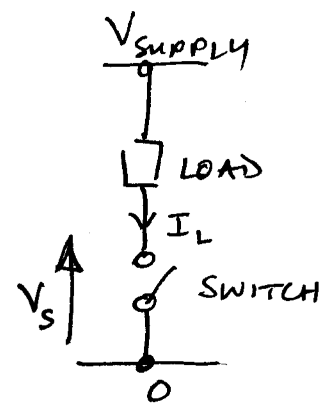
Switches

— Control power to load in "on"/"off" mode.



Ideal Switches

When "on" $I_L = \frac{V_{SUPPLY}}{R_L}$

When "off" $I_L = 0$

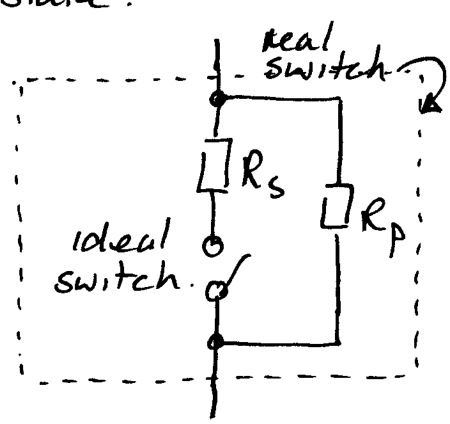
When "on" $V_S = 0$

when "off" $V_S = V_{SUPPLY}$.

- product of V_S + I_L is zero in both switch states so no power lost in switch.
- I_L, the "on" state current is determined by the external cct, not by the switch.

Real Switches

- real switches have some series resistance and some leakage in the "off" state.
- in most cases, R_P, the "off" state leakage can be neglected.
- R_S usually has to be considered because it causes power loss in the switch.



For a real switch $I_{ON} = \dfrac{V_{SUPPLY}}{R_{LOAD} + R_S}$.

Switch Types — mechanical
— electro-mechanical
— electronic.

(i) Mechanical
- mechanical force brings together two metal contacts.
- can be designed for currents in range ~ 10^{-3} to 10^{7} A
- very low contact resistances (R_S)
- very low leakage (very high R_P).
- need application of mechanical force to operate — inertia + elasticity limit switching rate to a few hundred Hz
- need for mechanical force requires some kind of mechanical linkage between switch + operator.

(ii) Electro-mechanical (relays).
- similar to mechanical except that mechanical force is provided by an electro-magnet.
- electro-magnet drive scheme offers possibility of remote operation.
- advantages of mechanical contacts — ie, low losses, — maintained.

Note that in both these switch types, the switch contacts can be, and usually are, insulated electrically from the control linkages or electro-magnet.

(iii) electronic switches

- many different types
- ones of interest here based on MOSFET and BJT transistors.
- can switch very quickly $> 10^9$ per second in a Pentium 4

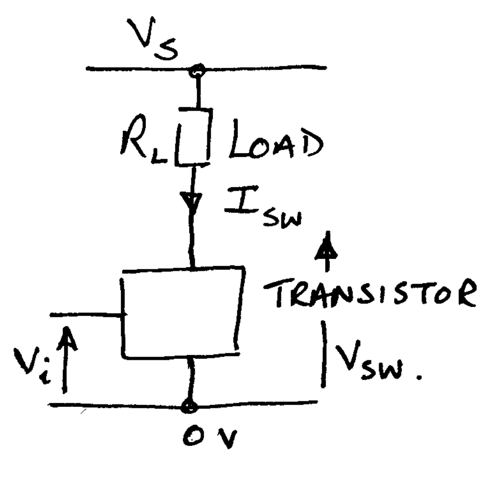
[most mechanical switches would fall to pieces well before 10^9 operations!]

- losses generally higher than in mechanical switches
- control input is electrically connected to one of the main current path terminals
- most electronic switches support current flow in one direction only.

[Note that the last two points might seem a bit inconvenient — as indeed they are. But the advantages and functionality that can be gained by using electronic switches are so great that designers have devised a number of ways of getting around them.]

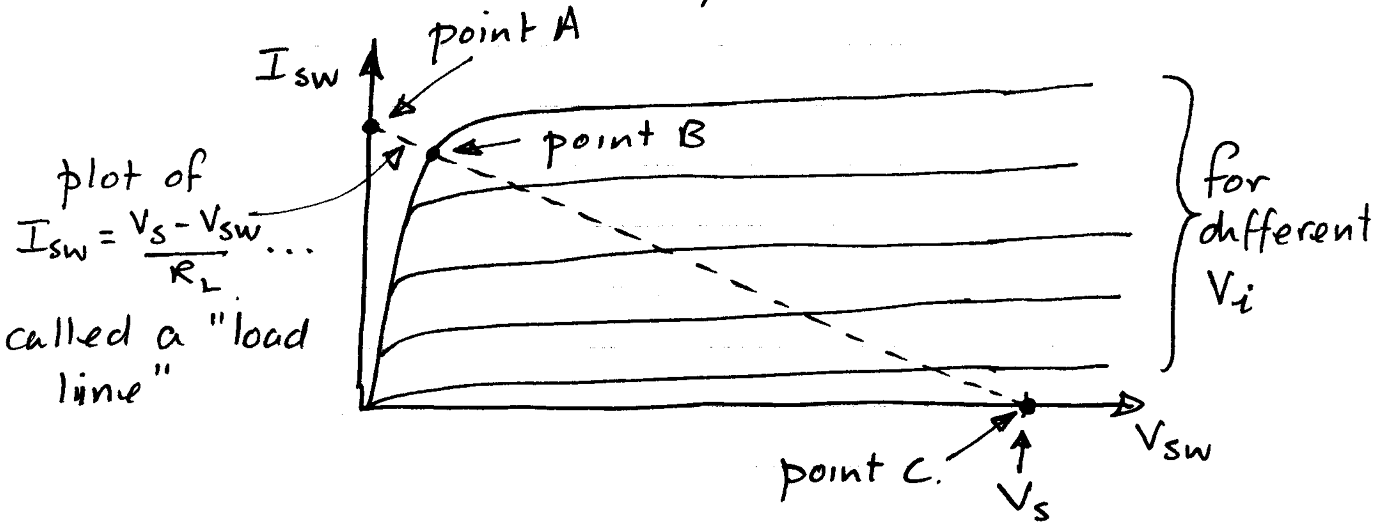
<u>MOSFET and BJT switches.</u>

The device is put into a circuit like: V_s is the supply voltage, V_i the control voltage and V_{SW} the voltage across the switch.



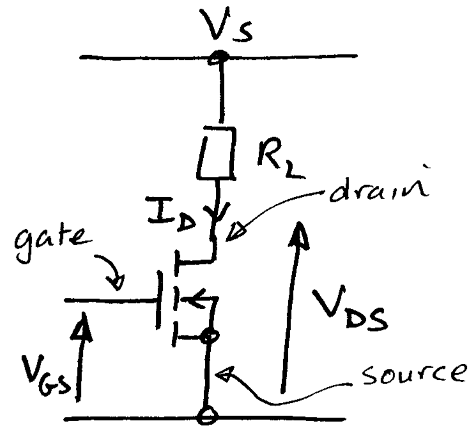
V_{sw} and I_{sw} are related by $I_{sw} = \frac{V_s - V_{sw}}{R_L}$

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



The switch is controlled by V_i. Point C is the "off" state 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 point B + point 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, on switching, get from one to the other as quickly as possible.

eg. A ZTX653 bipolar transistor is capable of dissipating 1W, can switch up to 2A at up to 100V — ie, can control 200W. The instantaneous VI product at the mid point between B + C would be 50W — enough to blow the transistor to smitherines if it was permitted to stay at that point. Designers ensure that the transistors survive by switching rapidly (usually in sub-microsecond times) between states. Thus the average energy in switching is small — more on this topic in EEE340.



MOSFET switches

The MOSFET behaves like a resistance when fully on (ie, at point B). Manufacturers specify this resistance as $r_{DS(ON)}$.

So $I_D = \dfrac{V_S}{R_L + r_{DS(ON)}}$

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 a 1 or 2% drop) but the effect on the transistor might be important because the power dissipated in the switch is

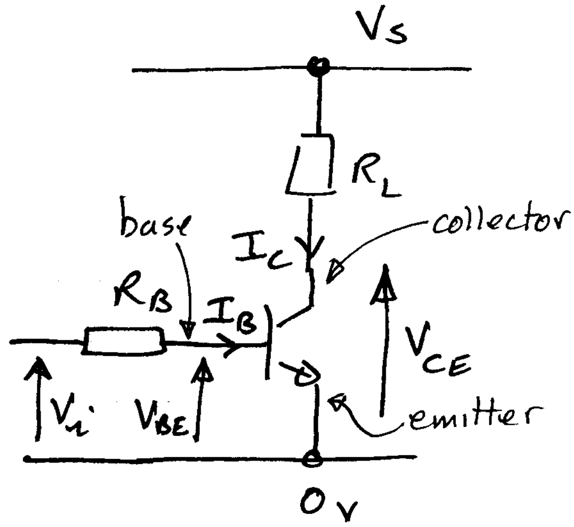
$$P_{DISS} = I_{D\,ON}^2 \, r_{DS(ON)}$$

and the switch must be capable of dissipating this energy.

To be sure that a MOSFET is fully "on", manufacturer's data should be consulted but for most MOSFETS in the $I_{D\,MAX} = 1$ to 20A range and $V_{DS\,MAX} = 10$ to 1000V range, a V_{GS} of 10V will turn the device fully on and a V_{GS} of 0V will turn it off. Since the gate terminal is insulated, no current is required to maintain the gate voltage. drive.

[Note, though, that the gate has capacitance associated with it and this capacitance complicates transient drive conditions — more on this in EEE340.]

BJT switches



When a BJT is fully "on" (ie, 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 I_C/I_B and its magnitude depends upon the particular transistor. For a 100V 2A device $V_{CE(SAT)}$ would be a couple of hundred mV. For a 1000V 20A device it would be nearer 1V.

So $$I_{C(ON)} = \frac{V_S - V_{CE(SAT)}}{R_L}$$

and $I_{C(OFF)} \approx 0$ because leakage is small.

The on-state power dissipated in the switch is $I_{C(ON)} \cdot V_{CE(SAT)}$ 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 into the transistor base. The BJT has a parameter called "static current gain", I_C/I_B, and 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 ...

$$I_c \approx V_S/R_L \quad (\text{assuming } V_S \gg V_{CE(SAT)}).$$

$$\therefore \text{minimum } I_B \text{ needed} = I_C/h_{FE} = \frac{V_S}{h_{FE} R_L}$$

and this current is controlled by R_B according to

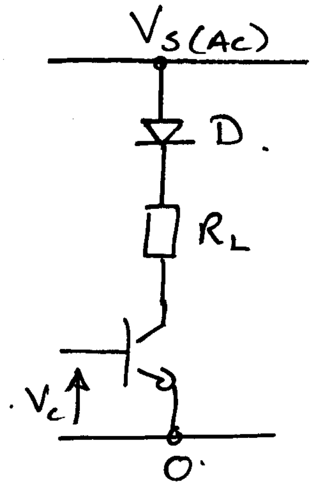
$$I_B = \frac{V_i - V_{BE}}{R_B}.$$

where V_i is the input drive voltage and V_{BE} is the voltage drop associated with a forward biassed p-n junction — ie, 0·6 to 0·7 V.

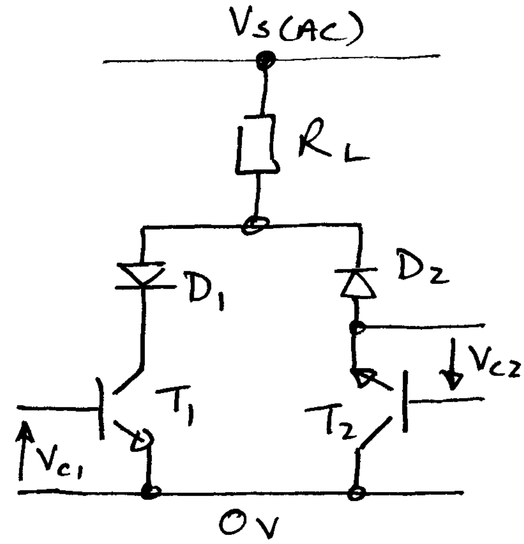
Usually a designer will make I_B two or three times the minimum value in order to be sure that the transistor is switched on properly under all circumstances.

Electronic switches with AC

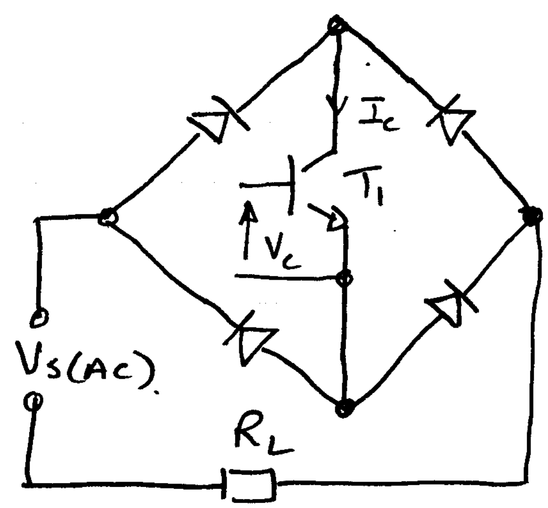
D ensures that the switch is not reverse biassed during negative half cycles... but the control is only half wave — the load can never be energised when V_s is in a -ve half cycle.



We could add a second diode and transistor — as over the page. Here D_1 and T_1 will operate for $V_{S(AC)}$ positive and D_2 and T_2 will operate for $V_{S(AC)}$ negative. The control input to T_2 is a bit awkwardly placed but it would not be impossible to devise an appropriate control cct for T_2.



An alternative full wave approach is to use a diode bridge with a single switch. 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.

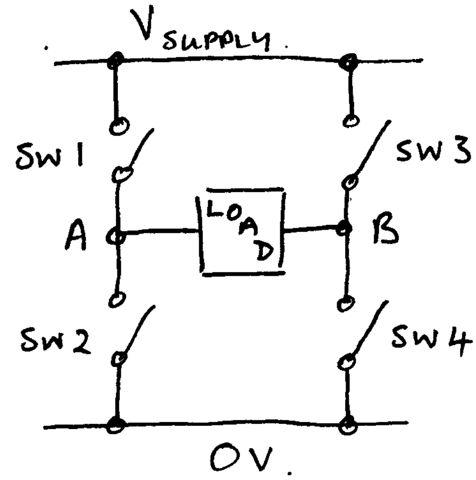


Again, the position of the control input terminals is a bit inconvenient but design of a suitable circuit would be relatively straightforward.

H-Bridge Circuits

H-Bridge circuits are often used to control dc motors from a d.c. supply.

— consist of four switches in an "H" shape — the load is the cross bar of the H.



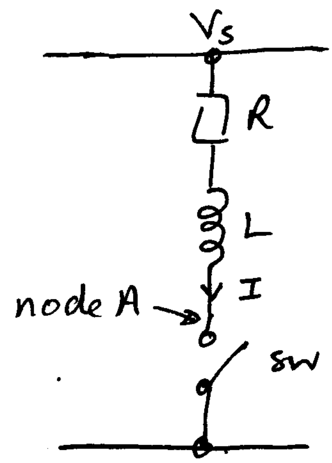
- for electric car application, V_{SUPPLY} might be 600V dc and peak currents might reach the high 10s of Amps.
- by controlling switches appropriately, current can be made to flow in either direction through the load (ie dc motors can be made to run in both directions). The average load power can also be controlled.

eg. if SW1 + SW4 are "on", current will flow through SW1 to A, through the load to B and then through SW4. Current can be made to flow from B to A by switching "off" SW1 + SW4 and switching "on" SW3 + SW2.

[NOTE If SW1 + SW2 (or SW3 + SW4) are ever allowed to be on simultaneously, a large "shootthrough" current will flow and the switches will be destroyed.... usually very violently.]

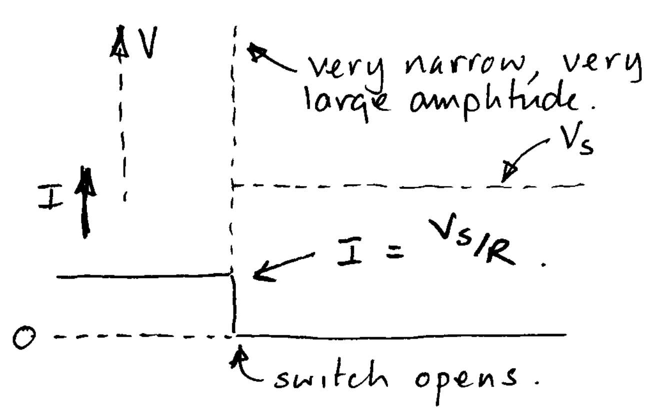
Switching inductive loads

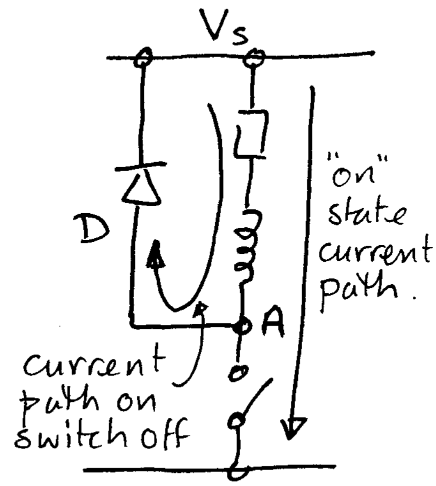
Inductors always try to keep current flowing. Since $V_L = L\frac{dI}{dt}$, if one tries to switch off a current – ie, make $\frac{dI}{dt} \Rightarrow \infty$, V_L will $\Rightarrow \infty$



Effectively what happens is as follows.

- When switch is "on", a current V_S/R flows in the circuit.

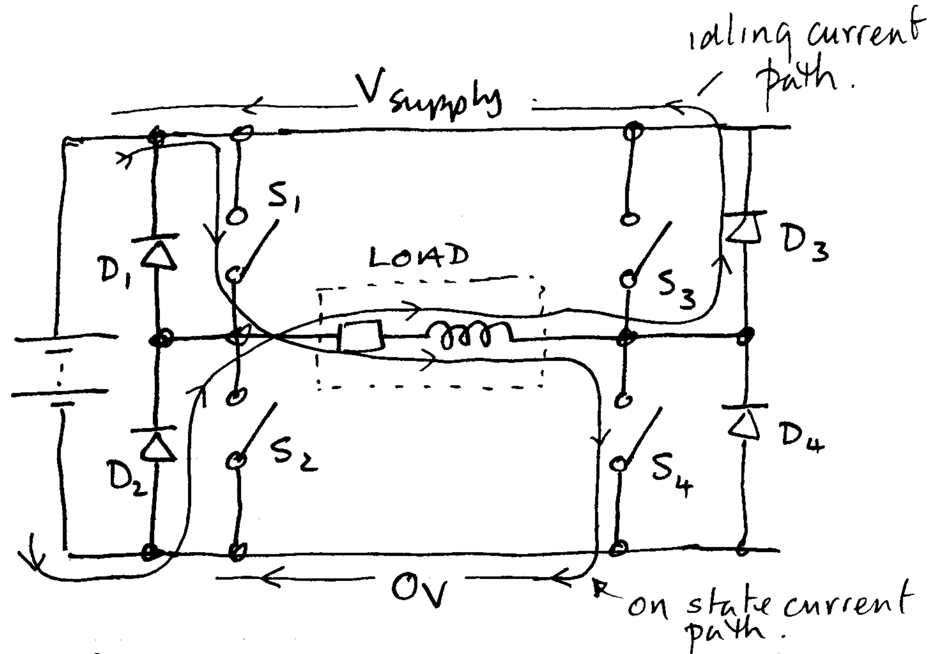




- when switch turns "off", L keeps pushing current into node A ... so charge on node A rapidly builds.
- Node A has only a small capacitance so a small amount of charge gives a big voltage (sometimes called a "back emf spike")
- Peak voltage can easily reach kV in system driven by 12V — voltage peak can damage switch or other components.
- Effect is controlled by providing an alternative current path on switch off. One way of doing this is to use an "idling" or "freewheeling" diode that is reverse biassed while the switch is on but conducts if the node A voltage tries to rise above Vs.
- Immediately after switch "off", the current through D is the same as the "on" state current was immediately before switch "off". This current then falls exponentially with a time constant L/R_T where R_T is the total resistance of the idling current path.

[NOTE: In some applications, these back emf spikes are useful. Examples are car ignition, electric fences, flyback converters (a kind of power supply), c.r.t. high voltage supply. In most applications, though, steps are taken to control them.]

It is the energy stored in the inductor that drives the "back emf" process and in the simple idling diode circuit above, this stored energy is dissipated in D and R_T. In an H-bridge circuit, load stored energy is returned to the supply...



For example, if S_1 + S_4 have been on for a long time (and S_2 + S_3 are off and stay off) the on-state and idling current paths are as indicated. Note that the idling current puts charge back into the battery source.

NOTE MOSFETs designed for power switching have an integral internal "body diode" but designers will often put external diodes in parallel with the MOSFET. This is because the structure is designed to be a good MOSFET; the diode is not optimised as a diode and some aspects of its performance are not as good as can be obtained with discrete diodes.