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 **translISTOR**.

- Thyristor has characteristics similar to a thyatron 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 (**pnnp** device) belongs to transistor (**pnp** or **nnp** device) family.

- This means that the thyristor is a solid state device like a transistor and has characteristics similar to that of a thyatron 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](image)
Thyristor Family Members

- **SCR**: Silicon Controlled Rectifier
- **DIA**: 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

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

Positive feedback

Trigger

Can not be turned off by control signal

Half-controllable

\[
I_{c1} = \alpha_1 I_A + I_{CBO1} \quad (1-1)
\]

\[
I_{c2} = \alpha_2 I_K + I_{CBO2} \quad (1-2)
\]

\[
I_K = I_A + I_G \quad (1-3)
\]

\[
I_A = I_{c1} + I_{c2} \quad (1-4)
\]

\[
I_A = \frac{\alpha_2 I_G + I_{CBO1} + I_{CBO2}}{1 - (\alpha_1 + \alpha_2)} \quad (1-5)
\]
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.
Typical Fully-Controlled Devices
Gate- Turn-Off Thyristor: GTO

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.
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

LM317T

Motor Leads

1 kΩ potentiometer

+12 to +24 VDC
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**

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Rated Max. Voltage</th>
<th>Rated Avg. Current</th>
<th>$R_{on}$</th>
<th>$Q_{g(typical)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRFZ48</td>
<td>60V</td>
<td>50A</td>
<td>0.018$\Omega$</td>
<td>110nC</td>
</tr>
<tr>
<td>IRF510</td>
<td>100V</td>
<td>5.6A</td>
<td>0.54$\Omega$</td>
<td>8.3nC</td>
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<tr>
<td>IRF540</td>
<td>100V</td>
<td>28A</td>
<td>0.077$\Omega$</td>
<td>72nC</td>
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<td>APT10M25BNR</td>
<td>100V</td>
<td>75A</td>
<td>0.025$\Omega$</td>
<td>171nC</td>
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<tr>
<td>IRF740</td>
<td>400V</td>
<td>10A</td>
<td>0.55$\Omega$</td>
<td>63nC</td>
</tr>
<tr>
<td>MTM15N40E</td>
<td>400V</td>
<td>15A</td>
<td>0.3$\Omega$</td>
<td>110nC</td>
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<tr>
<td>APT5025BN</td>
<td>500V</td>
<td>23A</td>
<td>0.25$\Omega$</td>
<td>83nC</td>
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<td>APT1001RB</td>
<td>1000V</td>
<td>11A</td>
<td>1.0$\Omega$</td>
<td>150nC</td>
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</tbody>
</table>
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 \( h_{FE} \) 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.
Switching Time Test of the MOSFET

(a)

-10V
Pulse Width $\leq 1\mu s$
Duty Factor $\leq 0.1\%$

(b)

$t_{d(on)}$  $t_r$  $t_{d(off)}$  $t_f$
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**

![IGBT schematic symbols](image)

**Equivalent circuit**

![IGBT equivalent circuit](image)

## Survey of Commercially Available IGBTs

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Rated Max. Voltage</th>
<th>Rated Avg. Current</th>
<th>Vr (typical)</th>
<th>t (typical)</th>
</tr>
</thead>
<tbody>
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<td><strong>Single-Chip Devices</strong></td>
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<tr>
<td>HGTG32N60E2</td>
<td>600V</td>
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<td>1200V</td>
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<td>3.2A</td>
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<tr>
<td><strong>Multiple-Chip Power Modules</strong></td>
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<td></td>
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</tr>
<tr>
<td>CM400HA-12E</td>
<td>600V</td>
<td>400A</td>
<td>2.7V</td>
<td>0.3µs</td>
</tr>
<tr>
<td>CM300HA-24E</td>
<td>1200V</td>
<td>300A</td>
<td>2.7V</td>
<td>0.3µs</td>
</tr>
</tbody>
</table>
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 $t = 0$

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

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

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