions differ only in the protection supply voltage range. The L types are designed to be supplied from the output of 5 V logic ICs, like the 74HC/HCT families. The S types are intended to be supplied with a nominal 10 V from either HEF4000 type logic, linear ICs (e.g operational amplifiers) or discrete circuits.

One additional benefit of the independent protection supply is that, unlike 3-pin L types, the input of a 5-pin L type can be as high as 11 V, allowing a significantly lower $R_{DS(ON)}$ to be achieved.

It is important to realise that, at high levels of input voltage, the MOSFET transfer characteristic of both L and S types will allow a very high current to flow during shorted load situations. This current, flowing through the resistance in the connections between the chip's source metalisation and the source pad on the pcb, will give a significant volt drop. Since the return for the protection supply will be to the pcb source bond pad, the volt drop will subtract from the effective protection supply voltage. To compensate for this effect, the minimum protection supply voltage, V_{PSP}, is increased at high levels of input voltage, V_{IS}. For example the minimum V_{PSP} of the BUK105-50L is 4 V if $V_{IS} \leq 5$ V. If, however, the input is taken to 7 V, to achieve an $R_{DS(ON)}$ of 50 mΩ, V_{PSP} must be ≥ 4.4 V. A curve in data (reproduced as Fig. 2) gives minimum V_{PSP} values for VIS from 0 to 11 V.

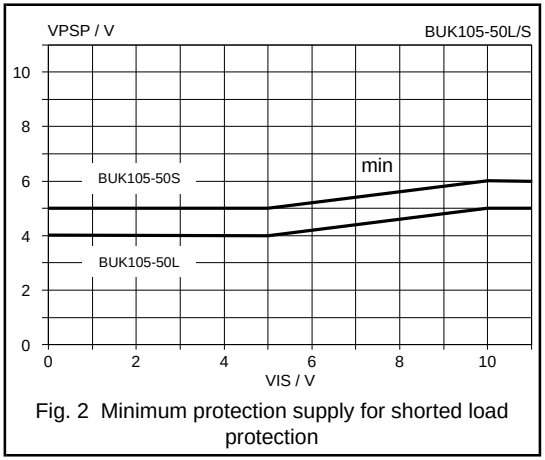


Fig. 2 Minimum protection supply for shorted load protection

The input, flag and protection supply pins are all protected against the effects of ESD by special diodes between the pin and source. It is important to realise that these devices are not designed to run in continuous forward or reverse conduction. This means that the continuous voltage between these pins and source should be > 0 and < 11 V.

Reverse Battery

There is always a risk that the car's battery could be reversed. If this happened to a system where a TOPFET is fitted then the TOPFET will survive provided:

- the current flowing through the body drain diode is restricted by the load to a level which does not cause the TOPFET to over dissipate,
- the current flowing out of the input, flag and protection supply pins is < 10 mA.

5.3.5 Driving TOPFETs

The output of a TOPFET is similar to that of a Power MOSFET. However, the TOPFET's protection features make the input characteristics significantly different. As a consequence, TOPFETs have different drive requirements. This fact sheet describes these requirements and suggests suitable drivers for the different TOPFET versions.

3-Pin TOPFET

Input requirements

3-pin TOPFETs can replace ordinary MOSFETs in many circuits if the driver can meet certain conditions. The first of these conditions is the need to keep within the TOPFET's V_{IS} ratings and in particular to keep the input positive with respect to the source. The second is the need to provide an adequate supply to the protection circuits even when the TOPFET has tripped and the input current is significantly higher.

Table 1 summarises these requirements. It gives the limiting values of V_{IS}, the minimum input voltage for valid protection in normal and latched mode and the normal and latched input currents for each 3-pin TOPFET.

Drivers

The complementary drive arrangement shown in Fig. 1 is well suited to the input requirements of 3-pin TOPFETs. The transistors shown are the output of a cmos IC gate, which for some TOPFETs may have sufficient drive. If not, a push pull drive with discrete devices should be used. Suitable cmos families are given in Table 1.

The BUK101-50DL has a very low input current requirement, achieved by increasing the value of the internal input resistor - at the expense of a significant increase in switching times. This means that this device can be driven from the output port of an 80C51 micro controller as shown in Fig. 2. Designers should be aware that other high resistance / low current TOPFETs could be produced if they are requested.

5-Pin TOPFET

Input Requirements

The requirements of a 5-pin TOPFET are somewhat different to that of a 3-pin device. The first major difference is that both the input and the protection pins need to be supplied. The second difference is that the input resistance is external and is selected by the designer. One requirement which remains is the need to keep both the input-source and protection-source voltages within the range 0 to 11 V.

The protection pin driver must be able to keep the voltage above V_{PSP} when supplying the protection current, I_{PS}. With the 5-pin device the protection supply is independent, so the current drawn when TOPFET trips does not change.

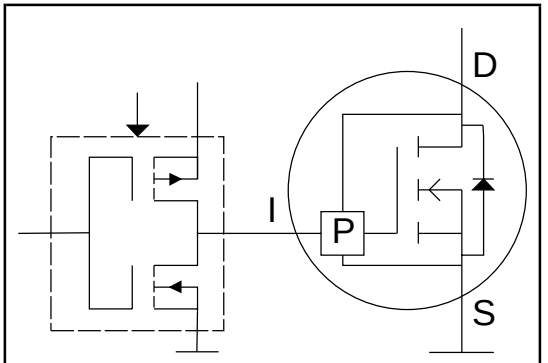


Fig. 1 Complementary driver for 3-pin TOPFET

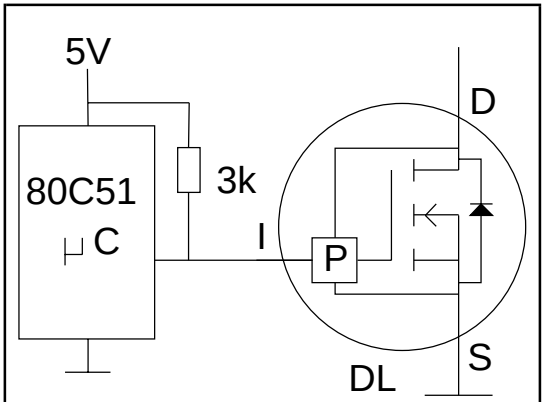


Fig. 2 Micro controller drive for 3-pin TOPFET

Type	Input voltage (V)				Input Current (mA)		Driver
	limiting value		for valid protection				
	min.	max.	normal	latched	normal	latched	
BUK100-50GS	0	11	5	3.5	1.0	5.0	HEF / Discrete
BUK101-50GS	0	11	5	3.5	1.0	4.0	HEF / Discrete
BUK102-50GS	0	11	5	3.5	1.0	20	Discrete
BUK100-50GL	0	6	4	3.5	0.35	2.0	HC/HCT
BUK101-50GL	0	6	4	3.5	0.35	2.0	HC/HCT
BUK102-50GL	0	6	4	3.5	0.35	10	Discrete
BUK101-50DL	0	6	4	3.5	0.35	0.65	Micro

Table 1 Input parameters of 3-pin TOPFETs

The input pin requirements depend on the mode of operation chosen by the designer. If the TOPFET is expected to turn itself off, in overtemperature or shorted load situations, then the output impedance of the drive needs to be > 2 kΩ. This will allow the TOPFET's internal turn-off transistor to pull the input pin low. If, however, the circuit uses the TOPFET flag to signal to the driver to turn off, then driver resistance can be very much lower.

Independent of which method is used for overload turn-off, there is a separate requirement to ensure adequate overvoltage clamping. If this feature is needed then the input to source resistance of the driver - when it is pulling the input low - needs to be > 100 Ω. If it is lower, then the TOPFET's internal clamping drive will be unable to raise the gate voltage high enough to turn the MOSFET on.

Drives

The drive for the protection pin can, most conveniently, be supplied by a cmos IC gate. A 74HC or HCT for L type devices or a HEF4000 series device for the S type. Care is needed however to ensure that the minimum protection voltage, V_{PSP}, requirements are still met when the input voltage, V_{IS} is high and the load is shorted.

A typical high impedance drive arrangement, which lets TOPFET protect itself against shorted load, overtemperature and overvoltage, is shown in Fig. 3.

One method of creating a fast drive is shown in Fig. 4. In this arrangement a NOR gate with a low impedance output stage drives the input via a 100 Ω resistor. One input of the NOR gate is connected to the flag pin and will be pulled high by the 10 kΩ pull-up resistor if the TOPFET indicates a fault. With one input high, the output of the gate will be low turning the TOPFET off. The 100 Ω resistor ensures that the overvoltage clamp is still operational.

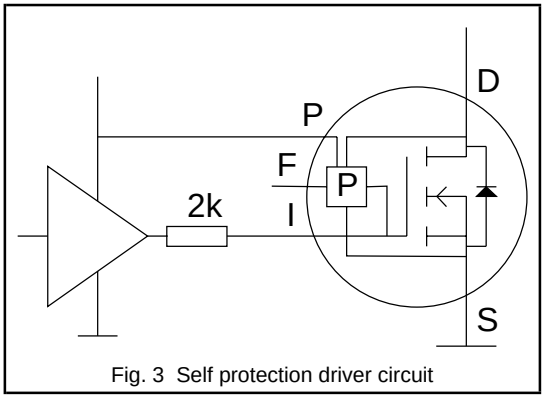


Fig. 3 Self protection driver circuit

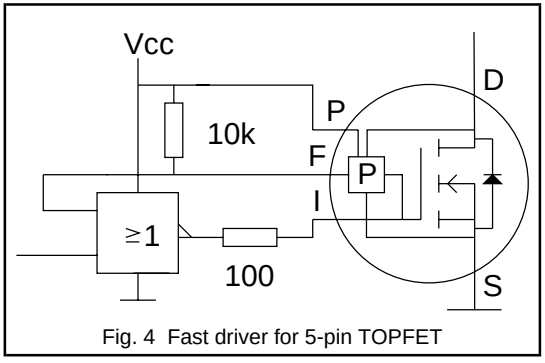


Fig. 4 Fast driver for 5-pin TOPFET

5.3.6 High Side PWM Lamp Dimmer using TOPFET

Although the 3-pin TOPFETs were designed for low side switch applications, they can, by using standard MOSFET bootstrap techniques, be used in applications which need high side control. One such application is the dimming of automotive headlamps and panel lamps. These applications need not only a high side switch but also slow, controlled switching to reduce problems of EMI.

This note will give details of a circuit which fulfils the operational requirements of this application and, because it uses a TOPFET, is well protected against shorted load and overvoltage faults.

Circuit Description

The circuit shown in Fig. 1 shows the high side PWM dimmer circuit. All the main components are shown, the only exception being the source of the PWM control signal. This could be either the system controller or a dedicated oscillator depending on the nature of the overall system. The circuit of Fig. 1 assumes that the signal is a rectangular pulse train of the required frequency and duty cycle, with an amplitude of 10 V.

The input signal is attenuated by R2 and R3 and fed to the base of Q1. The combination of R1 and Q1 will invert and level shift the signal and feed it to the input of the BUK101-50GS TOPFET.

D1, C1 and the TOPFET form the bootstrap circuit. The low end of C1 is connected to the TOPFET source. When TOPFET is OFF its source is close to ground, so C1 charges to Vbat via D1. When TOPFET turns ON, its source rises to nearly Vbat, lifting the high end of C1 well above Vbat. C1 can, therefore, provide more than enough voltage to drive the TOPFET input. In fact, when Vbat is higher than normal, the voltage would exceed the continuous V_{IS} rating of the BUK101-50GS, so D3 is included to restrict the input voltage to below 11 V.

Capacitor C2 adds to the Miller capacitance of Q1 and limits the rate of change of collector voltage. The TOPFET acts like a source follower circuit, so the load voltage rises and falls at the same rate as the collector-emitter voltage of Q1.

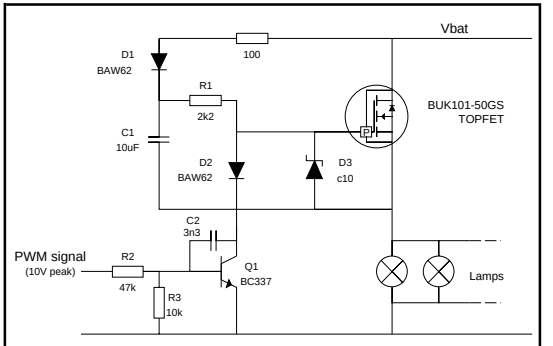


Fig. 1 High side lamp dimmer circuit

Component Values

With the components specified the circuit will operate at a frequency between 50 and 200 Hz and has rise and fall times of about 300 µs. This slow switching means that the minimum OFF time, for satisfactory bootstrap operation, is about 1 ms. At 50 Hz this gives a maximum duty cycle of 95%.

The value of C1 has been chosen to ensure that TOPFET input current does not cause the C1 voltage to fall significantly during the maximum ON time. This means that the lowest on state dissipation is being achieved. Lower values could be used but the voltage droop would be greater and care would be needed to ensure that the input voltage does not fall below the V_{ISP} of the TOPFET, otherwise the protection features may not function.

The rate of switching can be changed by adjusting the value of C2. Larger values would reduce switching speed. Considerable care is needed when switching times become very long because while the input voltage is below the V_{ISP} the TOPFET is unprotected. Switching times can be reduced to about 50 µs by reducing the value of C2 to 470 pF. To reduce the switching times further will mean a change to the input drive.

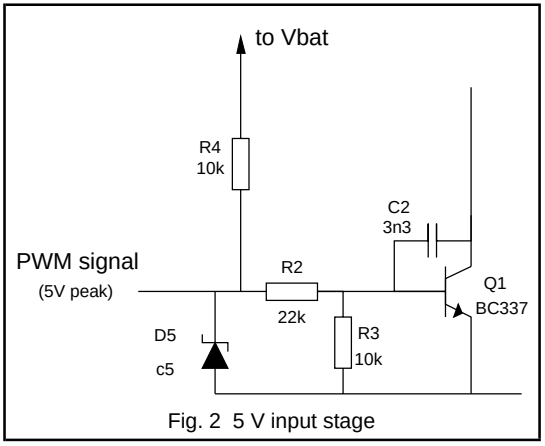


Fig. 2 5 V input stage

Switching rate, in particular the turn-off rate, is also influenced by the amplitude of the input signal. R2 and R3 have been chosen to give similar rise and fall times with an input of 10 V. If the input amplitude is lower the fall time would increase. This can be compensated for by lower attenuation. An input modified for 5 V input is shown in Fig. 2. This arrangement also includes D5 to clamp the input voltage to 5 V and R4 to allow the use of an open collector or drain drivers.

Operation in fault conditions

TOPFET will protect itself against high voltage supply line transients by partially turning on and restricting the applied voltage to about 60 V. In high side applications the remainder of high voltage may appear across the load. In many systems the grounding and smoothing arrangements will ensure that this will not be problem. In some configurations the TOPFET source will rise above ground while the input is held at ground. This means that the TOPFET input will be negative while its drain-source voltage is high. This may damage the TOPFET. This difficulty can be eliminated by the input circuit shown in Fig. 3. In this circuit diode D4 will turn off if the source voltage rises. The input is, therefore, no longer clamped by the drive and can rise with the source, eliminating the risk of damage.

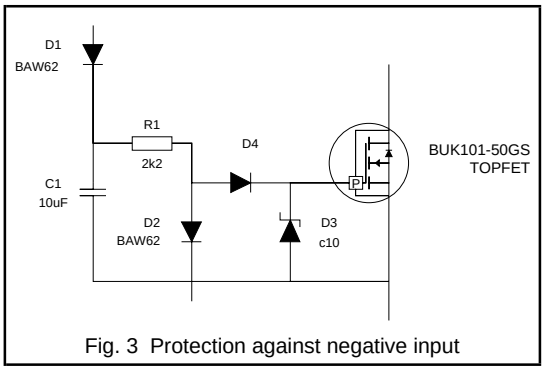


Fig. 3 Protection against negative input

If the load becomes short circuit, TOPFET will trip as soon as the temperature of the power part of the chip becomes too high. Since this circuit is a PWM controller the TOPFET will be reset at the end of the ON period. During the period between tripping and the start of the next cycle the TOPFET will cool. It will, therefore, turn on when the input goes high again and the short circuit current will flow until TOPFET is tripped once more.

TOPFET is able to withstand this type of operation for a considerable period of time but not necessarily indefinitely. The dissipation is considerable, the temperatures could be high and operating life may be affected. It is advisable, therefore, that short circuit operation is evaluated.

5.3.7 Linear Control with TOPFET

Although the pulse width modulation, PWM, method of motor speed control is often preferred over the linear method it is not without problems. Some of these are totally eliminated in linear controllers. However, linear control techniques have their own limitations. By using a Philips TOPFET as the power device some of the disadvantages are removed giving a fully protected, linear control system.

This note will compare linear and PWM controllers. It will then give details of a circuit based around a BUK105-50S which shows that, with a TOPFET, it is simple to produce a fully protected, linear controller for adjusting the speed of a car heater fan.

Linear and PWM Control

PWM is often selected as the method of controlling the speed of a brush motor because it is more efficient than linear control. The reduction in energy loss results from a reduction in the loss in the controlling power device. The loss is lower because the device is only transiently in the high dissipation state of being partially ON. To keep the loss as low as possible, the transition time needs to be kept short, implying fast switching and high values of dV/dt and dI/dt. It is these fast switching rates which create the electrical noise that can be such a problem in automotive applications.

Linear control does not create this noise because it holds the output at a steady value. The power device is continuously in the partially ON state and its dissipation is high. If, however, this heat can be handled and the inefficiency is acceptable then linear control may be the better choice.

Device Selection Factors

In PWM control, on-state dissipation is the major energy loss, so $R_{DS(ON)}$ is the main selection criterion. In linear control, maximum dissipation occurs when half the supply voltage is being dropped across the device. In this state $R_{DS(ON)}$ is not relevant as dissipation is being controlled by the load and the supply. The limiting factor in this case is the need to dissipate the energy and keep the junction temperature to a safe value. The selection, therefore, is based on junction to mounting base and mounting base to heatsink thermal resistance. $R_{DS(ON)}$ cannot be ignored, however, because it sets the residual voltage loss at maximum speed which can be important.

TOPFET in Linear Control

The circuit shown in Fig. 10. is a linear controller for a car heater fan based around a BUK105-50S. TOPFET is well suited to this application because it is a real power device in a real power package giving it good thermal characteristics and low $R_{DS(ON)}$. The 5-pin TOPFET is used because the protection circuits need to be supplied independently from the input. The on-chip overtemperature protection feature of TOPFET is precisely the protection strategy needed in this type of high dissipation application.

Input Pin

In this circuit the input of the TOPFET is connected, via R1 and D1, to the output of an operational amplifier. The TOPFET drain voltage is attenuated by R2/R3 and fed to the positive input of the amplifier. The negative input is connected to the wiper of the speed setting potentiometer. This TOPFET/op-amp arrangement creates a non-inverting amplifier with a gain of

$$gain = \frac{(R2 + R3)}{R3}$$

In such a low frequency system the presence of R1 at 2.2 kΩ will not have a significant effect on normal operation. However, if TOPFET is tripped, its internal gate source transistor will be turned on and, because R1 is greater than the 2 kΩ needed for self protection (see R_I in the data sheet), the MOSFET gate will be pulled down and the TOPFET will be OFF.

Diode D1 prevents the input of the TOPFET being pulled negative with respect to the source.

Protection Supply

To ensure that the overtemperature and shorted load protection circuits work, the protection supply pin needs to be connected to an adequate supply. To allow TOPFET to be reset, provision has to be made to switch this so it can fall below the minimum reset voltage, V_{PSR}. Possibly the easiest way to achieve this is by feeding the protection supply from a CMOS gate.

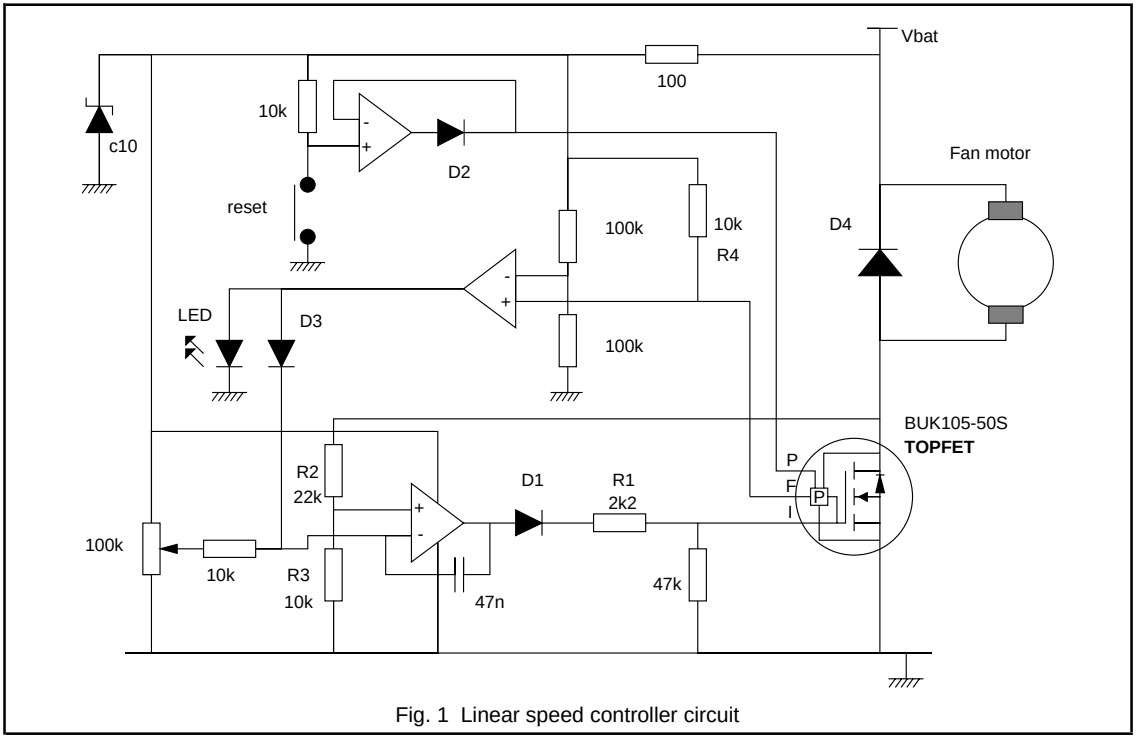


Fig. 1 Linear speed controller circuit

Two version of BUK105-50 are available, 'S' and 'L'. They differ in their protection supply requirements. L devices are designed to operate from a nominal 5 V. This makes them compatible with 5 V logic families like the 74HC and HCT series. L types can be driven at 10 V but as curves in the data show the protection characteristics are affected. On the other hand, S devices are designed to work with a nominal 10 V such as is available from HEF4000 logic gates.

If this circuit were part of a larger system then it is likely that such a gate would be available. In the circuit given here the protection pin is connected to the output of an op-amp wired as a non-inverting buffer. The buffer input is pulled up to the +ve rail with 10 kΩ. The protection supply can be taken low - to reset the TOPFET - by a pushbutton which grounds the input of the buffer.

Flag pin

In this circuit the flag pin is connected to a 10 kΩ pull-up resistor, R4. In a more sophisticated system this signal could then be fed to the input of a logic gate and used to inform the system controller of a fault condition. The controller could use this information to initiate a reset sequence or perhaps shut down the circuit and record the fact in a maintenance record store.

In this simpler system the flag output feeds the input of an op-amp wired as a comparator which in turn indicates a fault by lighting a LED. The output is also fed via D3 to the input of the speed controller op-amp. This overrides the signal from the speed adjusting potentiometer and takes the TOPFET input low. This arrangement has been used - even though the circuit has been designed to allow the TOPFET to self protect - to prevent the TOPFET from turning back on when there is no protection supply, for example during reset.

Drain pin

Freewheel diode D4 is needed if the energy stored in the motor inductance exceeds the TOPFET's non-repetitive inductive turn-off energy rating at the designed operating junction temperature. The overvoltage clamping of the TOPFET is still needed, however, to protect against supply line transients.

5.3.8 PWM Control with TOPFET

Speed control of permanent magnet dc motors is required in many automotive and industrial applications, such as blower fan drives. The need for protected load outputs in such systems can be met by using a TOPFET with its inherent protection against short circuit, overtemperature, overvoltage and ESD. In section 5.3.7 the two basic methods for speed control, linear and PWM, are compared and discussed and a circuit example for linear control is given. This section gives an example of a PWM drive circuit using a 5-pin TOPFET.

Circuit Description

The circuit shown in Fig. 1 contains all the elements needed to produce a PWM circuit which can control the speed of a heater fan motor. The power device, because it is a TOPFET, can survive if the load is partially or completed shorted, if overvoltage transients appear on the supply lines or if the cooling is, or becomes, insufficient.

In a PWM control system the supply to the motor has to be switched periodically at a frequency significantly above its mechanical time constant. The net armature voltage and thus the motor speed is controlled by the duty cycle, i.e. on-time/period, of the control signal. With the component values shown, the circuit operates at a frequency of 20kHz. This means that any mechanical noise created by the switching is ultrasonic. The main building blocks of the circuit are the PWM generator, the power driver and the interface between the two.

PWM Generator

In Fig. 1, OP1 together with T1 and T2 form a saw-tooth generator, whose frequency is determined by R1 and C1. OP2 compares the saw-tooth voltage waveform at its inverting input with the voltage determined by the potentiometer P1. The output of OP2 is high as long as the saw-tooth voltage is less than the P1 voltage. As a result, the higher the voltage at P1, the longer the positive pulse width and thus the higher the duty cycle of the signal at the output of OP2.

Interface PWM Generator - TOPFET

The output signal of OP2 is fed to emitter-followers T4 and T5. These act as a low impedance driver for the input of the TOPFET. The drive is needed to achieve the short switching times which keep the dynamic switching losses of the TOPFET below the on-state losses.

Resistor R15 is included between the driver T4/T5 and the TOPFET input to ensure proper function of the TOPFET's internal overvoltage protection. This overvoltage protection is an active clamp circuit that will try to pull up the gate of the TOPFET's power MOSFET (i.e. the input pin) if the drain-source voltage exceeds 50V. A minimum resistance of 100Ω between input and ground is needed for the active clamp to succeed.

If the load is shorted or the TOPFET's junction temperature is too high, the internal sensors of the TOPFET will detect it and inform the protection logic which will turn off the internal flag transistor. The flag pin, which is connected to the drain of this transistor, will be pulled high by resistor R16. This will turn on transistor T3 pulling the input to the driver stage, T4/T5, low and hence turning the TOPFET off.

The TOPFET will remain in this state - even if the error condition disappears - until a reset is applied. The 5-pin TOPFETs are reset by taking the protection SUPPLY pin below V_{PSR}. In this circuit this is done by closing the reset switch, pulling the protection pin to ground. In this state there is no protection supply so the TOPFET is unprotected. However, the TOPFET indicates the absence of a protection supply by the flag transistor remaining off. In this circuit this causes the drive to the TOPFET to be low hence the TOPFET will stay off. The TOPFET will resume normal operation when the reset switch is opened and the protection supply is re-established.

Power Stage

In this circuit, the main power switch is a BUK105-50L which has an $R_{DS(ON)}$ of 60 mΩ @ V_{IS} = 5 V. The L version of the BUK105 has been chosen so that the protection supply can be fed from the available 5 V supply. The maximum protection supply current, I_{PS}, is 350 μA, the voltage drop across R17 could be 0.42 V. Even if the voltage is regulated as low as 4.5 V, the protection supply will still be > 4 V, the minimum V_{PSP} for valid protection with a V_{IS} of 5 V.

If a lower $R_{DS(ON)}$ were needed this could be achieved by modifying the circuit to give a higher V_{IS} on the TOPFET. A V_{IS} = 7 V would give an $R_{DS(ON)}$ = 50 mΩ. An input voltage as high as 10 V could be used but any increase must be accompanied by an increase in the protection supply voltage. A curve showing the required V_{PSP} for the full range of input voltage is given in the data sheet.

The given circuit can be used in both 12V and 24V systems because, with an input voltage of 5V, the TOPFET is short circuit protected up to a supply voltage of 35V. However, if a supply this high is expected then the dissipation and voltage rating of the regulator would need to be studied.

D1 is a freewheel diode across the motor load which must be present even though the TOPFET has an internal clamp circuit. This is because the dissipation resulting from repetitively clamping at 20 kHz is very high, much higher than any power switch of this size would be able to handle. R18/C4 are optional devices that slow down switching, reducing dV/dt and hence RF noise emission.

Capacitor C5 helps to decouple the circuit from the supply and prevents excessive dI/dt on the power lines and the excessive voltage spikes it would produce.

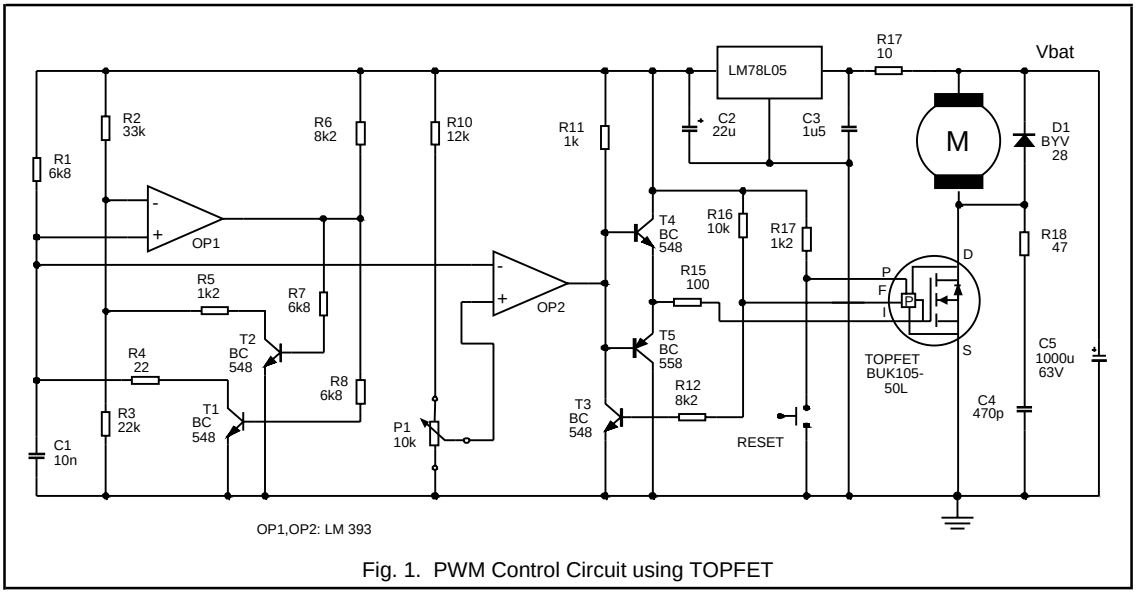


Fig. 1. PWM Control Circuit using TOPFET

5.3.9 Isolated Drive for TOPFET

An isolated drive for a power transistor is required if an electronic replacement of an electromechanical relay is to be realised. By using a TOPFET, with its integrated protection functions, in combination with an isolated input drive, the following advantages over an electromechanical relay can be achieved:

- o Permanent short circuit protection
- o Over temperature protection
- o Active clamping at inductive turn-off
- o Logic level control
- o Higher switching frequency

This section presents a complete circuit example of a transformer isolated drive. It also discusses other isolation techniques particularly in relation to meeting TOPFET's specific requirements.

Basic Methods for Isolated INPUT Drives

Opto-Isolated Drives

For this method a light emitter (e.g. LED or lamp) and a photo-device is needed. The latter can be subdivided into two groups:

Photo Resistors/Transistors

With these devices a 'switch' can be built to control the input voltage of a TOPFET. They cannot provide the power needed to drive the input so a separate supply is needed. In low side configurations this can be the main supply directly. In high side configurations an input voltage above main supply level is needed which could be generated by a charge pump. However, the supply connection needed for this type of opto-isolated drive is not needed with an electromechanical relay. So an opto-isolated drive with photo resistors/transistors cannot serve as a universal relay replacement.

Photo Cells

The drive energy from a control pin can be transferred to the input pin of a power device by means of photo cells. This would eliminate the need for the additional supply connection. Integrated devices exist that combine an LED and a chain of photo-cells. They are designed to drive ordinary power MOSFETs so their output current, due to the low efficiency of the photo-cells, is only a few μA. This is not enough to supply the protection circuits of a TOPFET so this method cannot be used to provide isolated drive for a TOPFET.

Transformer Isolated Drives

As with photo-cells, pulse transformers provide a means of transferring energy from the control pin to the input of the power device. However, the transfer efficiency of a pulse transformer is much higher, so the protection circuits of a TOPFET can be supplied satisfactorily.

Extremely small pulse transformers are now available, and some outlines are suitable for surface mount. It is, therefore, realistic and practical to use this method to create a relay replacement for high and low side configurations.

Circuit Description

Figure 1 shows a transformer-isolated drive circuit for TOPFET. As discussed above, a TOPFET in combination with this drive circuit can be employed either in high side or low side configuration without modifications on the driver side. The drive signal on the transformer's primary side is a pulse train that is rectified on the secondary side to provide a continuous input voltage V_{IS} for the TOPFET. For the given dimensioning, a pulse rate in the range of 100kHz is well suited. A high pulse rate is advantageous as it allows the dimensions of the transformer and smoothing capacitor, C2, to be minimised.

On the primary side, a voltage is applied to the transformer when T1 is on. The positive pulse amplitude is limited by D7 on the secondary side. The drain current of T1 and the transformer current are limited by R1.

During the off period of T1, the transformer's primary current freewheels through D1 and D2. Thus the absolute maximum value for the negative pulse amplitude on the primary winding is equal to the sum of breakdown voltage of zener diode D2 and forward diode drop across D1. At a duty cycle of 50%, this value should be at least as high as the positive pulse amplitude. This allows the primary current to reach zero and thus the magnetic flux in the core to be reset while T1 is off. The maximum off-state drain-source voltage of T1 occurs if the secondary winding of the transformer is left open. It is the sum of supply voltage VP, zener voltage of D2 and forward voltage drop across D1.

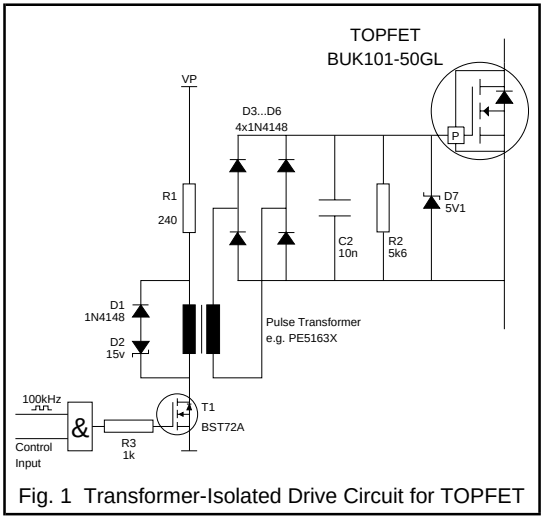


Fig. 1 Transformer-Isolated Drive Circuit for TOPFET

Using a bridge rectifier on the secondary side makes use of both positive and negative pulses to generate the input-to-source voltage V_{IS} for driving the TOPFET. This increases the efficiency. It also reduces the ripple on V_{IS}, therefore the ripple on the load current and hence the electromagnetic noise emission.

The minimum value for V_{IS} is set by the need to have enough voltage for correct operation of the TOPFET's overload protection circuits. The maximum is determined by the breakdown voltage of the ESD protection diode at the input pin. Taking this into account, V_{IS} should be within the range of 4V-6V in the case of the TOPFET type BUK101-50GL. In the given circuit the lower limit of V_{IS} is determined by the minimum supply voltage VP on the primary side, the transformer ratio, and the diode voltage drops at the bridge rectifier. Zener diode D7 ensures that V_{IS} cannot exceed the upper voltage limit.

The time constant of R2 and smoothing capacitor C2 determine the fall time of V_{IS} after the control input at the primary side goes low. A fall time significantly longer than that chosen here should be avoided for the following reason.

After a TOPFET has turned off to protect itself, it is latched off so it stays in the off-state as long as V_{IS} is high. To reset the TOPFET, V_{IS} must go low. In this circuit this happens when the control input at the primary side goes low, disconnecting the drive pulses from the gate of T1. On the secondary side, this allows C2 to be discharged by R2 and hence V_{IS} to decrease. When V_{IS} has fallen below the protection reset voltage level V_{ISR}, the fault latch will reset and an internal transistor, which holds the gate low, will turn off. The gate voltage will now rise to the C2 voltage and the TOPFET's output MOSFET will conduct again. The MOSFET will be fully off when V_{IS} falls below the TOPFET threshold voltage $V_{IS(TO)}$. In the range between V_{ISR} and $V_{IS(TO)}$ (max. 3.5V-1V for the BUK101-50GL) the output MOSFET may conduct while the protection circuits are non-active. For safe reset of a latched TOPFET with a shorted load, this V_{IS}-range must be passed through within a limited time interval. With the dimensioning of R2 and C2 shown in Fig. 1, this time interval is approximately 130 µs. The BUK101-50GL is guaranteed to withstand a hard short circuit for > 300 µs at a battery voltage of 35V and V_{IS}=5V. So the chosen values of R2 and C2 ensure safe turn-off of the TOPFET.

5.3.10 3 pin and 5 pin TOPFET Leadforms

The TOPFET (Temperature and Overload Protected MOSFET) range of devices from Philips Semiconductors is based on conventional vertical power MOSFET technology with the advantages of on-chip protection circuitry. Using this approach the devices are able to achieve the very low values of RDS(on) which are required in applications for automotive and other power circuits. TOPFET devices are currently available in two topologies for maximum compatibility with the requirements of circuit designers.

3-pin TOPFETs TO220	$R_{thj\text{-}mb}$ (K/W)	5-pin TOPFETs SOT263	$R_{thj\text{-}mb}$ (K/W)
BUK100-50GL	3.1	BUK104-50L	3.1
BUK100-50GS	3.1	BUK104-50S	3.1
BUK101-50GL	1.67	BUK105-50L	1.67
BUK101-50GS	1.67	BUK105-50S	1.67
BUK102-50GL	1.0	BUK106-50L	1.0
BUK102-50GS	1.0	BUK106-50S	1.0

Table 1. 3-pin and 5-pin TOPFET type ranges

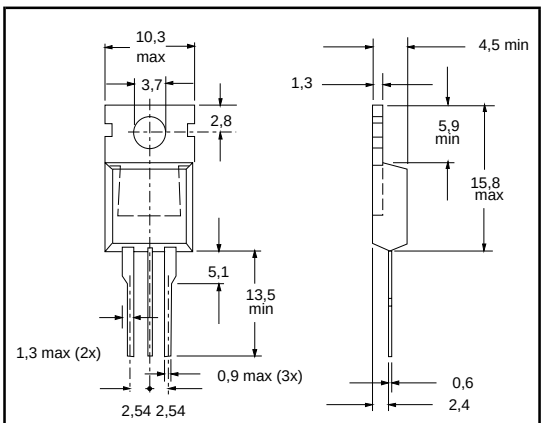


Fig. 1 TO220AB

The 3-pin TOPFETs are assembled in the standard TO220-AB package (Fig. 1), which is also sometimes known as SOT78. The 5-pin versions are assembled in the SOT263 PENTAWATT package (Fig. 2). Depending upon the load and the application the devices can be operated in free air or attached to a heatsink. When using a heatsink the advantage of these outlines lies in the very low thermal impedance which can be achieved. Table 1 shows the thermal resistances for the range of TOPFET devices.

Although these outlines are industry standards, on occasions users have the need to form the leads of the devices to accommodate a variety of assembly requirements. Philips Semiconductors can offer a number of standard pre-formed leadbend options to make the purchase and specification of leadformed devices easier.

These pre-forms satisfy the basic rules concerning the bending and forming of copper leads and ensure that, for example, the bend radius is not less than the thickness of the lead and that there is sufficient material at the base of the plastic moulding to enable the act of pre-forming to take place without damage to the crystal or its die attach and wire-bonding.

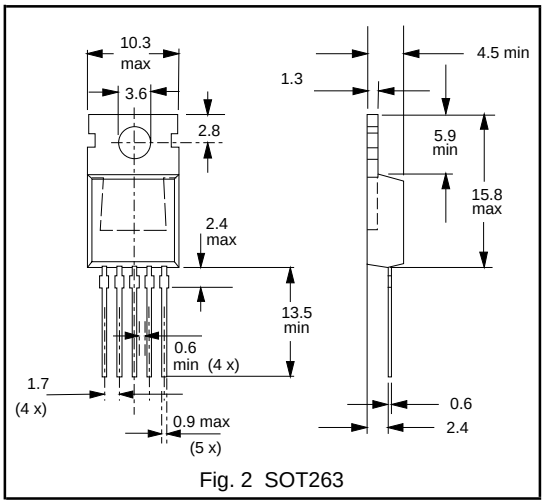


Fig. 2 SOT263

Figure 3 shows leadform option L02 for a TO220 type. A device with this standard leadbend can be ordered by specifying /L02 as the suffix for the device type. For example, a BUK101-50GL with this leadbend is specified by ordering type BUK101-50GL/L02.

In addition to this, there is often the necessity to crop the tab off the device to make a low profile version, when height above the pcb is restricted. Again, without control, there is a risk of fracturing the crystal during this process but Philips Semiconductors can offer this option (SOT226), shown in Fig. 4, which can be ordered by specifying the suffix /CR to the device type number, eg. BUK102-50GS/CR.

For surface mountable TOPFETs, the leadbend option L06 means that the device can be used in applications where a low profile is required. With this option an electrical contact

from the pcb to the tab of the device is possible. The device is shown in Fig. 5 and, for the BUK100-50GS would be specified as the BUK-100-50GS/CRL06.

For the 5-pin TOPFET the device is available in the leadbent SOT263 outline as standard (Fig. 6). For the leadform option the device type number is modified by the addition of the suffix P to the SOT263 type name, eg BUK104-50L (SOT263) becomes BUK104-50LP (leadbent SOT263).

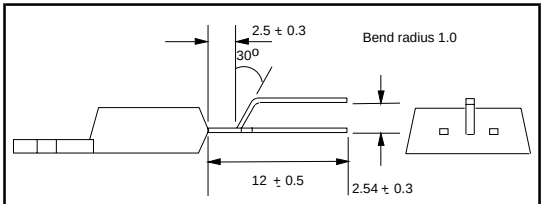


Fig. 3 TO220, L02 leadbend

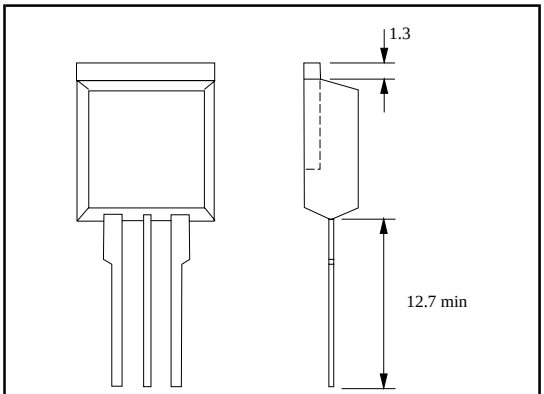


Fig. 4 SOT226

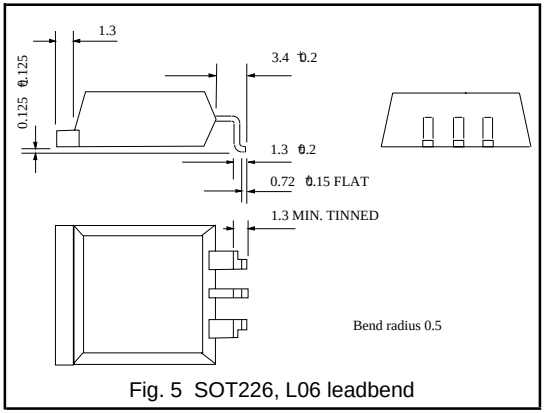


Fig. 5 SOT226, L06 leadbend

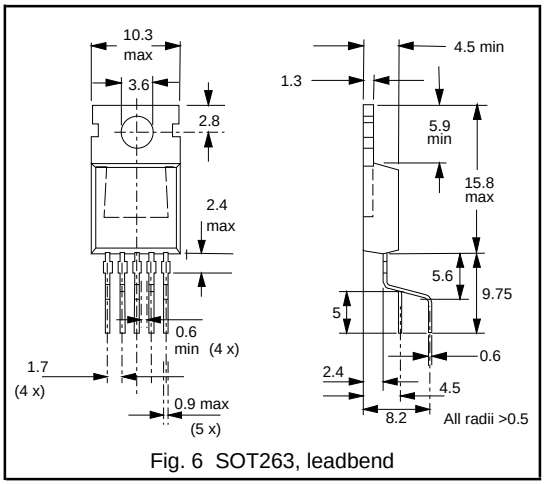


Fig. 6 SOT263, leadbend

5.3.11 TOPFET Input Voltage

Low side TOPFET data sheets specify that the voltage between the input and source pins should not be less than 0 V, in other words should not go negative. In many circumstances, sound layout using normal logic gates will ensure that this condition is always satisfied. However, in some situations it is difficult to design a circuit in which this condition is met under all conditions. This section explains the reason for the quoted rating and shows that it is a limit in only a few circumstances. The paper will also illustrate how negative inputs can be generated. Section 5.1.12 shows how negative inputs can be prevented and recommends a simple method of stopping a TOPFET being damaged if negative inputs do occur.

Reason for specification limit

All the pins of a low side TOPFET are protected against ESD. The input pin - the most sensitive pin of a normal MOSFET - is protected by a special diode connected between the input and the source. In the presence of an ESD pulse, this diode conducts and clamps the voltage on the input pin to a safe level.

The diode is formed by an area of n++ in a p+ region which is diffused into the n- epi layer, see Fig. 1. The input pin is connected to the n++ region and then to the rest of the circuits. The p+ region is connected by the metalisation to the source area of the power MOSFET part of the TOPFET. However, the p+ region also connects to the n- epi layer and hence to the drain via the n+ substrate. The ESD diode is formed by the n++ / p+ junction. However, the n++ and p+ diffusions in the n- epi also create a parasitic npn transistor. It is the presence of this transistor which makes the negative input rating necessary.

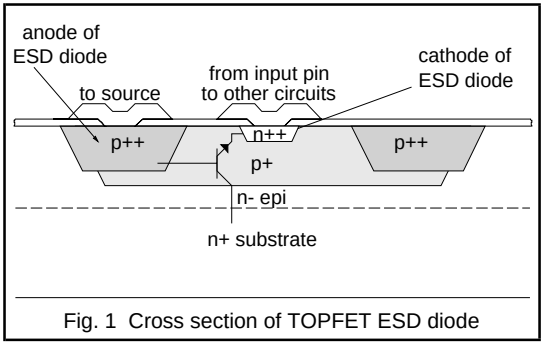


Fig. 1 Cross section of TOPFET ESD diode

With an input potential lower than the source potential, the input acts as an emitter, the drain as a collector and the source as a base, so the potential difference will act as bias for the parasitic transistor. The diffusion concentrations used to create a good ESD protection diode create a transistor with a limited forward SOA. The characteristics of the transistor mean that it can be damaged if its V_{CE} is greater than 30 V when its base is forward biased. For the TOPFET this means that damage could be caused only if the input goes negative while the drain voltage is > 30 V.

It should be noted that the conditions which may damage the transistor assume the impedance of the bias supply is low. If the bias is restricted the limits of SOA are different so the drain voltage needed for damage will be different. In any event at drain voltages < 30 V, a negative input will cause the parasitic transistor to conduct but will not cause damage.

Conditions creating negative input

The most obvious effect of the minimum V_{IS} is to preclude the use of negative drive to speed up turn off. However, this technique is only justifiable in very high frequency circuits and TOPFET is intended for use in DC or low frequency applications, so it is unlikely that this type of drive will be under consideration. The typical TOPFET driver stage will be unipolar using gates or discrete transistors from positive supply rails only. These drivers will turn the TOPFET off either by removing the drive and allowing TOPFET to turn itself off, via its internal pull down resistor, or by pulling the input to zero volts. It would appear, therefore, that negative inputs should not occur, but in some situations and with some circuit configurations they can.

High side circuits

A negative input can be created if an overvoltage transient is applied to an off-state TOPFET being used as a high side switch. A TOPFET will start to conduct if a supply line voltage transient exceeds its clamping voltage. The current now flowing through the TOPFET will also flow through the low side load, raising the source potential above ground. The driver stage may be designed to turn the TOPFET off by pulling the input to ground as in Fig. 2. If it is, then the conditions for harmful negative input have been created - the drain voltage is > 30 V, the input is at ground and the source potential is higher, so the input is negative.

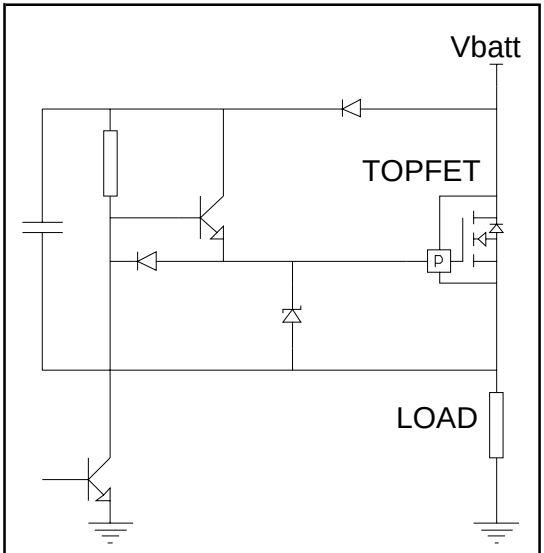


Fig. 2 Driver taking input to ground - high side

Low side circuits

In some circumstances it is possible to create negative input in a low side configuration. In the previous example it was a small current in relatively large resistance that raised the source above ground. The same effect can be created by a large current in the low, but not negligible, resistance of the wiring between the source pin and ground.

Systems are often configured with separate power and signal grounds and it is possible that the driver will be referenced to signal ground, see Fig. 3. In this case the TOPFET input will be pulled to signal ground potential when it is being turned off. The source will be connected to power ground and the common connection between the grounds may a considerable distance from the TOPFET. The resistance of the wiring will be low but even 20 mΩ may be significant if the current is high.

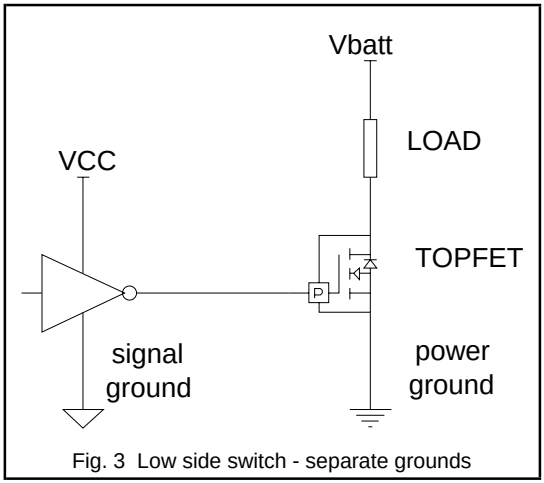


Fig. 3 Low side switch - separate grounds

There are two occasions when a large enough current could be flowing. The first is during the turn-on of a load with a high inrush current, for example a cold incandescent lamp. The second is when the load is shorted out. If the TOPFET turns off while this current is flowing, the energy in the inductance of the wiring from the load to the TOPFET drain would raise the drain voltage, possibly to greater than 30 V. The high current, as high as 60 A, in the source to ground wiring, say 20 mΩ, would raise the source 1.2 V above ground. So, the combination of conditions which may damage a TOPFET have been created.

The circuits and circumstances mentioned in this paper are only examples and other hazardous negative input situations will exist. Methods of preventing negative input and of stopping a TOPFET being damaged, if negative inputs do occur, is presented in section 5.1.12.

5.3.12 Negative Input and TOPFET

Low side TOPFET data sheets specify that the voltage between the input and source pins should not be less than 0 V, ie. should not go negative. This limit is needed to prevent the parasitic transistor, formed by the input ESD protection diode in the n- epi, being damaged in some circumstances. The reason for the limit and the causes of potentially damaging conditions are discussed more fully in section 5.3.11. This section will show how damaging negative inputs can be prevented and recommend a simple method of stopping low side TOPFETs being damaged if negative inputs do occur.

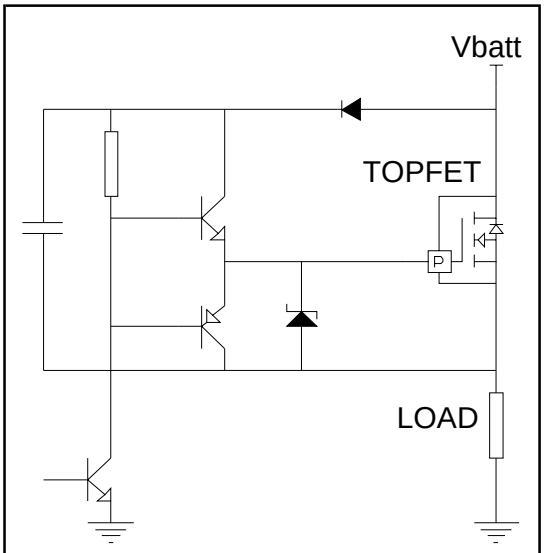


Fig. 1 High side driver taking input to source

Avoiding negative input

Section 5.3.11 gave examples of high and low side drive configurations which could, in some circumstances, generate a potentially damaging negative input. There are two ways to prevent the input from being taken too low. The first is to fit a diode in series with the input pin. The cathode of the diode would be connected to the TOPFET. The diode would conduct while the driver output was high but would turn off and isolate the input pin when the driver tried to pull the input low. The driver would now not be driving the TOPFET off but would be allowing it to turn itself off via its internal input - source resistor.

The second method is to arrange the drive so that it turns the TOPFET off by pulling the input to the source rather than to ground. The circuit shown in Fig. 1 shows a high side drive in which this has been achieved. The TOPFET is turned off by a pnp transistor being turned on and pulling the input to the source.

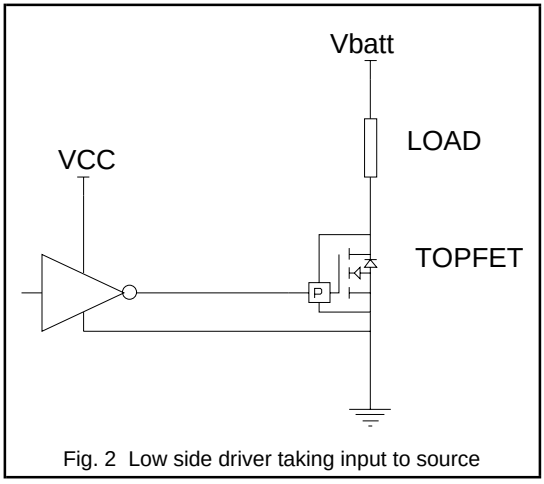


Fig. 2 Low side driver taking input to source

Figure 2 shows a low side drive where the GND pin of the cmos gate is connected as close as possible to the TOPFET source pin. Once more the effect is to turn off the TOPFET by pulling the input to source.

If negative inputs cannot be avoided

The technique of referencing drivers to the source pin helps prevent negative inputs being generated. It is used in most power MOSFET switching situations and should be used with TOPFET wherever possible. If negative inputs cannot be eliminated there are ways of preventing them from causing damage to a TOPFET.

Although published data gives 0 V as the lower limit of V_{IS}, lower values can be acceptable. The V_{IS} limit of 0 V ensures that the SOA of the parasitic transistor associated with the ESD diode is never exceeded. The arrangement shown in Fig. 3. can be used to ensure this. This shows the parasitic npn transistor of the TOPFET and two additional anti-parallel diodes in series with the input.

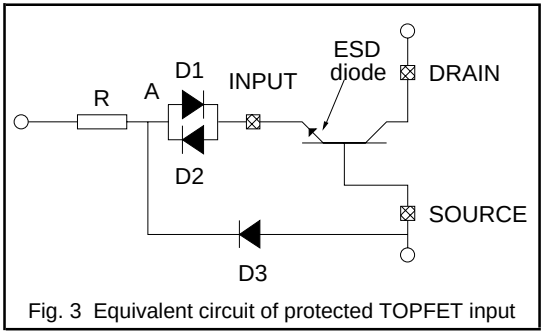


Fig. 3 Equivalent circuit of protected TOPFET input

If the drive voltage goes negative, the diode D1 (see fig. 3) is reverse biased and diodes D2 and D3 are forward biased. The voltage between Source and point A is limited by D3 and the current is limited by R. This voltage is divided between D2 and the base-emitter junction of the ESD diode. The current flowing through the ESD diode's base-emitter junction is therefore negligible and so the SOA of this transistor is not exceeded. This means that all the conditions needed to damage the device can be avoided and the TOPFET is protected against negative input.

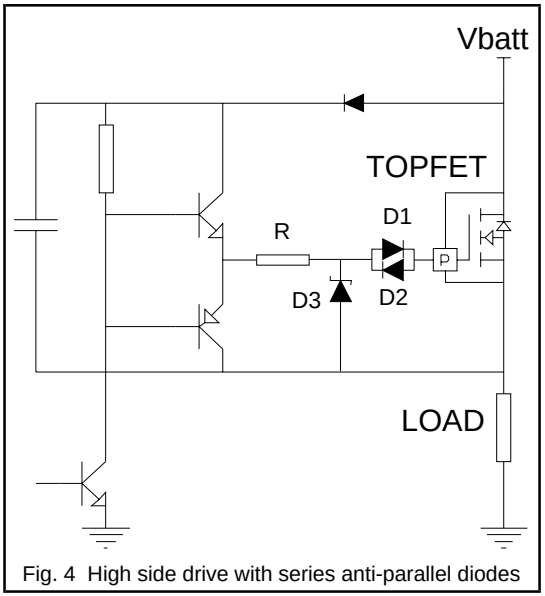


Fig. 4 High side drive with series anti-parallel diodes

In the normal on state, D1 will be forward biased but it will create a voltage drop of about 0.5 V between point A and the TOPFET input. To enable a 3 pin TOPFET to protect itself, its input must be >4.0 V so the designer needs to ensure that the voltage at A is >4.5 V.

During a normal turn-off the gate discharge current will flow through the forward biased D2. No special measures are needed to cope with D2's voltage drop because 0.5 V is well below the TOPFET's threshold voltage so it will be properly turned off if point A is taken to 0 V.

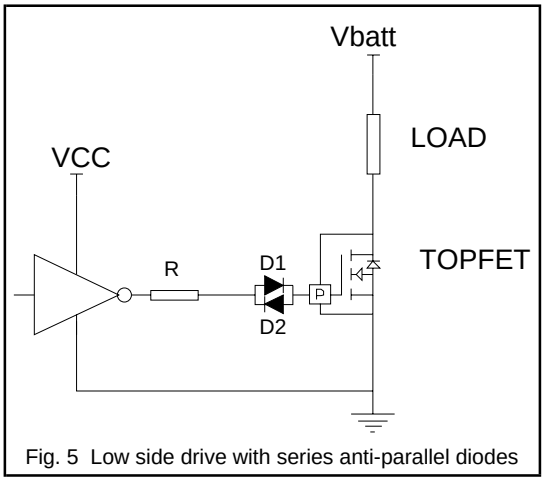


Fig. 5 Low side drive with series anti-parallel diodes

Figure 4 shows the high side drive of Fig. 1 modified to include the series anti-parallel diodes, D1 and D2. D3 is already present in the form of the input voltage limiting zener so the only extra components are the series anti-parallel diodes. A modified low side drive is shown in Fig. 5. Here D1 and D2 are fitted between the output of a cmos gate and the TOPFET input pin. In this circuit, diode limiting is provided by the bipolar parasitic diode inherent in cmos output stages.

Series resistor values

The recommended minimum resistor values are,

Types	Over-voltage transient	Minimum series resistor
3-Pin	< 200 V for 2 ms	50 Ω
3-Pin	< 300 V for 2 ms	300 Ω
5-Pin	< 100 V for 2 ms	200 Ω
5-Pin	< 200 V for 2 ms	1000 Ω
5-Pin	< 300 V for 2 ms	2000 Ω

If the negative voltage between point A and the source is present for a longer period of time than 2 ms then a larger value of series resistor may be required.

5.3.13 Switching Inductive Loads with TOPFET

If there is current flowing in the coil of a solenoid or a relay then there is energy stored in the inductance. At turn-off this energy has to be removed from the coil and dissipated somewhere. During this process, an extremely high voltage will be generated unless measures are taken to limit it. This voltage can lead to breakdown and, beyond a certain energy level, damage to the switching transistor. Common methods of controlling this voltage are a freewheel diode in parallel with the inductor or a suppressor diode in parallel with the switching transistor.

A TOPFET with its overvoltage clamping feature can save these extra elements, provided that its limiting values are not exceeded during the turn-off procedure. This section shows a simplified method of estimating the dissipated energy and the junction temperature rise in a TOPFET at inductive turn-off. The equations given here are first order approximations. They act as an aid in determining the need for an external freewheel or suppressor element.

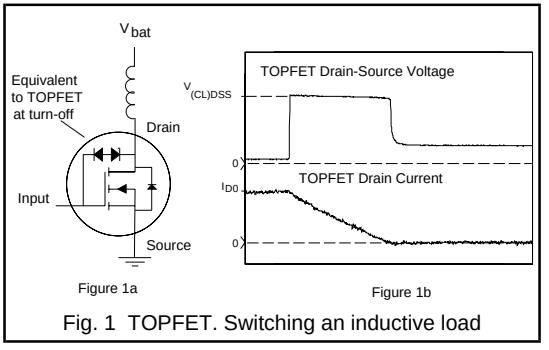


Fig. 1 TOPFET. Switching an inductive load

TOPFET behaviour

Figure 1 shows an equivalent circuit diagram and the shapes of drain current I_D and drain-source voltage V_{DS} versus time for a TOPFET switching an inductor. The overvoltage clamp feature of TOPFET is represented by a zener diode that drives the output power MOSFET into conduction if V_{DS} rises too high. In this state the TOPFET acts as an active clamp element, limiting its own V_{DS} to typically 60V.

Saving of external overvoltage protection

The TOPFET clamp feature is the only voltage limiting required if the energy associated with turn-off, E_{clamp}, does not increase the TOPFET's junction temperature too far. The following section shows how to estimate E_{clamp}. Limiting values for the energies E_{DSM} for non-repetitive clamping and E_{DRM} for repetitive clamping are stated in the data sheet. E_{DSM} relates to a peak junction temperature of 225˚C reached during clamping which is acceptable if it occurs only a few times in the lifetime of a device. Thus E_{DSM} should only be used when deciding on the necessity for external protection against overvoltage transients that occur extremely rarely.

However, when switching inductive loads, absorbing E_{clamp} is a normal condition. So to achieve the best longterm reliability, the peak junction temperature should not exceed 150˚C. A method for estimating the peak junction temperature is given later.

In this type of repetitive clamping application, the E_{DRM} rating in the data sheet can be compared with E_{clamp} to give an initial indication of need for external voltage limiting. This initial assessment should be followed by a temperature calculation to find the maximum allowable mounting base temperature and thus the heatsink requirements.

Estimation of clamping energy

The energy stored in the coil of a solenoid valve or a relay with the inductance L at a current I is:

$$E_L = \frac{1}{2} L I^2 \quad (1)$$

The clamping energy E_{clamp} in the TOPFET during an inductive turn-off follows from equation (1) and the fact that, during clamping, the battery also delivers energy to the TOPFET:

$$E_{clamp} = \frac{1}{2} L I_{D0}^2 \frac{V_{(CL)DSS}}{V_{(CL)DSS} - V_{bat}} \quad (2)$$

In (2) I_{D0} is the drain current at start of turn-off, $V_{(CL)DSS}$ the TOPFET's typical drain-source clamping voltage, V_{bat} the battery voltage and L the load inductance. Equation (2) assumes an inductor with no resistance. In practice, there will be some resistance, which will dissipate a fraction of E_{clamp}. Therefore, (2) represents a worst case situation.

Estimation of junction temperature

The peak junction temperature during clamping can be estimated by adding the maximum temperature rise ΔT_j to the average junction temperature, T_{j0}.

$$T_{j,pk} = T_{j0} + \Delta T_j \quad (3)$$

Measurements have shown that ΔT_j can be approximated by

$$\Delta T_j = \frac{5}{6} V_{(CL)DSS} \cdot I_{D0} \cdot Z_{th} \quad (4)$$

Where Z_{th} is the transient thermal impedance for a pulse width of $\frac{1}{3}$ of the time in clamping, which, for a coil resistance of zero Ohms, is:

$$t_{clamp} = \frac{L \cdot I_{D0}}{V_{(CL)DSS} - V_{bat}} \quad (5)$$

Average dissipation will make T_{j0} higher than the mounting base temperature T_{mb}, which can be assumed as constant, if the TOPFET is mounted on a heatsink. In repetitive switching applications, both on-state losses and turn-off losses contribute to the average dissipation. So T_{j0} will be:

$$T_{j0} = T_{mb} + \left(E_{clamp} \cdot f + I_{RMS}^2 \cdot R_{DS(ON)}\right) \cdot R_{th,j-mb} \quad (6)$$

In (6) I_{RMS} is the root mean square value of the load current and $R_{DS(ON)}$ is the on-state resistance of the TOPFET. In non repetitive applications, the average dissipation is the on state dissipation so T_{j0} is:

$$T_{j0} = T_{mb} + I_{D0}^2 \cdot R_{DS(ON)} \cdot R_{th,j-mb} \quad (7)$$

If these calculations indicate that the peak junction temperature is less than $T_{j\,max}$, then external voltage limiting is not needed.

Calculation examples

Both examples are carried out for V_{bat}=13 V and a BUK101-50GS with a clamping voltage of 60 V. For calculation of on-state losses, the maximum $R_{DS(ON)}$ at T_j=150˚C of 87.5 mΩ is taken.

Example 1: An inductor with L=10 mH is switched off non-repetitively at a dc current I_{D0}=7 A.

(5) gives t_{clamp} = 1.5 ms. The BUK101 data curve indicates a Z_{th} of about 0.28 K/W at $t_{clamp}/3$ = 500 µs. (4) then gives a ΔT_j of about 100 K. It is a non repetitive application so use (7) to find T_{j0}, which indicates that T_j is about 7˚C above T_{mb} due to on-state losses. From the ΔT_j and T_{j0} figures it can be inferred:
$T_{j,pk}$ < 150˚C for T_{mb} < (150-100-7)˚C = 43˚C.

Example 2: An inductor with L=3 mH is switched at I_{D0}=4 A and a frequency of 100Hz and a duty cycle of 0.5.

(2) yields a clamp energy of 31 mJ, which is less than the E_{DRM} rating of the BUK101 of 40 mJ so repetitive clamping is allowed. (6) yields that T_{j0} will be about 8 K above T_{mb}. From (4) and (5), ΔT_j can be estimated to be < 30 K. These figures imply that this load can be safely driven if the T_{mb} of the BUK101-50GS is < 112˚C.

5.3.14 Driving DC Motors with TOPFET

Examples for motor drive circuits using low side TOPFET have already been given in section 5.3.7: "Linear Control with TOPFET", and section 5.3.8: "PWM Control with TOPFET". This section discusses the characteristics of DC motors that have to be considered when designing a drive circuit with low side TOPFET and gives examples of some basic drive circuits.

Important motor characteristics

The permanent magnet motor is the most common type of motor for driving a wide range of applications including small industrial drives, cooling fans and model cars. Therefore, the following discussions are based on this type. The equivalent circuit of these motors is shown in Fig. 1, where R_A and L_A represent the resistance and inductance of the armature.

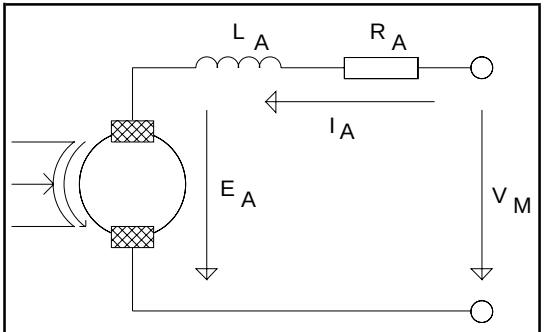


Fig. 1 Equivalent circuit for PM DC motor

Inrush current

Correct operation of some mechanical loads creates a special starting torque requirement for the motor. Since motor torque is proportional to motor current, high starting torque can only be achieved if the inrush current is allowed to be high. The TOPFETs BUK100...BUK106 do not use current limiting techniques to provide overload protection, so the inrush current they can deliver to a motor is limited only by the forward transconductance g_{fs}. To meet extreme starting torque requirements, an 'S'type with 10 V control is to be preferred over an 'L' type with 5 V control because 'S' types can deliver approximately twice the current of 'L' types. Typical currents can be judged from the data sheet $I_{D(SC)}$ in the section TRANSFER CHARACTERISTICS.

Stall current

The stall current of a dc motor is limited by the armature resistance, R_A in Fig. 1, and can reach values of 5-8 times the nominal current. This current will cause overheating in the motor which may damage the winding insulation or demagnetize the stator magnets.

The current would also cause extra dissipation in the driver but a TOPFET, with its over temperature protection, would survive a permanent stall condition. In addition, with careful thermal design, the TOPFET can also be used to prevent damage to the motor.

Inductive kick back at turn-off

The energy stored in the armature inductance, L_A, has to be removed when the motor is turning off. As in the case of inductive loads such as solenoid valves and relay coils, this is usually done by a freewheel diode. Provided that the energy is within its E_{DRM} rating, a TOPFET's overvoltage protection feature can be used instead of a freewheel diode. Section 5.3.13: "Switching Inductive Loads with TOPFET", covers this topic in more detail and gives a simple calculation method to assess the need for a freewheel diode. If overtemperature shutdown due to a stalled motor can occur, a freewheel diode is generally recommended. Without freewheel diode the TOPFET would have to absorb a very high energy at a junction temperature of at least 150 ˚C.

In the case of pulsed operation of the motor (e.g. pulse width modulation for speed control), the use of a freewheel diode is advisable. Without it, motor current ripple would be higher and the loss in the switching device could be as high as it would be in a linear control circuit.

Special effects of back EMF

Effects at running out

The back EMF, E_A, of a motor is proportional to the rotational speed. When the TOPFET is turned off, the motor acts as a generator and E_A can serve as the feedback signal in a PWM control system.

Although the back EMF voltage of many motors is, during normal running, below its terminal voltage, in some situations and with some motors the peak back EMF can exceed the terminal voltage. Shortly after turn-off these EMF peaks may even exceed the battery voltage plus one diode drop. In this case the EMF can supply current into the battery circuit by forward biasing the TOPFET's Source-Drain diode (see Fig. 2a). As a result of the internal structure of a low side TOPFET, the Source-Drain diode current will create a conduction path from the Input to the Drain. The current through this path can be limited to a safe

value by including a series resistance R_i as shown in Fig. 2a. Recommended values for R_i are 100Ω for 5V drivers and 220Ω for drivers above 6V.

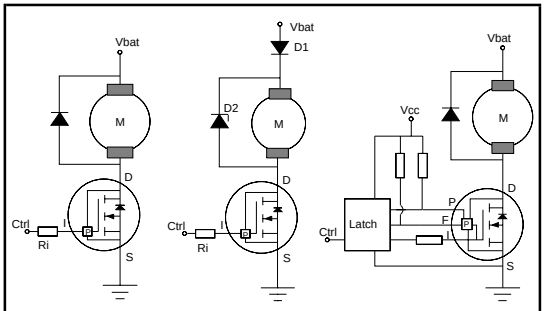
For 5 pin TOPFETs a path is also created from the Protection Supply and Flag pins. In this case, sufficient current limiting is often provided by the resistors that are fitted to connect the Flag and Protection Supply pins to Vcc (see Fig. 2c). The actual resistor values must be determined from consideration of the TOPFET and control circuit data sheets.

Effects of intermittent short circuit

When a TOPFET's short circuit protection has tripped due to a short circuited motor, the motor will continue to turn. In this situation the motor acts as a generator and its current is reversed. The motor will lose rotational energy and, if the short circuit remains long enough, will stop. In practice however, contact sparking can cause intermittent short circuits. In this case the short circuit may be interrupted before the motor has stopped. After the interruption the generator current will continue to flow, forced by the armature inductance L_A. A path for this negative current into the battery is provided via TOPFET's Source-Drain diode. As described in the above section, currents into Input, Protection Supply and Flag terminals should then be limited by means of series resistances.

Besides this, TOPFET's internal circuits are non-active while its Source-Drain diode is forward biased and a previous overload shutdown will not stay latched. As a consequence, a TOPFET that has turned off due to a short circuit across its motor load may turn on again if the short circuit opens before the motor has stopped. This behaviour will not damage the TOPFET. However, Figs 2b and 2c show ways of avoiding it if it is not acceptable.

The first method (Fig. 2b) is to avoid forward biasing of TOPFET's Source-Drain diode by means of a series diode D1. An alternative path for the generator current is provided by zener diode D2. (It is worth noting that interruption of the current path with D1 will be required in applications where reverse battery must not activate the motor.) If the inclusion of a power diode into the motor circuit is not acceptable the alternative shown in Fig. 2c can be used. In this approach the flag signal sets an external latch when the TOPFET is tripped by the short circuit. In this way the TOPFET status is stored even when its Source-Drain diode is forward biased. If the TOPFET is being driven from a microcontroller, the 'latch' function could be implemented in software.



a) Simplest circuit b) Reverse blocking c) External latching

Fig. 2 Basic motor drive circuits with TOPFET

5.3.15 An Introduction to the High Side TOPFET

The introduction of high side TOPFETs enhances the range of protected power MOSFETs available from Philips. These devices combine the real power handling ability of low $R_{DS(ON)}$ MOSFETs with protection circuits and the interfacing to allow ground referenced logic signals to control a high side switch.

Type range

Table 1 shows the range of high side TOPFETs. Included in the range are devices with on-state resistance in the range 38 to 220 mΩ. For each of the types an 'X' or 'Y' variant can be supplied ('Y' types have an additional internal resistor in the ground line). All the devices are 50 V types designed for use in 12 V automotive systems.

Type	$R_{DS(ON)}$ (mΩ)
BUK200-50X / BUK200-50Y	100
BUK201-50X / BUK201-50Y	60
BUK202-50X / BUK202-50Y	38
BUK203-50X / BUK203-50Y	220

Table 1. High side TOPFET type range

Features

Particular care has been taken during the development of the high side TOPFET to make a device which closely matches the requirements of the automotive designer.

Overload Protection -

High side TOPFETs are protected from the full range of overload conditions. Low level overloads which result in higher than expected dissipation can cause the TOPFET to overheat. In this case the overtemperature sensor will trip and the TOPFET will turn itself off until the chip temperature falls below the reset point. In the event of a medium level overload, which could allow a high current to flow, TOPFET will limit the current, and hence dissipation, to a level which allows the overtemperature sensor time to react and turn the TOPFET off until it cools sufficiently. In high overload situations, like hard short circuits, the voltage developed across the TOPFET will cause the short circuit detector to react and latch the TOPFET off until it is reset by toggling the input. Both modes of overload turn-off are reported by pulling the status pin low.

Supply undervoltage lockout -

If the battery to ground voltage is too low for its circuits to work correctly a high side TOPFET will turn off.

Open load detection -

TOPFET monitors its own on-state voltage drop. If the drop is too low, indicating that the current is very small probably because the load is open circuit, TOPFET will report this by pulling the status pin low.

Quiescent current -

One factor of great importance, particularly as the number of devices in a car increases, is quiescent current. In TOPFETs, the supply which feeds the circuits is turned off when the input is low. This reduces off state current consumption from typically 25 μA to less than 1 μA.

Ground resistor -

For the fullest protection against the harsh automotive electrical environment, it is often necessary to fit a resistor between the ground pin of a high side device and module ground. To help with this the Y types of the TOPFET range have this resistor integrated on the chip. Apart from the obvious saving in component count, this approach has the advantage that the resistor is now in a package where its dissipation can be easily handled. (This feature is particularly useful when long duration reverse battery situations are being considered).

Inductive load turn-off clamping -

TOPFETs have a network between the MOSFET gate and the ground pin. This network sets the maximum negative potential between the load and ground pins. If the potential tries to exceed this figure, for example during inductive load turn-off, TOPFET will partially turn on, clamping the voltage at the load pin.

EMC

Electromagnetic compatibility is an increasingly important factor in all electronic designs. EMC covers the immunity and the emissions, both conducted and radiated, of electronic units and systems. The directives and tests are rarely applicable to individual electronic components although the behaviour of devices can have a significant influence on EMC performance. In recognition of this, TOPFET has been designed to create as few EMC problems as possible.

	Test Voltage	Pulse width
Pulse 1a	-100 V	0.05 ms
Pulse 1b		2 ms
Pulse 2a	+100 V	0.05 ms
Pulse 2b		0.5 ms
Pulse 3a	-200 V	0.1 µs
Pulse 3b	+200 V	0.1 µs
Pulse 5	+46.5 V	400 ms

Table 2. TOPFET transient tests

Conducted immunity -

One area where TOPFET helps with EMC is with its inherent immunity to conducted transients. The voltage supply of a vehicle is notorious for its transients and circuits and systems have to be designed to handle them. On the TOPFET chip are separate circuits which allow the output MOSFET and the control circuits to withstand transients between the battery and both the load and ground pins. The range of transients which high side TOPFETs can survive is shown in Table 2.

Low emission -

High side switch devices generate their gate drive voltage with oscillators and charge pumps running at high frequency - often in excess of 1 MHz. Unless care is taken in the basic design of the device, emissions at the oscillator frequency or its harmonics can appear at the ground and load pins.

The TOPFET designers have taken the necessary care. The appropriate choice of oscillator and charge pump circuits and the inclusion of on-chip filtering have reduced emissions considerably. Some indication of the improvement can be obtained by simply looking at the current in the ground pin with an AC coupled current probe. Waveforms for the ground pin current of a Philips TOPFET and another manufacturer's high side switch are shown in Fig. 1.

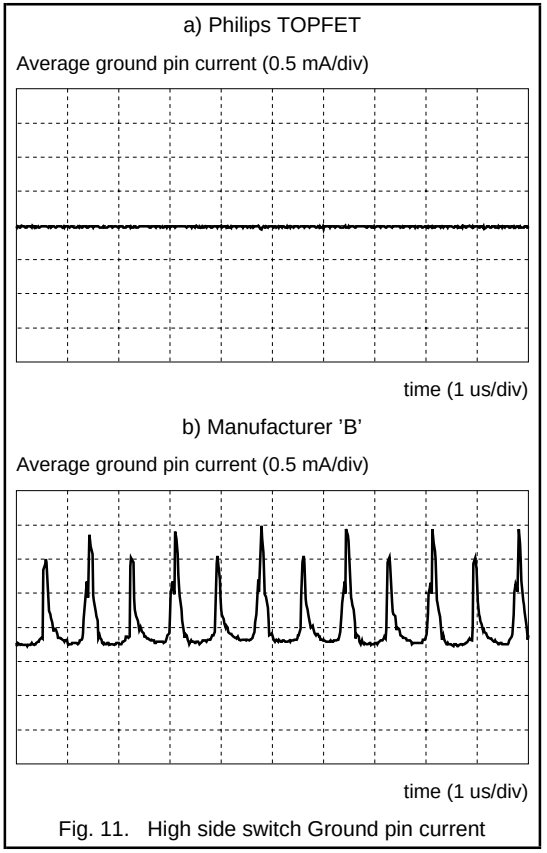


Fig. 11. High side switch Ground pin current

Conclusions

High side TOPFETs are real power devices designed for controlling a wide range of automotive loads. The care taken during their design means that TOPFETs are compatible with circuit designers' protection and EMC requirements.

5.3.16 High Side Linear Drive with TOPFET

This section describes a complete high side linear drive circuit using a TOPFET. A low side linear TOPFET drive circuit is described in section 5.3.7 and the principal pros and cons of linear versus PWM drivers are discussed there. The most important differences between high and low side linear drives are:

- The high side drive needs a charge pump circuit to provide an input voltage higher than the battery voltage.
- In the high side drive the load provides negative feedback for the output transistor. Therefore, the control loop circuit needed to maintain stability in a low side drive can be saved.

The circuit described in this paper was designed for and tested with a 200W fan motor for cars.

Circuit description

The complete high side linear drive circuit can be split up into two blocks:

- The drive circuit
- The charge pump

Drive circuit

Figure 1 shows the drive circuit. Motor speed is controlled by changing the TOPFET's input voltage and therefore its voltage drop. A 5-pin TOPFET is used because this type allows the protection circuit to be supplied independently of the input. This is necessary because in this application the input-source voltage may become too low to supply the protection circuit of a 3-pin TOPFET.

The TOPFET's input voltage and therefore the speed of the fan motor is determined by potentiometer R5. The TOPFET is operating as a source follower. The inherent negative feedback of this configuration will automatically ensure that the source potential will equal the input potential (minus the gate-source voltage) no matter what current is flowing in the motor.

An increase in motor load will tend to slow the motor reducing its back EMF and creating a demand for extra current. The extra current would increase the voltage drop across the TOPFET, lowering the source potential. Since the input potential has been set, the lower source potential increases the gate-source voltage turning the TOPFET on harder. The voltage drop will now reduce, returning the source - hence motor voltage - to its original value but at a higher current level. All of this means that even without an external feedback network, motor speed is inherently stable, although not absolutely constant, under the full range of motor loads.

Transistor T2 works as a current generator and supplies the protection circuit of the TOPFET. T2 is switchable via transistor T1 and Schottky diode D3. If the potentiometer is in position A, transistors T1 and T2 are switched off allowing R11 to pull the protection supply voltage to 0 V. This feature means the TOPFET, if it has tripped due to over temperature or overload, can be reset by turning the potentiometer to position A.

Position A is also the standby mode. With both transistors switched off, the drive circuit has a very small current consumption. This means that in standby the current consumption of the whole circuit (drive and charge pump) is about 0.3mA.

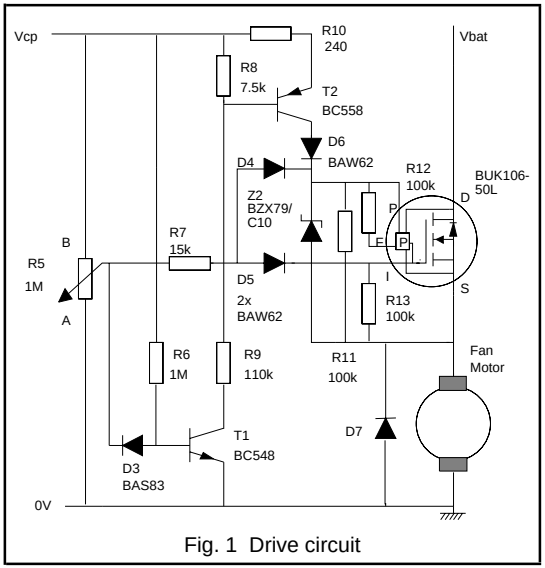


Fig. 1 Drive circuit

TOPFET interface

Negative potentials are not permitted between a TOPFET's protection supply (P), input (I) or flag (F) and its source. This must be considered, especially when designing high side drivers, where the source potential is determined by the load voltage.

If an overvoltage pulse occurs at the supply terminal while the TOPFET is off, the source potential will rise with the overvoltage as soon as the TOPFET's clamp voltage is exceeded. At this time the P,F and I pins should not be clamped with reference to ground, but should be allowed to rise with the source potential. In this circuit this is achieved by diodes D5 and D6 in the feeds to the I,P and F pins.

Zener diode Z2 limits the maximum protection supply and flag voltages to about 10 V and, via D4, the input-source voltage to about 10.6 V. Resistor R7 has a value high enough to allow the TOPFET's internal protection circuits to turn off the device in the event of an over temperature or short circuit load.

Charge pump

Figure 2 shows the charge pump circuit. IC1 works as an astable pulse generator at a frequency of 20 kHz which, together with D1, D2, C4, C5 produces a voltage doubler. The ICM7555 is a type with low current consumption. This is an important feature because the circuit consumes current, even when the driver circuit is in standby mode.

In its normal operating mode, the drive circuit has a typical current consumption of 1.5mA which determines the values of C4 and C5. R4 is included to limit the output current of IC1. The charge pump generates an output voltage of about 22V at a battery voltage of 12.6V. Z1, R1 and C1 will smooth and limit the supply to the circuit and provide protection from voltage spikes.

For correct operation of TOPFET's active protection circuits, sufficient voltage has to be applied to its protection pin. The minimum protection supply voltage for the BUK106-50L is 4V for input voltages Vis up to 6.5V (see data sheet Fig. 17). For the circuit presented and the component values given, this requirement is met with a battery voltage as low as 8 V. If operation at a lower battery voltage is needed then a voltage tripler charge pump could be used in place of the voltage doubler proposed in this paper.

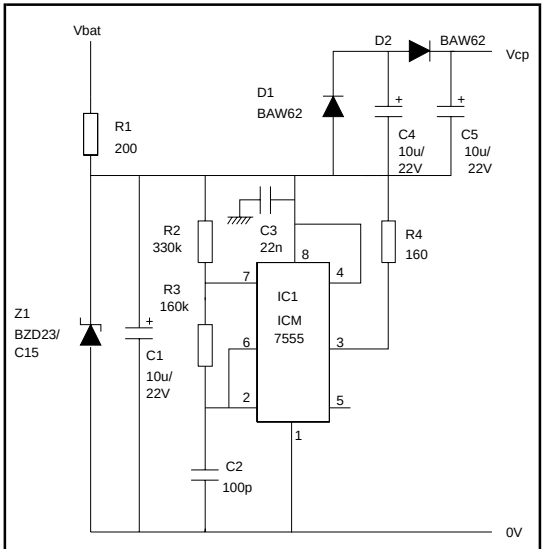


Fig. 2 Charge pump circuit

Automotive Ignition

5.4.1 An Introduction to Electronic Automotive Ignition

The function of an automotive ignition circuit is to provide a spark of sufficient energy to ignite the compressed air-fuel mixture at the appropriate time. Increasingly, electronics is being used to optimise the ignition event. This is now necessary to ensure conformance with emission regulations and to achieve maximum engine performance, fuel economy and engine efficiency. This section will look at some important aspects of the power stage of an electronic ignition system. Other sections in this chapter will look more closely at the power devices for this application.

Electronic ignition circuit

There are several different configurations for electronic ignition. Some are still being studied and there are several already in use. But by far the most common configuration for the power stage is that shown in Fig. 1. With this arrangement there is no distributor. The circuit shown is for a four cylinder engine and has two separate power circuits each feeding two cylinders. Extra power stages can be added for 6 and 8 cylinder engines. When one power stage fires, both plugs will spark but, by choosing pairs of cylinders which are 360° out of phase in the 4-stroke cycle, only one will have a mixture that can be ignited - the other will be approaching tdc at the end of the exhaust stroke.

Operation

During normal operation the transistor will be turned on some time before the spark is needed (t1 in Fig. 2). Current will now rise at a rate given by the equation

$$rate of rise = \frac{di}{dt} = \frac{V}{L} \qquad (1)$$

where V is the voltage across the primary of the coil. When the spark is needed (t3), the transistor is turned off. The current in the inductance will try to stop flowing but it can only change at the rate given by (1). This means that voltage on the primary is forced to become large and negative. Transformer action increases the secondary voltage until it reaches the voltage needed to create a spark at the plugs - minimum 5 kV but may be 10 to 30 kV. Current now flows through the spark and the secondary winding, the voltage now falls back to that necessary to maintain the current in the spark, t5. When all the coil energy has been delivered, t6, the voltage at the collector falls to the battery voltage.

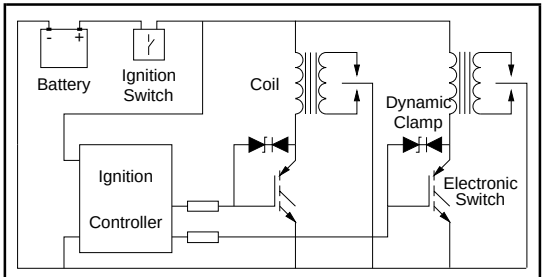


Fig. 1 Typical automotive ignition circuit

Spark energy

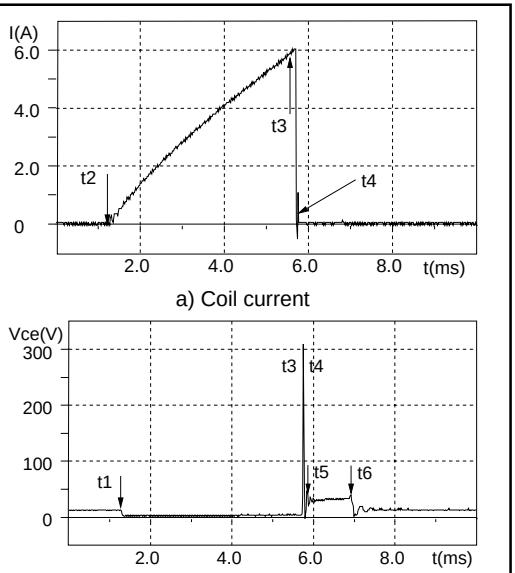
Under ideal conditions the mixture can be ignited with a spark energy of 0.3 mJ but, for reliable ignition under all possible engine conditions, spark energies in the range 60mJ to 150mJ are needed. The energy comes from the coil and is the energy stored as flux generated by the current that was allowed to build up in the primary. The energy stored in the magnetic field of the coil is:

$$E_{prim} = \frac{1}{2} L_{prim} i^2 \qquad (2)$$

Timing

The timing of the spark is one of the most critical factors in achieving optimum engine performance. The controller uses information about engine speed, temperature, fuel etc. to decide how far before tdc the spark is needed. It then uses data from crankshaft position sensors to decide when to signal for a spark.

One factor which the controller cannot control is the delay between it issuing the command to spark and the spark being generated. Part of this delay is the time it takes the transistor to start turning off together with the rate at which the transistor voltage rises. The controller can make allowance for this delay but in many systems this is no more than a fixed offset. In practice the delay will vary with variations in the drive circuit, temperature and between devices - with some transistor types being more susceptible to variation than others.



a) Coil current

b) Transistor collector voltage

Fig. 2 Ignition circuit waveforms

Dwell

As mentioned earlier, proper ignition means there must be enough energy stored in the coil when the spark is needed, so the transistor must be turned on soon enough to allow time for the current to reach the required level. However, turning on too soon will mean that the current is higher than it needs to be. Although proper spark timing and energy is more important, optimum coil current is also significant. Higher currents create higher loss which reduces efficiency and increases the problems of thermal management. They can also reduce the life and reliability of the coil and create major difficulties when designing for survival under fault conditions like open circuit secondary.

The time to turn on the transistor is governed by (1). Coil inductance is an attribute of the coil but the primary voltage depends on battery voltage and the voltage drop across the transistor. Battery voltage can vary widely and can be very low particularly during engine cranking. Ensuring that the circuit operates reasonably well at these low voltages means keeping the transistor voltage drop as low as possible.

Fault conditions

Automotive systems must be reliable. Achieving high reliability means designing systems that can survive all the operating environments that the automobile can produce. Some of the harshest conditions are the fault conditions.

Open circuit secondary

Disconnection of a spark plug lead means that the stored coil energy cannot be dissipated in the spark. Unless steps are taken to prevent it, the voltage will be forced higher until it reaches the breakdown voltage of the transistor. The combination of high current and voltage would probably destroy the device. The solution to this problem is to operate the transistor in dynamic clamping. This can be achieved either by connecting a network between collector and the gate/base or by using a device with the network already integrated into it. With this arrangement the voltage rises to the clamping voltage, the transistor then turns on partially, with enough drive to allow the coil current to flow at a collector emitter voltage equal to the clamping voltage. The clamping voltage is set higher than the voltage normally needed to generate the spark.

Reverse Battery

Another condition which must be survived is when the battery connections are reversed. Ideally no current should flow and this can be achieved with some transistors which have a reverse blocking voltage greater than the battery voltage. With many transistors, however, reverse blocking is not guaranteed and to block the current means adding a diode in series. This is rarely acceptable because the diode forward voltage drop adds too much to the effective voltage drop. The alternatives are to allow the current to flow either by using a transistor which is rated to operate with reverse current or by fitting a diode in anti-parallel with the transistor.

5.4.2 IGBTs for Automotive Ignition

This publication describes a range of power transistors for automotive ignition applications from Philips Semiconductors. This range of IGBTs has been specifically optimised for the demanding conditions of ignition circuits. The IGBT is a voltage controlled, low loss, high power transistor which gives the ease of drive and low conduction losses that are required in automotive ignition circuits. The Philips range of ignition IGBTs includes conventional IGBT devices with standard gate drive input. It also includes a range of standard and logic level input protected IGBTs with integral gate drain and gate source clamping diodes.

Introduction to the IGBT

The structure of an IGBT is similar to that of a Power MOSFET, both being created by the parallel connection of many thousands of identical cells. Figure 1 shows the cross section of one IGBT cell. The only difference between this drawing and one for a MOSFET would be the polarity of the substrate - the MOSFET would be n+ rather than the p+ of the IGBT. Since the gate structures are identical the IGBT like the MOSFET is a voltage driven device with an extremely high input impedance.

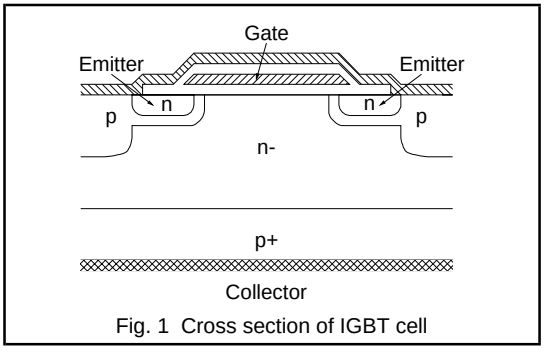


Fig. 1 Cross section of IGBT cell

Bipolar operation

Where the IGBT differs is in the characteristics of the output device. Conduction in a MOSFET is by majority carriers only but the p substrate silicon used for IGBTs promotes injection and gives bipolar conduction with both majority and minority carriers. The effect of this is to make the on state voltage drop of a high voltage IGBT much lower than that of the same size and voltage MOSFET. This feature is particularly useful in automotive ignition where high voltage devices are needed which can operate from low voltage supplies. In recognition of its combination of MOSFET input and bipolar output, the terminals of an IGBT are called Collector, Emitter and Gate.

Input Voltage

IGBTs, like MOSFETs, can have standard or logic level gate sensitivity. A standard device has a threshold voltage of typically 3.5 V - the threshold voltage is the gate voltage needed to allow the IGBT to conduct 1 mA, i.e just started to turn on. To be fully on, with an acceptable low V_{CE}, the gate voltage needs to be 8.5 V. In some situations, such as engine cranking, the battery voltage falls to less than 6 V and achieving adequate drive may be a problem.

An alternative would be to use a logic level IGBT which has a threshold of typically 1.5 V and is fully on with 5 V.

Another factor in the choice between standard or logic level, is that of noise immunity. In this application it can be very important that the IGBT is fully off, in a very low leakage state, when the driver stage output is LOW. Unfortunately, the LOW that a driver produces may not create a gate to emitter voltage of 0 V.

The threshold voltage of an IGBT falls as temperature rises. So the gate emitter voltage of a logic level IGBT (at $T_j = 120^{\circ}C$) needs to be < 0.7V to ensure that it is off. A standard level part, with its higher threshold, has more immunity and it would still be off if the voltage was < 1.4 V.

Turn off control

The time between the gate signal arriving at the IGBT and the collector voltage rising is known as the delay time, t_d. An ignition system produces a spark when the collector voltage rises. Since the timing of the spark is critical, it is advantageous to have good control of t_d. With the IGBT, unlike some other ignition switches, t_d is dominated by gate charge and so can be very low and is easily controlled by the resistance of the driver circuit.

Safe Operating Area

One of the worst situations for creating IGBT latch up is inductive turn off. Such a turn off takes place in electronic ignition. IGBTs, for ignition applications, are specified with a safe operating area (SOA) and limiting value of collector current that can be safely switched under clamped inductive load conditions (I_{CLM}). Providing that the device is operated within its safe operating area (SOA) dynamic latch-up (or SOA failure) cannot occur. Philips ignition IGBTs have a large turn-off SOA and a large energy handling capability making them easy to use in ignition circuits.

Feature	Advantage
IGBTs	
•Voltage driven	-Low gate drive power -Simple gate circuit
•Logic level capability	-Low battery operation
•Bipolar operation	-Low conduction loss -Small device size
•PowerMOS/bipolar structure	-Negligible Storage time -Reverse blocking -Energy handling
•Large SOA	-No snubber required -Design flexibility
Clamped IGBTs	
•Integral clamp diodes	-Design simplicity -Overvoltage protection -Clamp voltage control -Improved reliability -ESD protection

Table 1. Advantages of IGBTs

Reverse Battery

The n- p+ junction, see Fig. 1, which is inherent in the structure of the IGBT, creates a reverse blocking junction. This junction, although unable to support very high reverse voltages, is able to block voltages in excess of a battery voltage. This gives the IGBT a reverse battery blocking capability which ensures that reverse battery fault conditions will not give rise to high currents which could damage the IGBT or any other components in the ignition circuit.

Clamped IGBT

A refinement of the conventional IGBT is the clamped or protected IGBT. This is produced by adding extra processing stages which allows polysilicon diodes, of known breakdown voltage, to be integrated with the IGBT structure. A short chain of diodes is connected between the gate and the emitter. This gives ESD protection by clamping the voltage, which can be applied across the gate emitter oxide, to a safe value.

A much longer chain, with a combined breakdown voltage of several hundreds of volts, is connected between the collector and the gate. This chain makes the IGBT into a dynamic clamp - possibly the best way of ensuring survival during ignition faults like open circuit secondary. The position of the diode chains is shown in the circuit symbol, see Fig. 2.

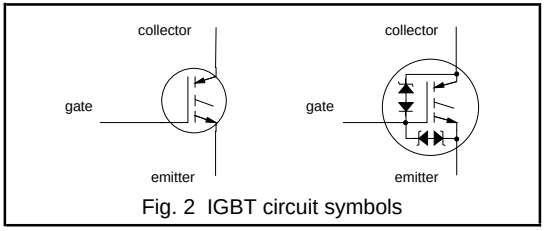


Fig. 2 IGBT circuit symbols

Conclusions

The Philips Semiconductors BUK854-500IS ignition IGBTs and clamped IGBTs BUK856-400IZ and BUK856-450IX are specifically designed to give a low loss, easy to drive and rugged solution to the demanding applications of automotive ignition circuits. IGBTs require the minimum of external components in the gate drive circuit and give negligible drive losses. The energy handling and reverse blocking capabilities of the device make it suitable for use in automotive environments - even under fault conditions. Voltage clamping and ESD protection give ease of design and use, improved reliability and performance in the ignition controller circuit.

5.4.3 Electronic Switches for Automotive Ignition

Earlier sections in this chapter have discussed the nature of automotive electronic ignition and looked at a range of IGBTs which have been optimised for use in this type of application. This section will compare ignition IGBTs with ignition darlington transistors and come to the conclusions that IGBTs have several advantages which would be useful to the automotive designer.

Darlington transistors

In the past, the darlington transistor has been the favoured power transistor for ignition applications. The darlington connection is, in fact, a cascade of two separate bipolar transistors. The combination increases the gain allowing the high voltage device to be controlled by a relatively low power driver stage.

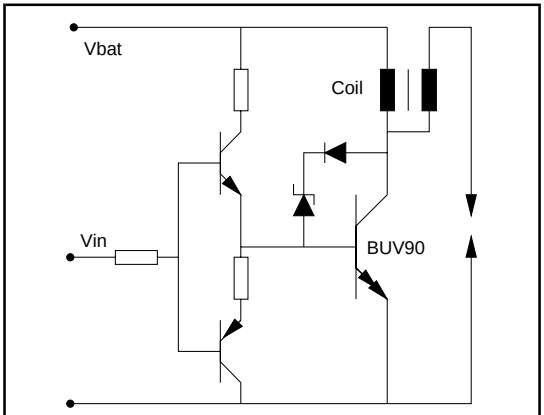


Fig. 1 Typical ignition circuit with darlington switch

As the darlington is a bipolar device it has a relatively low on-state voltage drop even though it can block a high voltage. The low voltage drop keeps conduction losses low and allows the ignition circuit to function at low battery voltages.

The disadvantage of a darlington is the complexity and cost of the base drive. Even though the gain is improved, by the darlington connection, a large gate current is still needed (approx. 100 mA) a circuit similar to that shown in Fig. 1 will be needed. It would be inefficient and costly to supply a current this large from the stabilised 5 V rail, so the supply could be the battery. This means that the drive dissipation when the transistor is on, is about 1.2 W and the average dissipation about 0.5 W. This level of dissipation requires a special driver IC or a circuit using discretes. All of this adds to the cost complexity and thermal problems of the ignition system.

The low on-state voltage drop of a bipolar device is the result of minority carrier injection. However, the minority carrier injection also introduces 'stored charge' into the device which must be removed at turn-off. The charge is extracted, at least partially, as negative base current during the period known as the storage time, t_s. How long this takes, depends on the amount of stored charge and the rate it is extracted. The amount of charge varies from device to device, with the level of the current and with temperature. The rate of extraction depends on the drive circuit and whether a 'simple' circuit like that of Fig. 1 is used or one which uses negative drive to remove the charge more quickly.

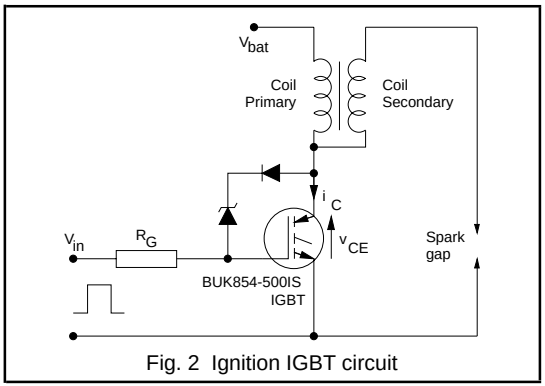


Fig. 2 Ignition IGBT circuit

Storage time adds to the delay between the input changing state and the spark being produced and the uncertainty in storage time, which results from the large number of variables, adds to the inaccuracy of the ignition timing.

Typical ignition darlingtons often include an internal antiparallel diode connected across the main emitter-collector terminals as shown in Fig. 1. This diode is not necessary for the normal operation of the ignition circuit and its function is simply to protect the darlington from reverse battery faults. However, during this condition, the diode does allow large reverse currents to flow through the ignition circuit.

IGBTs

The IGBT is a combination of bipolar transistor and Power MOSFET technologies. It has the advantage of the low on-state voltage drop of a bipolar darlington and can also be voltage driven in the same way as a Power MOSFET. This gives a highly efficient, easy to drive, minimum loss solution for the switching transistor in an ignition circuit.

A typical ignition circuit using the Philips BUK854-500IS IGBT is shown in Fig. 2; the saving in gate drive components is self evident. The need for a special driver stage is eliminated because drive dissipation for an IGBT will be approximately 10 μW which can be easily supplied by standard ICs. The BUK854-500IS has a voltage rating of 500V and standard gate threshold voltage, and is assembled in the TO220 package.

Clamped IGBTs

One of the most exciting features of IGBT technology is the ability to integrate protection functions into the IGBT to give significant advantages to the designer of power circuits. The BUK856-400IZ and BUK856-450IX are two such devices which have been specifically designed for automotive ignition circuits. The BUK856-400IZ is a logic level device, the BUK856-450IX has a standard gate threshold. The nominal clamp voltages are 400V and 450V respectively.

In these devices the dynamic clamp network shown in Fig. 2 is fabricated directly onto the IGBT. This gives guaranteed clamping of the IGBT at a fixed clamp voltage without the need for an external circuit. The clamp voltage is held to very tight tolerances over the full temperature range (-40˚C to +150˚C) required in automotive applications.

In both these devices gate-source protection diodes have also been incorporated into the structure of the devices to give full protection against ESD damage during handling and assembly of the device into engine management units.

IGBTs and darlingtons - A performance comparison

The performance of the BUK856-400IZ ignition IGBT has been compared with that of a typical ignition darlington in the ignition circuit of Fig. 1.

At turn-off the darlington switched considerably slower than the IGBT. The time between the input going low and the spark was 32 μs for the darlington and only 19 μs for the IGBT.

Table 1 shows a breakdown of the ignition system losses and demonstrates that whilst the device losses are slightly higher in the IGBT, the overall losses are higher in the darlington circuit due to extra loss in the base drive.

Power loss (W)	V_{clamp}=400V, I_{Cmax}=6.0A	
100Hz, (3000rpm)	IGBT	darlington
Conduction	1.37	1.16
Switching	0.71	0.79
Drive	0.00001	0.5
Total	2.08	2.45

Table 1. IGBT and darlington ignition circuit losses

Conclusion

Table 2 summarises the comparison between the IGBT and the darlington as the power switch in automotive ignition. The comparison shows that the darlington is good in the application but that the IGBT has some clear advantages making it significantly better.

	IGBT	darlington
Driver component count	Low	High
Speed of response, 'time to spark'	Fast	Slow
Total loss	Better	Good
Drive power	Low	High
Logic level operation	Yes	Yes
Open circuit load	Yes	Yes
Reverse blocking	Yes	No
Package size	Small	Large
Inbuilt voltage clamp	Possible	Possible
Inbuilt protection	Yes	No

Table 2. Performance comparison

Acknowledgments

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Preface

This book was prepared by the Power Semiconductor Applications Laboratory of the Philips Semiconductors product division, Hazel Grove. The book is intended as a guide to using power semiconductors both efficiently and reliably in power conversion applications. It is made up of eight main chapters each of which contains a number of application notes aimed at making it easier to select and use power semiconductors.

CHAPTER 1 forms an introduction to power semiconductors concentrating particularly on the two major power transistor technologies, Power MOSFETs and High Voltage Bipolar Transistors.

CHAPTER 2 is devoted to Switched Mode Power Supplies. It begins with a basic description of the most commonly used topologies and discusses the major issues surrounding the use of power semiconductors including rectifiers. Specific design examples are given as well as a look at designing the magnetic components. The end of this chapter describes resonant power supply technology.

CHAPTER 3 describes motion control in terms of ac, dc and stepper motor operation and control. This chapter looks only at transistor controls, phase control using thyristors and triacs is discussed separately in chapter 6.

CHAPTER 4 looks at television and monitor applications. A description of the operation of horizontal deflection circuits is given followed by transistor selection guides for both deflection and power supply applications. Deflection and power supply circuit examples are also given based on circuits designed by the Product Concept and Application Laboratories (Eindhoven).

CHAPTER 5 concentrates on automotive electronics looking in detail at the requirements for the electronic switches taking into consideration the harsh environment in which they must operate.

CHAPTER 6 reviews thyristor and triac applications from the basics of device technology and operation to the simple design rules which should be followed to achieve maximum reliability. Specific examples are given in this chapter for a number of the common applications.

CHAPTER 7 looks at the thermal considerations for power semiconductors in terms of power dissipation and junction temperature limits. Part of this chapter is devoted to worked examples showing how junction temperatures can be calculated to ensure the limits are not exceeded. Heatsink requirements and designs are also discussed in the second half of this chapter.

CHAPTER 8 is an introduction to the use of high voltage bipolar transistors in electronic lighting ballasts. Many of the possible topologies are described.

Table of Contents

CHAPTER 1 Introduction to Power Semiconductors 1

General 3

1.1.1 An Introduction To Power Devices 5

Power MOSFET 17

1.2.1 PowerMOS Introduction 19
1.2.2 Understanding Power MOSFET Switching Behaviour 29
1.2.3 Power MOSFET Drive Circuits 39
1.2.4 Parallel Operation of Power MOSFETs 49
1.2.5 Series Operation of Power MOSFETs 53
1.2.6 Logic Level FETS 57
1.2.7 Avalanche Ruggedness 61
1.2.8 Electrostatic Discharge (ESD) Considerations 67
1.2.9 Understanding the Data Sheet: PowerMOS 69

High Voltage Bipolar Transistor 77

1.3.1 Introduction To High Voltage Bipolar Transistors 79
1.3.2 Effects of Base Drive on Switching Times 83
1.3.3 Using High Voltage Bipolar Transistors 91
1.3.4 Understanding The Data Sheet: High Voltage Transistors 97

CHAPTER 2 Switched Mode Power Supplies 103

Using Power Semiconductors in Switched Mode Topologies 105

2.1.1 An Introduction to Switched Mode Power Supply Topologies 107
2.1.2 The Power Supply Designer's Guide to High Voltage Transistors 129
2.1.3 Base Circuit Design for High Voltage Bipolar Transistors in Power Converters 141
2.1.4 Isolated Power Semiconductors for High Frequency Power Supply Applications 153

Output Rectification 159

2.2.1 Fast Recovery Epitaxial Diodes for use in High Frequency Rectification 161
2.2.2 Schottky Diodes from Philips Semiconductors 173
2.2.3 An Introduction to Synchronous Rectifier Circuits using PowerMOS Transistors 179

Design Examples 185

2.3.1 Mains Input 100 W Forward Converter SMPS: MOSFET and Bipolar Transistor Solutions featuring ETD Cores 187
2.3.2 Flexible, Low Cost, Self-Oscillating Power Supply using an ETD34 Two-Part Coil Former and 3C85 Ferrite 199

Magnetics Design 205

2.4.1 Improved Ferrite Materials and Core Outlines for High Frequency Power Supplies 207

Resonant Power Supplies 217

2.5.1. An Introduction To Resonant Power Supplies 219
2.5.2. Resonant Power Supply Converters - The Solution For Mains Pollution Problems 225

CHAPTER 3 Motor Control 241

AC Motor Control 243

3.1.1 Noiseless A.C. Motor Control: Introduction to a 20 kHz System 245
3.1.2 The Effect of a MOSFET's Peak to Average Current Rating on Invertor Efficiency 251
3.1.3 MOSFETs and FREDFETs for Motor Drive Equipment 253
3.1.4 A Designers Guide to PowerMOS Devices for Motor Control 259
3.1.5 A 300V, 40A High Frequency Inverter Pole Using Paralleled FREDFET Modules 273

DC Motor Control 283

3.2.1 Chopper circuits for DC motor control 285
3.2.2 A switched-mode controller for DC motors 293
3.2.3 Brushless DC Motor Systems 301

Stepper Motor Control 307

3.3.1 Stepper Motor Control 309

CHAPTER 4 Televisions and Monitors 317

Power Devices in TV & Monitor Applications (including selection guides) 319

4.1.1 An Introduction to Horizontal Deflection 321
4.1.2 The BU25XXA/D Range of Deflection Transistors 331

4.1.3 Philips HVT's for TV & Monitor Applications 339
4.1.4 TV and Monitor Damper Diodes 345

TV Deflection Circuit Examples 349

4.2.1 Application Information for the 16 kHz Black Line Picture Tubes 351
4.2.2 32 kHz / 100 Hz Deflection Circuits for the 66FS Black Line Picture Tube 361

SMPS Circuit Examples 377

4.3.1 A 70W Full Performance TV SMPS Using The TDA8380 379
4.3.2 A Synchronous 200W SMPS for 16 and 32 kHz TV 389

Monitor Deflection Circuit Example 397

4.4.1 A Versatile 30 - 64 kHz Autosync Monitor 399

CHAPTER 5 Automotive Power Electronics 421

Automotive Motor Control (including selection guides) 423

5.1.1 Automotive Motor Control With Philips MOSFETS 425

Automotive Lamp Control (including selection guides) 433

5.2.1 Automotive Lamp Control With Philips MOSFETS 435

The TOPFET 443

5.3.1 An Introduction to the 3 pin TOPFET 445
5.3.2 An Introduction to the 5 pin TOPFET 447
5.3.3 BUK101-50DL - a Microcontroller compatible TOPFET 449
5.3.4 Protection with 5 pin TOPFETs 451
5.3.5 Driving TOPFETs 453
5.3.6 High Side PWM Lamp Dimmer using TOPFET 455
5.3.7 Linear Control with TOPFET 457
5.3.8 PWM Control with TOPFET 459
5.3.9 Isolated Drive for TOPFET 461
5.3.10 3 pin and 5 pin TOPFET Leadforms 463
5.3.11 TOPFET Input Voltage 465
5.3.12 Negative Input and TOPFET 467
5.3.13 Switching Inductive Loads with TOPFET 469
5.3.14 Driving DC Motors with TOPFET 471
5.3.15 An Introduction to the High Side TOPFET 473
5.3.16 High Side Linear Drive with TOPFET 475

Automotive Ignition 477

5.4.1 An Introduction to Electronic Automotive Ignition 479
5.4.2 IGBTs for Automotive Ignition 481
5.4.3 Electronic Switches for Automotive Ignition 483

CHAPTER 6 Power Control with Thyristors and Triacs 485

Using Thyristors and Triacs 487

6.1.1 Introduction to Thyristors and Triacs 489
6.1.2 Using Thyristors and Triacs 497
6.1.3 The Peak Current Handling Capability of Thyristors 505
6.1.4 Understanding Thyristor and Triac Data 509

Thyristor and Triac Applications 521

6.2.1 Triac Control of DC Inductive Loads 523
6.2.2 Domestic Power Control with Triacs and Thyristors 527
6.2.3 Design of a Time Proportional Temperature Controller 537

Hi-Com Triacs 547

6.3.1 Understanding Hi-Com Triacs 549
6.3.2 Using Hi-Com Triacs 551

CHAPTER 7 Thermal Management 553

Thermal Considerations 555

7.1.1 Thermal Considerations for Power Semiconductors 557
7.1.2 Heat Dissipation 567

CHAPTER 8 Lighting 575

Fluorescent Lamp Control 577

8.1.1 Efficient Fluorescent Lighting using Electronic Ballasts 579
8.1.2 Electronic Ballasts - Philips Transistor Selection Guide 587
8.1.3 An Electronic Ballast - Base Drive Optimisation 589

Index

Airgap, transformer core, 111, 113
Anti saturation diode, 590
Asynchronous, 497
Automotive
  fans
    see motor control
  IGBT, 481, 483
  ignition, 479, 481, 483
  lamps, 435, 455
  motor control, 425, 457, 459, 471, 475
  resistive loads, 442
  reverse battery, 452, 473, 479
  screen heater, 442
  seat heater, 442
  solenoids, 469
  TOPFET, 473
Avalanche, 61
Avalanche breakdown
  thyristor, 490
Avalanche multiplication, 134

Baker clamp, 138, 187, 190
Ballast
  electronic, 580
  fluorescent lamp, 579
  switchstart, 579
Base drive, 136
  base inductor, 147
  base inductor, diode assisted, 148
  base resistor, 146
  drive transformer, 145
  drive transformer leakage inductance, 149
  electronic ballast, 589
  forward converter, 187
  power converters, 141
  speed-up capacitor, 143
Base inductor, 144, 147
Base inductor, diode assisted, 148
Boost converter, 109
  continuous mode, 109
  discontinuous mode, 109
  output ripple, 109
Bootstrap, 303
Breakback voltage
  diac, 492
Breakdown voltage, 70
Breakover current
  diac, 492
Breakover voltage
  diac, 492, 592
  thyristor, 490

Bridge circuits
  see Motor Control - AC
Brushless motor, 301, 303
Buck-boost converter, 110
Buck converter, 108 - 109
Burst firing, 537
Burst pulses, 564

Capacitance
  junction, 29
Capacitor
  mains dropper, 544
CENELEC, 537
Charge carriers, 133
  triac commutation, 549
Choke
  fluorescent lamp, 580
Choppers, 285
Clamp diode, 117
Clamp winding, 113
Commutation
  diode, 164
  Hi-Com triac, 551
  thyristor, 492
  triac, 494, 523, 529
Compact fluorescent lamp, 585
Continuous mode
  see Switched Mode Power Supplies
Continuous operation, 557
Converter (dc-dc)
  switched mode power supply, 107
Cookers, 537
Cooling
  forced, 572
  natural, 570
Crest factor, 529
Critical electric field, 134
Cross regulation, 114, 117
Current fed resonant inverter, 589
Current Mode Control, 120
Current tail, 138, 143

Damper Diodes, 345, 367
  forward recovery, 328, 348
  losses, 347
  outlines, 345
  picture distortion, 328, 348
  selection guide, 345
Darlington, 13
Data Sheets
  High Voltage Bipolar Transistor, 92,97,331
  MOSFET, 69

dc-dc converter, 119
Depletion region, 133
Desaturation networks, 86
  Baker clamp, 91, 138
dI/dt
  triac, 531
Diac, 492, 500, 527, 530, 591
Diode, 6
  double diffused, 162
  epitaxial, 161
  schottky, 173
  structure, 161
Diode Modulator, 327, 367
Disc drives, 302
Discontinuous mode
  see Switched Mode Power Supplies
Domestic Appliances, 527
Dropper
  capacitive, 544
  resistive, 544, 545
Duty cycle, 561

EFD core
  see magnetics
Efficiency Diodes
  see Damper Diodes
Electric drill, 531
Electronic ballast, 580
  base drive optimisation, 589
  current fed half bridge, 584, 587, 589
  current fed push pull, 583, 587
  flyback, 582
  transistor selection guide, 587
  voltage fed half bridge, 584, 588
  voltage fed push pull, 583, 587
EMC, 260, 455
  see RFI, ESD
  TOPFET, 473
Emitter shorting
  triac, 549
Epitaxial diode, 161
  characteristics, 163
  dI/dt, 164
  forward recovery, 168
  lifetime control, 162
  operating frequency, 165
  passivation, 162
  reverse leakage, 169
  reverse recovery, 162, 164
  reverse recovery softness, 167
  selection guide, 171
  snap-off, 167
  softness factor, 167
  stored charge, 162
  technology, 162

ESD, 67
  see Protection, ESD
  precautions, 67
ETD core
  see magnetics

F-pack
  see isolated package
Fall time, 143, 144
Fast Recovery Epitaxial Diode (FRED)
  see epitaxial diode
FBSOA, 134
Ferrites
  see magnetics
Flicker
  fluorescent lamp, 580
Fluorescent lamp, 579
  colour rendering, 579
  colour temperature, 579
  efficacy, 579, 580
  triphosphor, 579
Flyback converter, 110, 111, 113
  advantages, 114
  clamp winding, 113
  continuous mode, 114
  coupled inductor, 113
  cross regulation, 114
  diodes, 115
  disadvantages, 114
  discontinuous mode, 114
  electronic ballast, 582
  leakage inductance, 113
  magnetics, 213
  operation, 113
  rectifier circuit, 180
  self oscillating power supply, 199
  synchronous rectifier, 156, 181
  transformer core airgap, 111, 113
  transistors, 115
Flyback converter (two transistor), 111, 114
Food mixer, 531
Forward converter, 111, 116
  advantages, 116
  clamp diode, 117
  conduction loss, 197
  continuous mode, 116
  core loss, 116
  core saturation, 117
  cross regulation, 117
  diodes, 118
  disadvantages, 117
  duty ratio, 117
  ferrite cores, 116
  magnetics, 213
  magnetisation energy, 116, 117

operation, 116
output diodes, 117
output ripple, 116
rectifier circuit, 180
reset winding, 117
switched mode power supply, 187
switching frequency, 195
switching losses, 196
synchronous rectifier, 157, 181
transistors, 118
Forward converter (two transistor), 111, 117
Forward recovery, 168
FREDFET, 250, 253, 305
bridge circuit, 255
charge, 254
diode, 254
drive, 262
loss, 256
reverse recovery, 254
FREDFETs
motor control, 259
Full bridge converter, 111, 125
advantages, 125
diodes, 126
disadvantages, 125
operation, 125
transistors, 126

Gate
triac, 538
Gate drive
forward converter, 195
Gold doping, 162, 169
GTO, 11
Guard ring
schottky diode, 174

Half bridge, 253
Half bridge circuits
see also Motor Control - AC
Half bridge converter, 111, 122
advantages, 122
clamp diodes, 122
cross conduction, 122
diodes, 124
disadvantages, 122
electronic ballast, 584, 587, 589
flux symmetry, 122
magnetics, 214
operation, 122
synchronous rectifier, 157
transistor voltage, 122
transistors, 124
voltage doubling, 122
Heat dissipation, 567
Heat sink compound, 567
Heater controller, 544
Heaters, 537
Heatsink, 569
Heatsink compound, 514
Hi-Com triac, 519, 549, 551
commutation, 551
dIcom/dt, 552
gate trigger current, 552
inductive load control, 551
High side switch
MOSFET, 44, 436
TOPFET, 430, 473
High Voltage Bipolar Transistor, 8, 79, 91, 141, 341
'bathtub' curves, 333
avalanche breakdown, 131
avalanche multiplication, 134
Baker clamp, 91, 138
base-emitter breakdown, 144
base drive, 83, 92, 96, 136, 336, 385
base drive circuit, 145
base inductor, 138, 144, 147
base inductor, diode assisted, 148
base resistor, 146
breakdown voltage, 79, 86, 92
carrier concentration, 151
carrier injection, 150
conductivity modulation, 135, 150
critical electric field, 134
current crowding, 135, 136
current limiting values, 132
current tail, 138, 143
current tails, 86, 91
d-type, 346
data sheet, 92, 97, 331
depletion region, 133
desaturation, 86, 88, 91
device construction, 79
dI/dt, 139
drive transformer, 145
drive transformer leakage inductance, 149
dV/dt, 139
electric field, 133
electronic ballast, 581, 585, 587, 589
Fact Sheets, 334
fall time, 86, 99, 143, 144
FBSOA, 92, 99, 134
hard turn-off, 86
horizontal deflection, 321, 331, 341
leakage current, 98
limiting values, 97
losses, 92, 333, 342
Miller capacitance, 139
operation, 150

optimum drive, 88
outlines, 332, 346
over current, 92, 98
over voltage, 92, 97
overdrive, 85, 88, 137, 138
passivation, 131
power limiting value, 132
process technology, 80
ratings, 97
RBSOA, 93, 99, 135, 138, 139
RC network, 148
reverse recovery, 143, 151
safe operating area, 99, 134
saturation, 150
saturation current, 79, 98, 341
secondary breakdown, 92, 133
smooth turn-off, 86
SMPS, 94, 339, 383
snubber, 139
space charge, 133
speed-up capacitor, 143
storage time, 86, 91, 92, 99, 138, 144, 342
sub emitter resistance, 135
switching, 80, 83, 86, 91, 98, 342
technology, 129, 149
thermal breakdown, 134
thermal runaway, 152
turn-off, 91, 92, 138, 142, 146, 151
turn-on, 91, 136, 141, 149, 150
underdrive, 85, 88
voltage limiting values, 130
Horizontal Deflection, 321, 367
base drive, 336
control ic, 401
d-type transistors, 346
damper diodes, 345, 367
diode modulator, 327, 347, 352, 367
drive circuit, 352, 365, 406
east-west correction, 325, 352, 367
line output transformer, 354
linearity correction, 323
operating cycle, 321, 332, 347
s-correction, 323, 352, 404
TDA2595, 364, 368
TDA4851, 400
TDA8433, 363, 369
test circuit, 321
transistors, 331, 341, 408
waveforms, 322

IGBT, 11, 305
automotive, 481, 483
clamped, 482, 484
ignition, 481, 483

Ignition
automotive, 479, 481, 483
darlington, 483
Induction heating, 53
Induction motor
see Motor Control - AC
Inductive load
see Solenoid
Inrush current, 528, 530
Intrinsic silicon, 133
Inverter, 260, 273
see motor control ac
current fed, 52, 53
switched mode power supply, 107
Irons, electric, 537
Isolated package, 154
stray capacitance, 154, 155
thermal resistance, 154
Isolation, 153

J-FET, 9
Junction temperature, 470, 557, 561
burst pulses, 564
non-rectangular pulse, 565
rectangular pulse, composite, 562
rectangular pulse, periodic, 561
rectangular pulse, single shot, 561

Lamp dimmer, 530
Lamps, 435
dI/dt, 438
inrush current, 438
MOSFET, 435
PWM control, 455
switch rate, 438
TOPFET, 455
Latching current
thyristor, 490
Leakage inductance, 113, 200, 523
Lifetime control, 162
Lighting
fluorescent, 579
phase control, 530
Logic Level FET
motor control, 432
Logic level MOSFET, 436

Magnetics, 207
100W 100kHz forward converter, 197
100W 50kHz forward converter, 191
50W flyback converter, 199
core losses, 208
core materials, 207
EFD core, 210
ETD core, 199, 207

flyback converter, 213
forward converter, 213
half bridge converter, 214
power density, 211
push-pull converter, 213
switched mode power supply, 187
switching frequency, 215
transformer construction, 215
Mains Flicker, 537
Mains pollution, 225
pre-converter, 225
Mains transient, 544
Mesa glass, 162
Metal Oxide Varistor (MOV), 503
Miller capacitance, 139
Modelling, 236, 265
MOS Controlled Thyristor, 13
MOSFET, 9, 19, 153, 253
bootstrap, 303
breakdown voltage, 22, 70
capacitance, 30, 57, 72, 155, 156
capacitances, 24
characteristics, 23, 70 - 72
charge, 32, 57
data sheet, 69
dI/dt, 36
diode, 253
drive, 262, 264
drive circuit loss, 156
driving, 39, 250
dV/dt, 36, 39, 264
ESD, 67
gate-source protection, 264
gate charge, 195
gate drive, 195
gate resistor, 156
high side, 436
high side drive, 44
inductive load, 62
lamps, 435
leakage current, 71
linear mode, parallelling, 52
logic level, 37, 57, 305
loss, 26, 34
maximum current, 69
motor control, 259, 429
modelling, 265
on-resistance, 21, 71
package inductance, 49, 73
parallel operation, 26, 47, 49, 265
parasitic oscillations, 51
peak current rating, 251
Resonant supply, 53
reverse diode, 73
ruggedness, 61, 73
safe operating area, 25, 74
series operation, 53
SMPS, 339, 384
solenoid, 62
structure, 19
switching, 24, 29, 58, 73, 194, 262
switching loss, 196
synchronous rectifier, 179
thermal impedance, 74
thermal resistance, 70
threshold voltage, 21, 70
transconductance, 57, 72
turn-off, 34, 36
turn-on, 32, 34, 35, 155, 256
Motor, universal
back EMF, 531
starting, 528
Motor Control - AC, 245, 273
anti-parallel diode, 253
antiparallel diode, 250
carrier frequency, 245
control, 248
current rating, 262
dc link, 249
diode, 261
diode recovery, 250
duty ratio, 246
efficiency, 262
EMC, 260
filter, 250
FREDFET, 250, 259, 276
gate drives, 249
half bridge, 245
inverter, 250, 260, 273
line voltage, 262
loss, 267
MOSFET, 259
Parallel MOSFETs, 276
peak current, 251
phase voltage, 262
power factor, 262
pulse width modulation, 245, 260
ripple, 246
short circuit, 251
signal isolation, 250
snubber, 276
speed control, 248
switching frequency, 246
three phase bridge, 246
underlap, 248
Motor Control - DC, 285, 293, 425
braking, 285, 299
brushless, 301
control, 290, 295, 303
current rating, 288

drive, 303
duty cycle, 286
efficiency, 293
FREDFET, 287
freewheel diode, 286
full bridge, 287
half bridge, 287
high side switch, 429
IGBT, 305
inrush, 430
inverter, 302
linear, 457, 475
logic level FET, 432
loss, 288
MOSFET, 287, 429
motor current, 295
overload, 430
permanent magnet, 293, 301
permanent magnet motor, 285
PWM, 286, 293, 459, 471
servo, 298
short circuit, 431
stall, 431
TOPFET, 430, 457, 459, 475
topologies, 286
torque, 285, 294
triac, 525
voltage rating, 288
Motor Control - Stepper, 309
bipolar, 310
chopper, 314
drive, 313
hybrid, 312
permanent magnet, 309
reluctance, 311
step angle, 309
unipolar, 310
Mounting, transistor, 154
Mounting base temperature, 557
Mounting torque, 514

Parasitic oscillation, 149
Passivation, 131, 162
PCB Design, 368, 419
Phase angle, 500
Phase control, 546
thyristors and triacs, 498
triac, 523
Phase voltage
see motor control - ac
Power dissipation, 557
see High Voltage Bipolar Transistor loss, MOSFET loss
Power factor correction, 580
active, boost converted, 581
Power MOSFET
see MOSFET
Proportional control, 537
Protection
ESD, 446, 448, 482
overvoltage, 446, 448, 469
reverse battery, 452, 473, 479
short circuit, 251, 446, 448
temperature, 446, 447, 471
TOPFET, 445, 447, 451
Pulse operation, 558
Pulse Width Modulation (PWM), 108
Push-pull converter, 111, 119
advantages, 119
clamp diodes, 119
cross conduction, 119
current mode control, 120
diodes, 121
disadvantages, 119
duty ratio, 119
electronic ballast, 582, 587
flux symmetry, 119, 120
magnetics, 213
multiple outputs, 119
operation, 119
output filter, 119
output ripple, 119
rectifier circuit, 180
switching frequency, 119
transformer, 119
transistor voltage, 119
transistors, 121

Qs (stored charge), 162

RBSOA, 93, 99, 135, 138, 139
Rectification, synchronous, 179
Reset winding, 117
Resistor
mains dropper, 544, 545
Resonant power supply, 219, 225
modelling, 236
MOSFET, 52, 53
pre-converter, 225
Reverse leakage, 169
Reverse recovery, 143, 162
RFI, 154, 158, 167, 393, 396, 497, 529, 530, 537
Ruggedness
MOSFET, 62, 73
schottky diode, 173

Safe Operating Area (SOA), 25, 74, 134, 557
forward biased, 92, 99, 134
reverse biased, 93, 99, 135, 138, 139

Saturable choke
triac, 523
Schottky diode, 173
bulk leakage, 174
edge leakage, 174
guard ring, 174
reverse leakage, 174
ruggedness, 173
selection guide, 176
technology, 173
SCR
see Thyristor
Secondary breakdown, 133
Selection Guides
BU25XXA, 331
BU25XXD, 331
damper diodes, 345
EPI diodes, 171
horizontal deflection, 343
MOSFETs driving heaters, 442
MOSFETs driving lamps, 441
MOSFETs driving motors, 426
Schottky diodes, 176
SMPS, 339
Self Oscillating Power Supply (SOPS)
50W microcomputer flyback converter, 199
ETD transformer, 199
Servo, 298
Single ended push-pull
see half bridge converter
Snap-off, 167
Snubber, 93, 139, 495, 502, 523, 529, 549
active, 279
Softness factor, 167
Solenoid
TOPFET, 469, 473
turn off, 469, 473
Solid state relay, 501
SOT186, 154
SOT186A, 154
SOT199, 154
Space charge, 133
Speed-up capacitor, 143
Speed control
thyristor, 531
triac, 527
Starter
fluorescent lamp, 580
Startup circuit
electronic ballast, 591
self oscillating power supply, 201
Static Induction Thyristor, 11
Stepdown converter, 109
Stepper motor, 309
Stepup converter, 109
Storage time, 144
Stored charge, 162
Suppression
mains transient, 544
Switched Mode Power Supply (SMPS)
see also self oscillating power supply
100W 100kHz MOSFET forward converter, 192
100W 500kHz half bridge converter, 153
100W 50kHz bipolar forward converter, 187
16 & 32 kHz TV, 389
asymmetrical, 111, 113
base circuit design, 149
boost converter, 109
buck-boost converter, 110
buck converter, 108
ceramic output filter, 153
continuous mode, 109, 379
control ic, 391
control loop, 108
core excitation, 113
core loss, 167
current mode control, 120
dc-dc converter, 119
diode loss, 166
diode reverse recovery effects, 166
diode reverse recovery softness, 167
diodes, 115, 118, 121, 124, 126
discontinuous mode, 109, 379
epitaxial diodes, 112, 161
flux swing, 111
flyback converter, 92, 111, 113, 123
forward converter, 111, 116, 379
full bridge converter, 111, 125
half bridge converter, 111, 122
high voltage bipolar transistor, 94, 112, 115, 118, 121, 124, 126, 129, 339, 383, 392
isolated, 113
isolated packages, 153
isolation, 108, 111
magnetics design, 191, 197
magnetisation energy, 113
mains filter, 380
mains input, 390
MOSFET, 112, 153, 33, 384
multiple output, 111, 156
non-isolated, 108
opto-coupler, 392
output rectifiers, 163
parasitic oscillation, 149
power-down, 136
power-up, 136, 137, 139
power MOSFET, 153, 339, 384
pulse width modulation, 108
push-pull converter, 111, 119

RBSOA failure, 139
rectification, 381, 392
rectification efficiency, 163
rectifier selection, 112
regulation, 108
reliability, 139
resonant
see resonant power supply
RFI, 154, 158, 167
schottky diode, 112, 154, 173
snubber, 93, 139, 383
soft start, 138
standby, 382
standby supply, 392
start-up, 391
stepdown, 109
stepup, 109
symmetrical, 111, 119, 122
synchronisation, 382
synchronous rectification, 156, 179
TDA8380, 381, 391
topologies, 107
topology output powers, 111
transformer, 111
transformer saturation, 138
transformers, 391
transistor current limiting value, 112
transistor mounting, 154
transistor selection, 112
transistor turn-off, 138
transistor turn-on, 136
transistor voltage limiting value, 112
transistors, 115, 118, 121, 124, 126
turns ratio, 111
TV & Monitors, 339, 379, 399
two transistor flyback, 111, 114
two transistor forward, 111, 117
Switching loss, 230
Synchronous, 497
Synchronous rectification, 156, 179
self driven, 181
transformer driven, 180

Temperature control, 537
Thermal
continuous operation, 557, 568
intermittent operation, 568
non-rectangular pulse, 565
pulse operation, 558
rectangular pulse, composite, 562
rectangular pulse, periodic, 561
rectangular pulse, single shot, 561
single shot operation, 561
Thermal capacity, 558, 568
Thermal characteristics
power semiconductors, 557
Thermal impedance, 74, 568
Thermal resistance, 70, 154, 557
Thermal time constant, 568
Thyristor, 10, 497, 509
'two transistor' model, 490
applications, 527
asynchronous control, 497
avalanche breakdown, 490
breakover voltage, 490, 509
cascading, 501
commutation, 492
control, 497
current rating, 511
dI/dt, 490
dIf/dt, 491
dV/dt, 490
energy handling, 505
external commutation, 493
full wave control, 499
fusing I^2t, 503, 512
gate cathode resistor, 500
gate circuits, 500
gate current, 490
gate power, 492
gate requirements, 492
gate specifications, 512
gate triggering, 490
half wave control, 499
holding current, 490, 509
inductive loads, 500
inrush current, 503
latching current, 490, 509
leakage current, 490
load line, 492
mounting, 514
operation, 490
overcurrent, 503
peak current, 505
phase angle, 500
phase control, 498, 527
pulsed gate, 500
resistive loads, 498
resonant circuit, 493
reverse characteristic, 489
reverse recovery, 493
RFI, 497
self commutation, 493
series choke, 502
snubber, 502
speed controller, 531
static switching, 497
structure, 489
switching, 489

switching characteristics, 517
synchronous control, 497
temperature rating, 512
thermal specifications, 512
time proportional control, 497
transient protection, 502
trigger angle, 500
turn-off time, 494
turn-on, 490, 509
turn-on dI/dt, 502
varistor, 503
voltage rating, 510
Thyristor data, 509
Time proportional control, 537
TOPFET
3 pin, 445, 449, 461
5 pin, 447, 451, 457, 459, 463
driving, 449, 453, 461, 465, 467, 475
high side, 473, 475
lamps, 455
leadforms, 463
linear control, 451, 457
motor control, 430, 457, 459
negative input, 456, 465, 467
protection, 445, 447, 451, 469, 473
PWM control, 451, 455, 459
solenoids, 469
Transformer
triac controlled, 523
Transformer core airgap, 111, 113
Transformers
see magnetics
Transient thermal impedance, 559
Transient thermal response, 154
Triac, 497, 510, 518
400Hz operation, 489, 518
applications, 527, 537
asynchronous control, 497
breakover voltage, 510
charge carriers, 549
commutating dI/dt, 494
commutating dV/dt, 494
commutation, 494, 518, 523, 529, 549
control, 497
dc inductive load, 523
dc motor control, 525
dI/dt, 531, 549
dIcom/dt, 523
dV/dt, 523, 549
emitter shorting, 549
full wave control, 499
fusing I^2t, 503, 512
gate cathode resistor, 500
gate circuits, 500
gate current, 491
gate requirements, 492
gate resistor, 540, 545
gate sensitivity, 491
gate triggering, 538
holding current, 491, 510
Hi-Com, 549, 551
inductive loads, 500
inrush current, 503
isolated trigger, 501
latching current, 491, 510
operation, 491
overcurrent, 503
phase angle, 500
phase control, 498, 527, 546
protection, 544
pulse triggering, 492
pulsed gate, 500
quadrants, 491, 510
resistive loads, 498
RFI, 497
saturable choke, 523
series choke, 502
snubber, 495, 502, 523, 529, 549
speed controller, 527
static switching, 497
structure, 489
switching, 489
synchronous control, 497
transformer load, 523
transient protection, 502
trigger angle, 492, 500
triggering, 550
turn-on dI/dt, 502
varistor, 503
zero crossing, 537
Trigger angle, 500
TV & Monitors
16 kHz black line, 351
30-64 kHz autosync, 399
32 kHz black line, 361
damper diodes, 345, 367
diode modulator, 327, 367
EHT, 352 - 354, 368, 409, 410
high voltage bipolar transistor, 339, 341
horizontal deflection, 341
picture distortion, 348
power MOSFET, 339
SMPS, 339, 354, 379, 389, 399
vertical deflection, 358, 364, 402
Two transistor flyback converter, 111, 114
Two transistor forward converter, 111, 117

Universal motor
back EMF, 531

starting, 528

Vacuum cleaner, 527
Varistor, 503
Vertical Deflection, 358, 364, 402
Voltage doubling, 122

Water heaters, 537

Zero crossing, 537
Zero voltage switching, 537