CHAPTER 10

SWITCHING TRANSISTOR CIRCUITS

Objectives

After completing this course, you will be able to:

- Describe and analyze the operation and use of n-channel enhancement mode MOSFETs and NPN transistors in switching circuits, including those which interface to outputs.
- Describe and analyze the operation and use of voltage comparator ICs.
- Compare the action of switching circuits based on MOSFETs, NPN transistors and voltage comparator ICs.
- Use data sheets to design switching circuits using MOSFETs, NPN transistors and comparators.

What is Switching Transistor Circuit?

A transistor switch, which is used for opening or closing of a circuit that means the transistor, is commonly used as a switch in the electronic devices only for the low voltage application because of its low power consumption. Transistor work as a switch when it is in cut off saturation region.

Working a transistor as a Switch

As one of the significant semiconductor devices, transistor has found use in enormous electronic applications such as embedded systems, digital circuits and control systems. In both digital and analog domains transistors are extensively used for different application usage like amplification, logic operations, switching and so on.

The Bipolar Junction Transistor or simply BJT is a three layers, three terminal and two junction semiconductor device. Almost in many of the applications these transistors are used for two basic functions such as switching and amplification.

The name bipolar indicates that two types of charge carriers are involved in the working of a BJT. These two charge carriers are holes and electrons where holes are positive charge carriers and electrons are negative charge carriers.

The transistor has three regions, namely base, emitter and collector. The emitter is a heavily doped terminal and emits electrons into the base. Base terminal is lightly doped and passes the emitter-injected electrons on to the collector. The collector terminal is intermediately doped and collects electrons from base. This collector is large as compared with other two regions so it dissipates more heat.

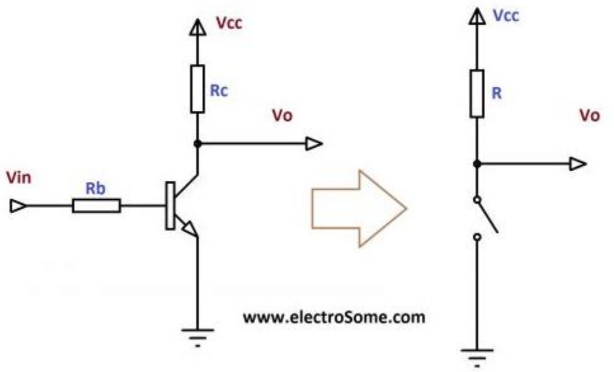
BJTs are of two types NPN and PNP, both functioning is same but differ in terms of biasing and power supply polarity. In PNP transistor, between two P- type materials N- type material is sandwiched whereas in case of NPN transistor P- type material sandwiched between two N- type materials. These two transistors can be configured into different types like common emitter, common collector and common base configurations.

Transistor as a Switch

A transistor is used for switching operation for opening or closing of a circuit. This type solid state switching offers significant reliability and lower cost as compared with conventional relays.

Both NPN and PNP transistors can be used as switches. Some of the applications use a power transistor as switching device; at that time it may necessary to use another signal level transistor to drive the high power transistor.

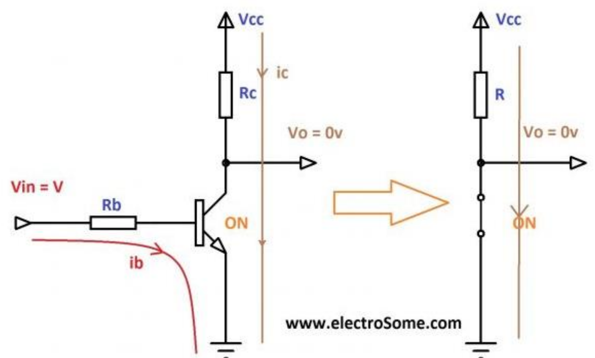
Circuit Diagram – Transistor as a Switch



From the above circuit we can see that the control input V_{IN} is given to base through a current limiting resistor Rb and Rc is the collector resistor which limits the current through the transistor. In most cases output is taken from collector but in some cases load is connected in the place of Rc.

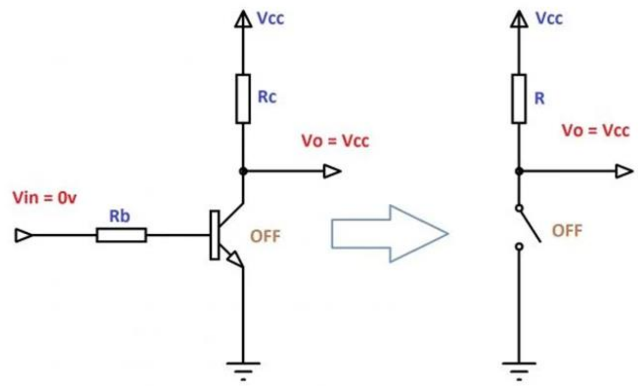
- ON = Saturation
- OFF = Cutoff

Transistor as a Switch – ON



Transistor will become ON (saturation) when a sufficient voltage V is given to input. During this condition the Collector Emitter voltage V_{ce} will be approximately equal to zero, ie the transistor acts as a short circuit. For a silicon transistor it is equal to 0.3v. Thus collector current $I_C = \frac{V_{CC}}{R_C}$ will flow.

Transistor as a Switch – OFF



Transistor will be in OFF (cutoff) when the input V_{IN} equal to zero. During this state transistor acts as an open circuit and thus the entire voltage V_{CC} will be available at collector.

NPN Transistor as a Switch

Based on the voltage applied at the base terminal of a transistor switching operation is performed. When a sufficient voltage ($V_{in} > 0.7V$) is applied between the base and emitter, collector to emitter voltage is approximately equal to 0. Therefore, the transistor acts as a short circuit. The collector current $\frac{V_{CC}}{R_C}$ flows through the transistor.

Similarly, when no voltage or zero voltage is applied at the input, transistor operates in cutoff region and acts as an open circuit. In this type of switching connection, load (here LED lamp) is connected to the switching output with a reference point. Thus, when the transistor is switched ON, current will flow from source to ground through the load.

PNP Transistor as a Switch

PNP transistor works same as NPN for a switching operation, but the current flows from the base. This type of switching is used for negative ground configurations. For the PNP transistor, the base terminal is always negatively biased with respect to the emitter. In this switching, base current flows when the base voltage is more negative. Simply a low voltage or more negative voltage makes transistor to short circuit otherwise it will be open circuited or high impedance state.

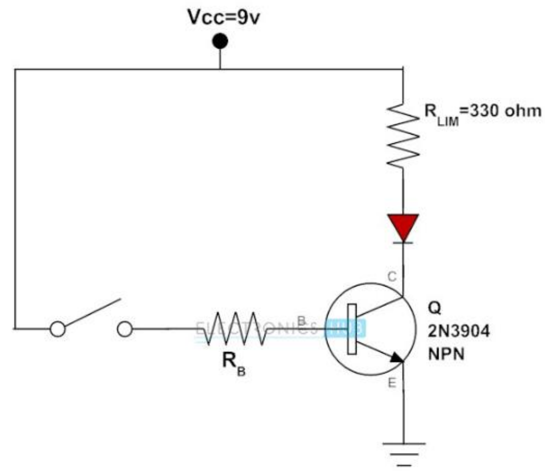
In this connection, load is connected to the transistor switching output with a reference point. When the transistor is turned ON, current flows from the source through transistor to the load and finally to the ground.

Common practical Examples of transistor as a Switch

Transistor to Switch LED

As discussed earlier that the transistor can be used as a switch. The schematic below shows how a transistor is used to switch the Light Emitting Diode (LED).

- When the switch at the base terminal is open, no current flows through the base so the transistor is in the cutoff state. Therefore, the circuit acts as open-circuit and the LED becomes OFF.
- When the switch is closed, base current starts flowing through the transistor and then drives into saturation results to LED become ON.
- Resistors are placed to limit the currents through the base and LED. It is also possible to vary the intensity of LED by varying the resistance in the base current path.

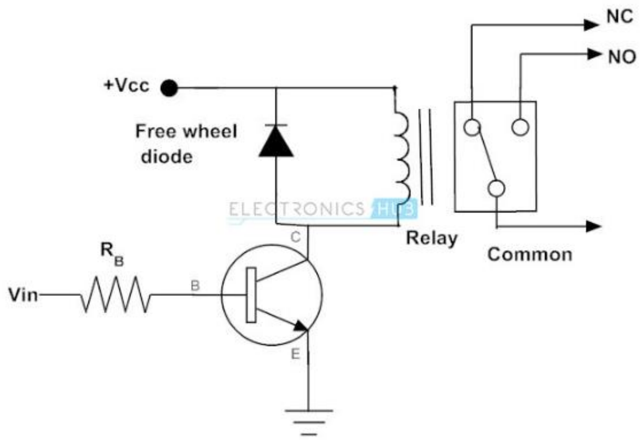


Transistor to Operate Relay

It is also possible to control the relay operation using a transistor. With a small circuit arrangement of a transistor able to energize the coil of the relay so that the external load connected to it is controlled.

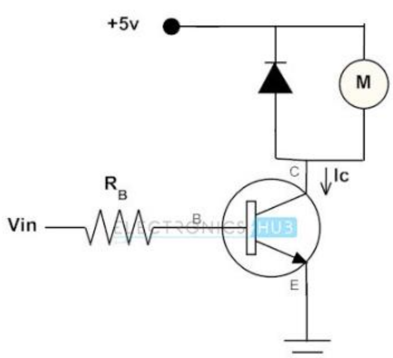
Consider the below circuit to know the operation of a transistor to energize the relay coil. The input applied at the base causes to drive the transistor into saturation region, which further results the circuit becomes short circuit. So the relay coil gets energized and relay contacts get operated.

In inductive loads, particularly switching of motors and inductors, sudden removal of power can keep a high potential across the coil. This high voltage can cause considerable damage to the rest circuit. Therefore, we have to use the diode in parallel with inductive load to protect the circuit from induced voltages of the inductive load.



Transistor to Drive the Motor

- A transistor can also use to drive and regulate the speed of the DC motor in a unidirectional way by switching the transistor in regular intervals of time as shown in the below figure.
- As mentioned in above, the DC motor is also an inductive load so we have to place a freewheeling diode across it to protect the circuit.
- By switching the transistor in cutoff and saturation regions, we can turn ON and OFF the motor repeatedly.
- It is also possible to regulate the speed of the motor from standstill to full speed by switching the transistor at variable frequencies. We can get the switching frequency from control device or IC like microcontroller.



N-Channel MOSFET

In this section we are going to investigate the operation of a different type of transistor which is called a MOSFET. This stands for Metal Oxide Semiconductor Field Effect Transistor, which is a bit of a mouthful, so we will simply refer to it as a MOSFET.

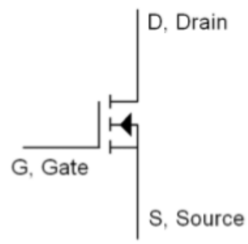
There are many different types of MOSFET available but we will be concentrating only on one type in this course the n-channel enhancement MOSFET. You will not be asked about any other type in an examination.

The symbol and picture for an n-channel enhancement mode MOSFET is shown opposite.

The leads for this type of transistor are labeled as: Gate (G), Drain (D) and Source (S).

The enhancement mode MOSFET has the property of being normally ‘OFF’ when the gate bias voltage is equal to zero.

A drain current will only flow when a gate voltage (V_{GS}) is applied to the gate terminal. This positive voltage reduces the overall resistance of the device allowing current to flow between the Drain (D) and Source (S). Increasing this positive gate voltage will cause an increase in the drain current, ID through the channel. The MOSFET, can also saturate when (V_{GS}) is increased sufficiently, when this occurs the resistance of the MOSFET reaches its lowest.



MOSFET Operation

The transfer characteristic of the MOSFET is similar to that of the NPN transistor, with one major difference; the linear region is very small, making it very unlikely that the MOSFET will operate in this region.

The exact voltages at which cut-off region ends and the saturation region starts are functions of the device itself, and therefore the transfer characteristic is given only for illustrative purposes.

MOSFET Switching Circuit Design Calculation

The only formula we need to design MOSFET circuits is the formula, which relates the Drain current ID to the input voltage VGS. The symbol g_M represents the trans-conductance of a MOSFET. Trans-conductance is the characteristic relating the current through the output of a MOSFET to the voltage across the input of a MOSFET and is measured in Siemens (S)

The formula is: $I_D = g_M(V_{GS} - 3)$

This formula can be rearranged to give

$$g_M = \frac{I_D}{V_{GS} - 3}$$

and

$$V_{GS} = \frac{I_D}{g_M} + 3$$

Only the first of these three formulae are provided in examinations, so if you need to calculate g_M or V_{GS} you can either remember the last two formulae or substitute into the formulae for I_D.

Enhancement mode MOSFETs make excellent electronics switches due to their low ‘ON’ resistance, extremely high ‘OFF’ resistance and extremely high input resistance. This input resistance is so high the gate current is negligible and can be assumed to be zero.

Major Advantage over NPN Transistor

Enhancement mode power MOSFETs have zero gate current and can be driven directly by input subsystems such as logic gates that can only provide a very small current. When used with sensing subsystems they do not load the sensing sub-system.

Power MOSFETs can handle very large currents and some are able to provide currents of 100 A or more.

Selecting a Suitable power MOSFET

As was the case with transistors, supplier’s catalogues and websites will reveal many pages dedicated to MOSFETS. So how do you select the most appropriate MOSFETs for your application?

There are two key points to consider:

i) The maximum drain current required for your load.

ii) The cost in relation to the maximum drain current available.

The investigations in this chapter will suggest using the IRF510 power MOSFET which has a high current capability and is relatively inexpensive. In fact its price and current capability is in the same range as the BD437 transistor and would probably provide a better choice.

Voltage Comparators

In the previous two sections we have concentrated on the ability of transistors and MOSFETs to produce a large output current from a small input current or voltage.

Sometimes the signal connected to these electronic switches takes much longer to increase. This can lead to problems with the transistor or MOSFET not fully switching on, causing them to overheat.

These slow changing signals usually come from sensing circuits involving LDRs and thermistors because light level and temperature do not usually change very quickly. We need a device that can convert these slow changing signals into fast changing signals. The device that allows us to do this is the voltage comparator.

The voltage comparator is contained in an integrated circuit (IC) and is usually supplied in plastic DIL (dual in line) packages containing one or more comparators.

A comparator has two power supply terminals, two inputs and an output.

The operation of the comparator is such that it amplifies any difference between the two input voltages by a very large amount, causing the output to be at one of the extremes of the power supply connected to it. This means that the output voltage will be either high or low and can only fall into one of the following categories.

Case 1:

If $V_+ > V_- \ then \ V_{OUT}$ will be at the positive saturation voltage.

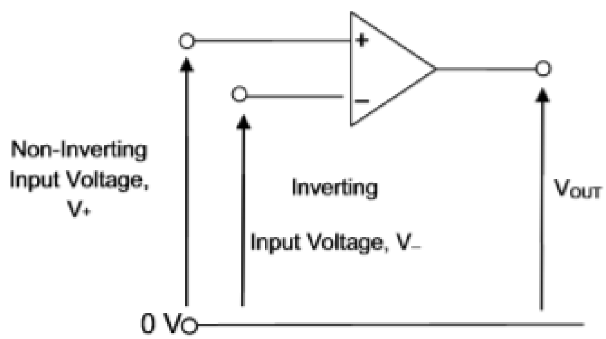
Case 2:

If $V_+ < \ V_- \ then \ V_{OUT}$ will be at 0 V.

A difference of just a few microvolts between the two inputs is enough to cause the output to swing rapidly from one state to another. The rapid transition makes the voltage comparator an ideal device to use with circuits employing slow response sensors like LDRs and thermistors. It converts an analogue input signal into a digital output signal.

Remember that if you are setting this circuit up, in practice you must connect the power supply to the comparator otherwise it will not work.

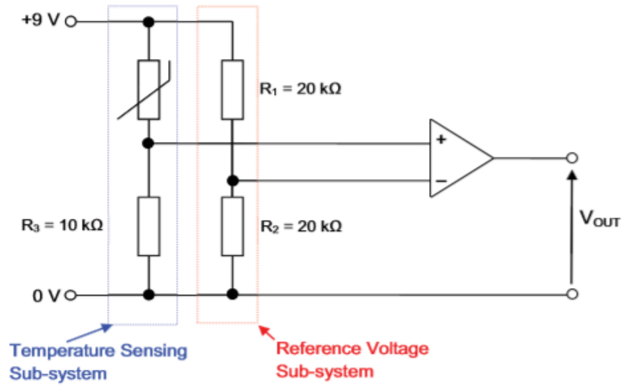
A comparator uses a second voltage divider to provide a reference voltage which controls the voltage at which the output of the comparator circuit changes.



In examinations this reference voltage will always be connected to the inverting input.

The circuit diagram, which may appear complicated at first glance, is shown below. The first voltage divider in the ‘blue’ box shows the temperature sensing circuit. You should realize that the voltage at the non-inverting “+” input of the comparator will increase as the temperature rises.

The second voltage divider shown in the ‘red’ box is a simple voltage divider containing two equal resistors. You should realize that the voltage at the inverting “–“ input of the comparator will be 4.5 V.

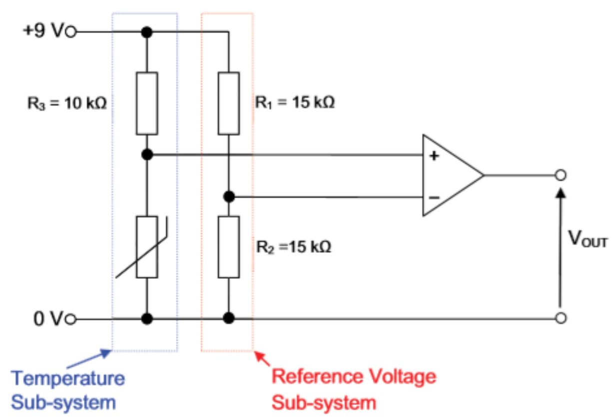


When the temperature is low, the resistance of the thermistor will be very high, the voltage at the output of the temperature sensing circuit will be low, and the output of the comparator will be at the minimum voltage of the power supply, because the voltage at the inverting "-" input will be higher than the voltage at the non-inverting "+" input.

As the temperature rises, the resistance of the thermistor begins to fall; this causes the voltage at the non-inverting "+" input to start to rise. When this voltage reaches just over 4.5 V, the voltage at the non-inverting "+" input will be bigger than the voltage at the inverting input and the output will increase to 9V, since $V_+ > V_-$.

This circuit provides a high output signal when the temperature is high, and could possibly be used as a simple fire alarm.

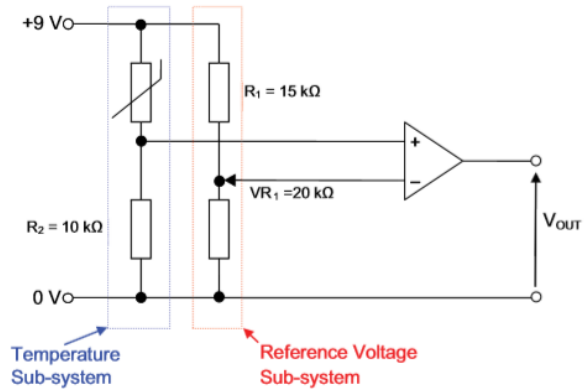
To change the circuit to provide the opposite behavior, switch the output of the comparator high when the temperature decreases, simply reverse the position of the thermistor and 10 kΩ resistor in the sensing circuit as shown below.



In both of the previous circuits there is no adjustment of the temperature at which the output of the comparator switches from high to low. It is quite easy to make this circuit adjustable, by making any one of the three resistors $R_1, R_2, or\ R_3$ variable.

Whichever one is chosen to be variable it will have the desired effect of either adjusting the voltage range of the temperature sensing circuit or changing the reference voltage at which the comparator switches.

An alternative way of producing the reference voltage is to use a potentiometer as shown in the following diagram. This has the advantage that the reference voltage can be varied over the full voltage supply range, making the circuit extremely flexible, and most importantly very sensitive.



In all of the above circuits we have not considered possible output devices that could be connected to the comparator.

The output current of many comparators is limited to about 50 mA. This is of no use for driving high powered output devices like motors, or solenoids. However, it is capable of driving LEDs, buzzers, and some low power lamps.

Using an OP-AMP as a comparator

The problem with using dedicated comparators is that they are open collector devices and are beyond the scope of this course. We will look at a more general device called an *operational amplifier* (op-amp for short) which can be configured as a comparator. We will look at op-amps in more detail in Component 2 of the course.

As was the case with transistors, supplier’s catalogues and websites will reveal many pages dedicated to op-amps. So how do you select the most appropriate op-amps for your application?

There are two key points to consider:

i) The saturation voltage

ii) The output current capability

The investigations in this chapter will suggest using the LM358 op-amp. Since most op-amps are unable to satisfy the requirement for saturation voltage and output current.

Video links:

BJT as a Transistor Switches

- ***https://youtu.be/sRVvUkK0U80***

How to identify PNP and NPN Transistors

- ***https://youtu.be/2vk7JS-0ir0***

How an NPN and PNP Transistor Work as switch

- ***https://youtu.be/vezptJWVqtg***

How to make 12V Relay Driver Circuit using Transistor

- ***https://youtu.be/I7f6P8Y4vJk***

MOSFETs and how to use them

- ***https://youtu.be/GrvvkYTW_0k***

Reference:

- ***http://resource.download.wjec.co.uk.s3.amazonaws.com/vtc/2016-17/16-17_1-8/discovering-electronics-chapter-4-digital.pdf***
- ***https://www.electronicshub.org/transistor-as-a-switch/***
- ***https://www.electronics-tutorials.ws/transistor/tran_4.html***