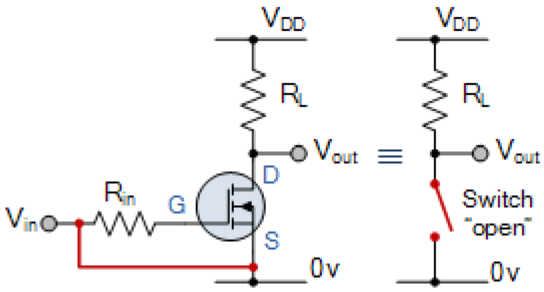
# MOSFET as a Switch




MOSFET's make very good electronic switches for controlling loads and in CMOS digital circuits as they operate between their cut-off and saturation regions.

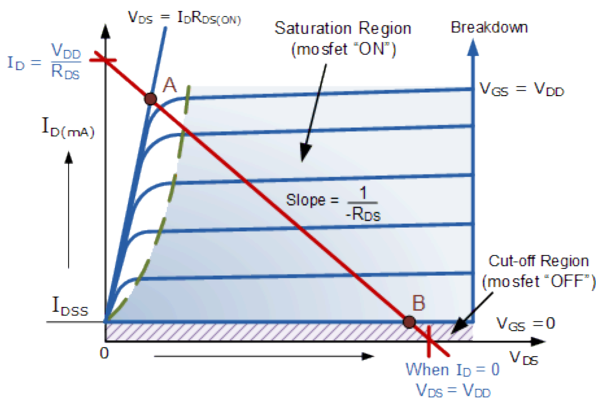
We saw previously, that the N-channel, Enhancement-mode MOSFET (e-MOSFET) operates using a positive input voltage and has an extremely high input resistance (almost infinite) making it possible to interface with nearly any logic gate or driver capable of producing a positive output.
We also saw that due to this very high input (Gate) resistance we can safely parallel together many different MOSFETS until we achieve the current handling capacity that we required.

While connecting together various MOSFETS in parallel may enable us to switch high currents or high voltage loads, doing so becomes expensive and impractical in both components and circuit board space. To overcome this problem **Power Field Effect Transistors** or **Power FET's** where developed.V

We now know that there are two main differences between field effect transistors, depletion-mode only for JFET's and both enhancement-mode and depletion-mode for MOSFETs. In this tutorial we will look at using the *Enhancement-mode MOSFET as a Switch*as these transistors require a positive gate voltage to turn "ON" and a zero voltage to turn "OFF" making them easily understood as switches and also easy to interface with logic gates.

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.

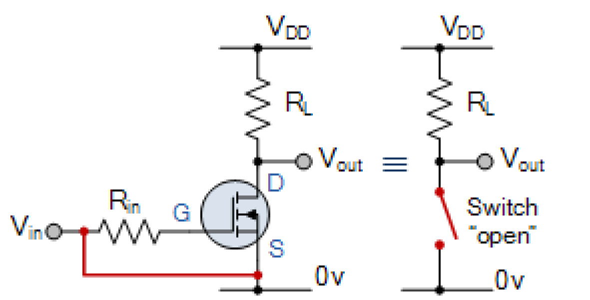
The drain current $I_D$ increases to its maximum value due to a reduction in the channel resistance. $I_D$ becomes a constant value independent of $V_{DD}$, and is dependent only on $V_{GS}$. Therefore, the transistor behaves like a closed switch but the channel ON-resistance does not reduce fully to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

### 1. 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



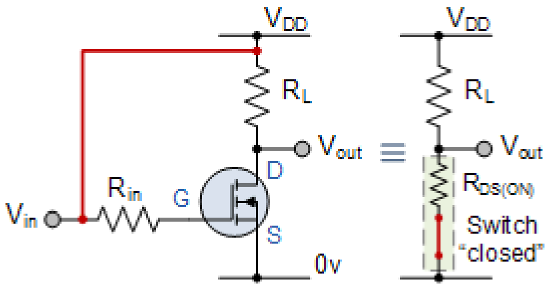

- The input and Gate are grounded ( 0V )
- Gate-source voltage less than threshold voltage $V_{GS} < V_{TH}$
- MOSFET is "OFF" ( Cut-off region )
- No Drain current flows ( $I_D$ = 0 Amps )
- $V_{OUT} = V_{DS} = V_{DD}$ = "1"
- MOSFET operates as an "open switch"

Then we can define the cut-off region or "OFF mode" when using an e-MOSFET as a switch as being, gate voltage, $V_{GS} < V_{TH}$ thus $I_D = 0$. 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**



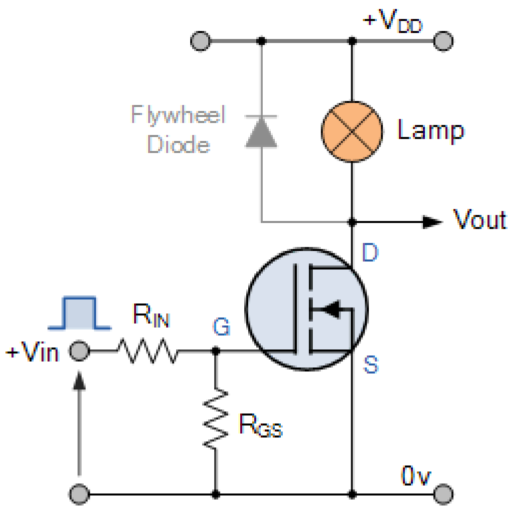

- The input and Gate are connected to $V_{DD}$
- Gate-source voltage is much greater than threshold voltage $V_{GS} > V_{TH}$
- MOSFET is "ON" ( saturation region )
- Max Drain current flows ( $I_D = V_{DD} / R_L$ )
- $V_{DS}$ = 0V (ideal saturation)
- Min channel resistance $R_{DS(on)} < 0.1\Omega$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

| MOSFET Type | $V_{GS}$ (+ve) | $V_{GS}$ (0V) | $V_{GS}$ (-ve) |
|---|---|---|---|
| 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.

**MOSFET as a Switch Example No1**

Lets assume that the lamp is rated at 6v, 24W and is fully "ON", the standard MOSFET has a channel on-resistance ( $R_{DS(on)}$ ) value of 0.1ohms. Calculate the power dissipated in the MOSFET switching device.

The current flowing through the lamp is calculated as:

$$P = V \times I_D$$

$$\therefore I_D = \frac{P}{V} = \frac{24}{6} = 4.0\,\text{amps}$$

Then the power dissipated in the MOSFET will be given as:

$$P = I^2.R$$

$$P_D = I_D^2 \times R_{DS}$$

$$\therefore P_D = 4^2 \times 0.1 = 1.6\,\text{watts}$$

You may be sat there thinking, well so what!, but when using the MOSFET as a switch to control DC motors or electrical loads with high inrush currents the "ON" Channel resistance ( $R_{DS(on)}$ ) between the drain and the source is very important. For example, MOSFETs that control DC motors, are subjected to a high in-rush current when the motor first begins to rotate, because the motors starting current is only limited by the very low resistance value of the motors windings.

As the basic power relationship is: $P = I^2R$, then a high $R_{DS(on)}$ channel resistance value would simply result in large amounts of power being dissipated and wasted within the MOSFET itself resulting in an excessive temperature rise, which if not controlled could result in the MOSFET becoming very hot and damaged due to a thermal overload.

A lower $R_{DS(on)}$ value for the channel resistance is also a desirable parameter as it helps to reduce the channels effective saturation voltage ( $V_{DS(sat)} = I_D * R_{DS(on)}$ ) across the MOSFET and will therefore operate at a cooler temperature. Power MOSFETs generally have a $R_{DS(on)}$ value of less than 0.01Ω which allows them to run cooler, extending their operational life span.

One of the main limitations when using a MOSFET as a switching device is the maximum drain current it can handle. So the $R_{DS(on)}$ parameter is an important guide to the switching efficiency of the MOSFET and is simply given as the ratio of $V_{DS} / I_D$ when the transistor is switched "ON".

When using a MOSFET or any type of field effect transistor for that matter as a solid-state switching device it is always advisable to select ones that have a very low $R_{DS(on)}$ value or at least mount them onto a suitable heatsink to help reduce any thermal runaway and damage. Power MOSFETs used as a switch generally have surge-current protection built into their design, but for high-current applications the bipolar junction transistor is a better choice.

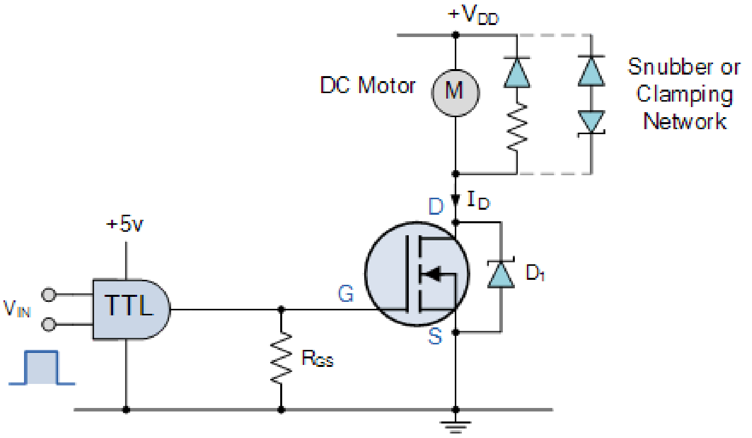
**Power MOSFET Motor Control**

Because of the extremely high input or gate resistance that the MOSFET has, its very fast switching speeds and the ease at which they can be driven makes them ideal to interface with op-amps or standard logic gates. However, care must be taken to ensure that the gate-source input voltage is correctly chosen because when using the **MOSFET as a switch** the device must obtain a low $R_{DS(on)}$ channel resistance in proportion to this input gate voltage.

Low threshold type power MOSFETs may not switch “ON” until a least 3V or 4V has been applied to its gate and if the output from the logic gate is only +5V logic it may be insufficient to fully drive the MOSFET into saturation. Using lower threshold MOSFETs designed for interfacing with TTL and CMOS logic gates that have thresholds as low as 1.5V to 2.0V are available.

Power MOSFETs can be used to control the movement of DC motors or brushless stepper motors directly from computer logic or by using pulse-width modulation (PWM) type controllers. As a DC motor offers high starting torque and which is also proportional to the armature current, MOSFET switches along with a PWM can be used as a very good speed controller that would provide smooth and quiet motor operation.

**Simple Power MOSFET Motor Controller**

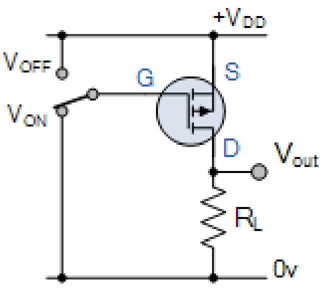



As the motor load is inductive, a simple flywheel diode is connected across the inductive load to dissipate any back emf generated by the motor when the MOSFET turns it “OFF”. A clamping network formed by a zener diode in series with the diode can also be used to allow for faster switching and better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

**P-channel MOSFET Switch**

Thus far we have looked at the N-channel MOSFET as a switch were the MOSFET is placed between the load and the ground. This also allows for the MOSFET’s gate drive or switching signal to be referenced to ground (low-side switching).



## P-channel MOSFET Switch

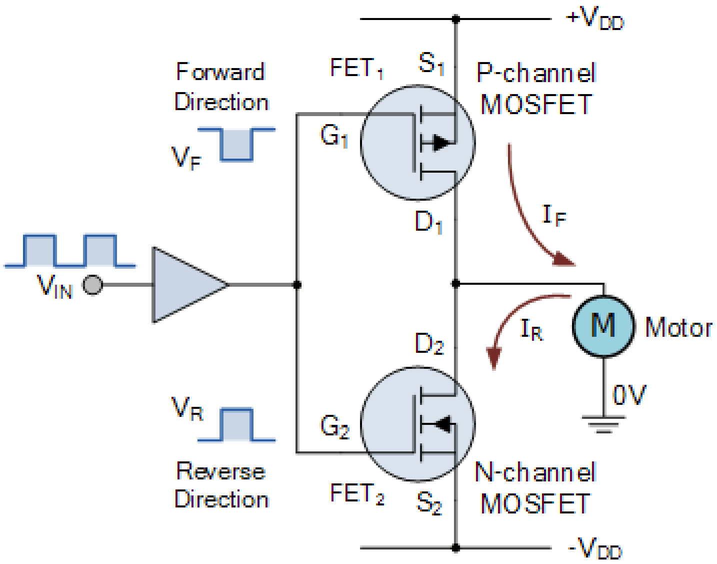
But in some applications we require the use of P-channel enhancement-mode MOSFET were the load is connected directly to ground. In this instance the MOSFET switch is connected between the load and the positive supply rail (high-side switching) as we do with PNP transistors.

In a P-channel device the conventional flow of drain current is in the negative direction so a negative gate-source voltage is applied to switch the transistor "ON".

This is achieved because the P-channel MOSFET is "upside down" with its source terminal tied to the positive supply $+V_{DD}$. Then when the switch goes LOW, the MOSFET turns "ON" and when the switch goes HIGH the MOSFET turns "OFF".

This upside down connection of a P-channel enhancement mode MOSFET switch allows us to connect it in series with a N-channel enhancement mode MOSFET to produce a complementary or CMOS switching device as shown across a dual supply.

**Complementary MOSFET Motor Controller**




The two MOSFETs are configured to produce a bi-directional switch from a dual supply with the motor connected between the common drain connection and ground reference. When the input is LOW the P-channel MOSFET is switched-ON as its gate-source junction is negatively biased so the motor rotates in one direction. Only the positive $+V_{DD}$supply rail is used to drive the motor.

When the input is HIGH, the P-channel device switches-OFF and the N-channel device switches-ON as its gate-source junction is positively biased. The motor now rotates in the opposite direction because the motors terminal voltage has been reversed as it is now supplied by the negative $-V_{DD}$ supply rail.

Then the P-channel MOSFET is used to switch the positive supply to the motor for forward direction (high-side switching) while the N-channel MOSFET is used to switch the negative supply to the motor for reverse direction (low-side switching).

There are a variety of configurations for driving the two MOSFETs with many different applications. Both the P-channel and the N-channel devices can be driven by a single gate drive IC as shown.

However, to avoid cross conduction with both MOSFETS conducting at the same time across the two polarities of the dual supply, fast switching devices are required to provide some time difference between them turning "OFF" and the other turning "ON". One way to overcome this problem is to drive both MOSFETS gates separately. This then produces a third option of “STOP” to the motor when both MOSFETS are “OFF”.

**Complementary MOSFET Motor Control Table**

| MOSFET 1 | MOSFET 2 | Motor Function |
|---|---|---|
| OFF | OFF | Motor Stopped (OFF) |
| ON | OFF | Motor Rotates Forward |
| OFF | ON | Motor Rotates Reverse |
| ON | ON | NOT ALLOWED |

Please note it is important that there are no other combination of inputs allowed at the same time as this may cause the power supply to become shorted out, as both MOSFETS, $FET_1$ and $FET_2$ could be switched “ON” together resulting in: ( fuse = bang! ), be warned.