ELG4139: Power Diodes and Power Transistors

Thyristors; Power Diodes; Power Bipolar Transistors (BJTs)
Power Metal Oxide Semiconductor Field Effect Transistors (MOSFETs);
Insulated Gate Bipolar Transistors (IGBTs); Gate Turn-Off Thyristors (GTOs)

Selection Criteria

Voltage Rating

Current Rating

Switching Speeds

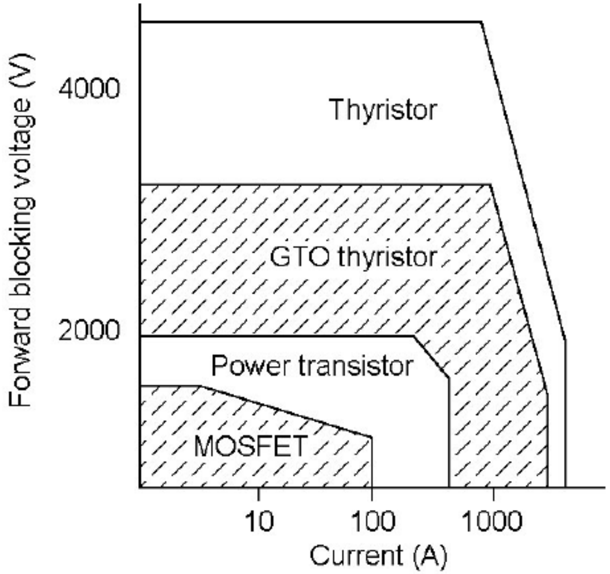
On-State Voltage

Switching Frequency

Transistor or Diode

Magnetic Components

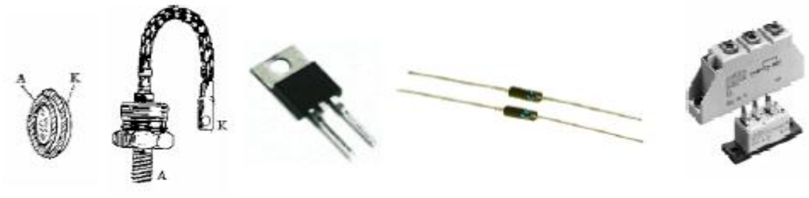
Capacitor Selection



Comparisons of power electronics devices

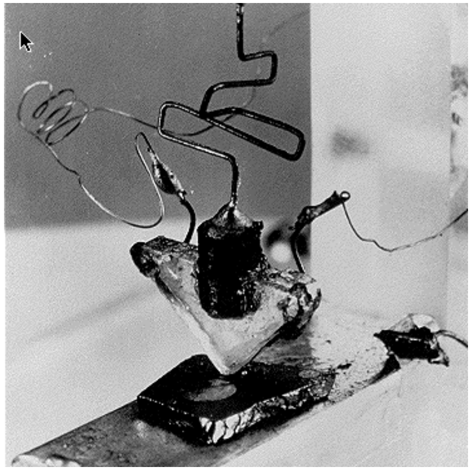
Power Electronic Devices

Uncontrolled Device: Power Diode



Half-Controlled Device: Thyristor

Fully-Controlled Devices

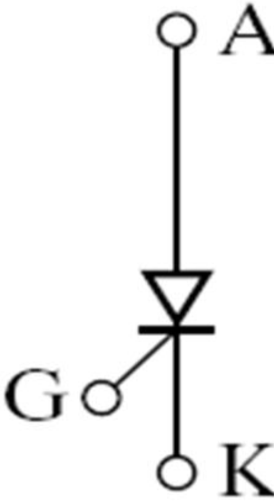


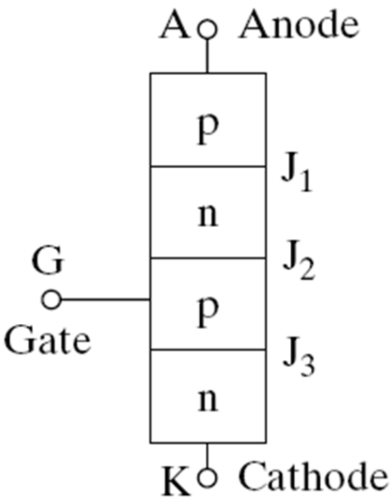
The Thyristor

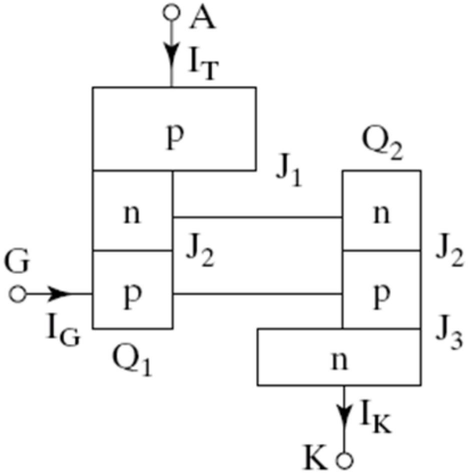
- **Thyristor**, a three terminal, four layers solid state semiconductor device, each layer consisting of alternately N-type or P-type material, for example P-N-P-N, that can handle high currents and high voltages, with better switching speed and improved breakdown voltage .
- The name ‘thyristor’, is derived by a combination of the capital letters from **THYRatron** and **transISTOR**.
- Thyristor has characteristics similar to a thyratron tube which is a type of gas filled tube used as a high energy electrical switch and controlled rectifier.
- From the construction view point, a thyristor (**pnpn** device) belongs to transistor (**pnp** or **npn** device) family.
- This means that the thyristor is a solid state device like a transistor and has characteristics similar to that of a thyratron tube.

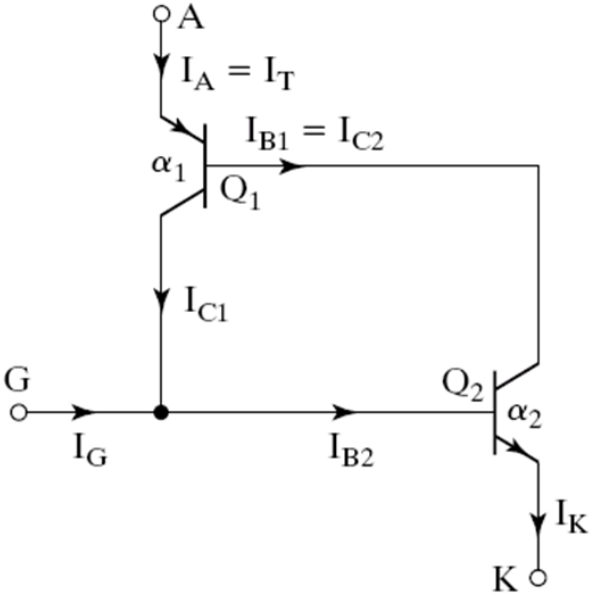
Thyristors

- Most important type of power semiconductor device.
- Have the highest power handling capability. They have a rating of 5000V / 6000A with switching frequencies ranging from 1KHz to 20KHz.
- Is inherently a slow switching device compared to BJT or MOSFET.
- Used as a latching switch that can be turned on by the control terminal but cannot be turned off by the gate.



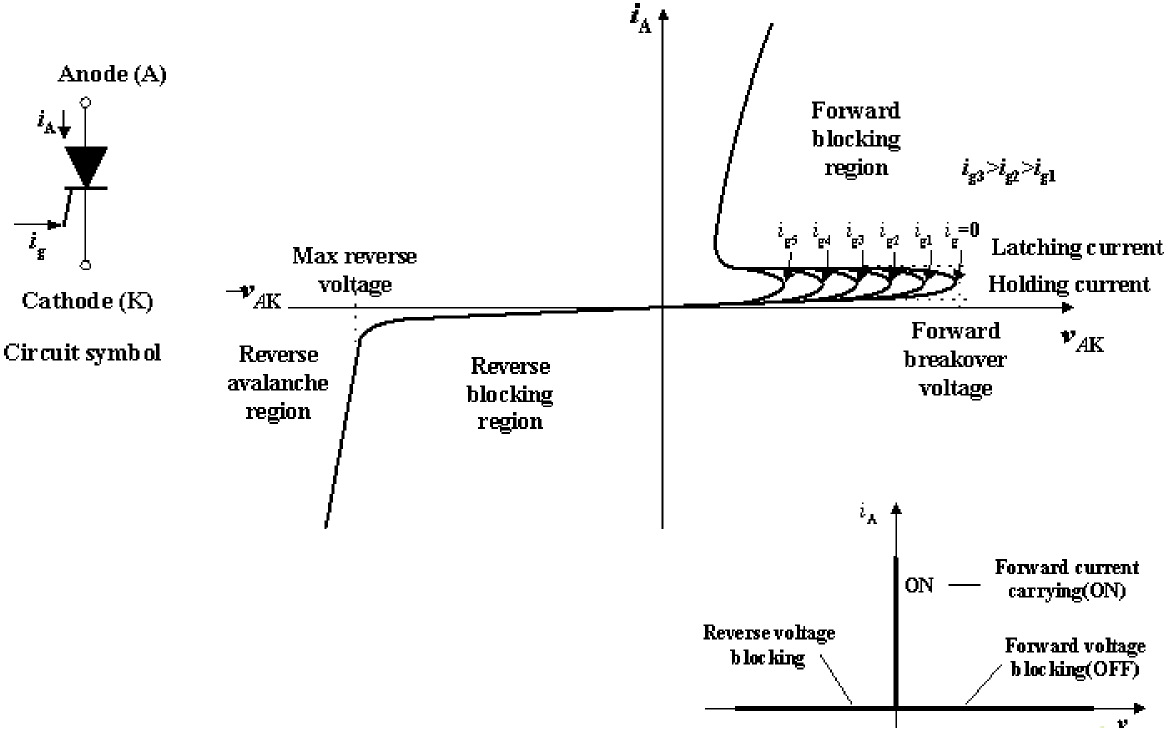






Methods of Thyristor Turn-on

- Thermal Turn-on.
- Light.
- High Voltage.
- Gate Current.
- dv/dt.

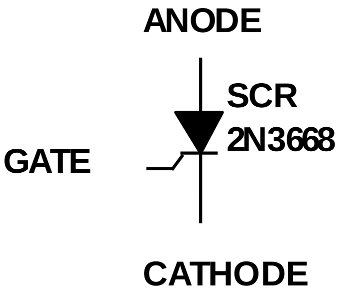


Thyristors -SCR Symbol and Terminal Characteristics

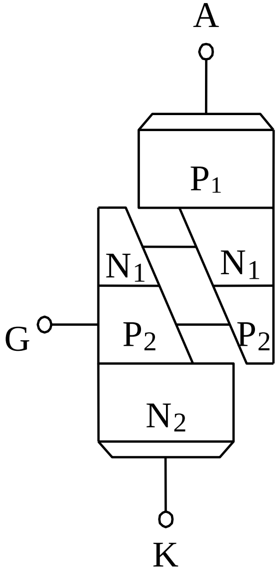
Thyristor Family Members

- SCR: Silicon Controlled Rectifier
- DIAC: Diode on Alternating Current
- TRIAC: Triode for Alternating Current
- SCS: Silicon Control Switch
- SUS: Silicon Unilateral Switch
- SBS: Silicon Bidirectional Switch
- SIS: Silicon Induction Switch
- LASCS: Light Activated Silicon Control Switch
- LASCR: Light Activated Silicon Control Rectifier
- SITh: Static Induction Thyristor
- RCT: Reverse Conducting Thyristor
- GTO: Gate Turn-Off Thyristor
- MCT: MOSFET Controlled Thyristor
- ETOs: Emitter Turn ON Thyristor

The Thyristor: Structure and Model

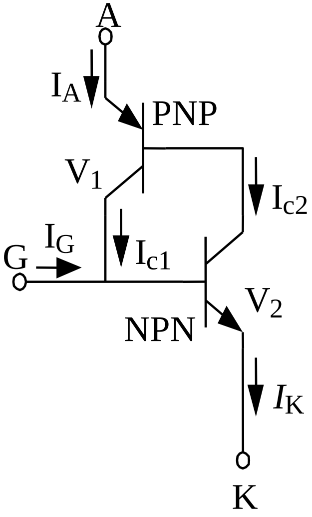


Structure

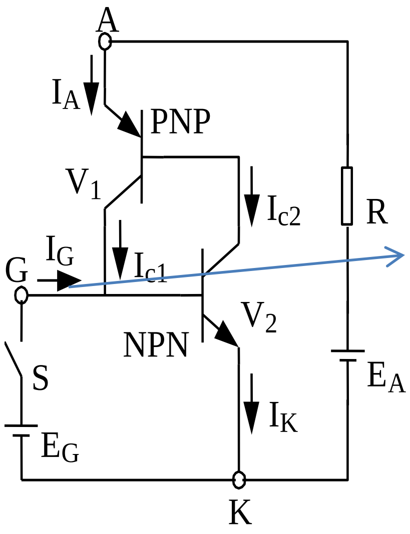


a)

Equivalent circuit



b)



Equivalent circuit: A pnp transistor and an npn transistor interconnected together

Positive feedback

Trigger

Can not be turned off by control signal

Half-controllable

$$I_{c1} = \alpha_1 I_A + I_{CBO1} \qquad (1\text{-}1)$$

$$I_{c2} = \alpha_2 I_K + I_{CBO2} \qquad (1\text{-}2)$$

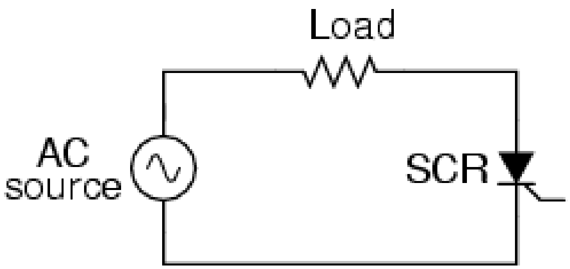
$$I_K = I_A + I_G \qquad (1\text{-}3)$$

$$I_A = I_{c1} + I_{c2} \qquad (1\text{-}4)$$

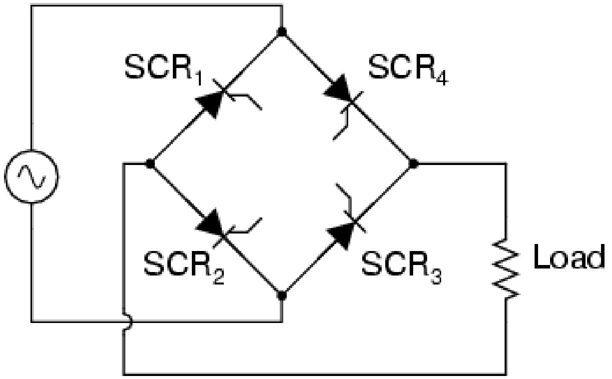
$$I_A = \frac{\alpha_2 I_G + I_{CBO1} + I_{CBO2}}{1 - (\alpha_1 + \alpha_2)} \qquad (1\text{-}5)$$

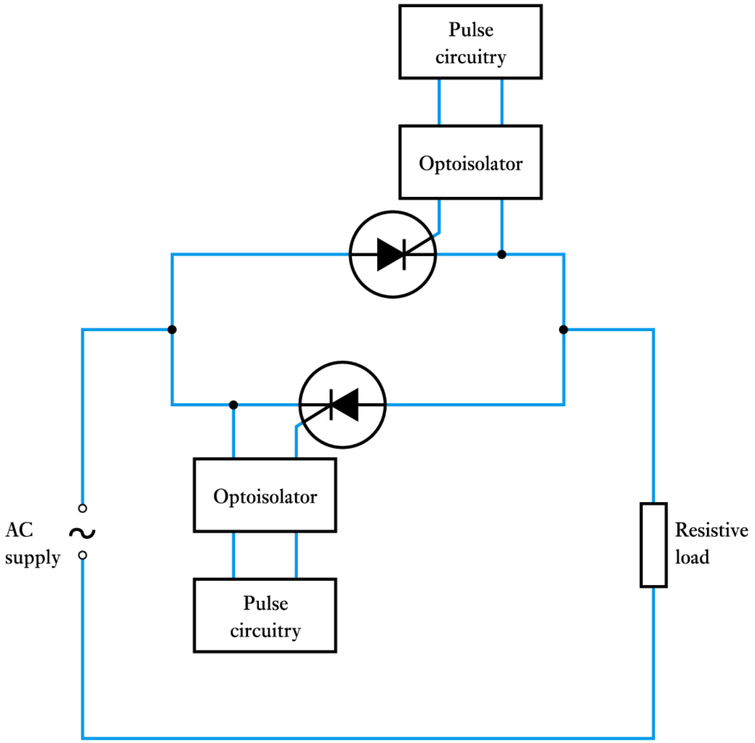
Silicon Controlled Rectifier

Industrially SCRs are applied to produce DC voltages for motors from AC line voltage. As rectifier, they can be half-wave rectifiers and full-wave rectifier.



Controlled bridge rectifier

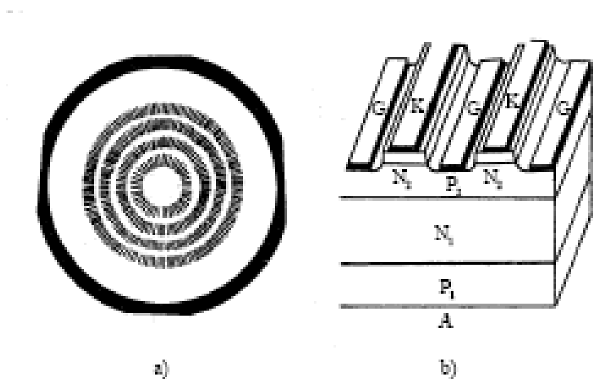




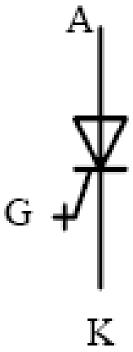
Typical Fully-Controlled Devices

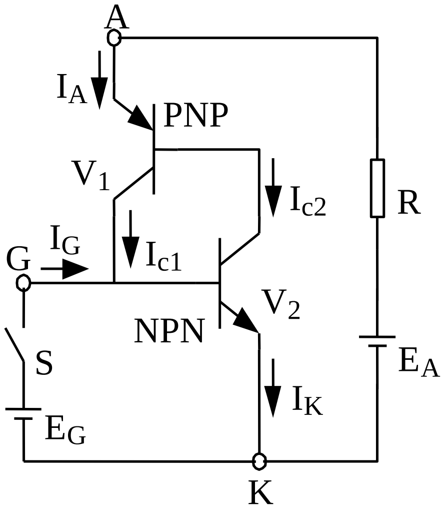
Gate- Turn-Off Thyristor: GTO

Structure



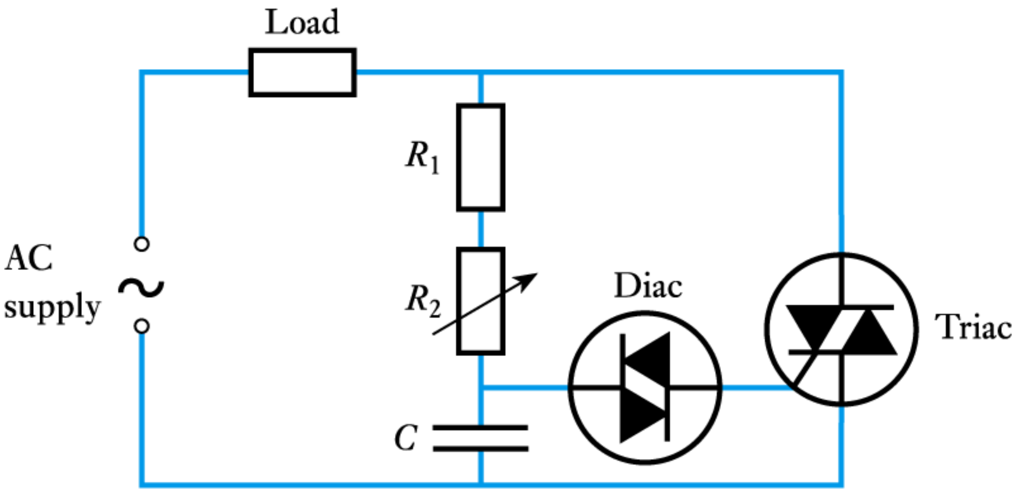
Symbol

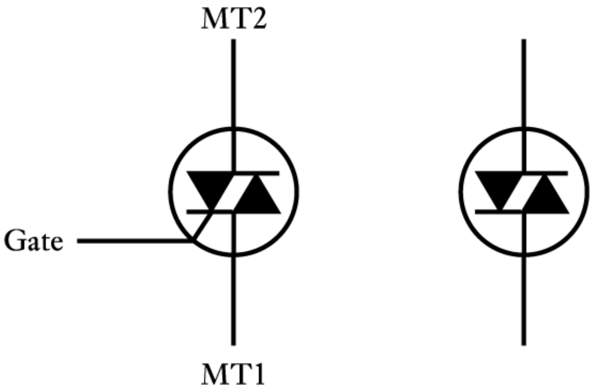




Major difference from conventional thyristor: The gate and cathode structures are highly inter-digitated , with various types of geometric forms being used to layout the gates and cathodes.

Triac





(a) A triac

(b) A diac

Resembles a bidirectional thyristor; allows full-wave control using a single device often used with a bidirectional trigger diode (a diac) to produce the necessary drive pulses this breaks down at a particular voltage and fires the triac.

Application: DC Motor Driver

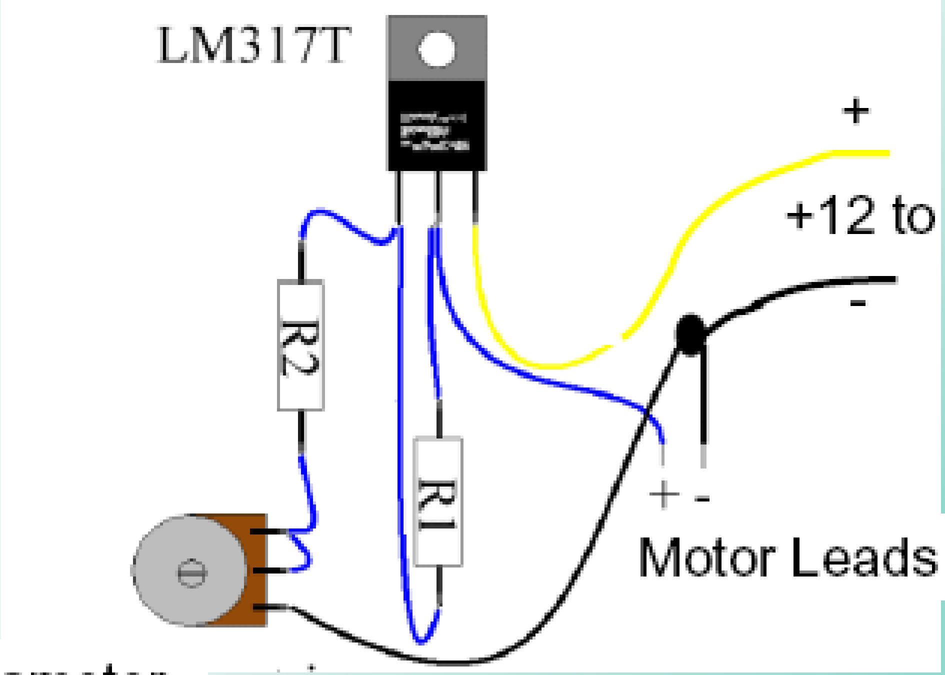
- DC motor speed generally depends on a combination of the voltage and current flowing in the motor coils and the motor loads or braking torque.
- The speed of the motor is proportional to the voltage, and the torque is proportional to the current.
- A rectifier is one or more diodes arranged for converting AC to DC.
- The current used to drive the DC motor typically comes from:

  Fixed voltage: Battery; Voltage regulator.

  Adjustable voltage: PWM current source; Silicon controlled rectifier modulated AC source.

DC Motors Current Drives

R1 = 260Ω
R2 = 1kΩ

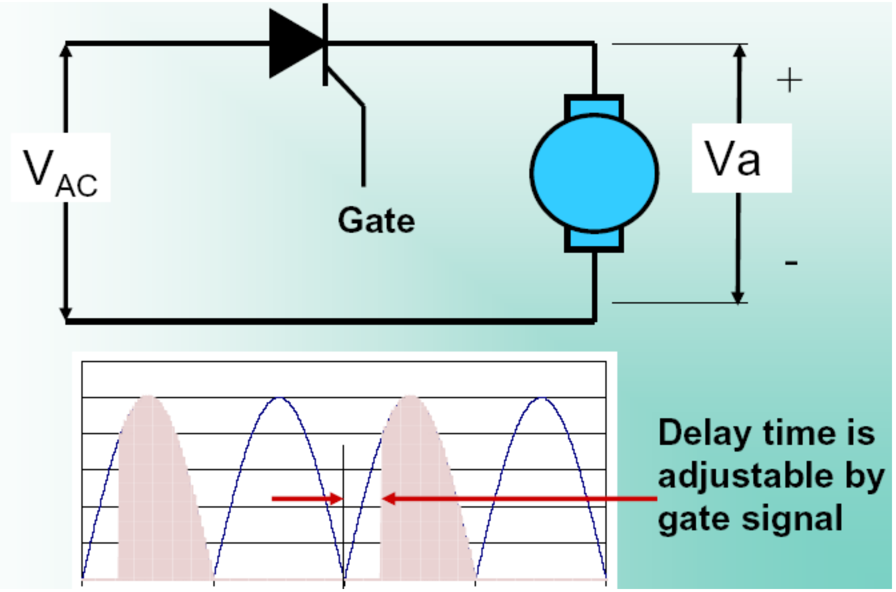


+12 to +24 VDC

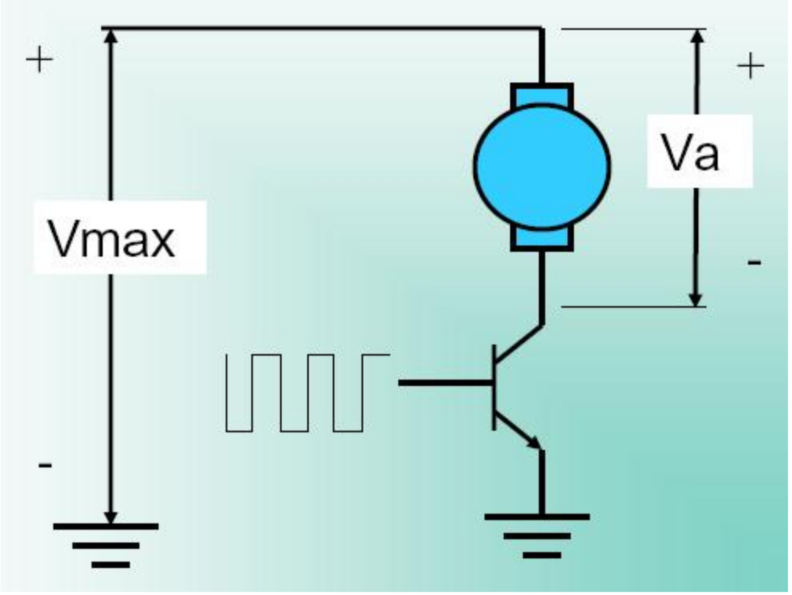
Motor Leads

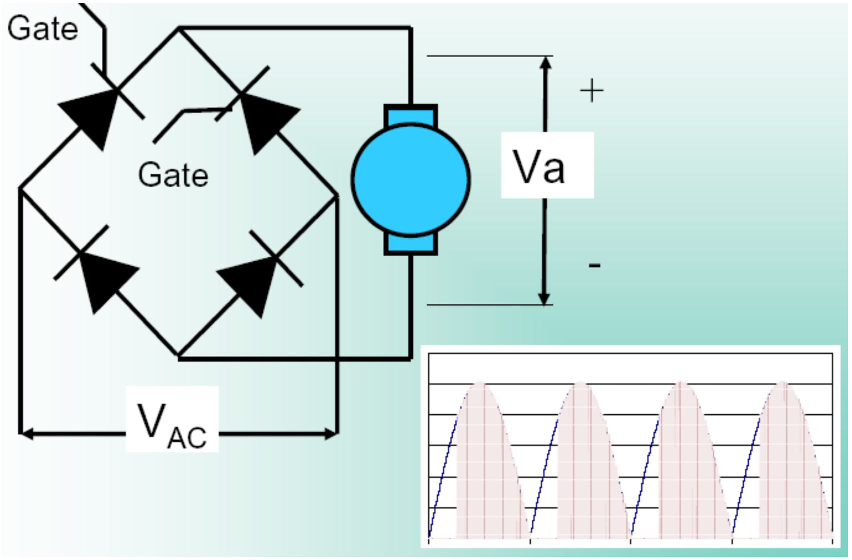
1 kΩ potentiometer

DC Motors Current Drives



Delay time is adjustable by gate signal





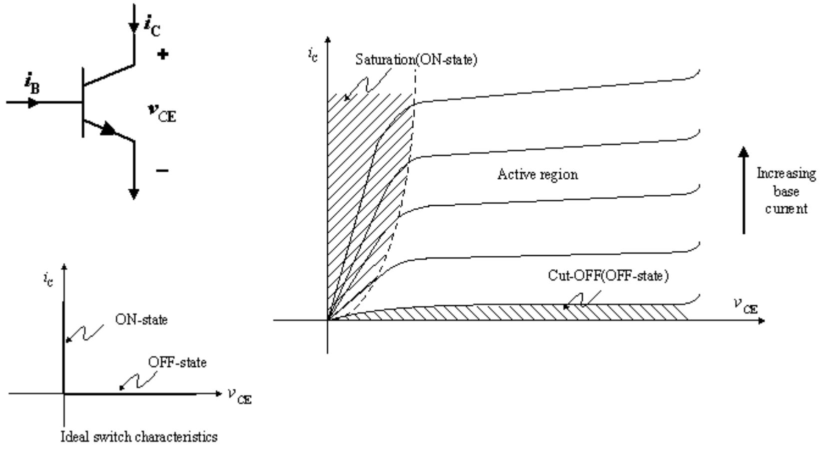
Power Transistors

- **MOSFET:** Metal Oxide Semiconductor Field Effect Transistor
- (Below few hundreds voltages; Switching frequencies in excess of 100 kHz)
- **IGBT:** Insulated Gate Bipolar Transistor (Very large voltage; current and power extending MW; switching below few tens of kHz)
- **IGCT:** Integrated Gate Controlled Thyristor (Utility applications of few MWs).
- **GTO:** Gate-Turn Off Thyristor (Utility applications of few MWs).

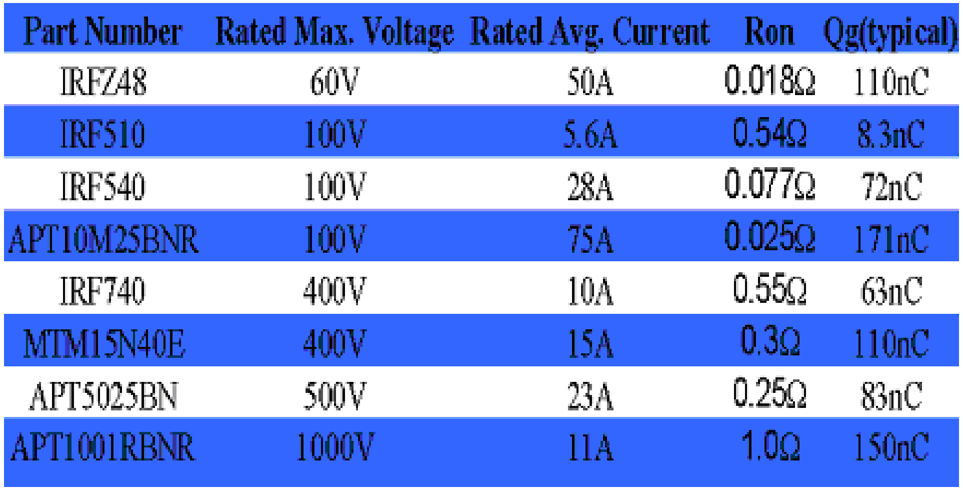
Power BJTs

The circuit symbol for the BJTs and its steady state *v-i* characteristics are as shown.

BJT Symbol and i-v Characteristics



Survey of Commercially Available MOSFETs



Part Number	Rated Max. Voltage	Rated Avg. Current	Ron	Qg(typical)
IRFZ48	60V	50A	0.018Ω	110nC
IRF510	100V	5.6A	0.54Ω	8.3nC
IRF540	100V	28A	0.077Ω	72nC
APT10M25BNR	100V	75A	0.025Ω	171nC
IRF740	400V	10A	0.55Ω	63nC
MTM15N40E	400V	15A	0.3Ω	110nC
APT5025BN	500V	23A	0.25Ω	83nC
APT1001RBNR	1000V	11A	1.0Ω	150nC

Power BJTs

As shown in the i-v characteristics, a sufficiently large base current results in the device being fully ON. This requires that the control circuit to provide a base current that is sufficiently large so that

$$I_B > \frac{I_C}{h_{FE}}$$

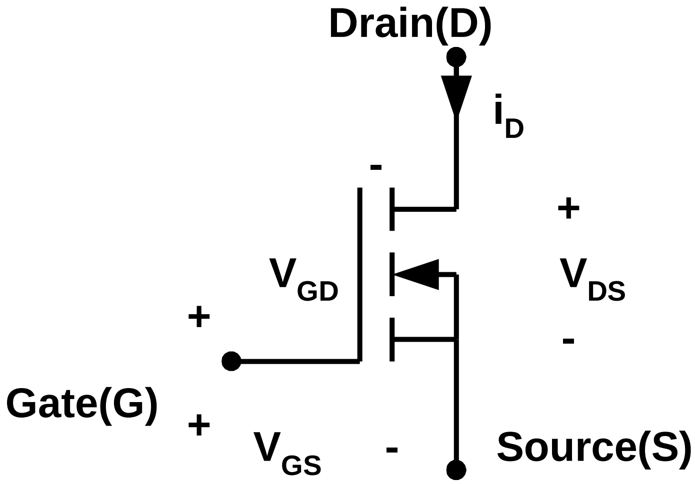
where h_{FE} is the dc current gain of the device

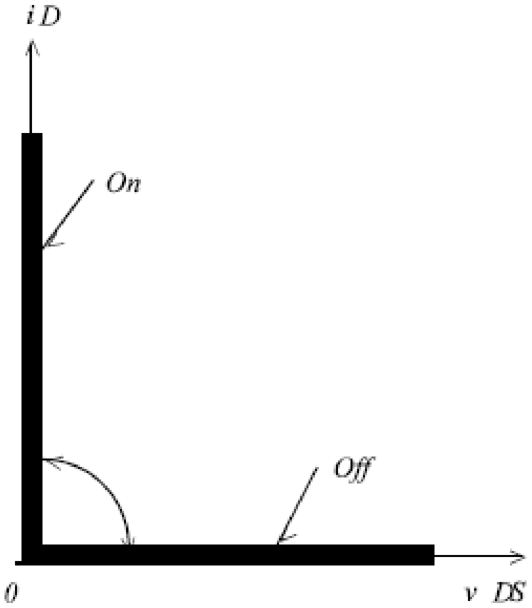
BJTs are current-controlled devices, and base current must be supplied continuously to keep them in the ON state: The dc current gain hFE is usually only 5-10 in high-power transistors.
BJTs are available in voltage ratings up to 1400V and current ratings of a few hundred amperes.

- BJT has been replaced by MOSFET in low-voltage (< 500V) applications
- BJT is being replaced by IGBT in applications at voltages above 500V

Power MOSFETs

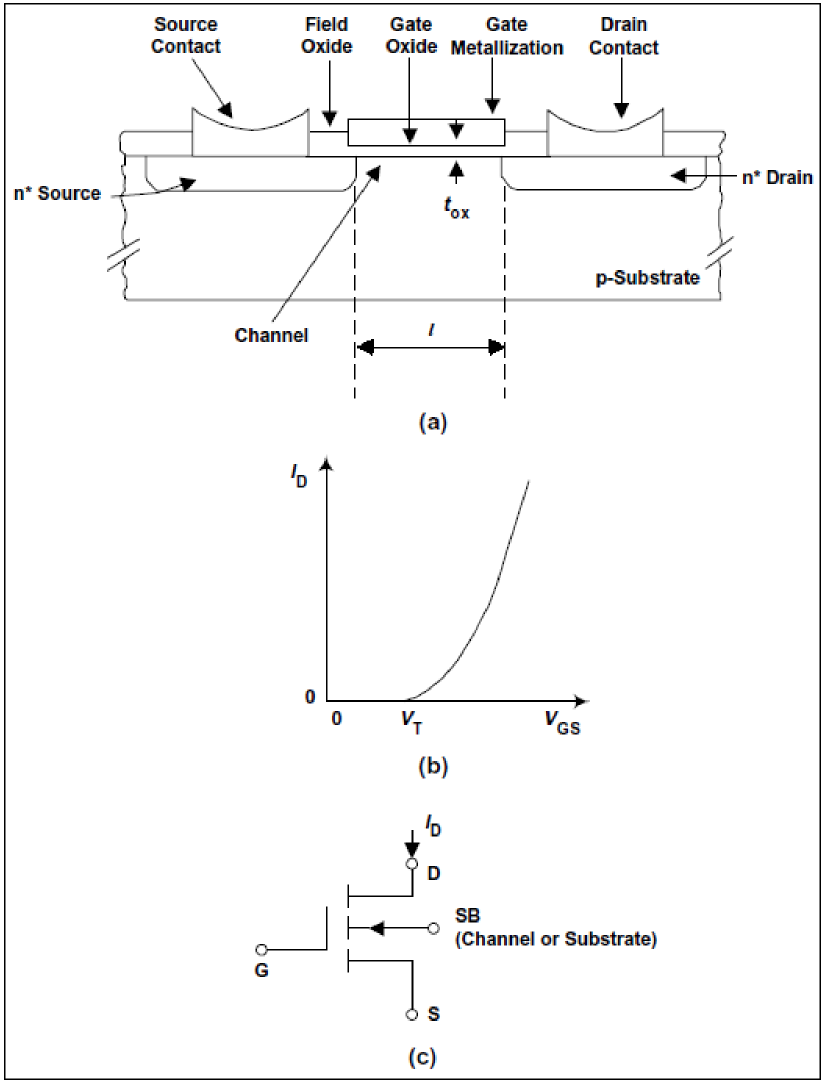
The circuit symbol for the MOSFETs and its steady state v-i characteristics are as shown.



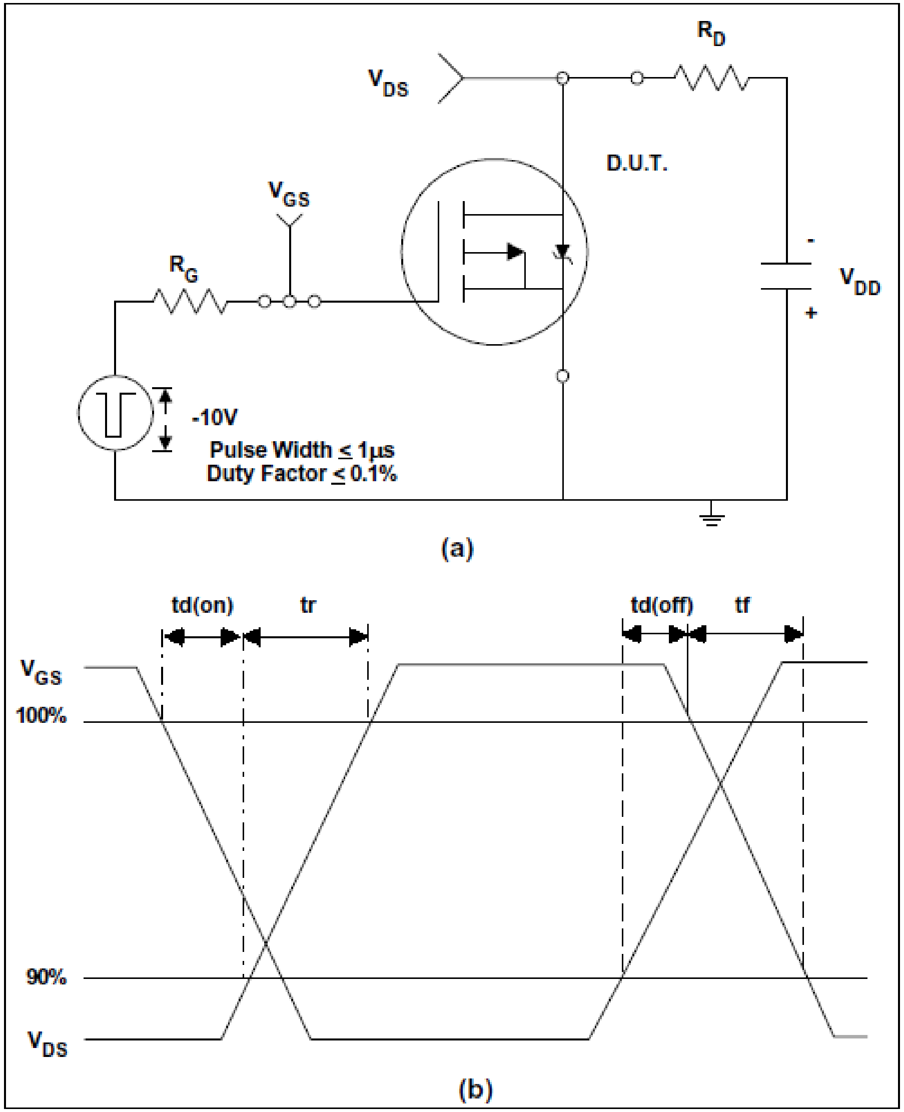


Power MOSFET is a voltage controlled device.
MOSFET requires the continuous application of a gate-source voltage of appropriate magnitude in order to be in the ON state.
The switching times are very short, being in the range of a few tens of nanoseconds to a few hundred nanoseconds depending on the device type.

MOSFETS


Source Contact
Field Oxide
Gate Oxide
Gate Metallization
Drain Contact
n* Source
n* Drain
t_{ox}
p-Substrate
Channel
l
(a)
I_D
0
0
V_T
V_{GS}
(b)
I_D
D
SB
(Channel or Substrate)
G
S
(c)

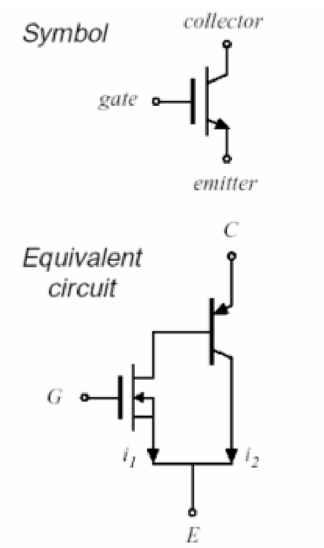
Switching Time Test of the MOSFET

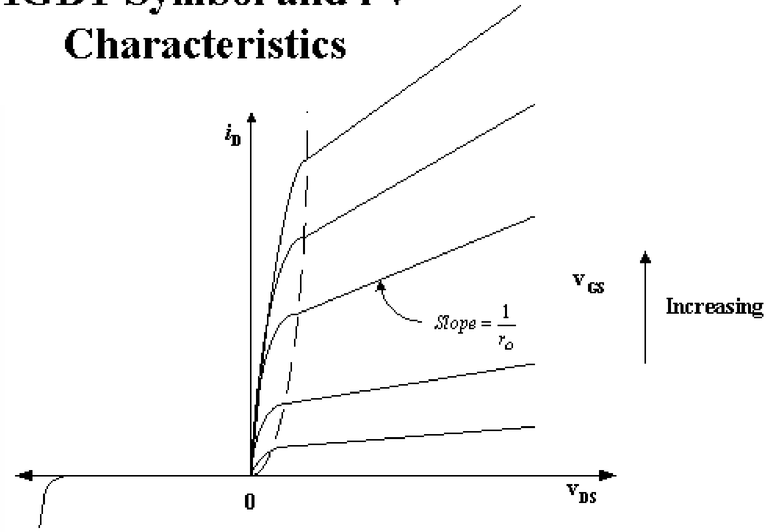


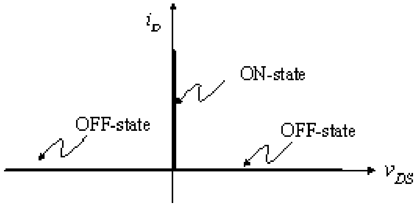
IGBTs

The circuit symbol for the IGBTs and its steady state *v-i* characteristics are as shown.

IGBT Symbol and i-v Characteristics







The IGBT has some of the advantages of the MOSFET and the BJT combined.

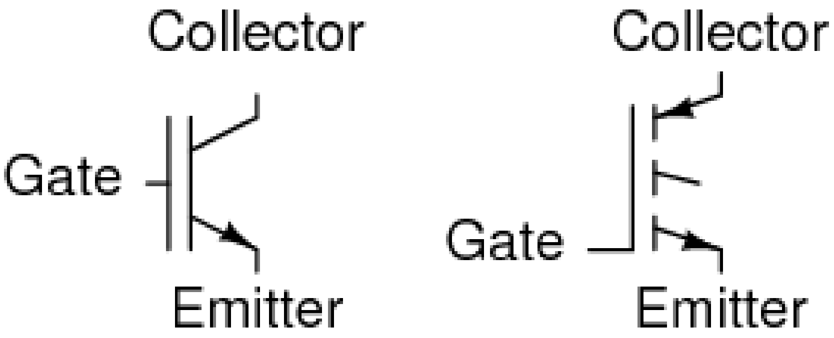
Similar to the MOSFET, the IGBT has a high impedance Gate, which requires only a small amount of energy to switch the device.

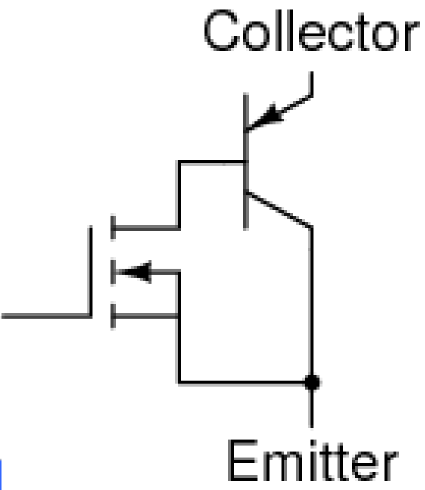
Like the BJT, the IGBT has a small ON-state voltage even in devices with large blocking voltage ratings (for example, V_{ON} is 2-3V in a 1000-V device).

IGBTs

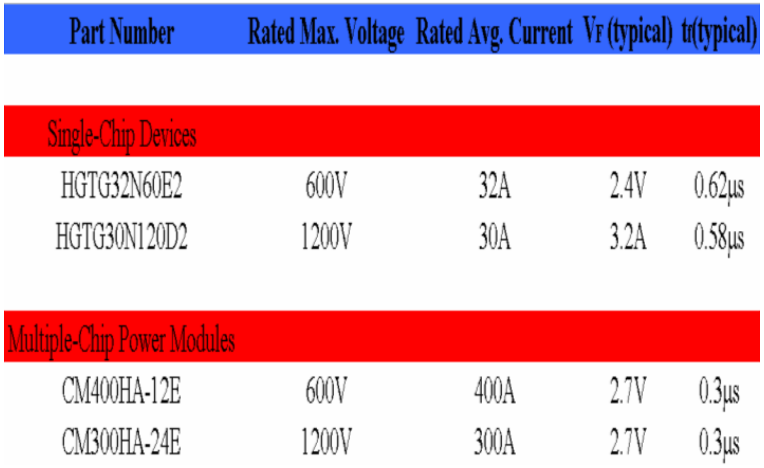
Schematic symbols

Equivalent circuit





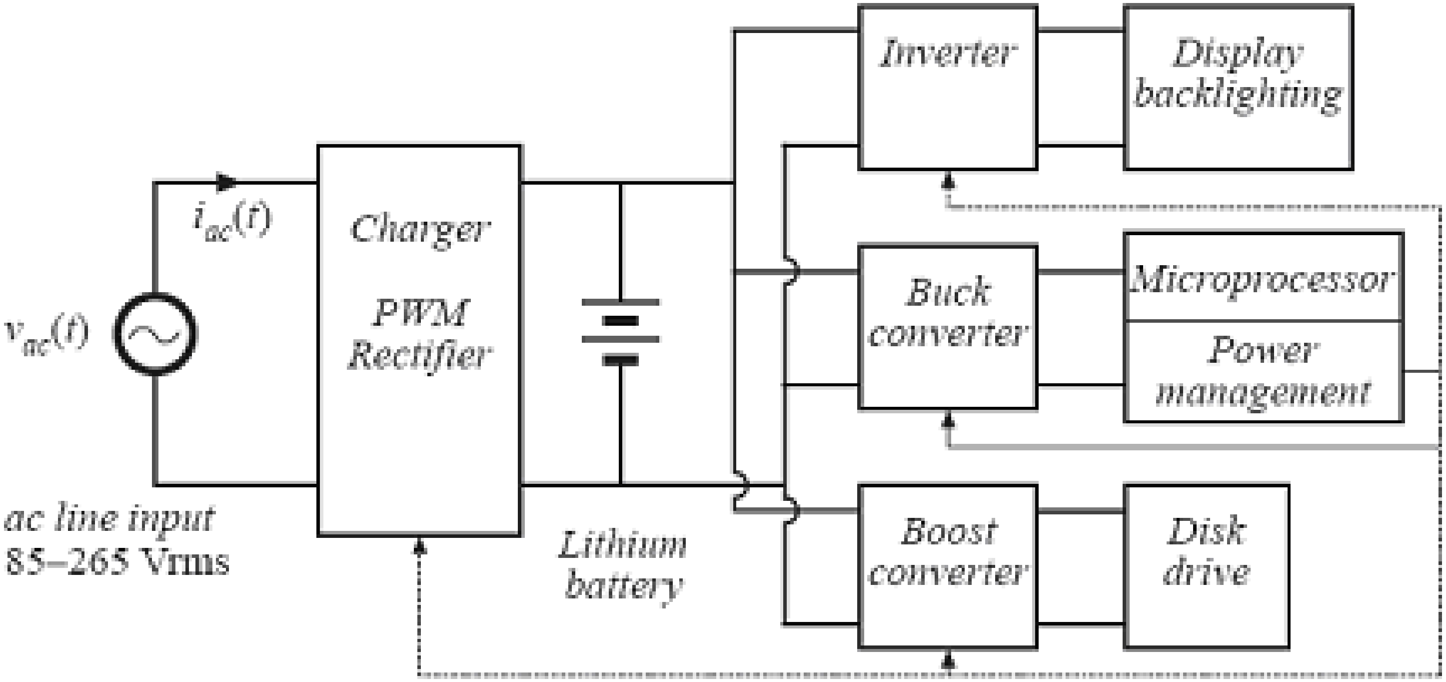
Survey of Commercially Available IGBTs



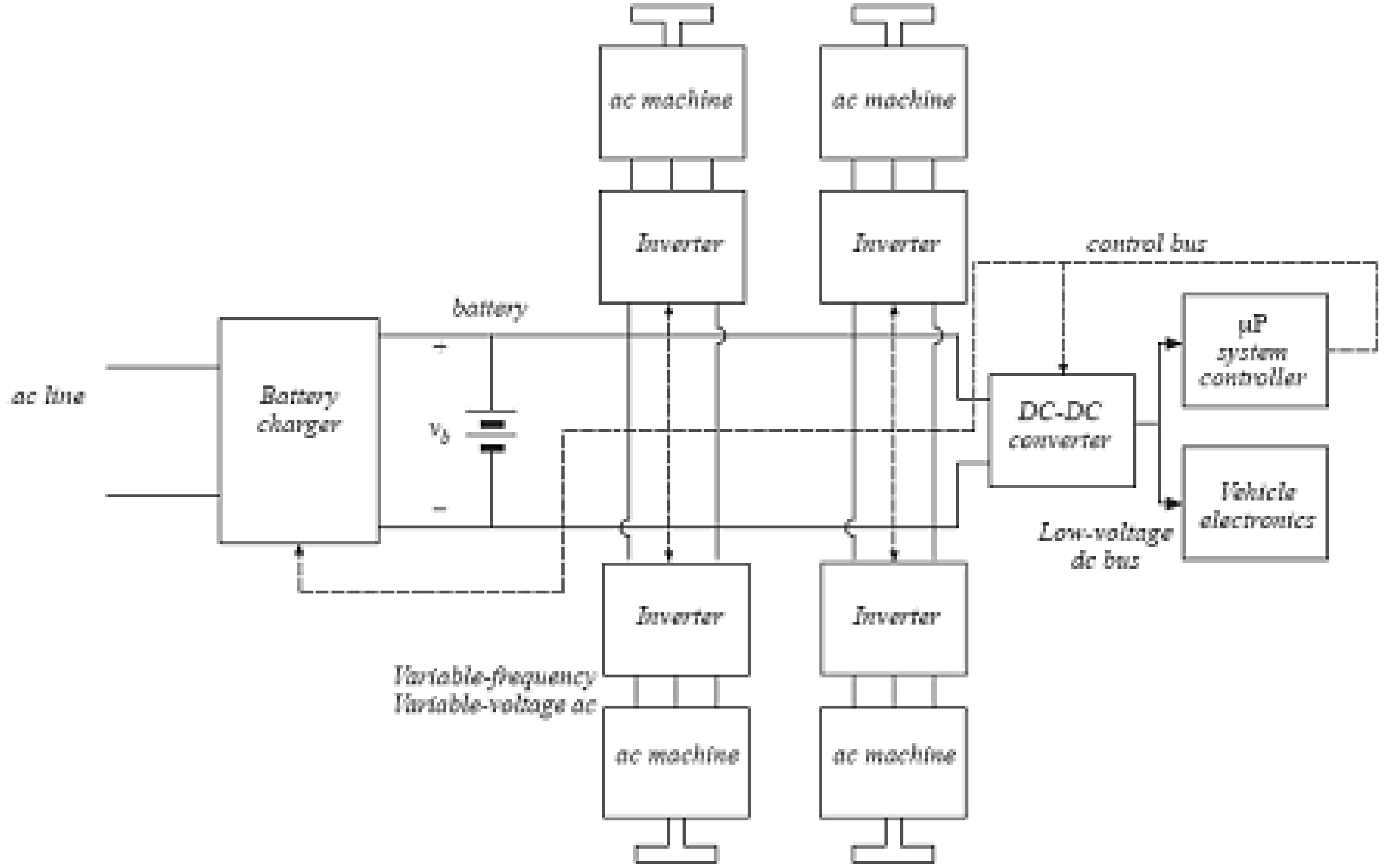
Part Number	Rated Max. Voltage	Rated Avg. Current	V_F (typical)	t_f(typical)
Single-Chip Devices				
HGTG32N60E2	600V	32A	2.4V	0.62μs
HGTG30N120D2	1200V	30A	3.2A	0.58μs
Multiple-Chip Power Modules				
CM400HA-12E	600V	400A	2.7V	0.3μs
CM300HA-24E	1200V	300A	2.7V	0.3μs

Example Application 1

Power Electronics of a Laptop Power Supply System



Example Application 2
An Electric Vehicle Power and Drive System



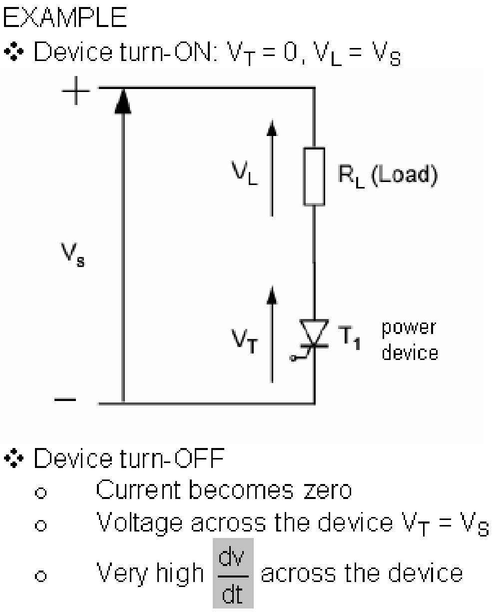
Transient Protection of Power Devices

Snubber circuit limits $\frac{dv}{dt}$ $\frac{di}{dt}$

as well as voltage and peak current in a switching device to safe specified limits!

Switching device's $\frac{dv}{dt}$

Rating is significant during the switching device (thyristor) turn-OFF process. Voltage can increase very rapidly to high levels. If the rate rise is excessive, it may cause damage to the device.



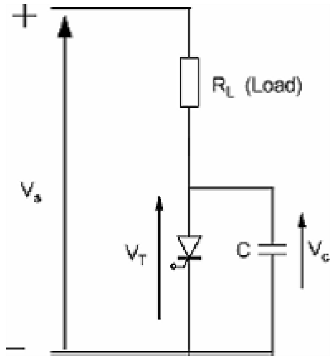
EXAMPLE

- Device turn-ON: $V_T = 0$, $V_L = V_S$

- Device turn-OFF
  - Current becomes zero
  - Voltage across the device $V_T = V_S$
  - Very high $\frac{dv}{dt}$ across the device

Transient Protection of Power Devices

TURN-OFF SNUBBER CIRCUIT ADDED



- Now when device turn-OFF, capacitor voltage is charged to V_S through R_L

i.e.

$$V_c = V_s\left(1 - e^{-t/CR_L}\right)$$

Rate of change of V_C with time

$$\frac{dV_c}{dt} = \frac{V_s}{CR_L} e^{-t/CR_L}$$

Maximum rate of change of V_C occurs at t = 0

$$\left.\frac{dV_c}{dt}\right|_{\max} = \frac{V_s}{CR_L}$$

Value of the capacitor may be chosen to limit the rate of rise of $\frac{dV_C}{dt}$ (thus protecting the switching device)

Minimum value of C to limit $\frac{dV_C}{dt}$ to a specified value is given by

$$C = \frac{V_s}{R_L} \frac{1}{\left.\frac{dV_c}{dt}\right|_{\max}}$$

Assignment in the Lab

- Use Multisim to investigate the speed of an n-channel enhanced mode MOSFET (IRF530N) in response to an input of 500 kHz, 50% duty cycle, 12 Vpeak, load = 6 ohm, Vcc = 12 V.