Switches

These notes discuss mechanical, electromechanical and electronic switches concentrating on bipolar junction transistors (BJTs) and MOSFETs. The concept of an ideal switch is first introduced and each type of switch is evaluated agains the ideal as a mechanism of comparison. Real switches are discussed in terms of their useful life, isolation of the controlled and controlling parameter and switching speed.

Similar arguments apply to JFETs, IGBTs and Valves as apply to MOSFETs and BJTs however they are not discussed. Phase controlled switches (Triacs, Thyristors etc.) can be found in later modules.

Ideal Switches

The purpose of a switch is to control power in a load in and "on"/"off/" sense.

When "on" $I_L = \frac{V_{supply}}{R_L}$
When "off" $I_L = 0$
When "on" $V_s = 0$
When "off" $V_s = V_{supply}$

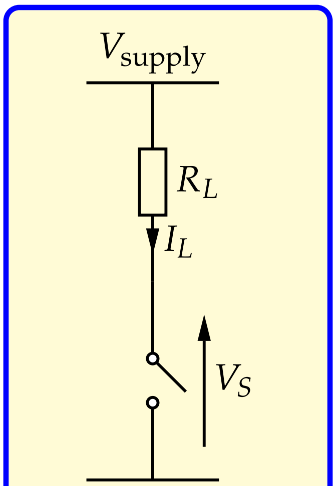


Figure 1: A generic switching circuit.

The product of V_s and I_L in both switch states is zero so no power is dissipated in the switch. The "on" state current is determined by the external circuit (i.e. the load resistor), not by the switch. The ideal switch has no "leakage" current (a current that flows even when the switch is off). The idea switch also has no voltage or current limits.

Real Switches

Real switches have some series resistance and some leakage in the "off" state. In most cases, R_P (Fig. 2), the "off" state leakage can be neglected. R_s, the series resistance, usually has to be included because it is responsible for power dissipation in the switch. Power dissipation leads to the generation of heat, which the designer must account for. For a real switch

$$I_{on} = \frac{V_{supply}}{R_{Load} + R_s} \tag{1}$$

Switch Types

There are three switch types discussed in this course, mechanical, electromechanical and electronic.

Mechanical switches are characterised by

- A mechanical force brings two metal contacts together each of these is connected to a conductor. This is exemplified by toggle switches and push switches etc.
- A design current in the range 10^{-3} to 10^{+7} A.
- Very low contact resistance (R_s).
- Very low leakage resistance (high R_p).
- The requirement for mechanical force to be applied to a linkage between the switch and the operator.
- Inertia and elasticity limit the switching rate to a few hundred Hz.

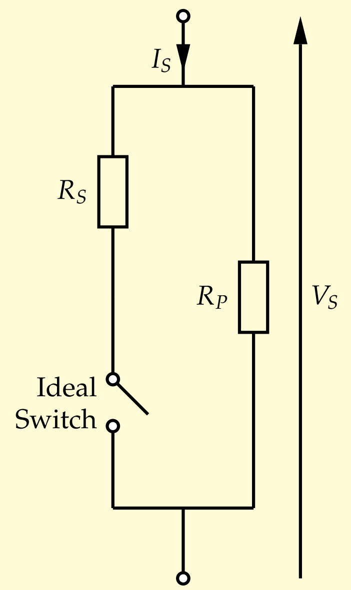


Figure 2: A model of a real switching circuit.

Electromechanical switches (relays) are characterised by

- A mechanical force brings two metal contacts together each of these is connected to a conductor and the mechanical force is provided by an electromagnet. This is exemplified by relays.
- A design current in the range 10^{-3} to 10^{7} A.
- Very low contact resistance (R_s).
- Very low leakage resistance (high R_p).
- The possibility of remote operation due to the electromagnet drive scheme while maintaining the advantages of mechanical contacts.

Note that in both mechanical and electromechanical switches, the switch contacts can be, and usually are, electrically insulated from the control linkages or electromagnet!

Electronic switches are characterised by

- A great variety of types of switch.
- Ones of interest here are based on MOSFET and BJT transistors.
- Fast switching. More than 10^9 switching cycles per second. (Most mechanical switches are incapable of more than 10^5 mechanical operations.

- Much higher losses than in mechanical switches (generally speaking).
- The control input being electrically connected to one of the main current path terminals.
- Support of current flow in only one direction.

These last two points are somewhat inconvenient. However the advantages and functionality that can be gain by using electronic switches are so great that designers have devised a number of ways to get round the problems.

MOSFET and BJT Switches

The device is put into a circuit like Fig. 3. V_s is the supply voltage, V_i is the control voltage and V_{sw} is the voltage across the switch. V_{sw} and I_{sw} are related by

$$I_{sw} = \frac{V_s - V_{sw}}{R_L} \qquad (2)$$

There is also a second relationship between V_{sw} and I_{sw} defined by the output characteristics of the transistor. Both transistor types have the same shape of output characteristics

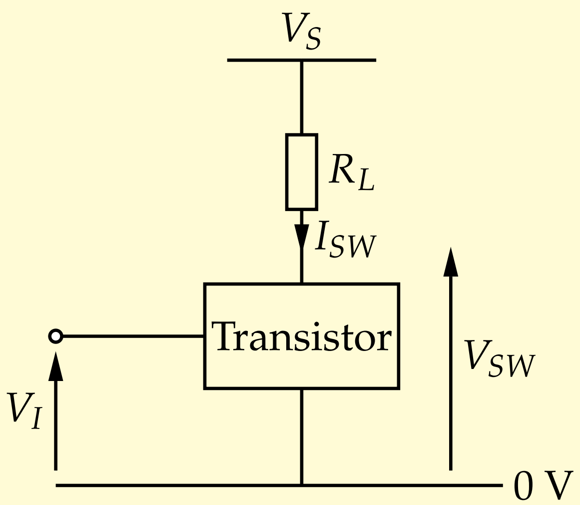


Figure 3: A generic electronic switching circuit.

The switch is controlled by V_i. Point C is the "off" stage point. If V_i is increased, I_{sw} will increase and V_{sw} will decrease until, eventually point B is reached. Point B is the real "on" state working point. Point A is the ideal "on" state working point so point B should be close to point A. In the region between points B and C, there is a significant VI product being dissipated within the switch and designers go to considerable lengths to keep the devices either at point B or at Point C and when moving between B and C the switching circuit is designed to allow the switch to chance I_{sw} as fast as possible in order to minimise power dissipation in the switch.

For example a ZTX653 bipolar transistor is capable of dissipating 1 W, can switch up to 2 A at up to 100 V i.e. it can control 200 W in a load. The instantaneous VI product at the mid point between B and C would be 50 W which is enough to destroy the transistor in considerably less than 1 second. Therefore the working point must not be allowed to linger between B and C. Designers ensure that the transistors survive by switching rapidly (usually in less

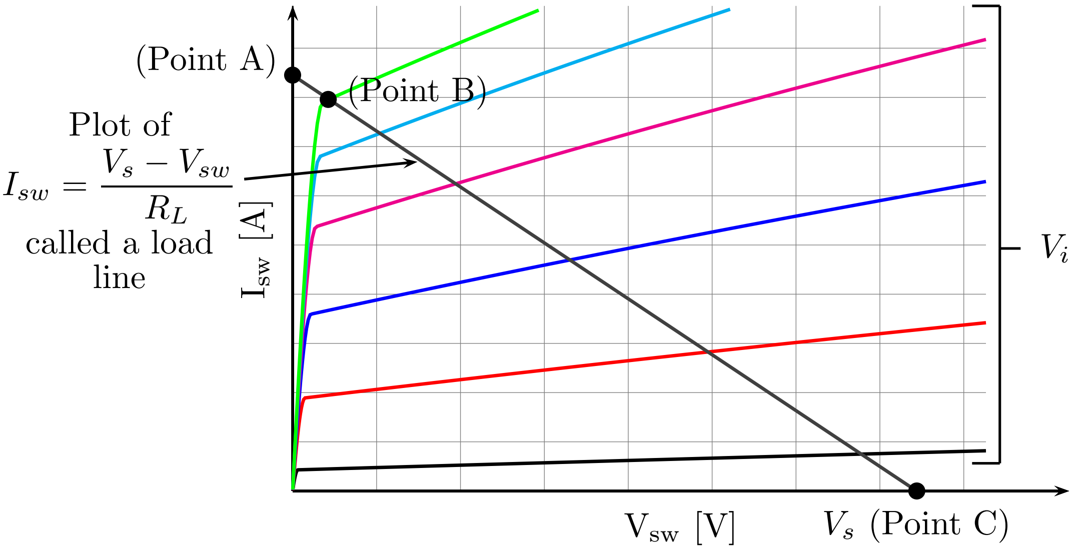


Figure 4: Example of Transistor Output Characteristics.

than 1 μs) between states. This makes the average energy dissipated in the switch small.

MOSFET Switches

The MOSFET behaves like a resistance when fully on (i.e. at point B). Manufacturers specify this resistance as $r_{ds(on)}$. The expression for the load line becomes,

$$I_D = \frac{V_s}{R_L + r_{ds(on)}} \tag{3}$$

when in the "on" state and, since leakage is usually negligible, $I_D \approx 0$ in the "off" state.

The effect of $r_{DS(on)}$ on load power is usually small (may be 1 or 2%) but the effect on the transistor may be important because the power disipated in it is,

$$P_{sw} = I^2_{D(on)}\, r_{DS(on)} \tag{4}$$

and the switch must be capable of dissipating this energy. To be sure that a MOSFET is fully "on", the manufacturers datasheet should be consulted but, for most MOSFETs in the $I_{D(max)} = 1 - 20$ A range and $V_{DS(max)} = 10 - -1000$ V range, a V_{GS} of 10 V will

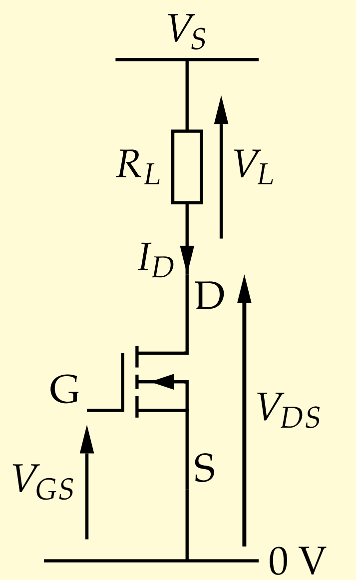


Figure 5: MOSFET switching circuit.

turn the device fully on and a V_{GS} of 0 V will turn it fully off. Since te gate terminal is insulated, no current is require to *maintain* the gate voltage drive. Note though that the gate has capacitance associated with it which complicates transient (switching) conditions. A more thorough discussion of switching circuits will be undertaken in later modules.

BJT Switches

When a BJT is fully "on" (i.e. at point B) the voltage across it is $V_{CE(sat)}$, the saturated on-state voltage drop. $V_{CE(sat)}$ is approximately constant for a constant ratio of I_C/I_B and its magnitude depends upon the particular transistor. For a 100 V, 2 A device $V_{CE(sat)}$ would be a couple of hundred millivolts. For a 1000 V 20 A device it would be around 1 V.

$$I_{C(on)} = \frac{V_s - V_{CE(sat)}}{R_L} \tag{5}$$

and $I_{C(off)} \approx 0$ because leakage is small. The on-state power dissipated in the switch is $I_{C(on)}\,V_{CE(sat)}$ and the device must be capable of dissipating this energy. To be sure the BJT is fully on, the designer must ensure that sufficient I_B is driven in to the transistor base. The BJT has a parameter called "static current gain", I_C/I_B which is given the symbol h_{FE}. This tells the designer the base current required to support a particular collector current. So for a BJT the design process would be

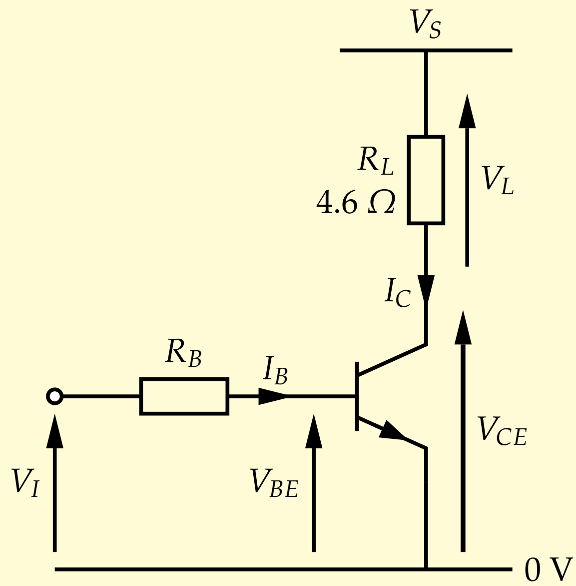


Figure 6: BJT switching circuit.

$$I_C = \frac{V_s - V_{CE(sat)}}{R_L} \tag{6}$$

$$\therefore \text{ minimum } I_B \text{ needed } = \frac{I_C}{h_{FE}} = \frac{V_s - V_{CE(sat)}}{h_{FE}\,R_L} \tag{7}$$

This current is controlled by R_B according to

$$I_B = \frac{V_i - V_{BE}}{R_B} \tag{8}$$

where V_i this the input drive voltage and V_{BE} is the voltage drop associated with a forward biased p-n junction - i.e. 0.6 - 0.7 V. Usually a designer will make I_B two or three times the minimum value in order to be user the transistor is switched on properly under all circumstances.

Electronic Switches with AC

Often current must be controlled in AC systems. Examples are numerous including for example heating and air handling applications. In the circuit of Fig. 7 the diode, D_1 ensures that the switch is not reverse biassed during negative half cycles. However the control is only half wave - the load can never by energised when V_S is in the negative half cycle. Therefore half of the potential load dissipation is unavailable, which is highly undesirable.

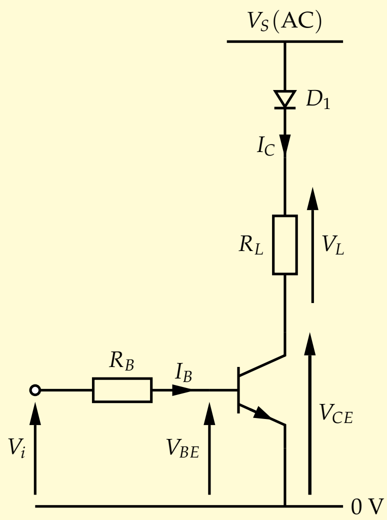
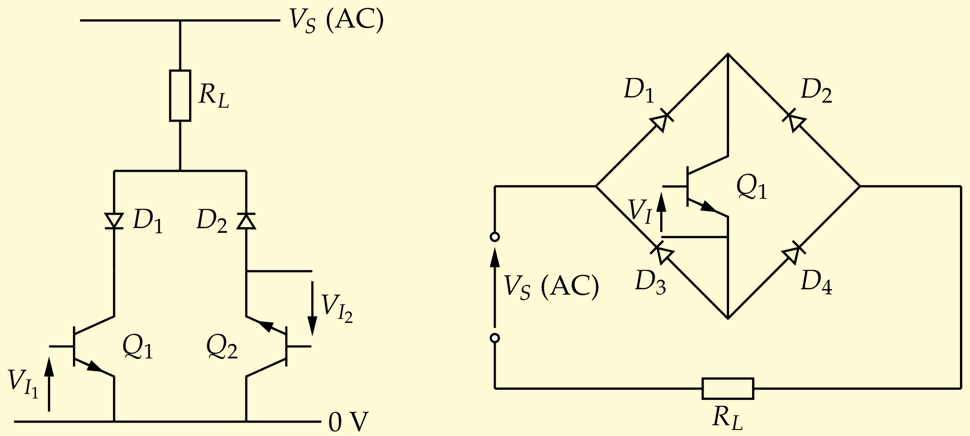


Figure 7: Half Wave Rectifying BJT AC Switching Circuit

We could add a second diode as in Fig 8a. Here D_1 and Q_1 will operate when $V_{s(AC)}$ is positive and D_2 and T_2 will operate when $V_{s(AC)}$ is negative. The control input to Q_2 is somewhat complicated but it is not impossible to devise an appropriate control circuit. Often, especially in mains or 3ϕ equipment opto-isolators or pulse transformers are used to electrically isolate the drive circuit from the switching transistor. An alternative full



(a) Two transistor AC switching circuit.

(b) Diode bridge switching circuit.

Figure 8: Two Full Wave AC Switching Circuits.

wave approach is to use the four diode bride with a single switch showin in Fig. 8b. The diode bridge ensures that whatever the instantaneous polarity of V_S, I_C is always in the same direction. The current through R_L alternates. This circuit has similar difficulties with the control input terminals, but a suitable control circuit is relatively straightforward.

H-Bridge Circuits

H-Bridge circuit are often used to control d.c. motors from a d.c.

- The H-bridge consist of four switches in an “H” shape. The load forms the cross bar of the H.
- For electric car applications V_S may be in the region of 600 V dc and peak currents may reach 50 A.
- By controlling switches appropriately, current can be made to flow in either direction through the load. Therefore d.c. motors can be made to run in both directions. The average load power can also be controlled by using pulse width modulation techniques. This allows maximisation of torque while controlling speed.

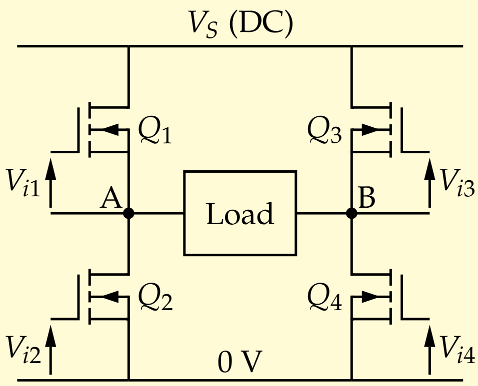


Figure 9: H-Bridge Circuit

To understand the operation imagine Q1 and Q4 are “on”. Current will flow through Q1 to A, through the load to B and then through Q4. Current can be made to flow from B to A by switching “off” Q1 and Q4 and switching “on” Q3 and Q2. Note if Q1 and Q2 or Q3 and Q4 are ever permitted to be on simultaneously, a large “shoot-through” current will flow and, if there is nothing else to limit the current, the switches will be destroyed, usually very violently.

Switching Inductive Loads

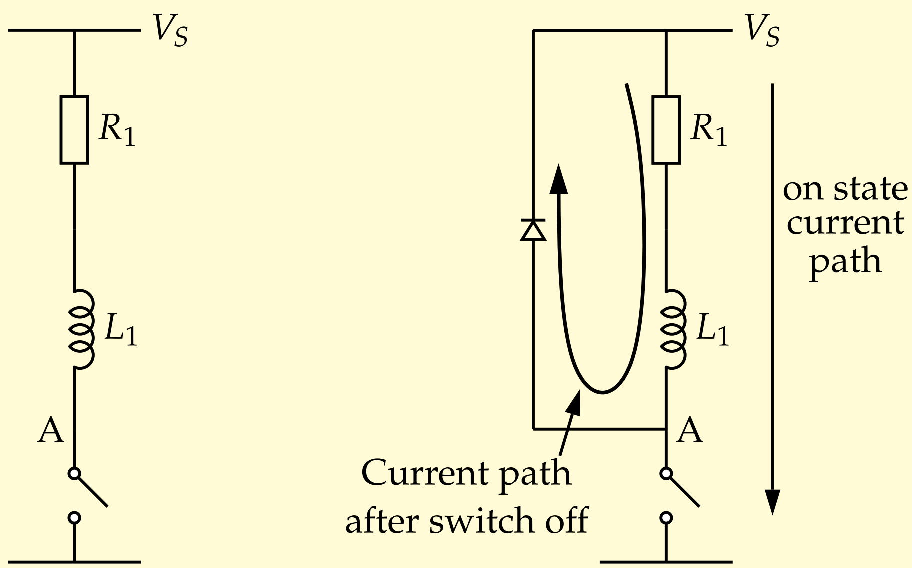
Inductors always try to keep current flowing in them or more precisely inductors generate a voltage across their terminals which acts to oppose any change in current through the inductor. Since

$$V_L = L\frac{\mathrm{d}i}{\mathrm{d}t} \tag{9}$$

if one tries to switch off a current, i.e. make $\mathrm{d}i/\mathrm{d}t \to \infty$, $V_L \to \infty$. Effectively what happens is as follows:

- When the switch is “on”, a current V_s/R_L flows in the circuit.
- When the switch turns “off”, L keeps pushing current into node A... so charge builds on node A very rapidly.

- Node A has only a small capacitance (this is stray or parasitic capacitance between the node and the other parts of the circuit) so a small amount of charge yields a big voltage ($I = C\mathrm{d}V/\mathrm{d}t$) which is sometimes called a "back emf spike".
- Peak voltage can easily reach several kilovolts in a system driven by 12 V. The voltage spikes can damage or destroy the switch and other components.
- The effect can be controlled by providing an alternative pathway for current leaving the inductor when the switch turns "off". One way is to use an "idling" or "free wheeling" diode that is reverse biassed while the switch is on by conducts if the voltage on node A rises above V_S.
- Immediately after switch "off", the current through D is the same as in the "on" stage immediately before switch "off". The current then falls exponentially with a time constant of L/R_T where R_T is the total resistance of the idling current pathway.



(a) Switch circuit with inductive load. (b) Inductive load and free wheeling diode.

Figure 10: Switch circuits with and without "back emf" protection.

In some applications, these back emf spikes are useful. Examples include car ignition, electric fences, flyback converters (a kind of switched mode power supply), and CRT and VFD display power supplies. In most applications however attempts are made to control them.

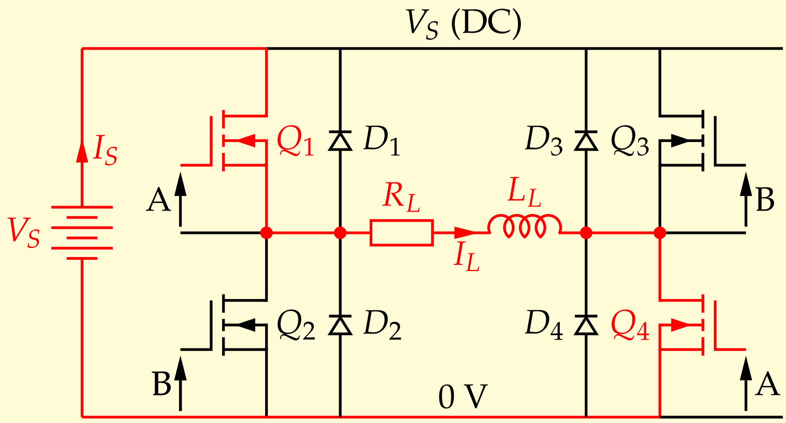


Figure 11: H-bridge with free wheeling diodes, switches conducting.

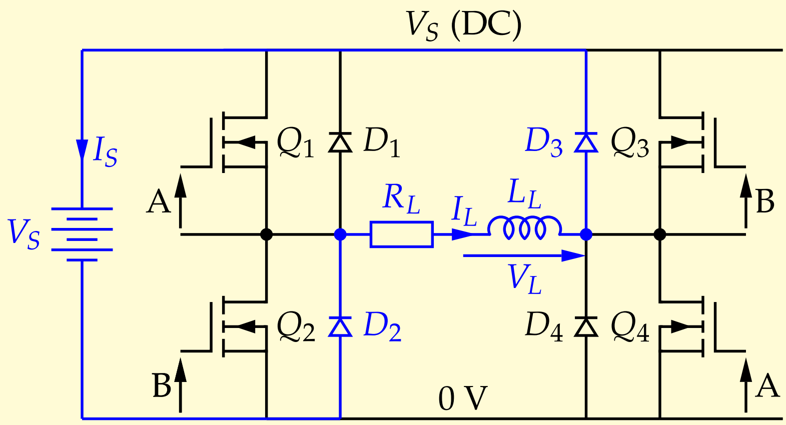


Figure 12: H-bridge with free wheeling diodes, diodes conducting.

The energy stored in the inductor drives the "back emf" process and in the simple idling diode circuit of Fig. 10b this energy is dissipated in D_1 and R_T. In an H-bridge circuit, energy stored in the load is returned to the supply. For example if Q_1 and Q_4 have been on for a long time and Q_2 and Q_3 are off and stay off, the on state and idling current paths are shown in Figs. 11 and 12, note that the idling current acts to charge up the power supply (either a battery or a bench power-supply etc.)