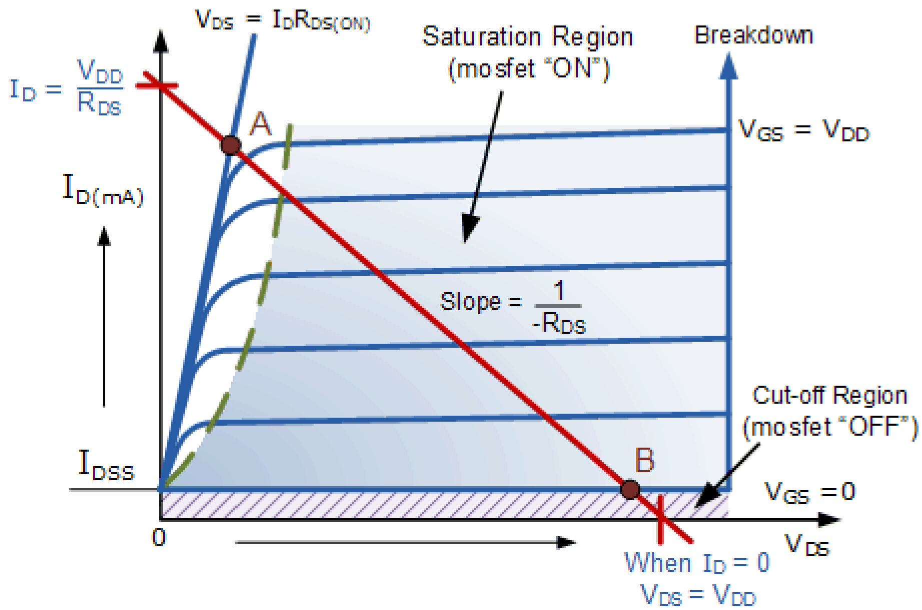
MOSFET AS A SWITCH

The operation of the enhancement-mode MOSFET, or e-MOSFET, can best be described using its I-V characteristics curves shown below. When the input voltage, (V_{IN}) to the gate of the transistor is zero, the MOSFET conducts virtually no current and the output voltage (V_{OUT}) is equal to the supply voltage V_{DD}. So the MOSFET is “OFF” operating within its “cut-off” region.

MOSFET Characteristics Curves



The minimum ON-state gate voltage required to ensure that the MOSFET remains “ON” when carrying the selected drain current can be determined from the V-I transfer curves above. When V_{IN} is HIGH or equal to V_{DD}, the MOSFET Q-point moves to point A along the load line.

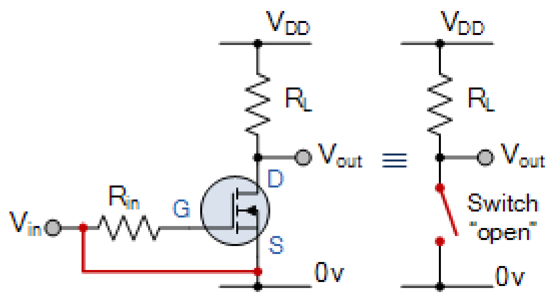
The drain current I_D increases to its maximum value due to a reduction in the channel resistance. I_D becomes a constant value independent of V_{DD}, and is dependent only on V_{GS}. Therefore, the transistor behaves like a closed switch but the channel ON-resistance does not reduce fully to zero due to its $R_{DS(on)}$ value, but gets very small.

Likewise, when V_{IN} is LOW or reduced to zero, the MOSFET Q-point moves from point A to point B along the load line. The channel resistance is very high so the transistor acts like an open circuit and no current flows through the channel. So if the gate voltage of the MOSFET toggles between two values, HIGH and LOW the MOSFET will behave as a “single-pole single-throw” (SPST) solid state switch and this action is defined as:

Cut-off Region

Here the operating conditions of the transistor are zero input gate voltage (V_{IN}), zero drain current I_D and output voltage $V_{DS} = V_{DD}$. Therefore for an enhancement type MOSFET the conductive channel is closed and the device is switched “OFF”.

Cut-off Characteristics



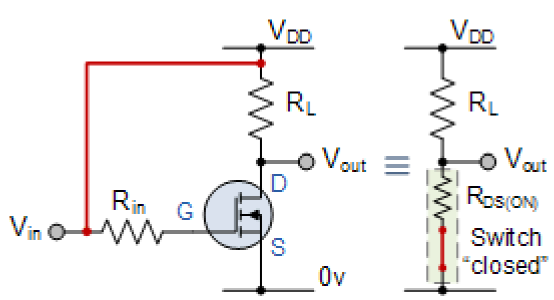
- The input and Gate are grounded (0V)
- Gate-source voltage less than threshold voltage $V_{GS} < V_{TH}$
- MOSFET is "OFF" (Cut-off region)
- No Drain current flows (I_D = 0 Amps)
- $V_{OUT} = V_{DS} = V_{DD}$ = "1"
- MOSFET operates as an "open switch"

Then we can define the cut-off region or "OFF mode" when using an e-MOSFET as a switch as being, gate voltage, $V_{GS} < V_{TH}$ and $I_D = 0$. For a P-channel enhancement MOSFET, the Gate potential must be more positive with respect to the Source.

2. Saturation Region

In the saturation or linear region, the transistor will be biased so that the maximum amount of gate voltage is applied to the device which results in the channel resistance $R_{DS(on}$ being as small as possible with maximum drain current flowing through the MOSFET switch. Therefore for the enhancement type MOSFET the conductive channel is open and the device is switched "ON".

Saturation Characteristics



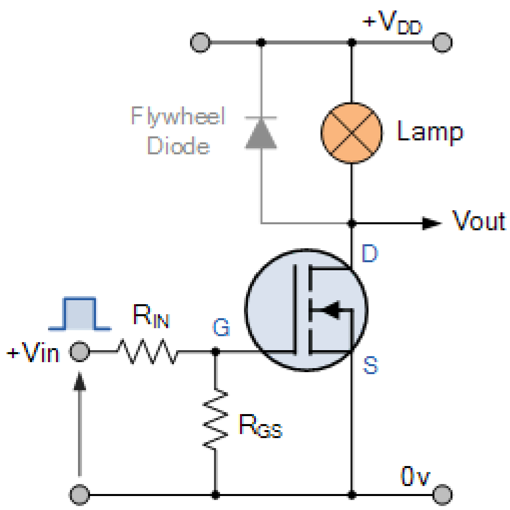
- The input and Gate are connected to V_{DD}
- Gate-source voltage is much greater than threshold voltage $V_{GS} > V_{TH}$
- MOSFET is "ON" (saturation region)
- Max Drain current flows ($I_D = V_{DD} / R_L$)
- V_{DS} = 0V (ideal saturation)
- Min channel resistance $R_{DS(on)} < 0.1\Omega$
- $V_{OUT} = V_{DS} \cong 0.2V$ due to $R_{DS(on)}$
- MOSFET operates as a low resistance "closed switch"

Then we can define the saturation region or "ON mode" when using an e-MOSFET as a switch as gate-source voltage, $V_{GS} > V_{TH}$ and I_D = Maximum. For a P-channel enhancement MOSFET, the Gate potential must be more negative with respect to the Source.

By applying a suitable drive voltage to the gate of an FET, the resistance of the drain-source channel, $R_{DS(on)}$ can be varied from an "OFF-resistance" of many hundreds of kΩ, effectively an open circuit, to an "ON-resistance" of less than 1Ω, effectively acting as a short circuit.

When using the MOSFET as a switch we can drive the MOSFET to turn “ON” faster or slower, or pass high or low currents. This ability to turn the power MOSFET “ON” and “OFF” allows the device to be used as a very efficient switch with switching speeds much faster than standard bipolar junction transistors.

An example of using the MOSFET as a switch



In this circuit arrangement an Enhancement-mode N-channel MOSFET is being used to switch a simple lamp “ON” and “OFF” (could also be an LED).

The gate input voltage V_{GS} is taken to an appropriate positive voltage level to turn the device and therefore the lamp load either “ON”, (V_{GS} = +ve) or at a zero voltage level that turns the device “OFF”, (V_{GS} = 0V).

If the resistive load of the lamp was to be replaced by an inductive load such as a coil, solenoid or relay a “flywheel diode” would be required in parallel with the load to protect the MOSFET from any self generated back-emf.

Above shows a very simple circuit for switching a resistive load such as a lamp or LED. But when using power MOSFETs to switch either inductive or capacitive loads some form of protection is required to prevent the MOSFET device from becoming damaged. Driving an inductive load has the opposite effect from driving a capacitive load.

For example, a capacitor without an electrical charge is a short circuit, resulting in a high “inrush” of current and when we remove the voltage from an inductive load we have a large reverse voltage build up as the magnetic field collapses, resulting in an induced back-emf in the windings of the inductor.

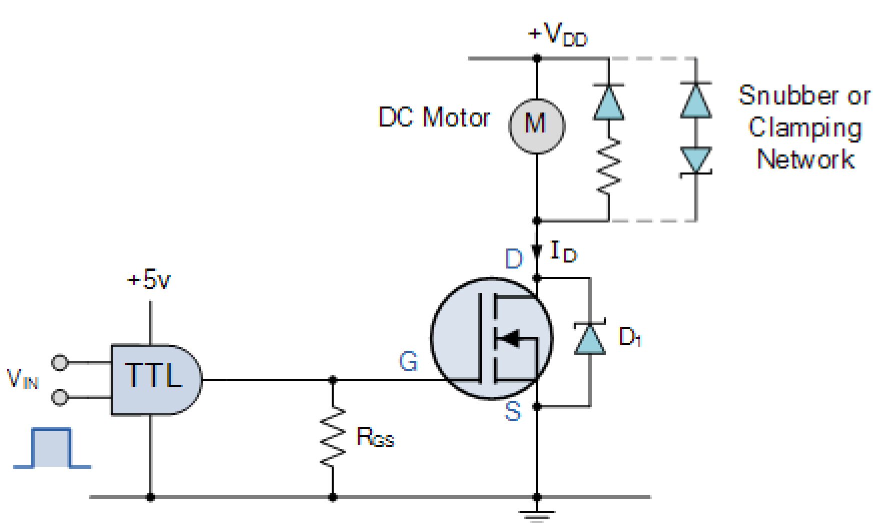
Then we can summarise the switching characteristics of both the N-channel and P-channel type MOSFET within the following table.

N-channel Enhancement	ON	OFF	OFF
N-channel Depletion	ON	ON	OFF
P-channel Enhancement	OFF	OFF	ON
P-channel Depletion	OFF	ON	ON

Note that unlike the N-channel MOSFET whose gate terminal must be made more positive (attracting electrons) than the source to allow current to flow through the channel, the conduction through the P-channel MOSFET is due to the flow of holes. That is the gate terminal of a P-channel MOSFET must be made more negative than the source and will only stop conducting (cut-off) until the gate is more positive than the source.

So for the enhancement type power MOSFET to operate as an analogue switching device, it needs to be switched between its “Cut-off Region” where: V_{GS} = 0V (or V_{GS} = -ve) and its “Saturation Region” where: $V_{GS(on)}$ = +ve. The power dissipated in the MOSFET (P_D) depends upon the current flowing through the channel I_D at saturation and also the “ON-resistance” of the channel given as $R_{DS(on)}$. For example.

Simple Power MOSFET Motor Controller



As the motor load is inductive, a simple flywheel diode is connected across the inductive load to dissipate any back emf generated by the motor when the MOSFET turns it “OFF”. A clamping network formed by a zener diode in series with the diode can also be used to allow for faster switching and better control of the peak reverse voltage and drop-out time.

For added security an additional silicon or zener diode D_1 can also be placed across the channel of a MOSFET switch when using inductive loads, such as motors, relays, solenoids, etc, for suppressing over voltage switching transients and noise giving extra protection to the MOSFET switch if required. Resistor R_{GS} is used as a pull-down resistor to help pull the TTL output voltage down to 0V when the MOSFET is switched “OFF”.

Insulated Gate Bipolar Transistor or IGBTs

The IGBT is a power switching transistor which combines the advantages of MOSFETs and BJTs for use in power supply and motor control circuits

The *IGBT Transistor* takes the best parts of these two types of common transistors, the high input impedance and high switching speeds of a MOSFET with the low saturation voltage of a bipolar transistor, and combines them together to produce another type of transistor switching device that is capable of handling large collector-emitter currents with virtually zero gate current drive.

Typical IGBT

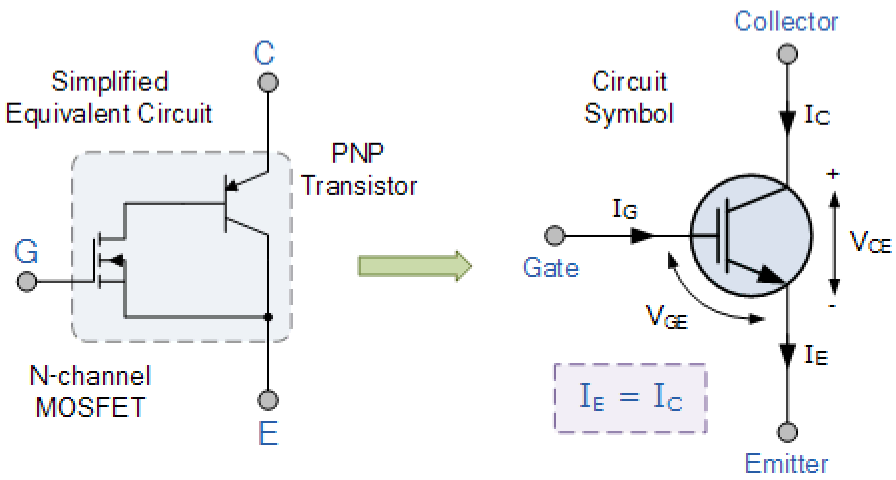
The *Insulated Gate Bipolar Transistor*, (IGBT) combines the insulated gate (hence the first part of its name) technology of the MOSFET with the output performance characteristics of a conventional bipolar transistor, (hence the second part of its name).

The result of this hybrid combination is that the “IGBT Transistor” has the output switching and conduction characteristics of a bipolar transistor but is voltage-controlled like a MOSFET.

IGBTs are mainly used in power electronics applications, such as inverters, converters and power supplies, were the demands of the solid state switching device are not fully met by power bipolars and power MOSFETs. High-current and high-voltage bipolars are available, but their switching speeds are slow, while power MOSFETs may have higher switching speeds, but high-voltage and high-current devices are expensive and hard to achieve.

The advantage gained by the insulated gate bipolar transistor device over a BJT or MOSFET is that it offers greater power gain than the standard bipolar type transistor combined with the higher voltage operation and lower input losses of the MOSFET. In effect it is an FET integrated with a bipolar transistor in a form of Darlington type configuration as shown.

Insulated Gate Bipolar Transistor



As a result the terminals are labelled as: **Collector**, **Emitter** and **Gate**. Two of its terminals (C-E) are associated with the conductance path which passes current, while its third terminal (G) controls the device.

The amount of amplification achieved by the *insulated gate bipolar transistor* is a ratio between its output signal and its input signal. For a conventional bipolar junction transistor, (BJT) the amount of gain is approximately equal to the ratio of the output current to the input current, called Beta.

For a metal oxide semiconductor field effect transistor or MOSFET, there is no input current as the gate is isolated from the main current carrying channel. Therefore, an FET's gain is equal to the ratio of output current change to input voltage change, making it a transconductance device and this is also true of the IGBT. Then we can treat the IGBT as a power BJT whose base current is provided by a MOSFET.

The **Insulated Gate Bipolar Transistor** can be used in small signal amplifier circuits in much the same way as the BJT or MOSFET type transistors. But as the IGBT combines the low conduction loss of a BJT with the high switching speed of a power MOSFET an optimal solid state switch exists which is ideal for use in power electronics applications.

Also, the IGBT has a much lower "on-state" resistance, R_{ON} than an equivalent MOSFET. This means that the I^2R drop across the bipolar output structure for a given switching current is much lower. The forward blocking operation of the IGBT transistor is identical to a power MOSFET.

When used as static controlled switch, the insulated gate bipolar transistor has voltage and current ratings similar to that of the bipolar transistor. However, the presence of an isolated gate in an IGBT makes it a lot simpler to drive than the BJT as much less drive power is needed.

An insulated gate bipolar transistor is simply turned "ON" or "OFF" by activating and deactivating its Gate terminal. Applying a positive input voltage signal across the Gate and the Emitter will keep the device in its "ON" state, while making the input gate signal zero or slightly negative will cause it to turn "OFF" in much the same way as a bipolar transistor or eMOSFET. Another advantage of the IGBT is that it has a much lower on-state channel resistance than a standard MOSFET.

PNEUMATIC SOLENOIDS

Pneumatic systems used in industry are commonly powered by compressed air or compressed inert gases. A centrally located and electrically powered compressor powers cylinders, air motors, and other pneumatic devices. A pneumatic system controlled through manual or automatic solenoid valves is selected when it provides a lower cost, more flexible, or safer alternative to electric motors and actuators. They are widely used as linear actuators in the field of robotics. Pneumatic cylinders are available in a variety of sizes. They are strong, durable, simple mechanisms, with many industrial applications. One advantage of pneumatics is that unlike motors or servos, they can generally hold their position once pressurized, without requiring additional power.

Many Robotics Competitions allow use of pneumatics, so it is not far-fetched to consider their use in homemade robot.

Pneumatic Actuated

Pneumatic actuation refers to a valve being tripped through the use of compressed air (gas). At a particular point in an industrial or manufacturing process, compressed air is released, causing a valve to open or close. The combination of solenoids and pneumatics is twofold. Solenoid valves are used in pneumatic processes and solenoid valves and pneumatic valves are used in combination. The combined valve is called a piloted valve. The larger solenoid valve is triggered by the smaller pneumatic valve. The pneumatic valve can act as an air cylinder contained in a main valve. A pneumatic solenoid valve is also referred to as a compressed air pilot valve.

OTHER ALTERNATIVE LINIAR ACTUATORS TO GET YOUR BOT MOVING

1) Motorized Threaded Rods

You can make a powerful linear actuator with a threaded rod, some matching nuts, and a battery operated drill. Or you could make a very precise one using a stepper motor, which is exactly what you see on many 3D printers.

3) Scotch Yokes

Many robots use motors or servos as actuators, both of which provide rotational motion. You can turn that rotation into a linear motion with a mechanism called a Scotch Yoke. The Scotch Yoke has a rod with a rectangular slot cut in a “yoke” in the middle of it. A pin on a rotating wheel is inserted in the slot, and when the wheel turns, the rod moves back and forth. This mechanism is used in many reciprocating tools.

Scotch Yoke mechanisms have advanced robotics applications such as mimicking the dorsal movement of dolphins for propulsion in dolphin-like robots. One such example is the very clever beak mechanism in RobotGrrl’s RoboBrrd. The video below is part of the build tutorial for RoboBrrd. I’ve started it at the point where the Scotch Yoke mechanism is demonstrated.

4) Solenoids

A solenoid is an electric coil which, when energized, either pulls or pushes an iron or steel plunger. The plunger can be spring-loaded so that it returns when the solenoid is not energized. Solenoids are used in electric locks in cars and security doors, old door bells, electrically controlled valves, and many other applications.

Perhaps the most fun application of a solenoid I've ever seen is in Spazzi, the solenoid-powered dance bot, created by Marek Michalowski of BeatBots.

5) Pneumatic Muscles

Soft robotics techniques are becoming more prevalent, so I'll wrap up this list with an example from the Harvard Soft Robotics Toolkit. You can use a braided mesh tube with a skinny balloon inside and the ends clamped to create a pneumatic muscle. When the balloon is inflated, it cannot expand along its length because it is clamped to the braid. It can only expand radially, causing the braid to contract.