Power Electronics

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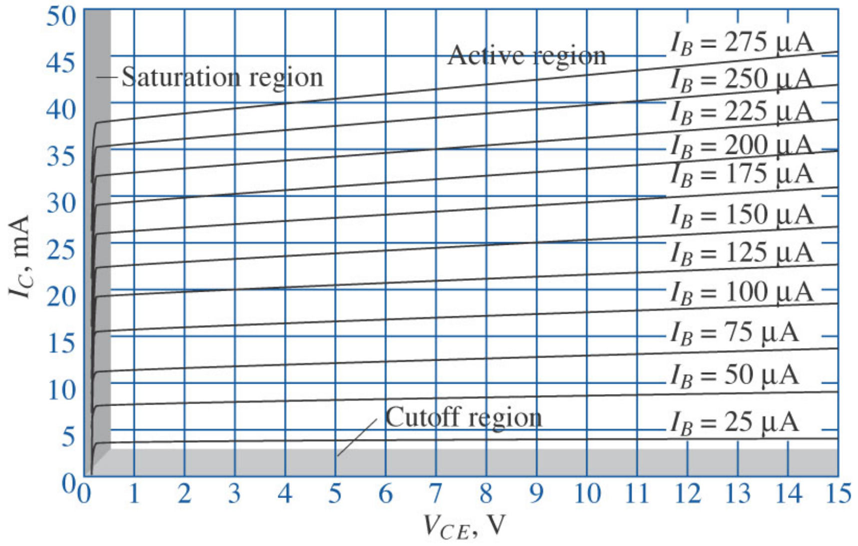
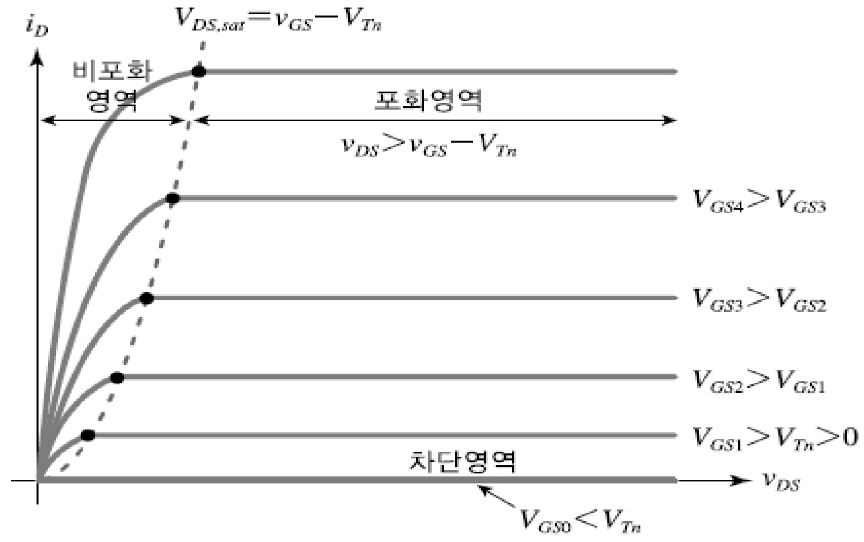
Electronically Controlled Switches, BJT and FET



(b) [2]



[그림 5-6] 증가형 N 채널 MOSFET의 전류-전압 특성 곡선

BJT

$I_B > \theta_{ON}$ ➔ saturation region ➔ short circuit

$I_B < \theta_{OFF}$ ➔ cutoff region ➔ open circuit

FET

$V_{GS} > \theta_{ON}$ ➔ ohmic region ➔ short circuit

$V_{GS} < \theta_{OFF}$ ➔ cutoff region ➔ open circuit

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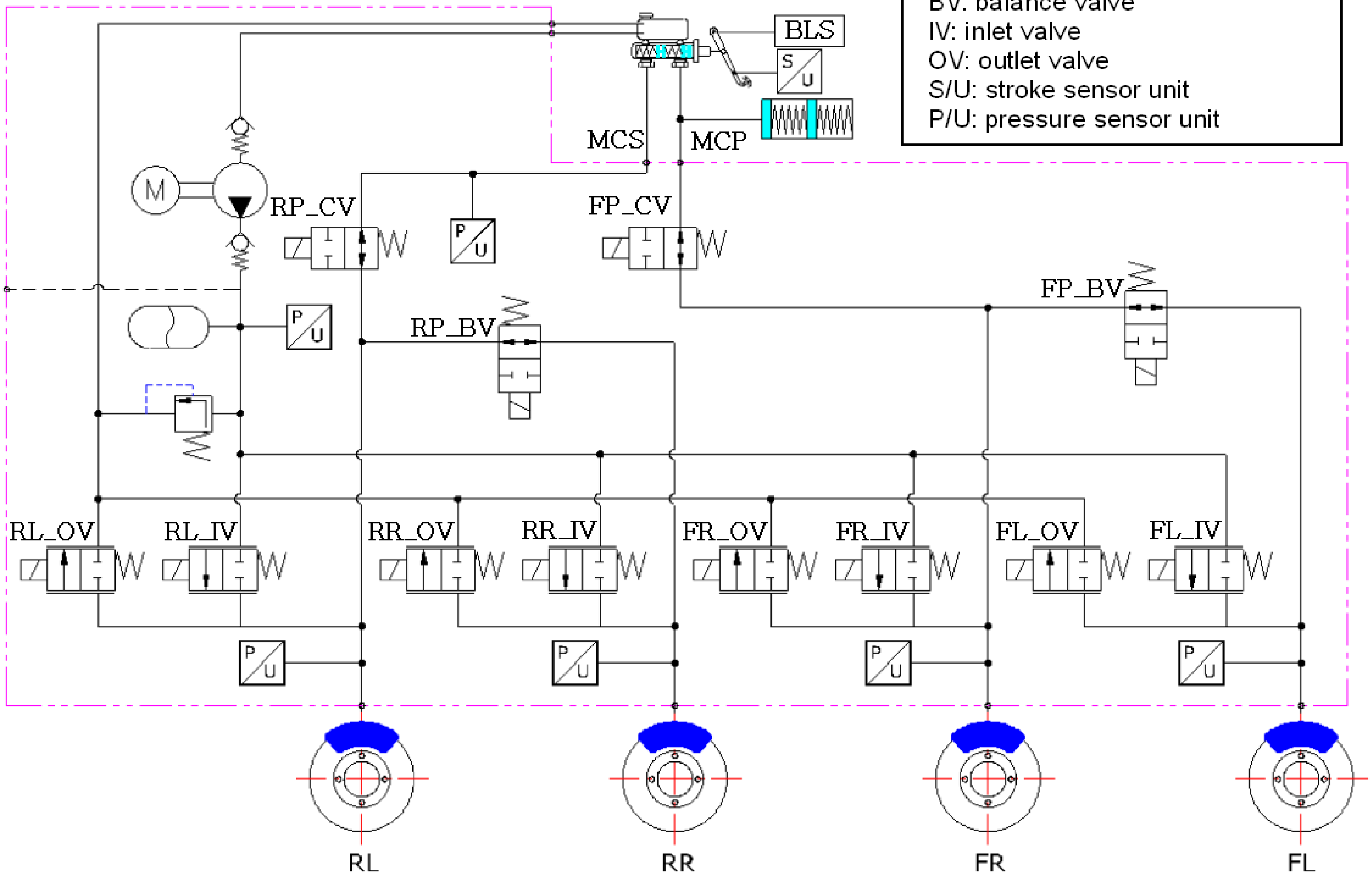
Hydraulic Circuit of EHB [1]



CV: cut valve
BV: balance valve
IV: inlet valve
OV: outlet valve
S/U: stroke sensor unit
P/U: pressure sensor unit

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Hydraulic Circuit of EHB [1]

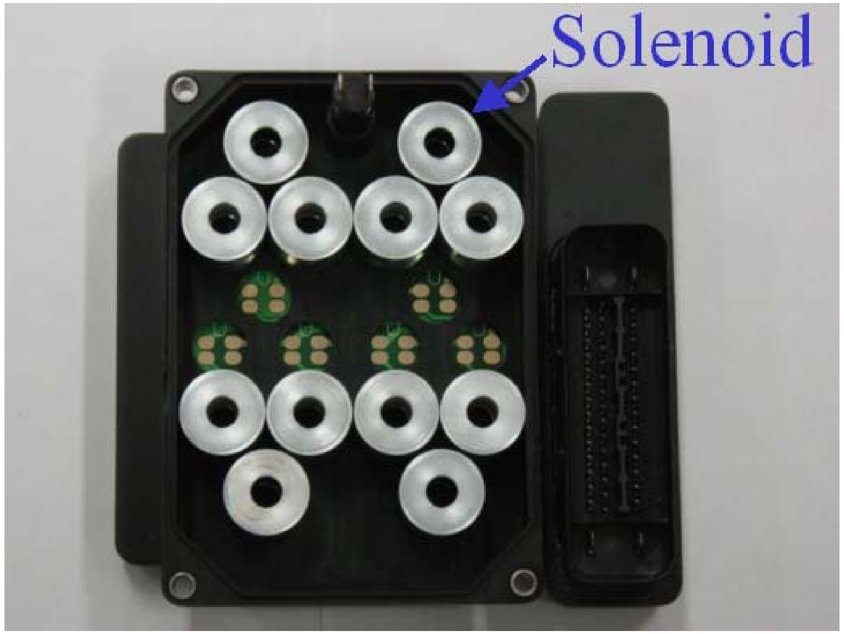
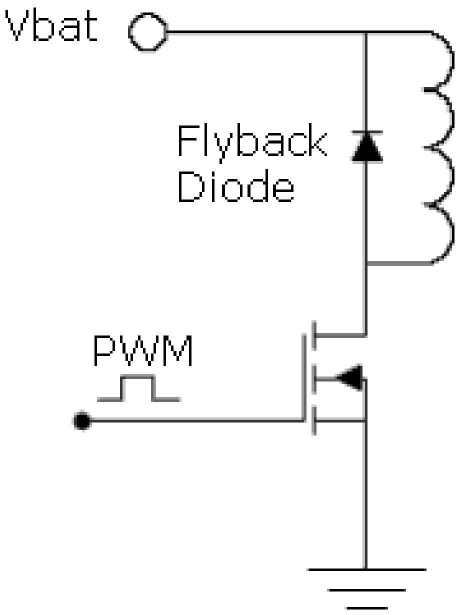
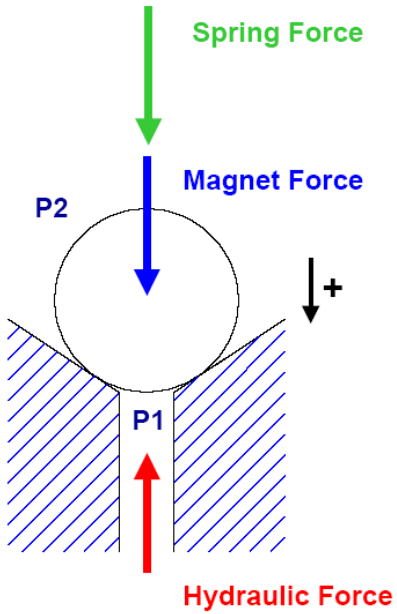


Figure 15. Solenoids installed on the HECU.



Solenoid driving circuit



Forces related with valve

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Solenoid Driving [1]

PWM (Pulse Width Modulation)

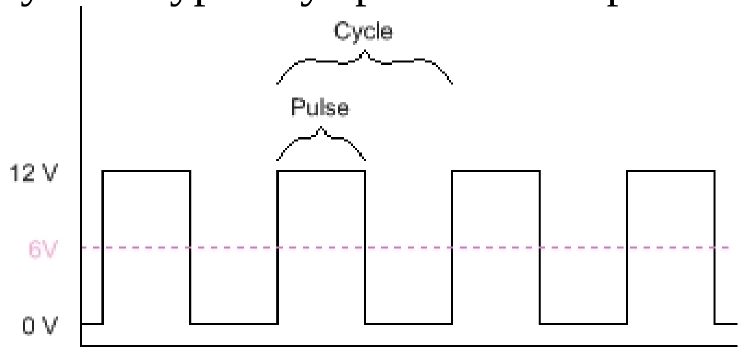
PWM or Pulse Width Modulation refers to the concept of rapidly pulsing the digital signal of a wire to simulate a varying voltage on the wire. This method is commonly used for driving motors, heaters, or lights in varying intensities or speeds.

A few terms are associated with PWM:

Period - how long each complete pulse cycle takes

Frequency - how often the pulses are generated. This value is typically specified in Hz (cycles per second).

Duty Cycle - refers to the amount of time in the period that the pulse is active or high. Duty Cycle is typically specified as a percentage of the full period.



Duty Cycle = Pulse / Cycle * 100
Frequency = Cycles / Second

http://www.acroname.com/robotics/info/concepts/pwm.html

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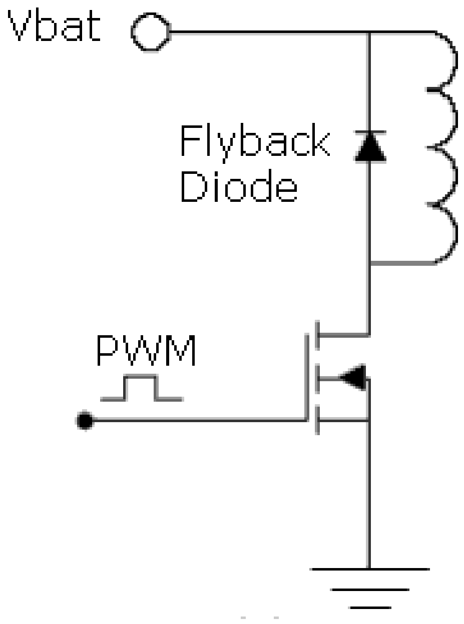
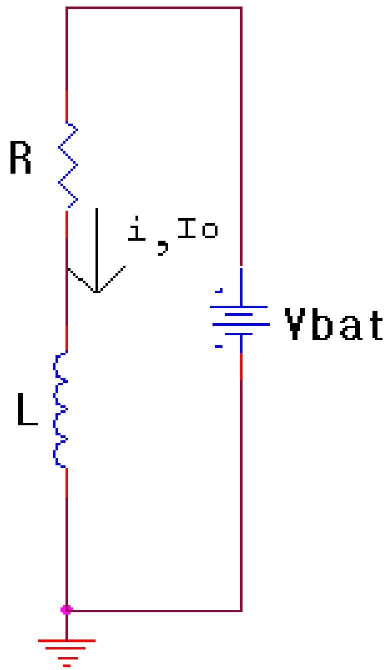
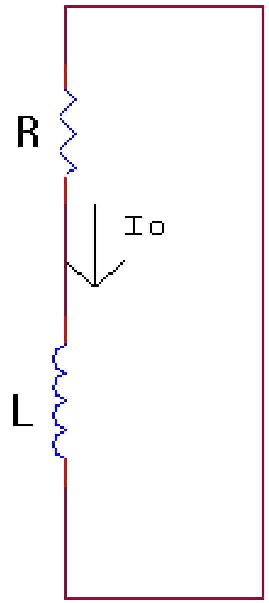
Solenoid Driving [1]



Solenoid driving circuit



ON state



OFF state

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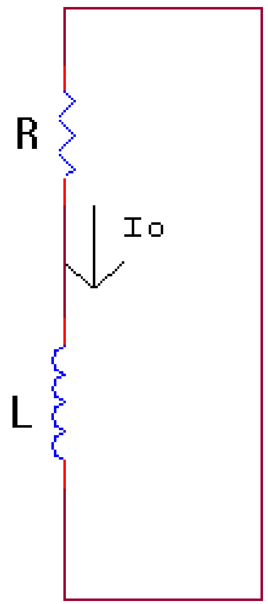
Solenoid Driving [1]



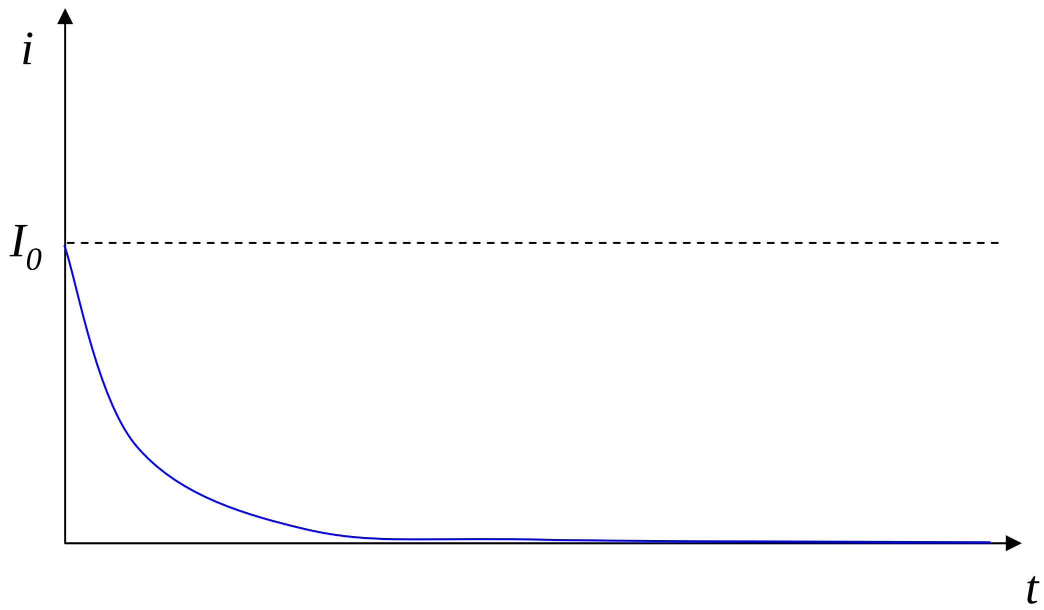
OFF state

$$Ri + L\frac{di}{dt} = 0 \quad \Rightarrow \quad i + \tau\frac{di}{dt} = 0 \quad \text{where, } \tau = \frac{L}{R}$$

A 1st-order source-free circuit had the form $Ae^{-\frac{t}{\tau}}$

t=0 일 때, $i(0) = A = I_0 \quad \Rightarrow \quad A = I_0$

$$i(t) = I_0 e^{-\frac{t}{\tau}}$$



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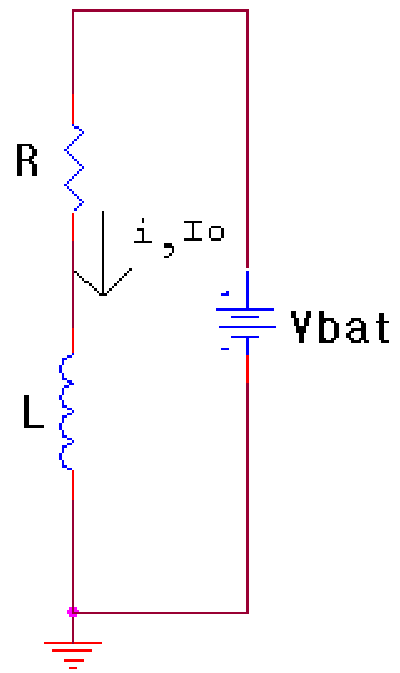
Solenoid Driving [1]



ON state

$$Ri + L\frac{di}{dt} = V_{BAT} \Rightarrow i + \tau\frac{di}{dt} = I_S \quad \text{where, } \tau = \frac{L}{R}, I_S = \frac{V_{BAT}}{R}$$

The complete response for 1st-order circuit with DC forcing functions will have the form $B + Ae^{-\frac{t}{\tau}}$

$i(t) = B + Ae^{-\frac{t}{\tau}}$ 을 윗 식에 대입하면,

$$\left(B + Ae^{-\frac{t}{\tau}}\right) + \tau\left(-\frac{A}{\tau}e^{-\frac{t}{\tau}}\right) = I_S \Rightarrow B = I_S$$

t=0 일 때, $i(0) = I_S + A = I_0 \Rightarrow A = (I_0 - I_S)$

$$i(t) = I_S + (I_0 - I_S)e^{-\frac{t}{\tau}} = I_0 e^{-\frac{t}{\tau}} + I_S\left(1 - e^{-\frac{t}{\tau}}\right)$$

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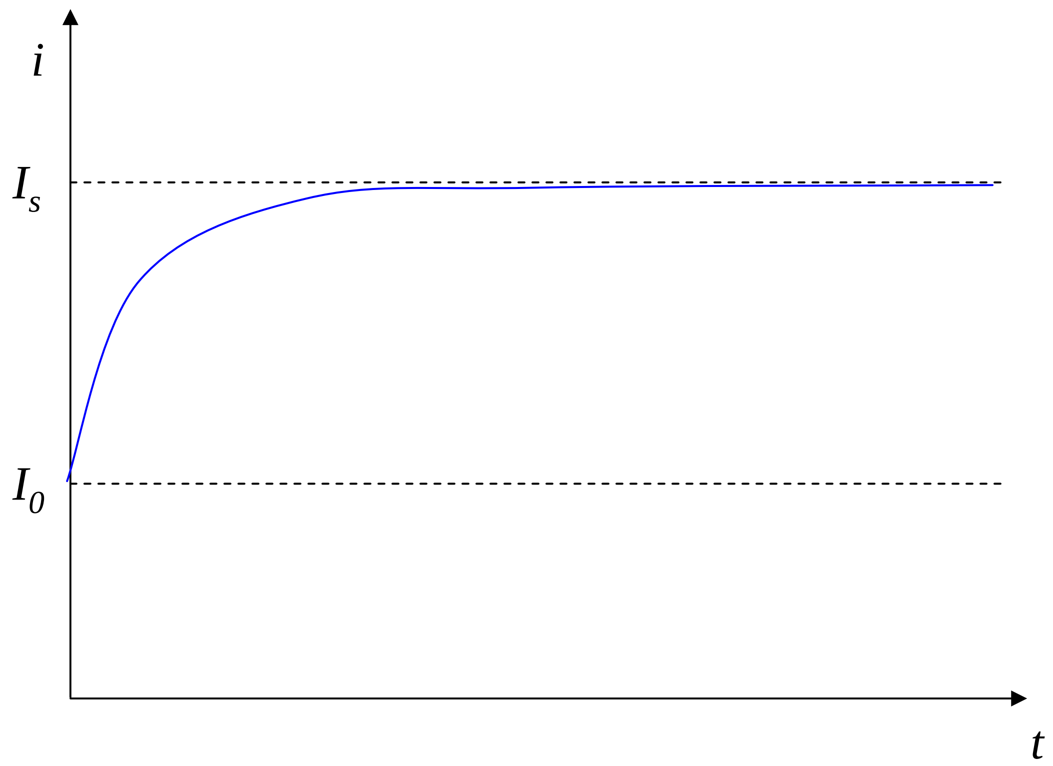
Solenoid Driving [1]

$$i(t) = I_S + (I_0 - I_S)e^{-\frac{t}{\tau}} = I_0 e^{-\frac{t}{\tau}} + I_S\left(1 - e^{-\frac{t}{\tau}}\right)$$

$$= (I_0 - I_0) + I_S + (I_0 - I_S)e^{-\frac{t}{\tau}}$$

$$= I_0 + (I_S - I_0) - (I_S - I_0)e^{-\frac{t}{\tau}}$$

$$= I_0 + (I_S - I_0)\left(1 - e^{-\frac{t}{\tau}}\right)$$



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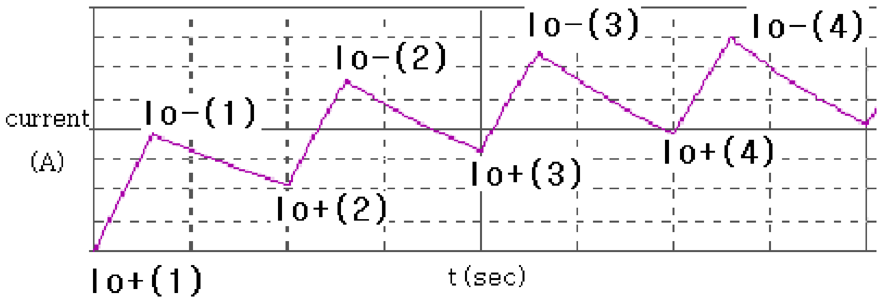
Sequence of Initial Current [1]

The initial current of each PWM period can be calculated recursively from the first period as below :

δ : duty ratio



$$I_{0+}(1) = 0$$

$$I_{0-}(1) = Is - Ise^{-\frac{\delta T}{\tau}}$$

$$I_{0+}(2) = Ise^{-\frac{(1-\delta)T}{\tau}} - Ise^{-\frac{T}{\tau}}$$

$$I_{0-}(2) = Is - Ise^{-\frac{\delta T}{\tau}} + Ise^{-\frac{T}{\tau}} - Ise^{-\frac{T+\delta T}{\tau}}$$

$$I_{0+}(3) = Ise^{-\frac{(1-\delta)T}{\tau}} - Ise^{-\frac{T}{\tau}} + Ise^{-\frac{(1-\delta)T+T}{\tau}} - Ise^{-\frac{2T}{\tau}}$$

$$I_{0-}(3) = Is - Ise^{-\frac{\delta T}{\tau}} + Ise^{-\frac{T}{\tau}} - Ise^{-\frac{T+\delta T}{\tau}} + Ise^{-\frac{2T}{\tau}} - Ise^{-\frac{2T+\delta T}{\tau}}$$

$$I_{0+}(4) = Ise^{-\frac{(1-\delta)T}{\tau}} - Ise^{-\frac{T}{\tau}} + Ise^{-\frac{T+(1-\delta)T}{\tau}} - Ise^{-\frac{2T}{\tau}} + Ise^{-\frac{2T+(1-\delta)T}{\tau}} - Ise^{-\frac{3T}{\tau}}$$

...

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Sequence of Initial Current [1]

n^{th} initial current is the summation of geometric series.

$$I_{0+}(3) = Is\,e^{-\frac{(1-\delta)T}{\tau}} - Is\,e^{-\frac{T}{\tau}} + Is\,e^{-\frac{(1-\delta)T+T}{\tau}} - Is\,e^{-\frac{2T}{\tau}}$$

$$\Rightarrow I_{0+}(3) = \boxed{Is\left(e^{-\frac{(1-\delta)T}{\tau}} - e^{-\frac{T}{\tau}}\right)} + \boxed{Is\left(e^{-\frac{(1-\delta)T}{\tau}} - e^{-\frac{T}{\tau}}\right)}\,e^{-\frac{T}{\tau}}$$

$$I_{0+}(n) = Is\left(e^{-\frac{(1-\delta)T}{\tau}} - e^{-\frac{T}{\tau}}\right)\frac{1-e^{-\frac{(n-1)T}{\tau}}}{1-e^{-\frac{T}{\tau}}} \qquad (3\text{-}1)$$

$$I_{0-}(3) = Is - Is\,e^{-\frac{\delta T}{\tau}} + Is\,e^{-\frac{T}{\tau}} - Is\,e^{-\frac{T+\delta T}{\tau}} + Is\,e^{-\frac{2T}{\tau}} - Is\,e^{-\frac{2T+\delta T}{\tau}}$$

$$I_{0-}(n) = Is\left(1-e^{-\frac{\delta T}{\tau}}\right)\frac{1-e^{-\frac{nT}{\tau}}}{1-e^{-\frac{T}{\tau}}} \qquad (3\text{-}2)$$

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Sequence of Initial Current [1]

- The current integration of n^{th} PWM ON state

$$I_{ON} = \int_0^{\delta T} \{ \frac{V_{BAT}}{R} - \frac{V_{BAT}}{R} e^{-\frac{t}{\tau}} + \frac{V_{BAT}}{R} (e^{-\frac{(1-\delta)T}{\tau}} - e^{-\frac{T}{\tau}}) \frac{1 - e^{-\frac{(n-1)T}{\tau}}}{1 - e^{-\frac{T}{\tau}}} e^{-\frac{t}{\tau}} \} dt$$

- The current integration of n^{th} PWM OFF state

$$I_{OFF} = \int_0^{(1-\delta)T} \{ \frac{V_{BAT}}{R} (1 - e^{-\frac{\delta T}{\tau}}) \frac{1 - e^{-\frac{nT}{\tau}}}{1 - e^{-\frac{T}{\tau}}} e^{-\frac{t}{\tau}} \} dt$$

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Average Solenoid Current [1]

By dividing the summation of I_{ON} and I_{OFF} by the period T, the average solenoid current at time index n

$$i(n) = \frac{V_{BAT}}{R}\delta\{1 + \frac{\tau}{\delta T}(1 - e^{\frac{\delta T}{\tau}})e^{-\frac{nT}{\tau}}\} \xrightarrow{nT=t} i(t) = \frac{V_{BAT}}{R}\delta\{1 + \frac{\tau}{\delta T}(1 - e^{\frac{\delta T}{\tau}})e^{-\frac{t}{\tau}}\} \quad (4\text{-}2)$$

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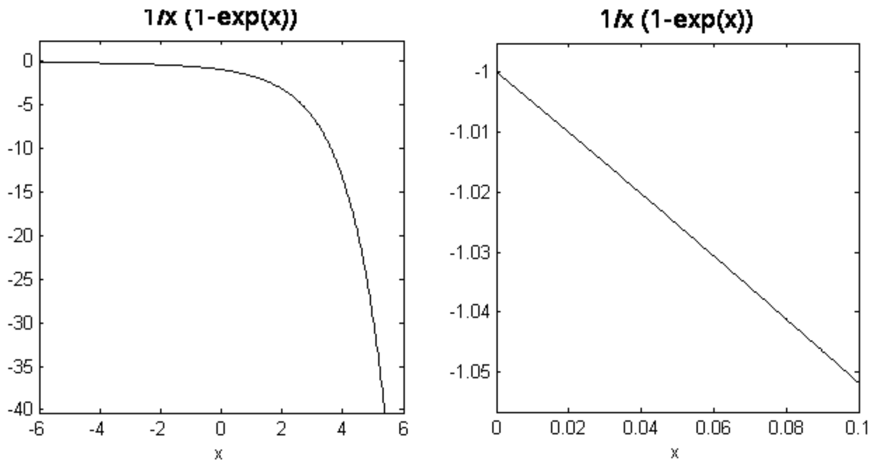
Average Solenoid Current [1]

$$i(t) = \frac{V_{BAT}}{R}\delta\{1 + \boxed{\frac{\tau}{\delta T}(1 - e^{\frac{\delta T}{\tau}})}\ e^{-\frac{t}{\tau}}\} \qquad (4\text{-}2)$$

$$\xrightarrow{\frac{\delta T}{\tau}=x} \quad \frac{1}{x}(1 - e^{x})$$



■If the PWM period T is sufficiently smaller than the solenoid time constant τ, x has a very small value and the coefficient becomes –1.

Ex) In our case, τ=0.003, T=0.00005 → x<0.017

$$i(t) = \frac{V_{BAT}}{R}\delta\{1 + \frac{\tau}{\delta T}(1 - e^{\frac{\delta T}{\tau}})\ e^{-\frac{t}{\tau}}\} \qquad (4\text{-}2) \quad \Rightarrow \quad i(t) = \frac{V_{BAT}}{R}\delta(1 - e^{-\frac{t}{\tau}}) \qquad (5\text{-}1)$$

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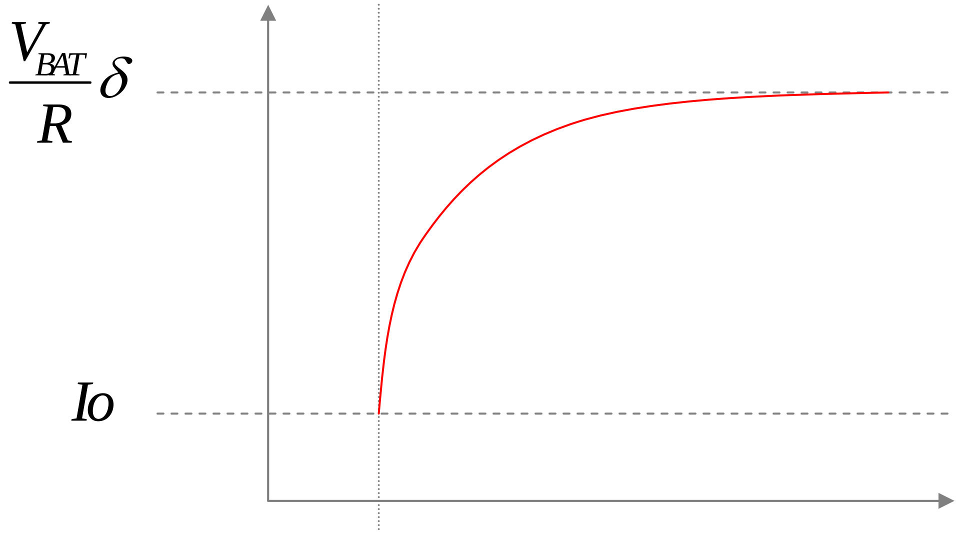
Average Solenoid Current [1]

If there is non-zero initial current at first period, the average solenoid current is modified as below:

$$
\begin{aligned}
i(t) &= \frac{V_{BAT}}{R}\delta + \left(Io - \frac{V_{BAT}}{R}\delta\right)e^{-\frac{t}{\tau}} \\
&= Io + \left(\frac{V_{BAT}}{R}\delta - Io\right)\underbrace{\boxed{\left(1 - e^{-\frac{t}{\tau}}\right)}}_{\text{Envelop}} \qquad (5\text{-}2)
\end{aligned}
$$



- The saturated current is in linear relation with duty-ratio
- The envelop of solenoid current, in other words, the average current changes from the initial current to the saturated current exponentially
- If PWM frequency is sufficiently high, the average current has the same time constant with the instant solenoid current.

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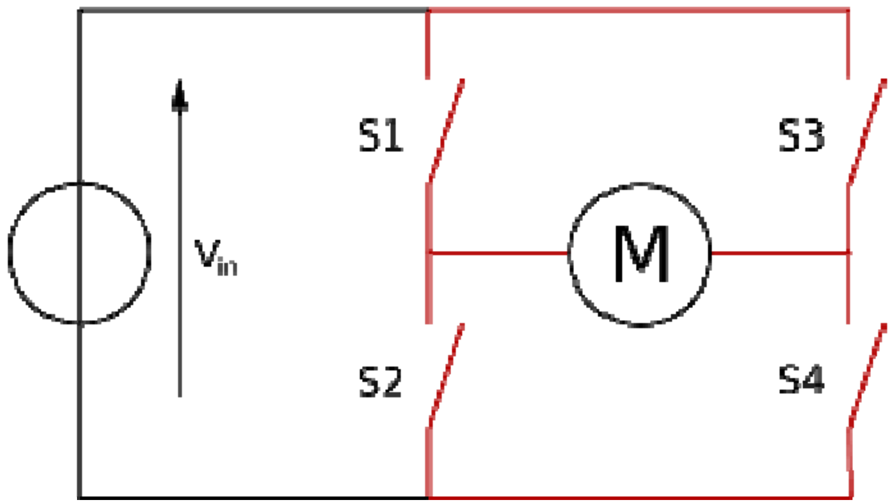
H Bridge

An **H bridge** is an electronic circuit that enables a voltage to be applied across a load in either direction. These circuits are often used in robotics and other applications to allow DC motors to run forwards and backwards. H bridges are available as integrated circuits, or can be built from discrete components.

http://en.wikipedia.org/wiki/H_bridge



Structure of an H bridge (highlighted in red)

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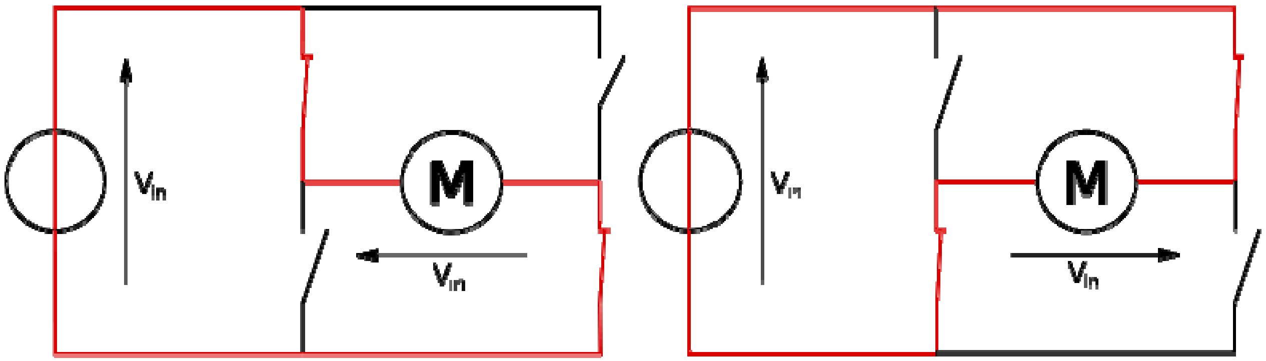
H Bridge

S1	S2	S3	S4	Result
1	0	0	1	Motor moves right
0	1	1	0	Motor moves left
0	0	0	0	Motor free runs
0	1	0	1	Motor brakes
1	0	1	0	Motor brakes



The two basic states of an H bridge

http://en.wikipedia.org/wiki/H_bridge

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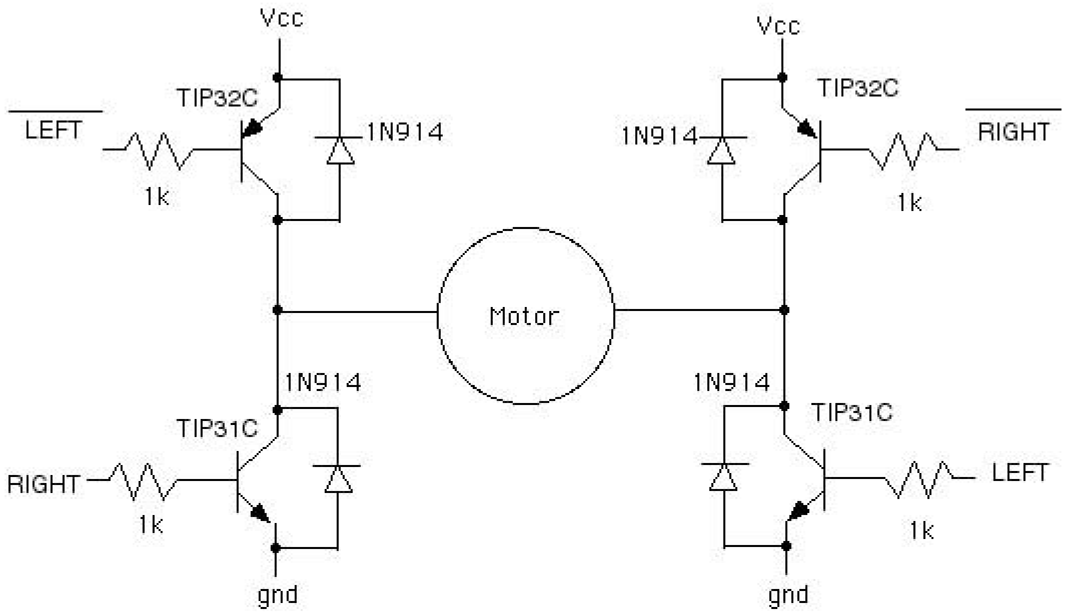
H Bridge

A solid-state H bridge is typically constructed using opposite polarity devices, such as PNP BJTs or P-channel MOSFETs connected to the high voltage bus and NPN BJTs or N-channel MOSFETs connected to the low voltage bus.

http://en.wikipedia.org/wiki/H_bridge



http://people.ece.cornell.edu/land/courses/ece4760/FinalProjects/s1999/bell/abell.cnazarian.ee476.finalproject.rccar.html

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H Bridge

The **most efficient MOSFET designs use N-channel MOSFETs on both the high side and low side** because they typically have a third of the ON resistance of P-channel MOSFETs.

This requires a more complex design since the gates of the high side MOSFETs must be driven positive with respect to the DC supply rail.

However, many **integrated circuit MOSFET drivers** include a charge pump within the device to achieve this.

http://en.wikipedia.org/wiki/H_bridge

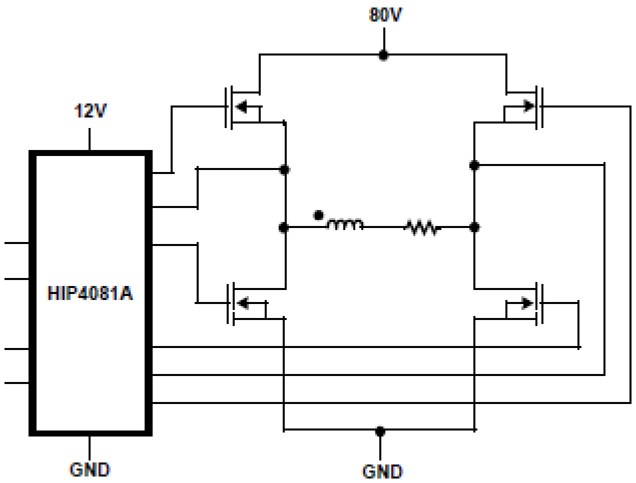
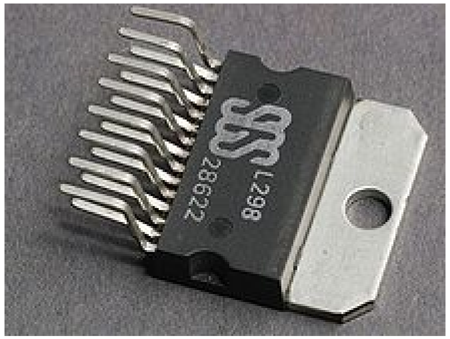


FIGURE 1. HIP4081A SIMPLIFIED APPLICATION DIAGRAM

http://www.intersil.com/data/an/an9405.pdf



Typical solid-state H bridge

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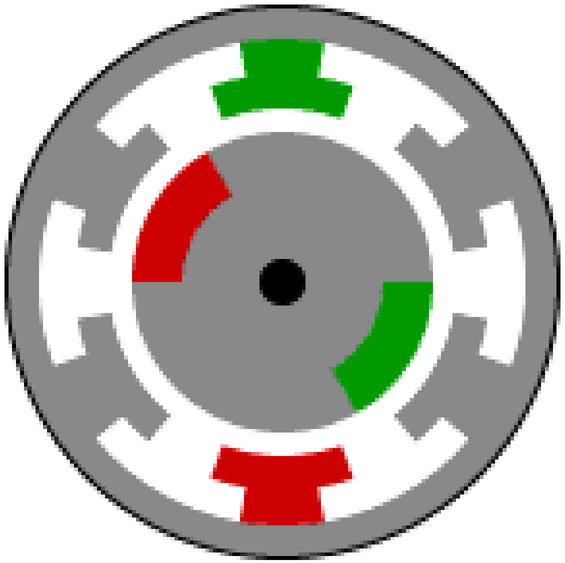
BLDC Motor



http://ccie-accreditation.org/anonymizer-wind-inrunner-bldc/

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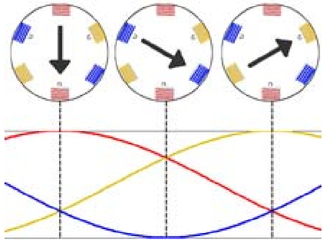
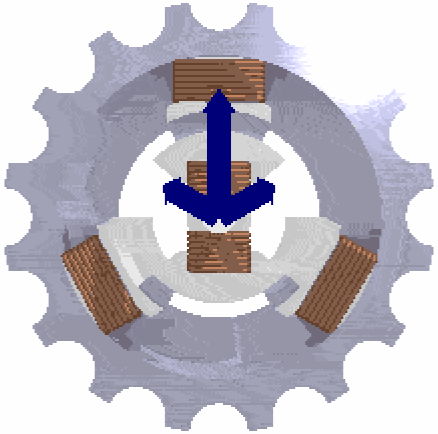
BLAC Motor

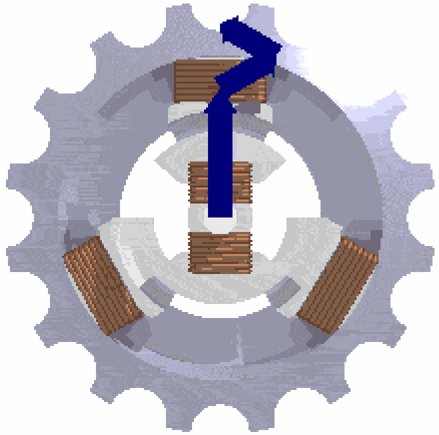


A 3-phase power supply provides a rotating magnetic field in an induction motor.
http://en.wikipedia.org/wiki/Asynchronous_motor

A symmetric **rotating magnetic field** can be produced with as few as three coils. The three coils will have to be driven by a **symmetric 3-phase AC sine current system**, thus each phase will be shifted 120 degrees in phase from the others.
http://en.wikipedia.org/wiki/Rotating_magnetic_field



Sine wave current in each of the coils produces sine varying magnetic field on the rotation axis. Magnetic fields add as vectors.



Vector sum of the magnetic field vectors of the stator coils produces **a single rotating vector** of resulting rotating magnetic field.

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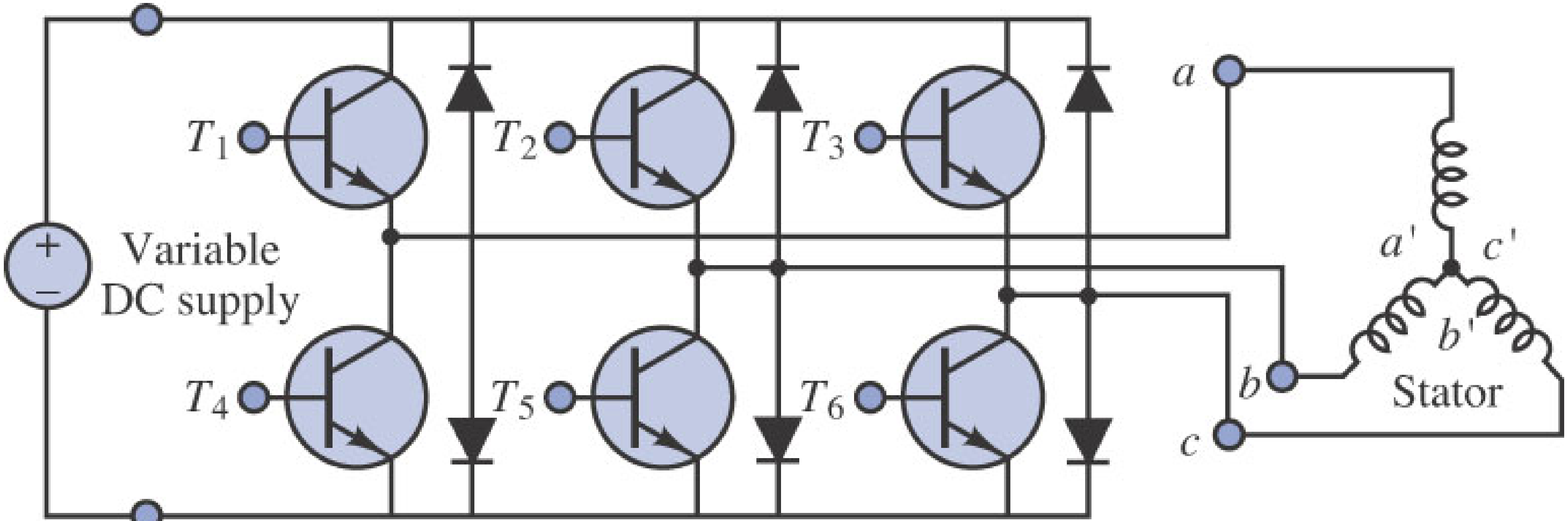
3-Phase Bridge [2]



Transistor supply for brushless DC motor

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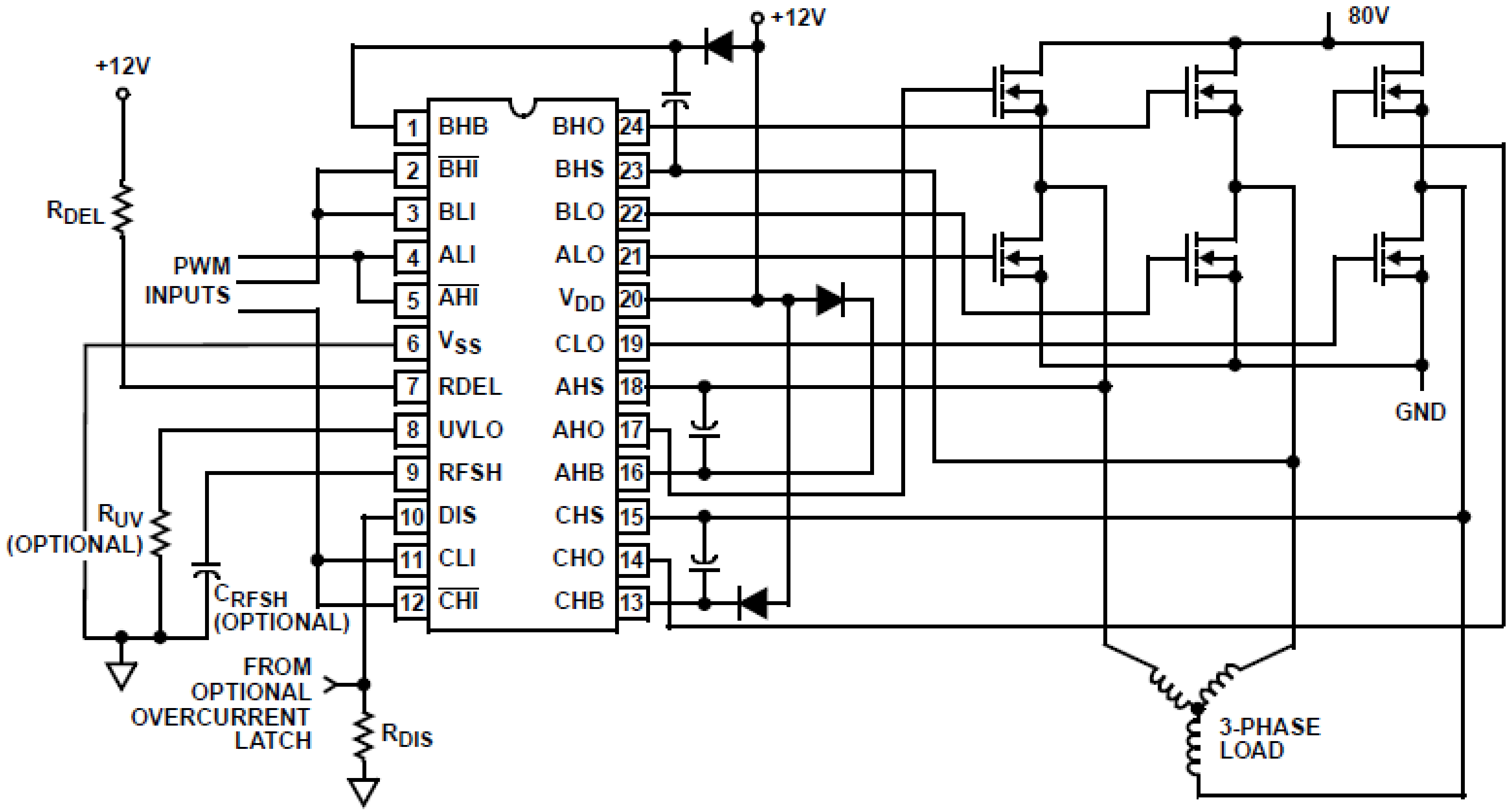
3-Phase Bridge [2]



http://www.intersil.com/data/an/an9642.pdf

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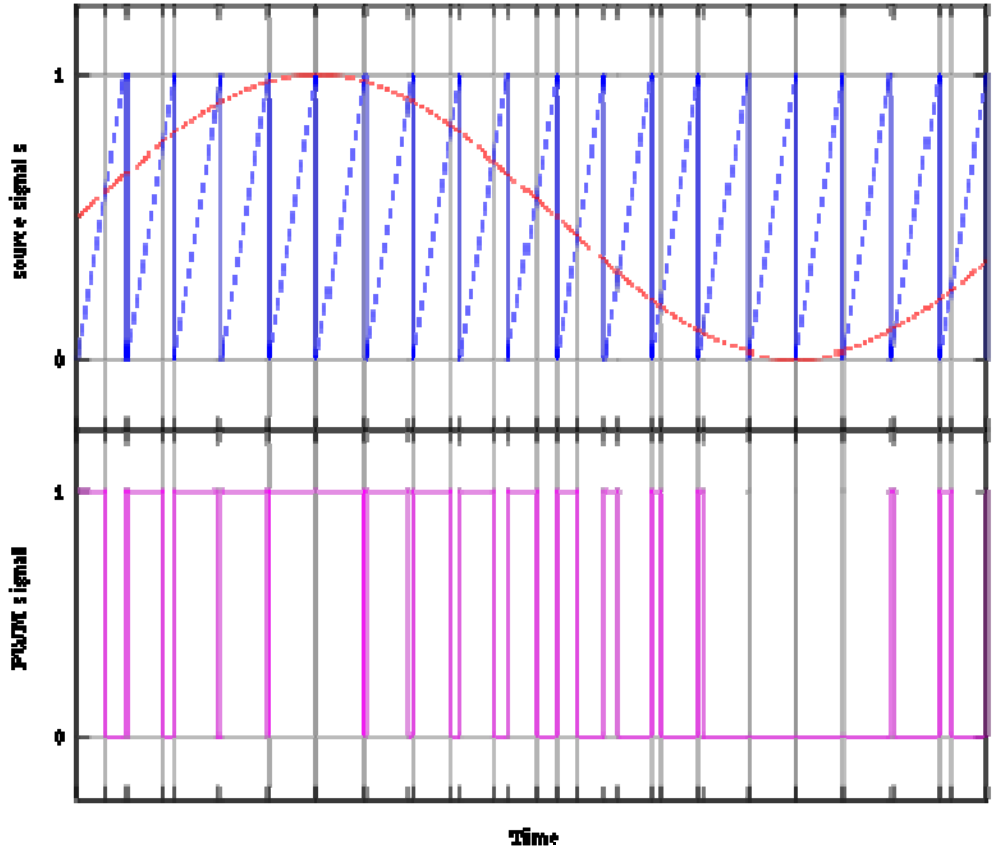
3-Phase Driver [2]



A simple method to generate the PWM pulse train corresponding to a given signal is the intersective PWM: the signal (here the red sinewave) is compared with a sawtooth waveform (blue). When the latter is less than the former, the PWM signal (magenta) is in high state (1). Otherwise it is in the low state (0). http://en.wikipedia.org/wiki/Pulse-width_modulation

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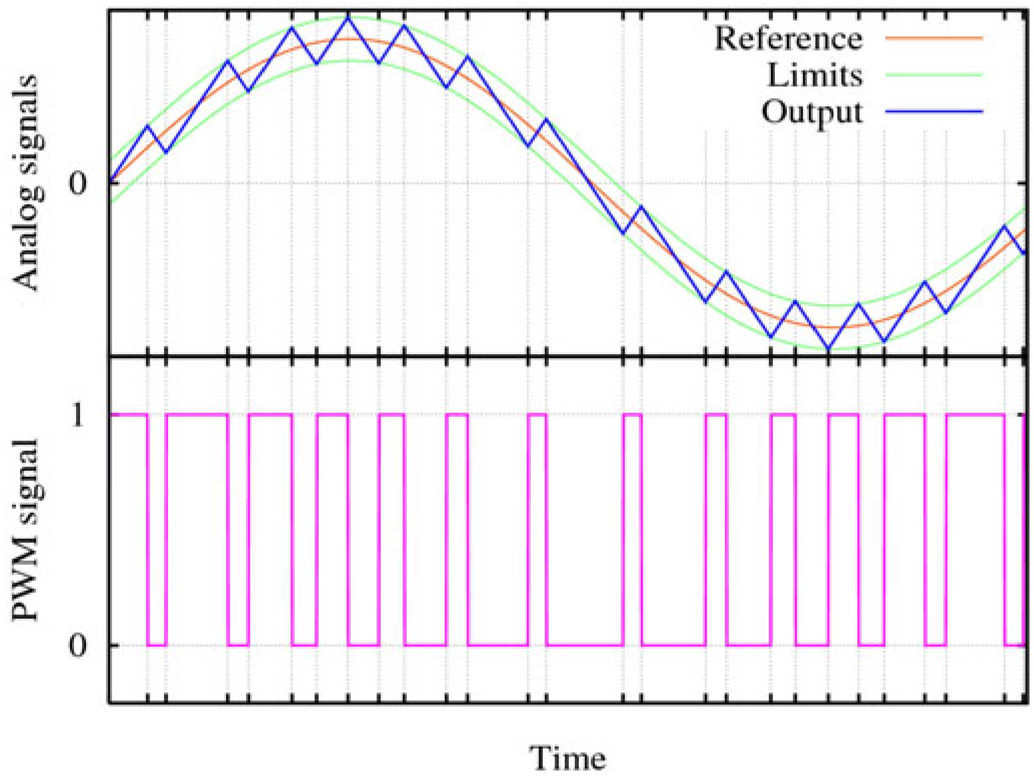
3-Phase Driver [2]



Principle of the delta PWM. The output signal (blue) is compared with the limits (green). These limits correspond to the reference signal (red), offset by a given value. Every time the output signal reaches one of the limits, the PWM signal changes state.
http://en.wikipedia.org/wiki/Pulse-width_modulation

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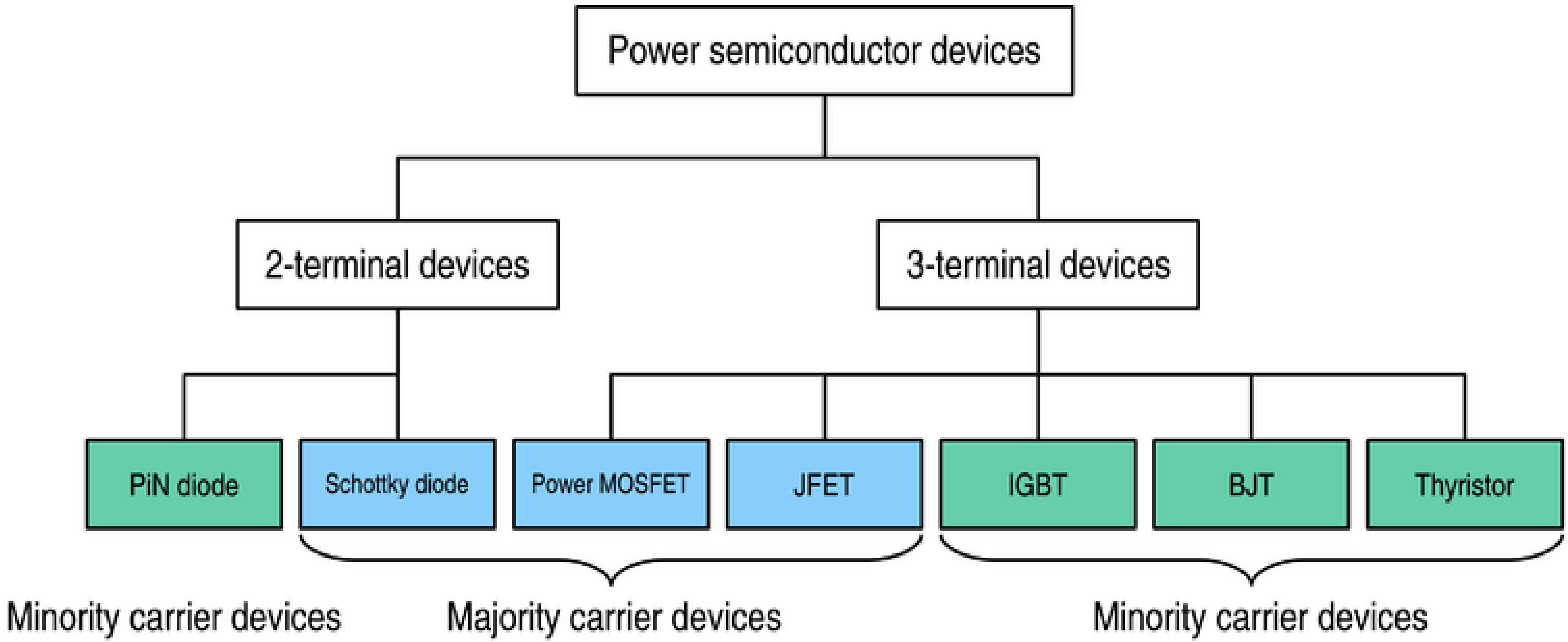
Power Semiconductor Device



http://en.wikipedia.org/wiki/Power_semiconductor_device

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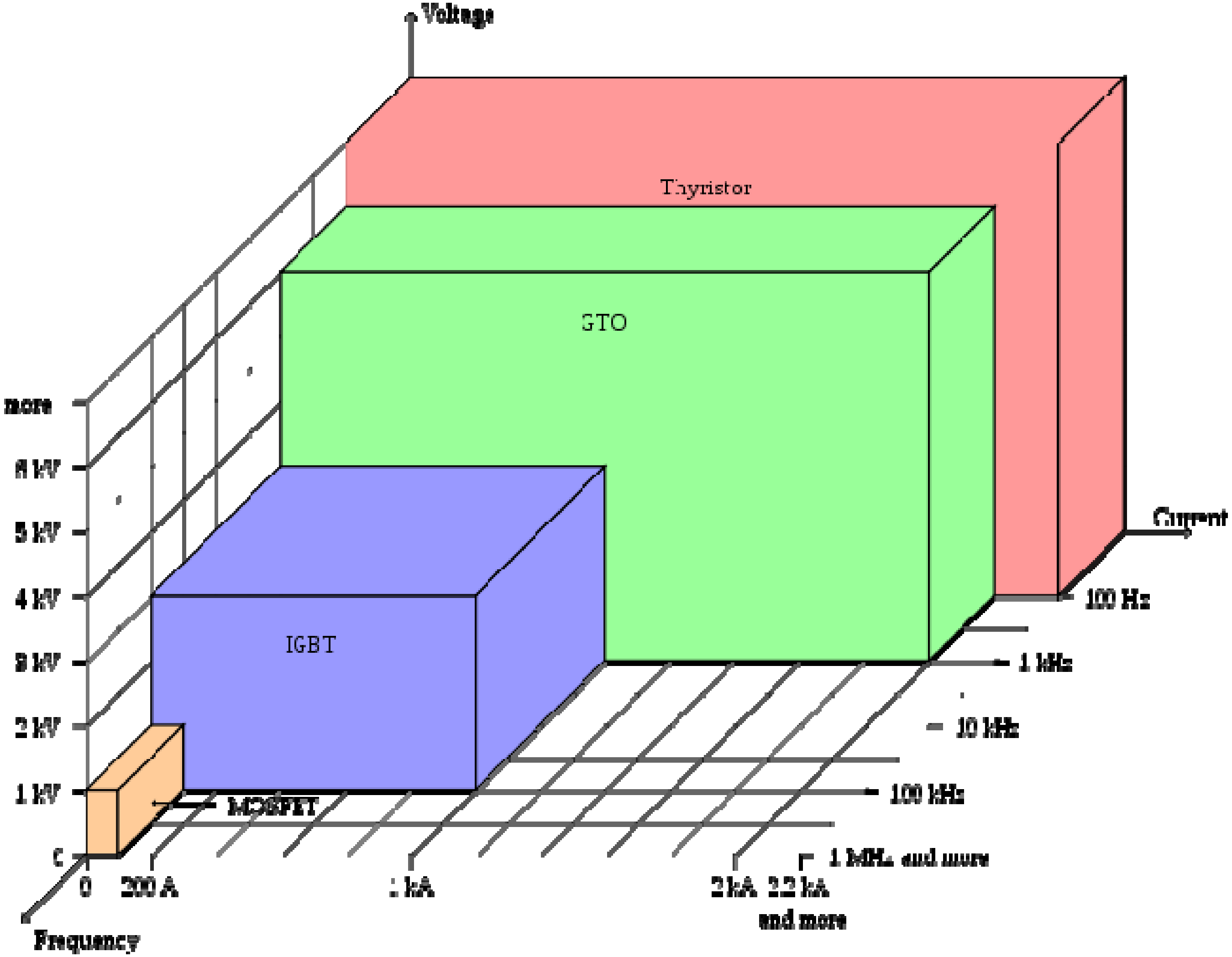
Power Semiconductor Device



http://en.wikipedia.org/wiki/Power_semiconductor_device

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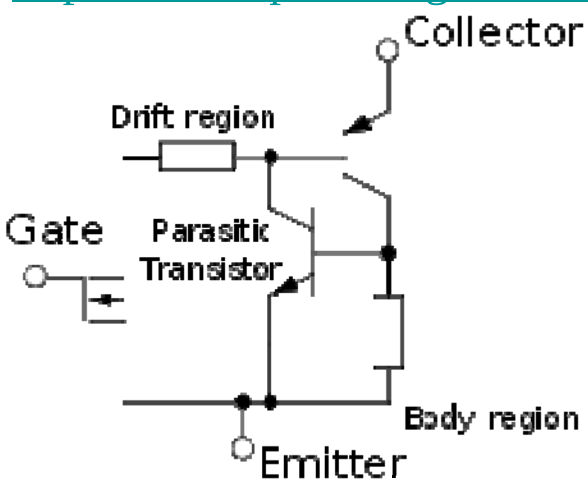
Power Semiconductor Device: IGBT

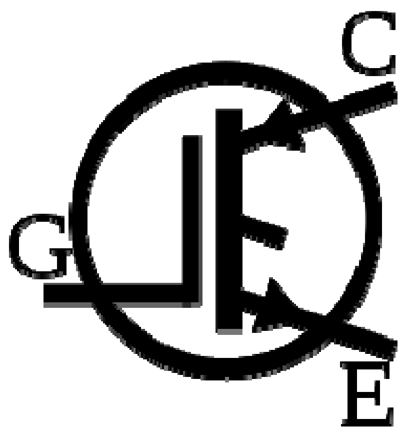
The **IGBT(insulated gate bipolar transistor)** combines the simple gate-drive characteristics of the MOSFETs with the high-current and low–saturation-voltage capability of bipolar transistors by combining an isolated gate FET for the control input, and a bipolar power transistor as a switch, in a single device.

It switches electric power in many modern appliances: **electric cars**, trains, variable speed refrigerators, air-conditioners and even stereo systems with switching amplifiers. Since it is designed to rapidly turn on and off, amplifiers that use it often synthesize **complex waveforms with pulse width modulation** and low-pass filters.

http://en.wikipedia.org/wiki/Insulated-gate_bipolar_transistor



Equivalent circuit for IGBT



Electronic symbol for IGBT

Small IGBT module, rated up to 30 A, up to 900 V

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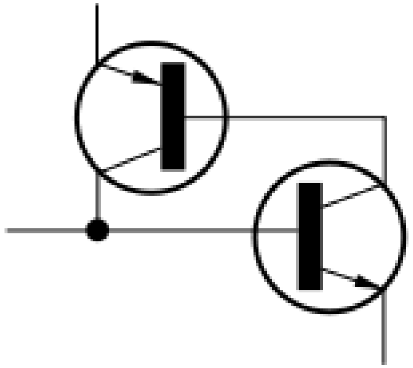
Power Semiconductor Device: Thyristor

A **thyristor** is a solid-state semiconductor device with four layers of alternating N and P-type material. They act as bistable switches, conducting when their gate receives a current pulse, and continue to conduct while they are forward biased (that is, while the voltage across the device is not reversed).

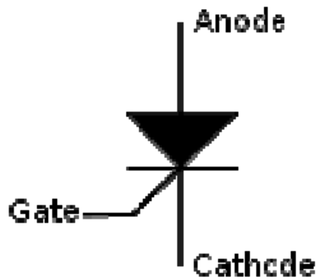
Some sources define **silicon controlled rectifiers (SCR)**.The name "silicon controlled rectifier" or **SCR** is General Electric's trade name for a type of thyristor.

The operation of a thyristor can be understood in terms of **a pair of tightly coupled bipolar junction transistors**, arranged to cause the self-latching action.

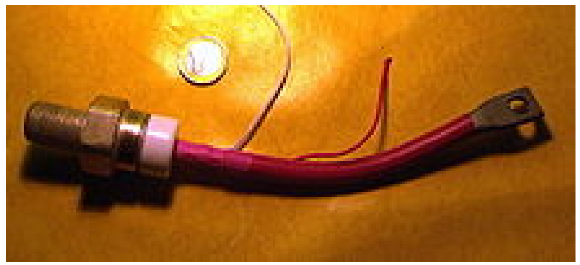
http://en.wikipedia.org/wiki/Thyristor



Equivalent circuit for IGBT



Circuit symbol for a thyristor



A high power SCR

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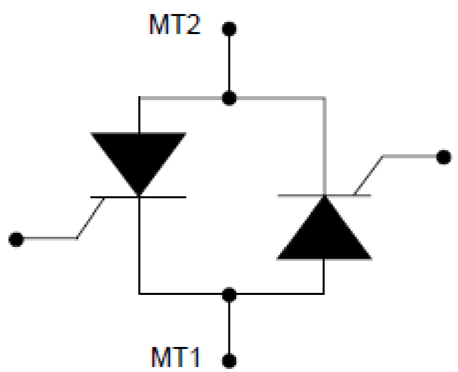
Power Semiconductor Device: TRIAC

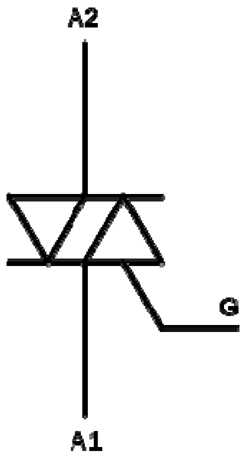
TRIAC (**Triode for Alternating Current**) is an electronic component which can conduct current in either direction when it is triggered (turned on), and is formally called a **bidirectional triode thyristor** or **bilateral triode thyristor**.

It can be triggered by either a positive or a negative voltage being applied to its *gate* electrode. Once triggered, the device continues to conduct until the current through it drops below a certain threshold value, the holding current, such as at the end of a half-cycle of alternating current (AC) mains power.

http://en.wikipedia.org/wiki/TRIAC



Anti parallel thyristor representation of a triac



TRIAC schematic symbol

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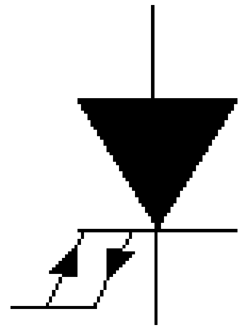
Power Semiconductor Device: GTO

A **gate turn-off thyristor (GTO)** is a special type of thyristor, a high-power semiconductor device. GTOs, as opposed to normal thyristors, are fully controllable switches which can be turned on and off by their third lead, the GATE lead.

Thyristors can only be turned ON and cannot be turned OFF. Thyristors are switched ON by a gate signal, but even after the gate signal is de-asserted (removed), the thyristor remains in the ON-state until any turn-off condition occurs (which can be the application of a reverse voltage to the terminals, or when the current flowing through (forward current) falls below a certain threshold value known as the "holding current"). Thus, a thyristor behaves like a normal semiconductor diode after it is turned on or "fired".

http://en.wikipedia.org/wiki/Gate_turn-off_thyristor



GTO thyristor symbol

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참고자료

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