EEE118: Electronic Devices and Circuits

Lecture XII

James E Green

Department of Electronic Engineering
University of Sheffield
j.e.green@sheffield.ac.uk

Review

- Considered the four modes of operation of a BJT.
- Looked at examples of the input, output and transfer characteristics of a BJT.
- Developed a large signal model for a BJT which can be used to solve switching problems.
- Noted some of the limitations of the model in the saturation
- Developed a large signal model of a MOSFET.
- Briefly observed some differences between MOSFET and BJT characteristics.
- Discussed an ideal switch
- Considered the non-idealities of a switch
- Discussed the properties of two classes of ‘switch’: Mechanical and Electro-Mechanical.

Outline

Electronic Switches

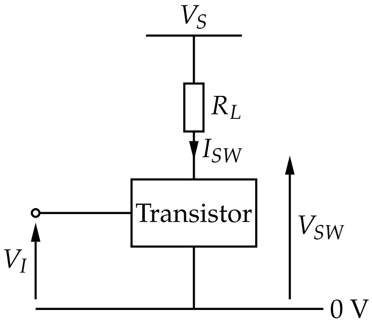
- Many different types (BJT, MOSFET, JFET, Valve, Triac, Thyristor, "Solid State Relay (SSR)"...)
- Interested here in MOSFET and BJT.
- Electronic switches can change state very quickly c.f mechanical switches $> 10^9$ operations *per second* in a modern PC.
- Most mechanical switches would not last 1/1000th of this number of operations!
- Losses in electrical switches considerably greater than mechanical switches.
- The control input is electrically connected to one of the main current path terminals. (Emitter or Source) is common to input network and to output network).
- Most electronic switches support current flow in one direction only (not SSR, it is a compound device).

MOSFET and BJT Switches

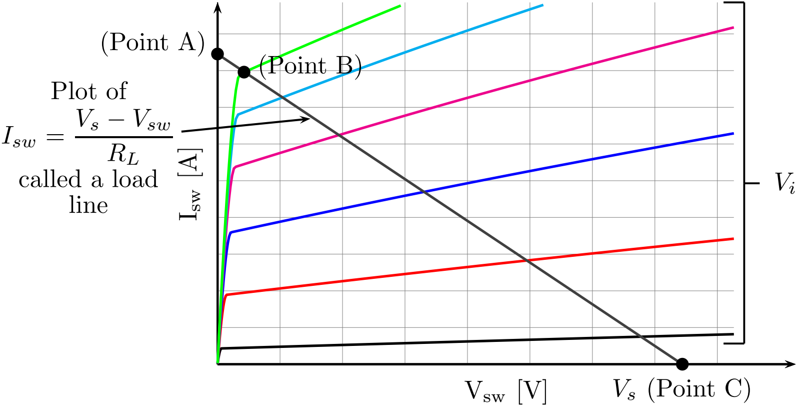
The connection of the control input to the controlled output and the single direction of current flow is inconvenient, however the advantages of electrical switches are so great that designers have developed a number of ways around these problems.

The device is placed into the circuit (right). In which 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

$$I_{SW} = \frac{V_S - V_{SW}}{R_L} \quad (1)$$



There is also a second relationship between V_{SW} and I_{SW} defined by the output characteristics of the transistor.



Notes on the Output Characteristic

- The switch is controlled by V_I (which is equal to V_{BE} in this example).
- Point C is the “off state” point.
- Point B is the real “on state” point.
- Point A is the ideal on state point.
- As V_I is increased, I_C will increase and V_{CE} will decrease until point B is reached.
- The dots on the diagram can be thought of as several different operating points but they are not quiescent conditions as the changes are large compared to the non-linearity of the transistor characteristics.

Notes on the Output Characteristic II

- The operating point moves across a non-linear portion of the characteristics (it's a large signal problem)
- The locus - the path - of the operating point across the output characteristics is called the "load line". It is defined by the load resistance and the supply voltage (V_S).
- The load line is straight - no surprise - it represents a resistance as a function of V and I... Ohm's law.
- In the region between B and C there is a significant $V\,I$ product.
- The designer must keep the transistor at point B or point C and move between them as fast as possible.

Power Dissipation

- The ZTX653 (from Lecture 10) can dissipate 1 W.
- And can carry 2 A...
- At up to 100 V (V_{CE}).
- So it can control 200 W in the load.
- The instantaneous power in the transistor mid-way between B and C would be 50 W.
- Which is sufficient to blow the transistor to pieces.

The designer must ensure the transistor switches quickly to keep the average energy in any switching cycle below the permissible limit. More on this in "EEE340: Analogue and Switching Circuits" now called "EEE223: Energy Management and Conversion".

MOSFET Switches

- From Lecture 10 the MOSFET behaves like a resistance when "on" (linear region) i.e. at point B.
- Manufactures specify $R_{DS(on)}$.
- I_D is given by,

$$I_D = \frac{V_S}{R_L + R_{DS(on)}} \tag{2}$$

when in the "on" state

- $I_D = 0$ in the "off" state.
- The effect of $R_{DS(on)}$ on load power is small (1 – 2% drop).
- The effect on the transistor is

$$P = I_{D(on)}^2 R_{DS(on)} \tag{3}$$

which may be significant.

MOSFET Switches II

- To ensure the MOSFET is fully "on" the datasheet should be consulted or output characteristics obtained by experiment. A V_{GS} of $7 - 10$V will probably be sufficient to switch the transistor under most circumstances.
- Since the gate is insulated from the source and drain, no current is required to maintain the gate drive voltage (MOSFETs have no equivalent of I_B).
- Note that the gate has capacitance associated with it and this capacitance complicates transient drive conditions. More in "EEE340: Analogue and Switching Circuits" now called "EEE223: Energy Management and Conversion".

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 value of h_{FE}
- The value of h_{FE} depends on the particular transistor.

$$I_{C(on)} = \frac{V_S - V_{CE(sat)}}{R_L} \quad (4)$$

- $I_{C(off)} = 0$ because the leakage is small.
- To be sure the BJT is fully on, the designer must ensure there is sufficient base current available.
- The base current is determined by

$$I_B = \frac{I_C}{h_{FE}} \quad (5)$$

BJT Switch Design Process

First estimate I_C,

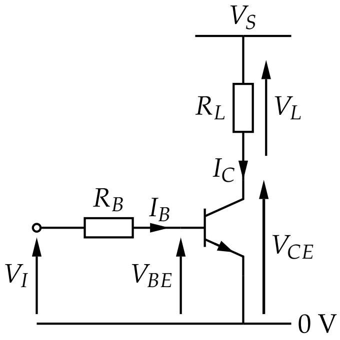
$$I_C \approx \frac{V_S}{R_L} \text{ if } V_S >> V_{CE(sat)} \qquad (6)$$

then calculate the required base current,

$$\therefore \text{min } I_B = \frac{I_C}{h_{FE}} = \frac{V_S}{h_{FE}\,R_L} \qquad (7)$$

I_B is controlled by

$$I_B = \frac{V_I - V_{BE}}{R_B} \qquad (8)$$



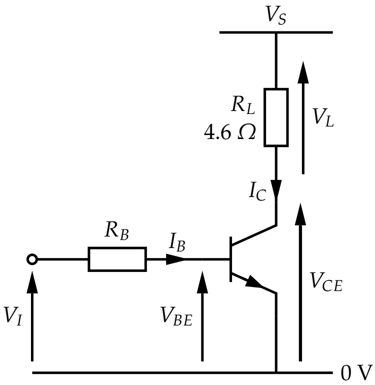
Where V_I is the input voltage and V_{BE} is the voltage associated with the forward biased base emitter junction (0.7 V). Usually it is necessary to make I_B several times the minimum value to make the transistor switch properly under all circumstances.

Switching Transistor Example: Part One

For the following BJT switching circuit find the,

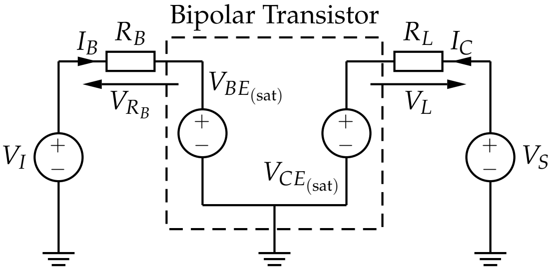
- collector current
- load power
- switch "on" state power loss
- range of possible base currents
- maximum value of R_B

$$V_S = 48 \text{ V}, \ h_{FE} = 35 - 170,$$
$$V_{CE(sat)} = 0.21 \text{ V}, \ V_{BE(sat)} = 0.7 \text{ V},$$
$$V_I = 10 \text{ V}.$$



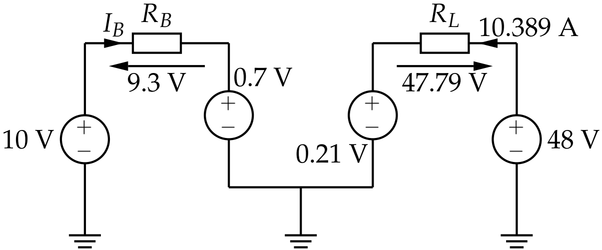
Solution

The “on” state or “saturation” large signal model can be drawn (if necessary)



For the collector current, apply Ohm’s law to the collector circuit:

$$I_C = \frac{V_S - V_{CE(\text{sat})}}{R_L} = \frac{48 - 0.21}{4.6} = 10.389 \text{ A} \quad (9)$$



For the load power,

$$P_L = \frac{V_L^2}{R_L} = \frac{(48 - 0.21)^2}{4.6} = 496.49 \text{ W} \tag{10}$$

For the transistor on state power loss,

$$P_T = V_{CE(sat)} \cdot I_C = 0.21 \cdot 10.389 = 2.182 \text{ W} \tag{11}$$

For the minimum I_B (need to use max h_{FE}),

$$I_B = \frac{I_C}{h_{FE(\mathrm{max})}} = \frac{10.389}{170} = 61.11\ \mathrm{mA} \tag{12}$$

For the maximum I_B (need to use min h_{FE}),

$$I_B = \frac{I_C}{h_{FE(\mathrm{min})}} = \frac{10.389}{35} = 296.82\ \mathrm{mA} \tag{13}$$

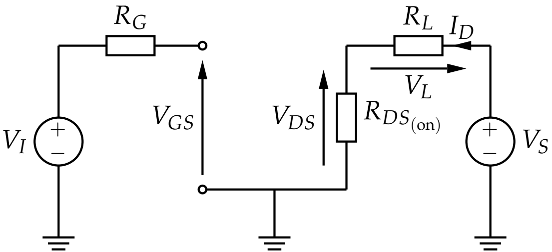
For the max permissible value of R_B (use $I_{B(max)}$),

$$R_B = \frac{V_I - V_{BE(sat)}}{I_{B(max)}} = \frac{10 - 0.7}{296.82 \times 10^{-3}} = 31.33\ \Omega. \tag{14}$$

Always assume worst case h_{FE} in a switching problem.

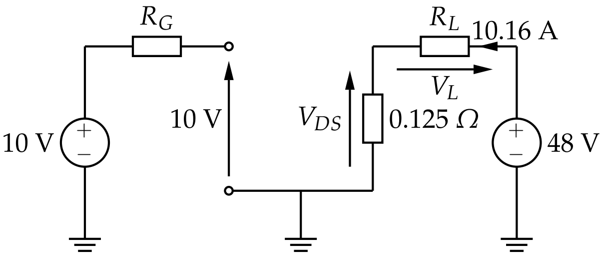
Switching Transistor Example: Part Two

What would the new load power and transistor power be if the BJT was replaced with a MOSFET where $R_{DS(on)} = 0.125\ \Omega$?



For the drain current,

$$I_D = \frac{V_S}{R_{DS(on)} + R_L} = \frac{48}{0.125 + 4.6} = 10.158\ \mathrm{A} \qquad (15)$$



The power in the load resistance,

$$P_L = \frac{V_L^2}{R_L} = \frac{\left(V_S - \left(R_{DS(on)}\, I_D\right)\right)^2}{R_L} \tag{16}$$

$$= \frac{(48 - (0.125 \cdot 10.158))^2}{4.6} = 474.72 \text{ W} \tag{17}$$

The power loss in the FET is,

$$P_T = I_D^2\, R_{DS(on)} = 10.158^2 \cdot 0.125 = 12.9 \text{ W} \tag{18}$$

What value of $R_{DS(on)}$ for the MOSFET would yield the same on state loss as the BJT in part one?

Use the *BJT* current and power loss figures to find an equivalent resistance value

$$P_T = 2.181 \text{ W} \tag{19}$$

$$I_D = 10.398 \text{ A} \tag{20}$$

$$R_{DS(on)} = \frac{P_T}{I_D^2} = \frac{2.181}{10.389^2} = 0.0202\ \Omega \tag{21}$$

Homework 4

It should be possible to *start* Homework 4.

It should also be possible to start the Transistors as Switches and Amplifiers problem sheet.

Review

- Discussed the properties of the third class of 'switch': Electronic.
- Considered how the switching action of a transistor is represented on the output characteristics.
- Introduced the idea of a 'load line'.
- Considered power dissipation in the "on" state
- Provided design equations for MOS and BJT switches using a large signal model. Note that in general design work it is often unnecessary to actually draw out this model.
- Performed switching circuit example calculation (exam/tutorial sheet style)