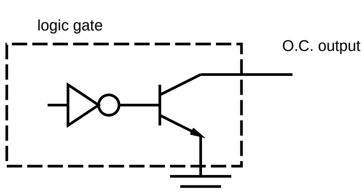
Transistor Switches

This lecture describes the design of bipolar and FET transistor switches.
After this lecture you should be able to design a transistor power switch including determining minimum V_{CE} or V_{DS}, minimum current gain or V_{GS}, power dissipation, and maximum heat sink thermal resistance.

In many applications it is sufficient for the controller to switch a DC output on or off. Some output devices (e.g. LED's) only require a few milliamps at low DC voltages and can be driven directly by the output of a logic gate. However, often more power is required than can be supplied by an ordinary logic gate.

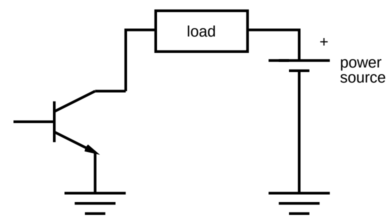
Open Collector Outputs

The simplest way to switch moderate amounts of power is to use a logic gate with an open-collector output. The outputs of these devices are the collector terminals of transistors whose emitters are connected to ground. Open collector outputs can therefore be used to "sink" an externally-supplied voltage to ground. Depending on the device and the logic family (e.g. a 74LS06), these can control up to 30 volts and sink 100–300 mA.



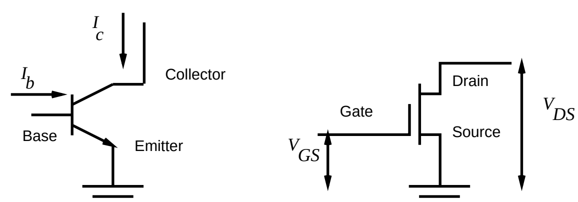
MOSFET and Bipolar Transistor Power Switches

When larger currents need to be switched, a bipolar or MOSFET power-switching transistor can be used. When used as switches the transistors are biased so that they are either fully on or fully off. The discussions below show typical specifications for two medium-power switching transistors, a common bipolar NPN device (2N3055) and an n-channel enhancement-mode MOSFET (RFP15N06L).



Maximum Voltage

In the off state no current flows through the transistor and the full supply voltage appears across the transistor. It is necessary to ensure that this voltage does not exceed the manufacturer's rating. In the case of the 2N3055 NPN transistor the maximum collector-to-emitter voltage is 60V and for the RFP15N06L MOSFET the drain-source breakdown voltage is also 60V. MOSFET devices are available with maximum ratings of V_{DS} of several hundred volts.

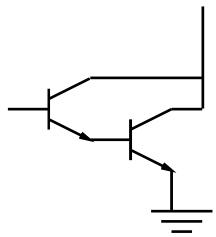


Switching the Transistor

In the on (saturated) state it is necessary to ensure that the base current (in the case of a bipolar transistor) or the gate voltage (in the case of a MOSFET) is sufficiently high to turn the transistor fully on. The manufacturer will specify the minimum current gain (50) for the NPN transistor (the ratio of collector to base current) from which the minimum base current can be computed or the gate-to-source threshold voltage (2V) that makes the MOSFET saturate.

Exercise: A 2N3055 is used as a switch and must control a current of 2A. What is the minimum required base current? What will happen if a lower base current is applied?

If the digital logic cannot supply sufficient current to the bipolar transistor or voltage to the MOSFET to saturate it, then additional circuitry (usually an additional transistor) will be required to drive the device. The configuration of two NPN transistors shown below is called a "Darlington pair."



Power Dissipation

When the transistor is turned on current will flow through the device and, since the transistor has a finite resistance, there will be a voltage drop and the transistor will consume some power. It is important to ensure that this power can be safely dissipated without causing the transistor to overheat and fail. The power dissipation will the product of the current through the transistor and the voltage drop across it.

For an NPN transistor the manufacturer specifies the collector-to-emitter voltage when the transistor is fully on (0.4V) as well as a maximum collector current (10A). For a MOSFET the manufacturer specifies the drain-to-source resistance (0.14 Ω) and a maximum drain current (15A).

Exercise: A bipolar transistor with a maximum V_{BE} of 0.2 volts is used to switch a current of 10 A. What is the power dissipated in the transistor when it is on? When it is off? If a MOSFET with an $R_{DS_{ON}}$ of 0.05 Ω is controlling a current of 5 A, What is the power dissipated in the transistor when it is on? When it is off?

The manufacturer also specifies a maximum junction temperature (200 C) and a maximum power dissipation (about 100W and about 30W for the two devices).

The junction temperature can be computed using the formula:

$$T_J = T_A + (\theta_{JC} + \theta_{CS} + \theta_{SA})P \quad (1)$$

where T_J is the junction temperature, T_A is the ambient (air) temperature, θ_{JC} is the junction-to-case thermal resistance (in degrees/Watt) as given by the transistor manufacturer, θ_{CS} is the case-to-heatsink thermal resistance (depends on mounting method) and θ_{SA} is the heatsink-to-air thermal resistance as given by the heat sink manufacturer.

T_JC is on the order of 1 or 2 degrees per watt, T_SA ranges from 100 for simple clip-on heat sinks to less than 1 for large multi-fin models. T_CS is usually negligible.

Exercise: A transistor switch must dissipate 40 W. The maximum junction temperature is 200C. The transistor package has a thermal resistance of 1 degrees/W. The switch must operate over the temperature range of -40 to +40 C. How should you specify the heat sink?

Pulse Width Modulation

In some cases it is necessary that the controller supply an actuator with a variable voltage. An efficient method to do this is to switch the output on and off at a high frequency (say, 50 kHz) and vary the duty cycle. The duty cycle (the percentage of time that the voltage is on) can be varied by either changing the pulse width if the frequency is constant (PWM) or by varying the frequency if the pulse width is constant. As an example, if the supply voltage was 12 volts and the output voltage had a 25% duty cycle the average output voltage would be 3 volts.

Some loads (such as incandescent lighting or resistive heaters) can tolerate a time-varying supply voltage. But often it is necessary to smooth out (filter) the supplied voltage by using inductors and/or capacitors to store energy during 'on' period and release it during the 'off' period.

A microcomputer-based controller can be used to implement a PWM analog output with a minimum of additional hardware since the only requirement is a standard binary (on/off) output.

Pulse width modulation is also relatively efficient. Since the switching devices are either fully off (no current) or on (no voltage drop), little power is consumed by this type of control device.

The are some disadvantages to using PWM. One is that the output signal will contain a "ripple" component at the switching frequency. Another is the additional complexity of the software that must control the PWM output signal's frequency and duty cycle.