

POWER ELECTRONICS OVERVIEW

- Introduction
 - Definition and concepts of Power Electronics/Electronics Power Conversion
 - Application
- Power semiconductor switches
 - Diodes, Thyristors, controllable switches: ratings, applications
 - Gate/base drivers
 - Losses
 - Snubbers
- PE System simulation
- Reading material:
 - Mohan
 - (Chapter 1,2 and 4)
 - Paper:
 - Bose, B.K.: "Energy, Environment, and Advances in Power Electronics", IEEE Transaction on Power Electronics. Vol.15, No.4, July 2000.

POWER ELECTRONICS

- DEFINITION: To convert, i.e. to *process* and *control* the flow of electric power by supplying voltage s and currents in a form that is optimally suited for *user loads*.
- Sometimes known as “Electronics Power Conversion” systems. Basic block diagram shown in Figure 1.

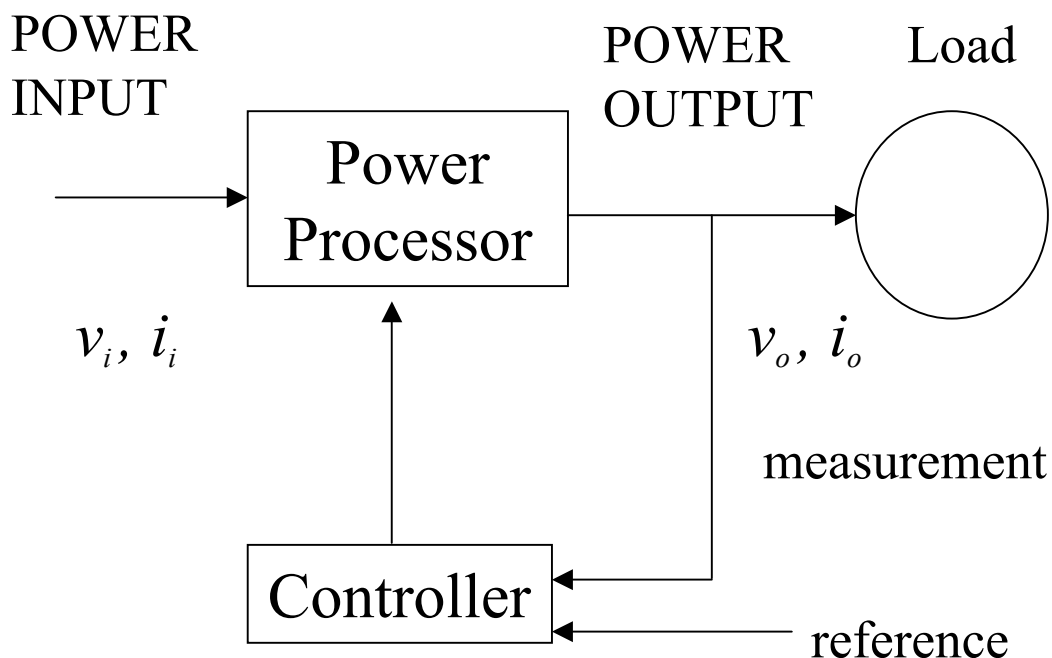


Figure 1

Goal of electronic power conversion systems

- To convert electrical energy from one form to another, from the source to load with highest efficiency, high availability and high reliability with the lowest cost, smallest size and weight.
- Static applications
 - involves non-rotating or moving mechanical components.
 - E.g. rectifiers, inverters, choppers, cycloconverters.
- Drive applications
 - intimately contains moving or rotating components such as motors.
 - E.g. DC drives, AC drives, Permanent magnet motor drives.

Applications

- Power generation and transmission (HVDC)
- Uninterruptable power supplies (UPS)
- DC power supplies
- Energy conservation (ballast, pumps, compressors, air-condition)
- Transportation (Electric car, trains)
- Process control and factory automation
- Electroplating, Welding
- Heating, cooling
- Utility-related application

Current issues related to power electronics: Energy scenario

- Energy Scenario.
 - Need to reduce dependence on fossil fuel (coal, natural gas, oil) and nuclear power resource (uranium).
 - Depletion of these sources is expected (see Bose paper).
 - Effort to tap renewable energy resources such as solar, wind, fuel-cell etc. need to be increased.
 - Energy saving: 15-20% of electricity can be saved by PE applications.
 - E.g. variable speed drives (air conditioned, fans, pumps). Variable speed compressor aircond system saves up to 30% of energy compared to conventional thermostat-controlled system.
 - electrical lighting using electronics ballast can boost the efficiency of fluorescent lamp by 20%.

Environmental issues

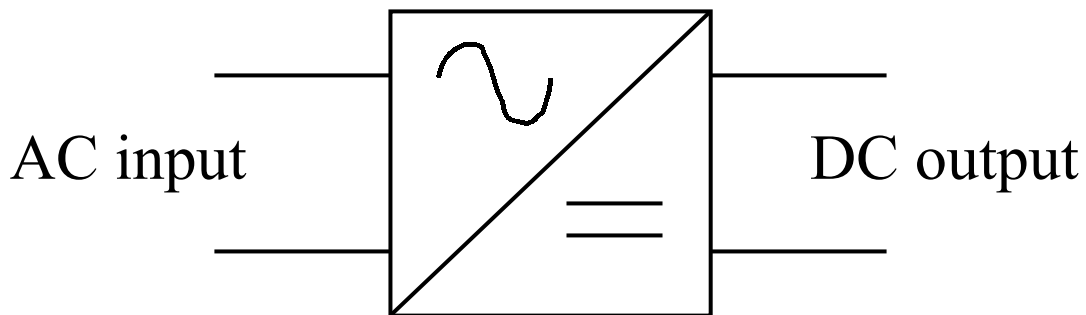
- Environment issues
 - Nuclear safety. Nuclear plants can remain radioactive for thousands of years.
 - Burning of fossil fuel emits gases such as CO₂, CO (oil burning), SO₂, NO_x (coal burning) etc.
 - Creates global warming (green house effect), acid rain and urban pollution from smokes.
 - One way to reduce the problem is to promote renewable energy resources.
 - To mitigate the pollution problem, centralization of power stations to remote non-urban are needed. Stringent controls can be imposed on central power plants.
 - Special effort is needed to reduce pollution in cities by enforcing the use of electric vehicle.

PE growth

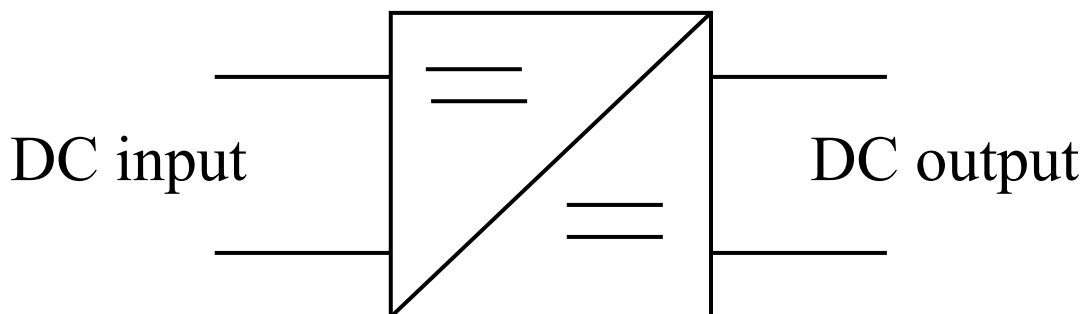
- PE rapid growth due to:
 - Advances in power (semiconductor) switches
 - Advances in microelectronics (DSP, VLSI, microprocessor/microcontroller, ASIC)
 - New ideas in control algorithms
 - Demand for new applications
- PE is an interdisciplinary field:
 - Digital/analogue electronics
 - Power and energy
 - Microelectronics
 - Control system
 - Computer, simulation and software
 - Solid-state physics and devices
 - Packaging
 - Heat transfer

Power Electronics Converters

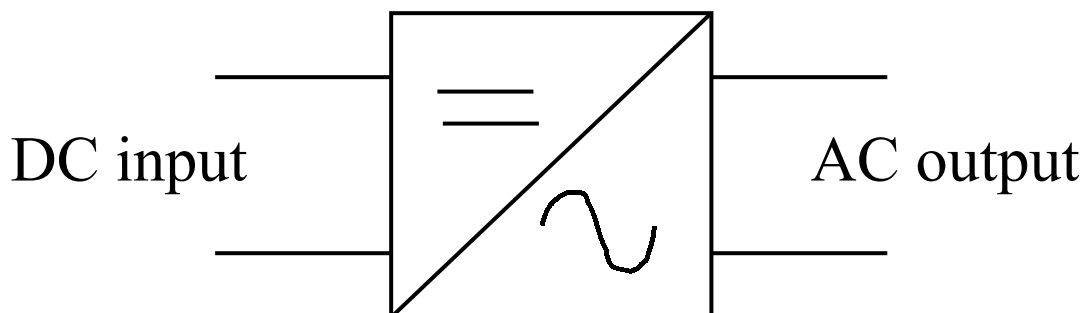
AC to DC: RECTIFIER



DC to DC: CHOPPER

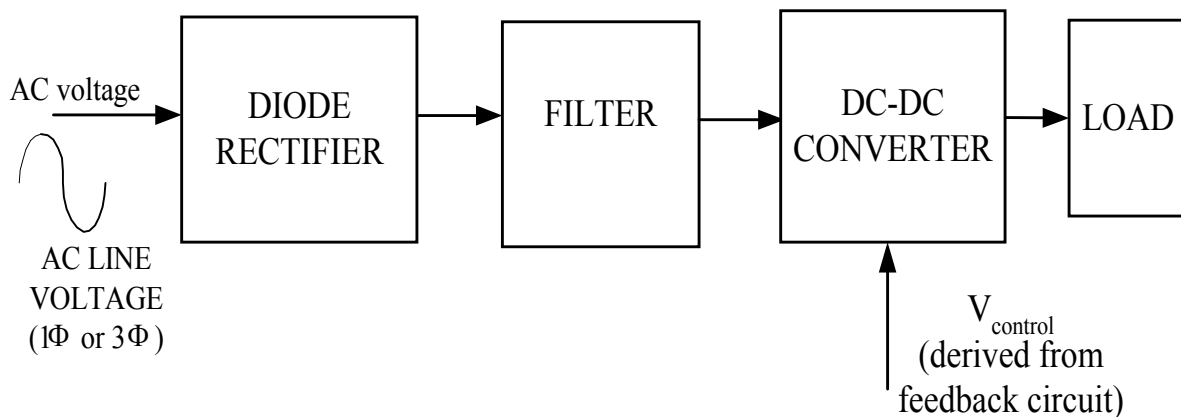


DC to AC: INVERTER

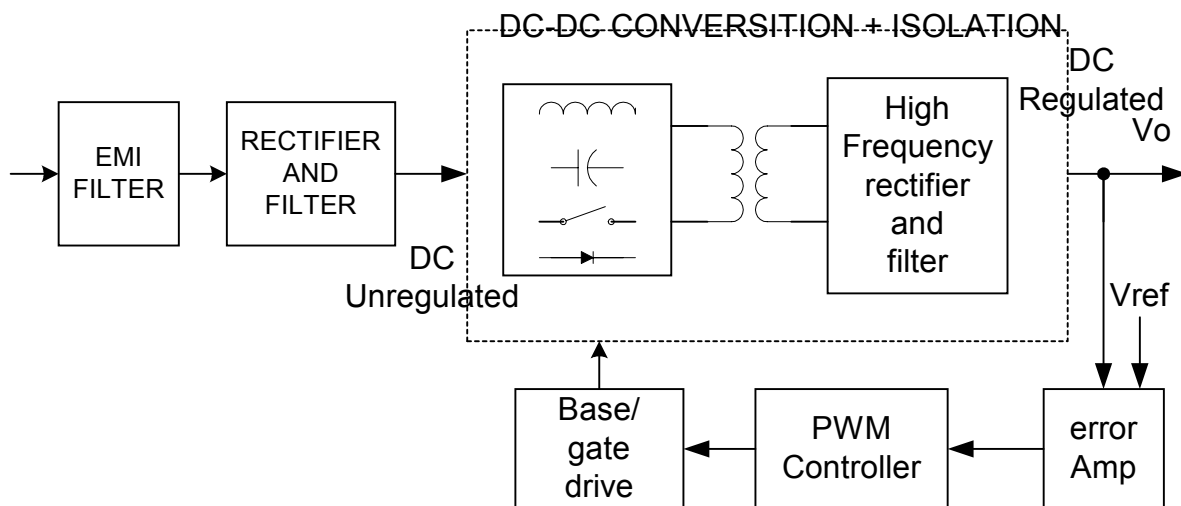


Application example: Static converter

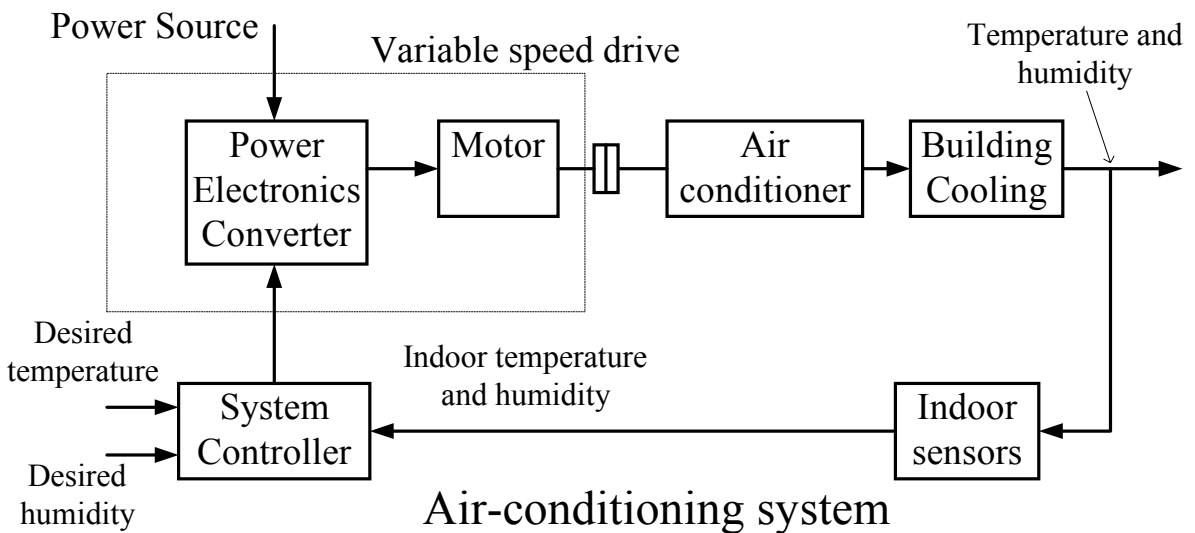
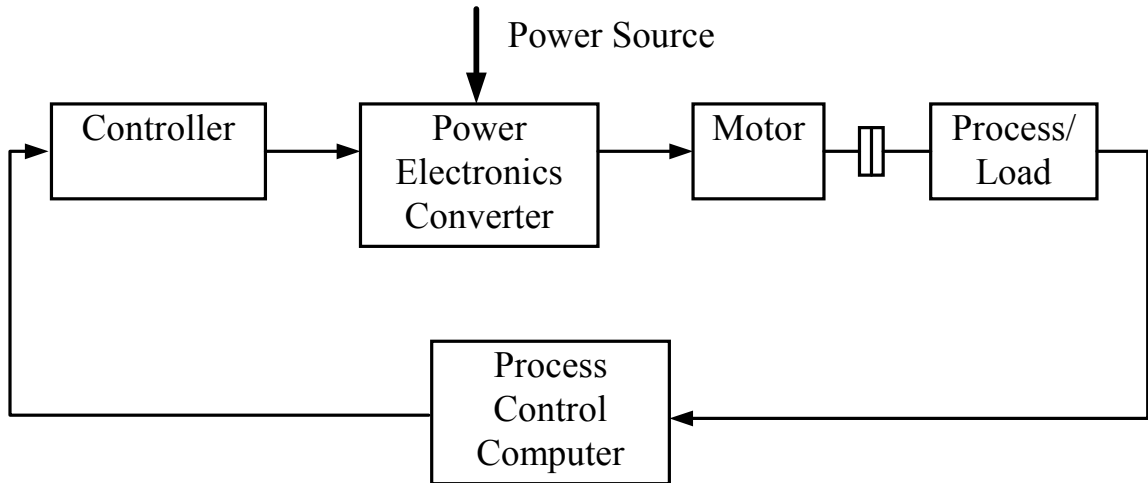
DC to DC converter



Switched-mode power supply



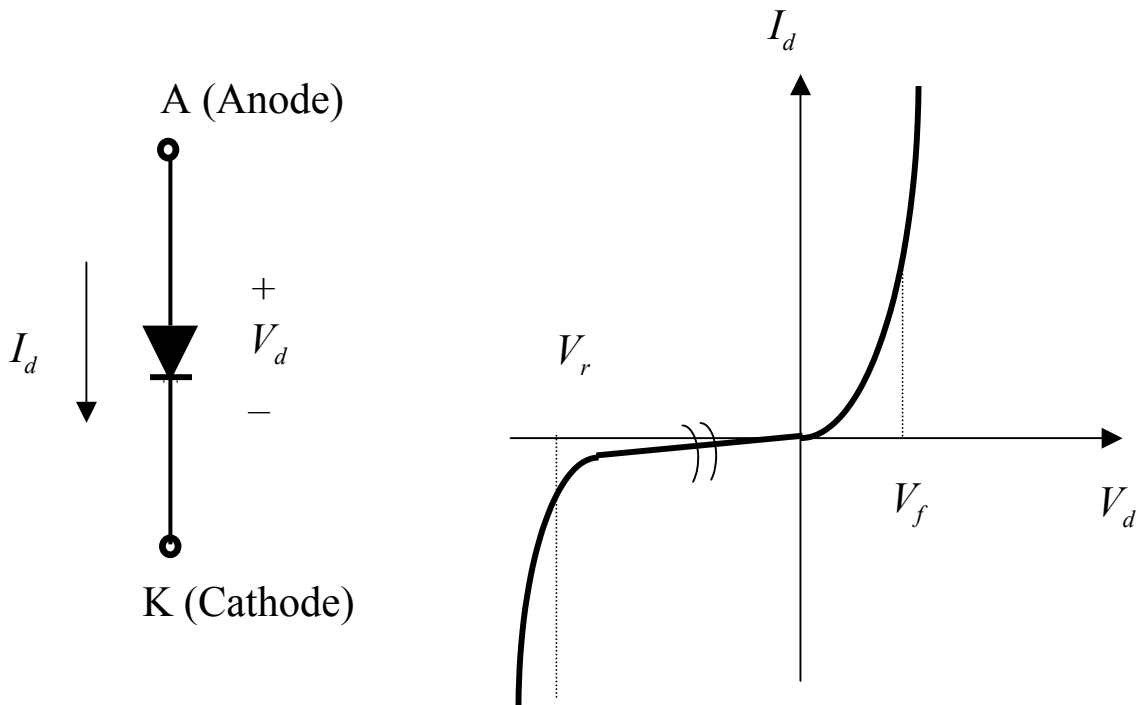
Application example: Variable speed drive system



Power semiconductor devices (Power switches)

- Power switches are the work-horses of PE systems.
- PE switches works in two states only:
 - Fully on (conducting);
 - Fully off (blocking)
- Can be categorised into three group
 - Diode : on and off states controlled by power circuit only
 - Thyristor (SCR) : Latched on by low-power control signal but must be turned off by power circuit. Cannot be turned off by control signal.
 - Controllable switches: Can be turned on and off by low-power control signals (e.g. BJT, MOSFET, IGBT, GTO)

Power Diode

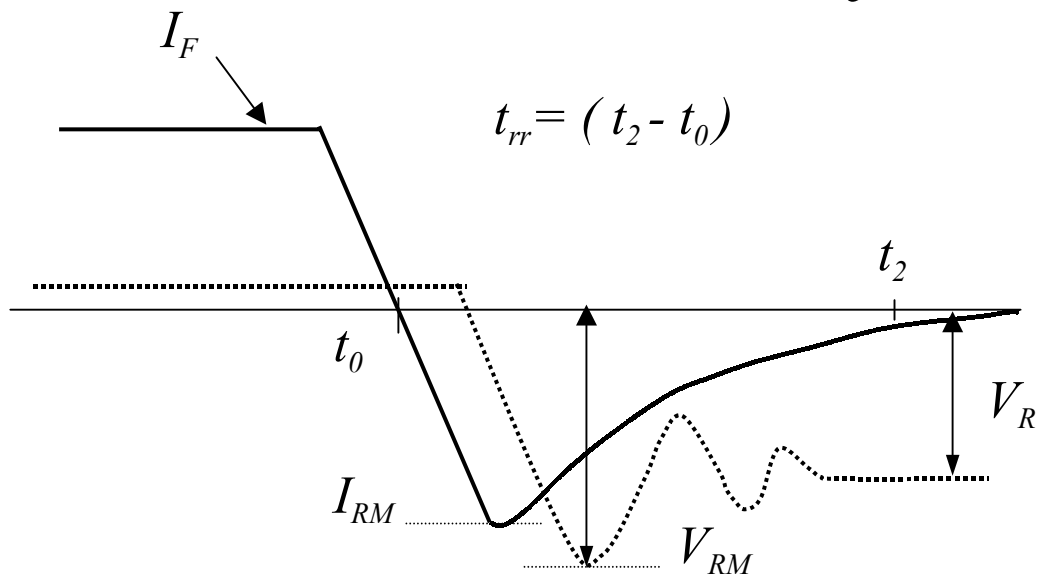


Diode: Symbol

v - i characteristics

- When diode is forward biased, it conducts current with a small forward voltage (V_f) across it (0.2-3V)
- When reversed (or blocking state), a negligibly small leakage current (μA to mA) flows until the reverse breakdown occurs. Diode should not be operated at reverse voltage greater than V_r

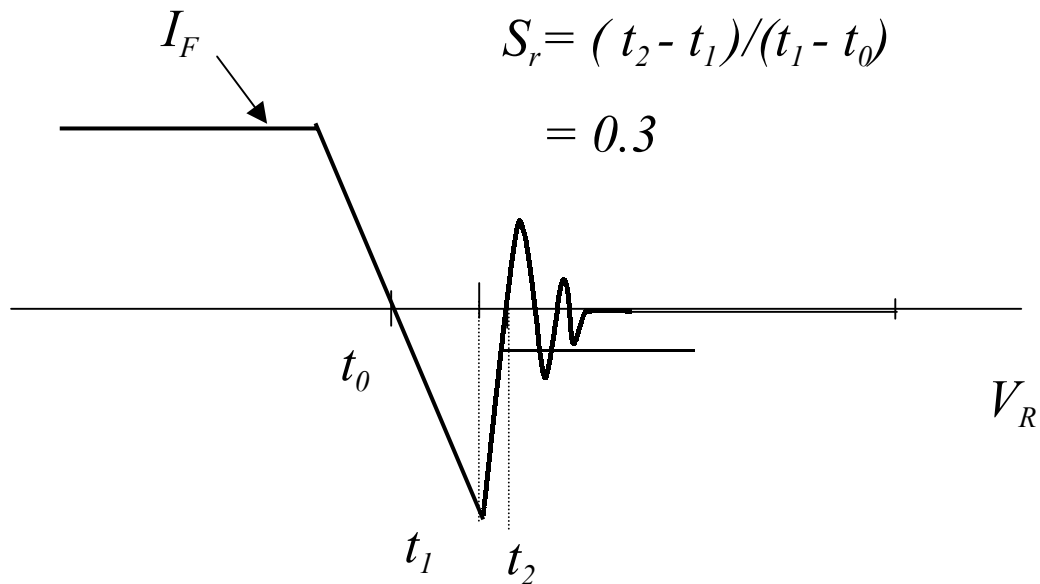
Reverse Recovery



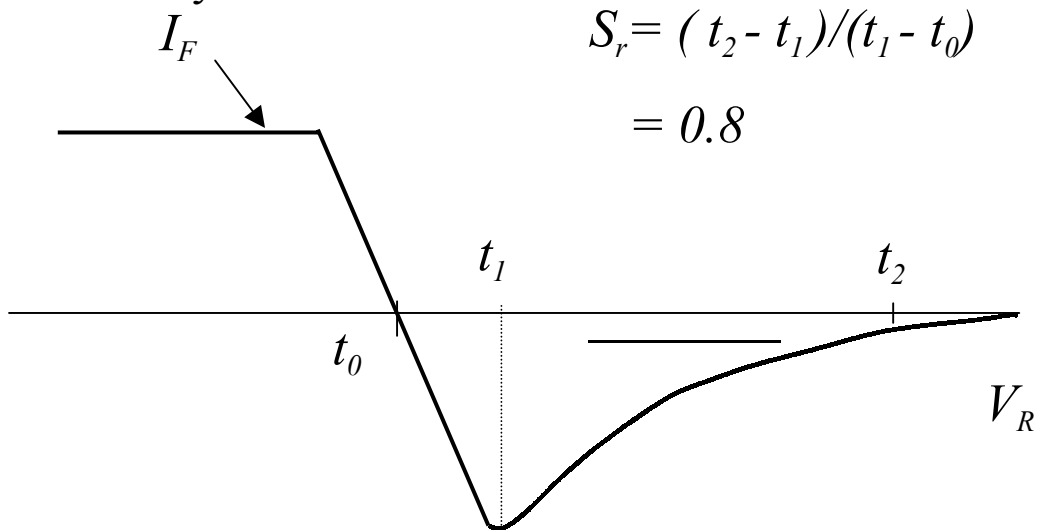
- When a diode is switched quickly from forward to reverse bias, it continues to conduct due to the *minority carriers* which remains in the p-n junction.
- The minority carriers require finite time, i.e, t_{rr} (reverse recovery time) to recombine with opposite charge and neutralise.
- Effects of reverse recovery are increase in switching losses, increase in voltage rating, over-voltage (spikes) in inductive loads

Softness factor, S_r

Snap-off



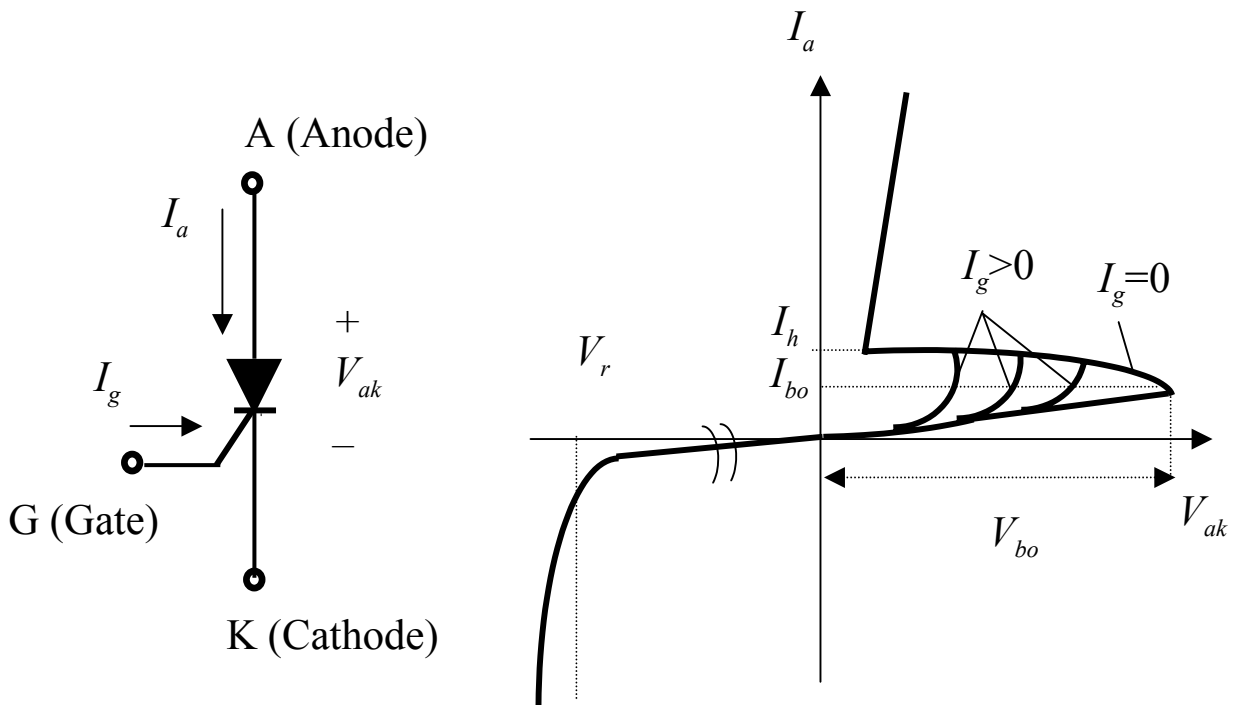
Soft-recovery



Types of Power Diodes

- Line frequency (general purpose):
 - on state voltage very low (below 1V)
 - large t_{rr} (about 25us)
 - very high current (up to 5kA) and voltage (5kV) ratings
 - Used in line-frequency (50/60Hz) applications such as rectifiers
- Fast recovery
 - very low t_{rr} (<1us).
 - Power levels at several hundred volts and several hundred amps
 - Normally used in high frequency circuits
- Schottky
 - very low forward voltage drop (typical 0.3V)
 - limited blocking voltage (50-100V)
 - Used in low voltage, high current application such as switched mode power supplies.

Thyristor (SCR)



Thyristor: Symbol

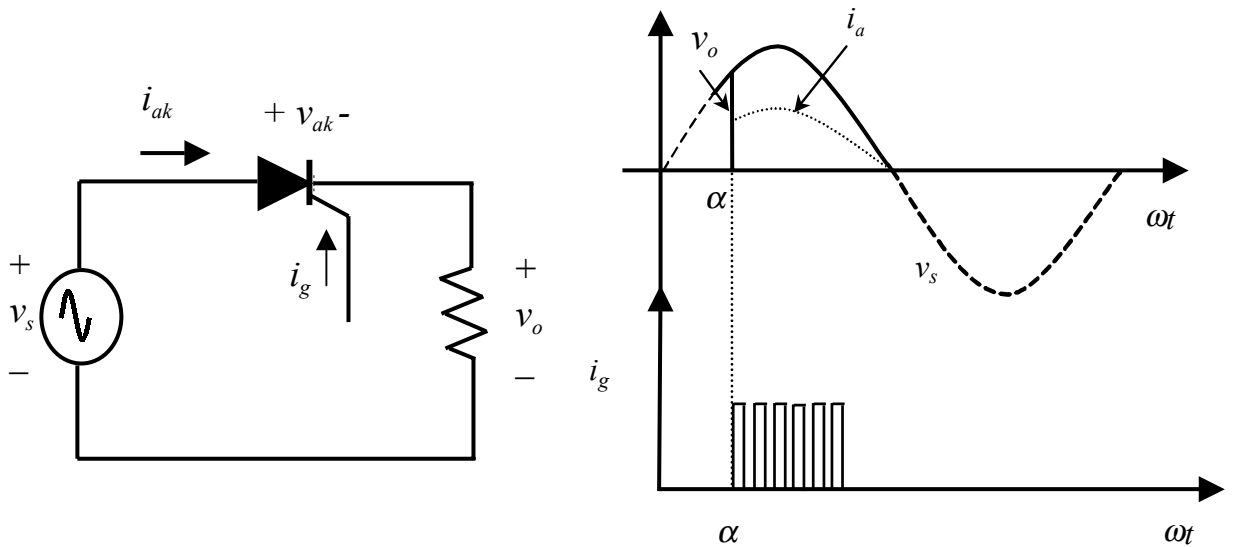
v-i characteristics

- Thyristors can only be turned on with two conditions:
 - the device is in forward blocking state (i.e V_{ak} is positive)
 - a positive gate current (I_g) is applied at the gate
- Once conducting, the anode current is **LATCHED** (continuously flowing).

Turning on/off mechanism

- In reverse -biased mode, the SCR behaves like a diode. It conducts a small leakage current which is almost dependent of the voltage, but increases with temperature.
- When the peak reverse voltage is exceeded, avalanche breakdown occurs, and the large current will flow.
- In the forward biased mode, with no gate current present (i.e. in the untriggered state, the device exhibits a leakage current.
- If the forward breakover voltage (V_{bo}) is exceeded, the SCR “self-triggers” into the conducting state and the voltage collapses to the normal forward volt-drop, typically 1.5-3V. The presence of any gate current will reduce the forward breakover voltage.

Thyristor Conduction



- Thyristor cannot be turned off by applying negative gate current. It can only be turned off if I_a goes negative (reverse)
 - This happens when negative portion of the of sine-wave occurs (natural commutation),
- Another method of turning off is known as “forced commutation”,
 - The anode current is “diverted” to another circuitry.

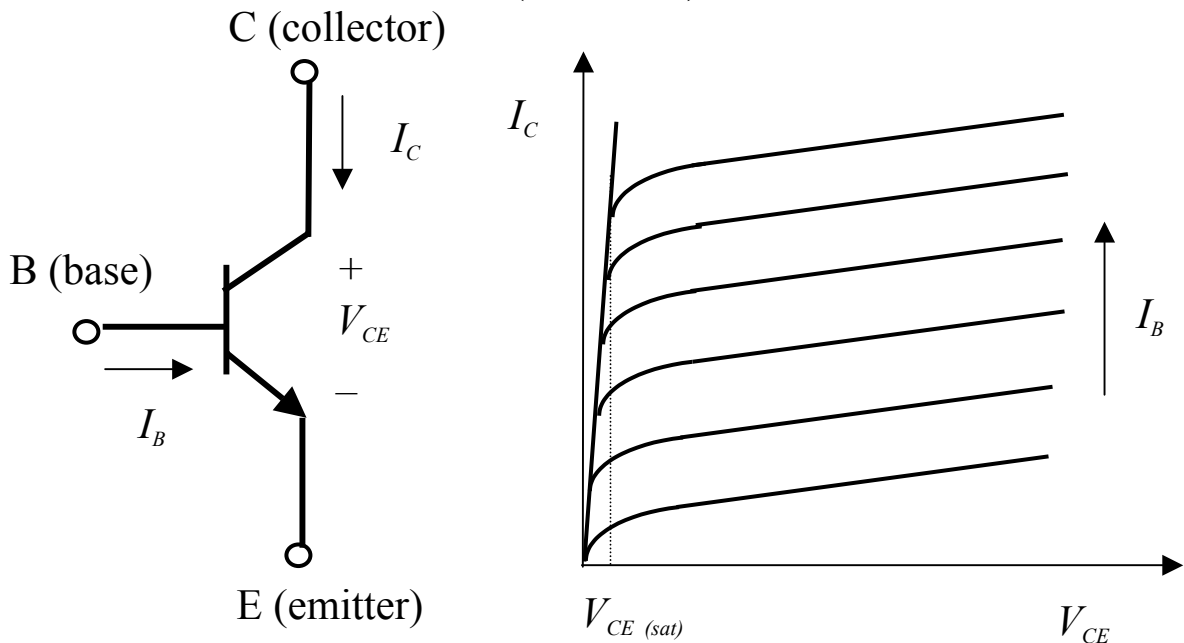
Types of thyristors

- Phase controlled
 - rectifying line frequency voltage and current for ac and dc motor drives
 - large voltage (up to 7kV) and current (up to 4kA) capability
 - low on-state voltage drop (1.5 to 3V)
- Inverter grade
 - used in inverter and chopper
 - Quite fast. Can be turned-on using “force-commutation” method.
- Light activated
 - Similar to phase controlled, but triggered by pulse of light.
 - Normally very high power ratings
- TRIAC
 - Dual polarity thyristors

Controllable switches (power transistors)

- Can be turned “ON” and “OFF” by relatively very small control signals.
- Operated in SATURATION and CUT-OFF modes only. No “linear region” operation is allowed due to excessive power loss.
- In general, power transistors do not operate in latched mode.
- *Traditional devices:* Bipolar junction transistors (BJT), Metal oxide silicon field effect transistor (MOSFET), Insulated gate bipolar transistors (IGBT), Gate turn-off thyristors (GTO)
- *Emerging (new) devices:* Gate controlled thyristors (GCT).

Bipolar Junction Transistor (BJT)



BJT: symbol (npn)

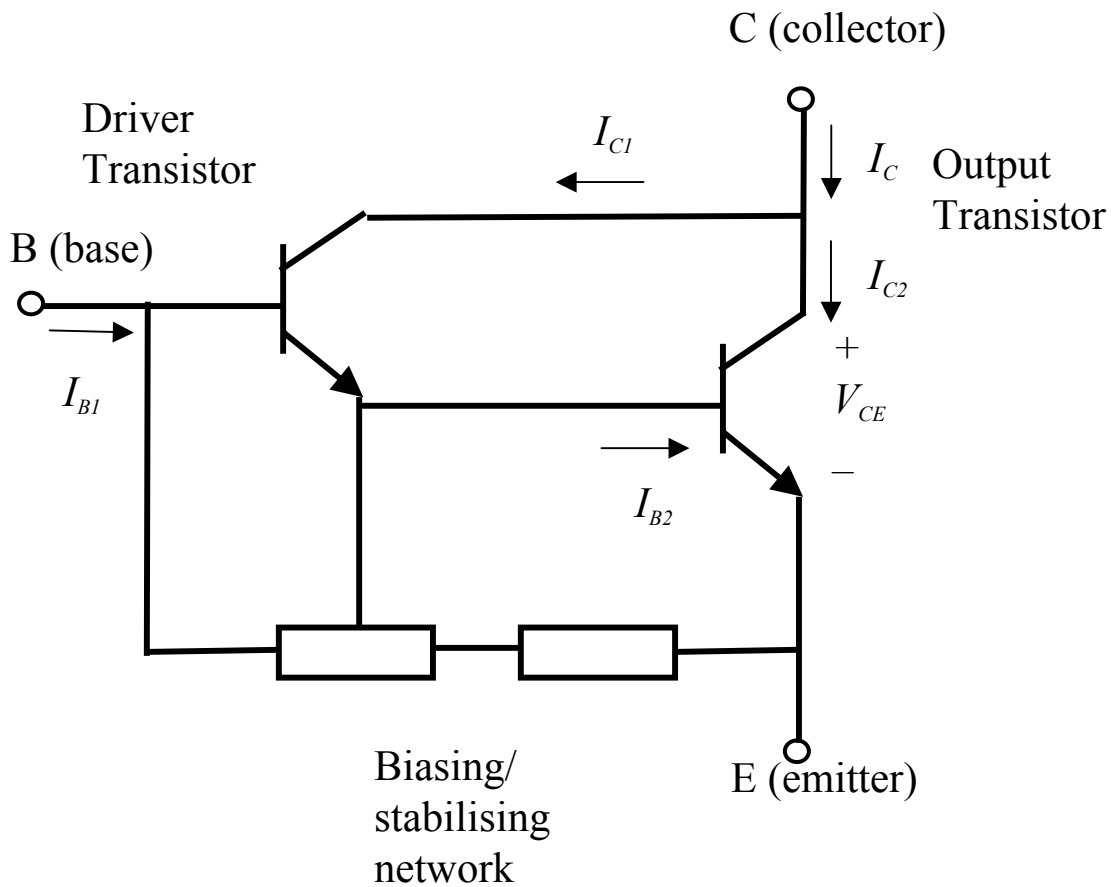
v-i characteristics

- Ratings: Voltage: $V_{CE} < 1000$, Current: $I_C < 400A$. Switching frequency up to 5kHz. Low on-state voltage: $V_{CE(sat)} : 2-3V$
- Low current gain (β). Need high base current to obtain reasonable I_C . Expensive and complex base drive circuit.
- Not popular in new products.

BJT characteristics

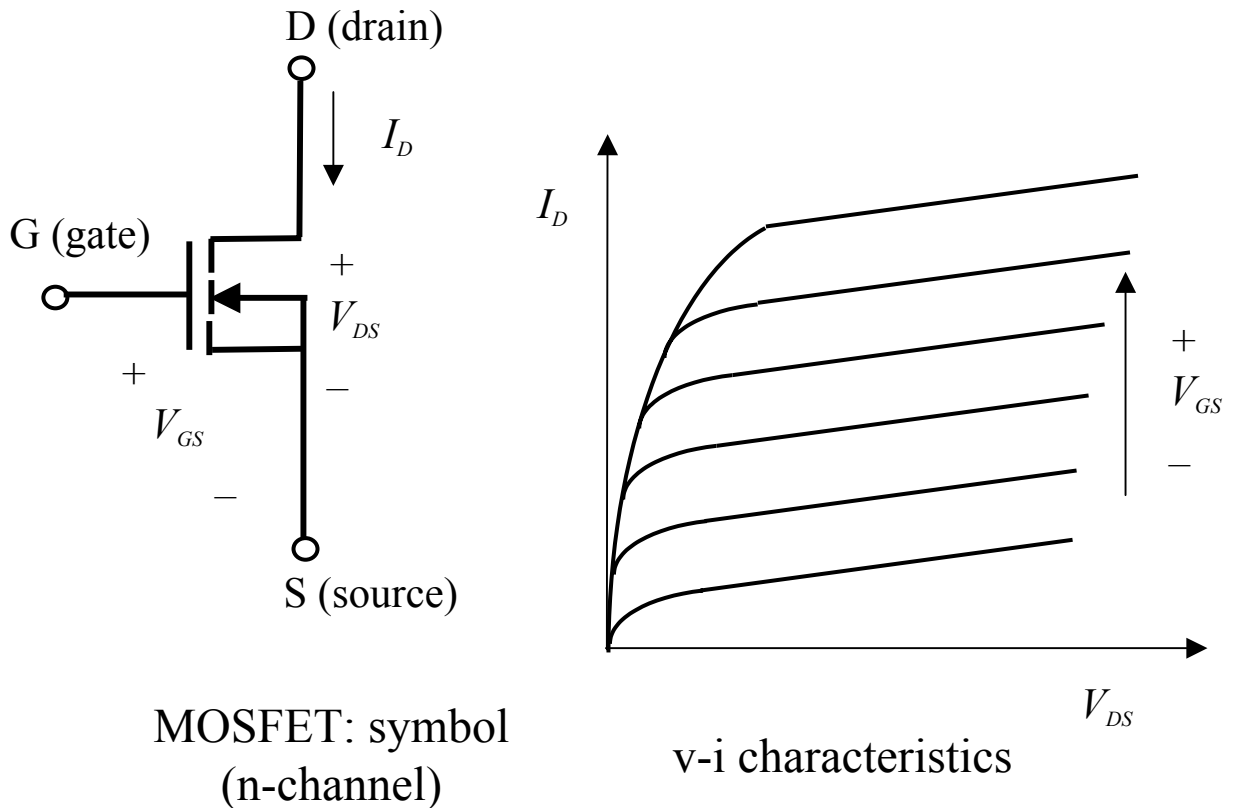
- To turn on/off the device, a base drive circuit is connected to the base and emitter terminal.
- To turn on, current is injected into the base terminal. When turned on, conventional current passes from collector to emitter.
- To turn-off, the base current is removed.
- The current gain of a BJT tends to be low when operated in the saturated ON condition. $\beta < 10$ is common. It deteriorates as voltage ratings increase.
- It is normal to use Darlington connection for higher current gain.

BJT Darlington pair



$$\begin{aligned}
 \beta &= I_c / I_{B1} = (I_{c1} + I_{c2}) / I_{B1} = \frac{I_{c1}}{I_{B1}} + \frac{I_{c2}}{I_{B1}} \\
 &= \beta_1 + \left(\frac{I_{c2}}{I_{B2}} \right) \cdot \left(\frac{I_{B2}}{I_{B1}} \right) = \beta_1 + \beta_2 \cdot \left(\frac{I_{B1} + I_{c1}}{I_{B1}} \right) \\
 &= \beta_1 + \beta_2 \cdot (1 + \beta_1) \\
 \Rightarrow \beta &= \beta_1 + \beta_2 + \beta_1\beta_2
 \end{aligned}$$

Metal Oxide Silicon Field Effect Transistor (MOSFET)

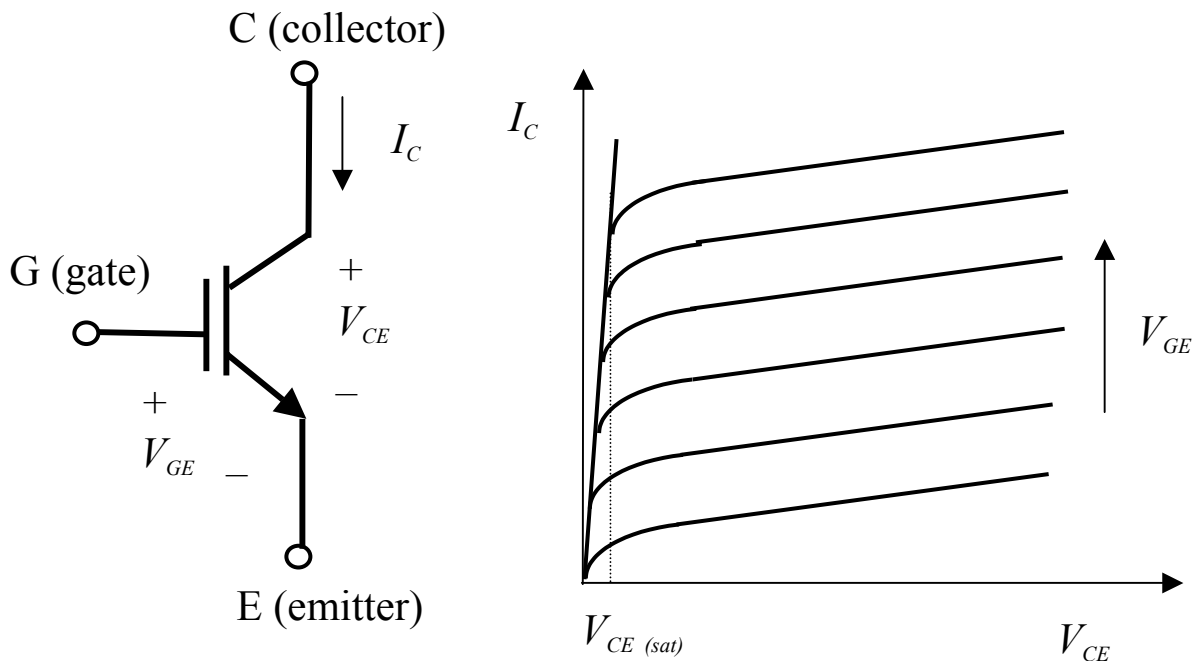


- Ratings: Voltage $V_{DS} < 500V$, current $I_{DS} < 300A$.
- Very fast device: $> 100KHz$. For some low power devices (few hundred watts) may go up to MHz range.

MOSFET characteristics

- Turning on and off is very simple. Only need to provide $V_{GS} = +15V$ to turn on and $0V$ to turn off. Gate drive circuit is simple.
- Basically low voltage device. High voltage device are available up to $600V$ but with limited current. Can be paralleled quite easily for higher current capability.
- Internal (dynamic) resistance between drain and source during on state, $R_{DS(ON)}$, limits the power handling capability of MOSFET. High losses especially for high voltage device due to $R_{DS(ON)}$.
- Dominant in high frequency application ($>100kHz$). Biggest application is in switched-mode power supplies.

Insulated Gate Bipolar Transistor (IGBT)



IGBT: symbol

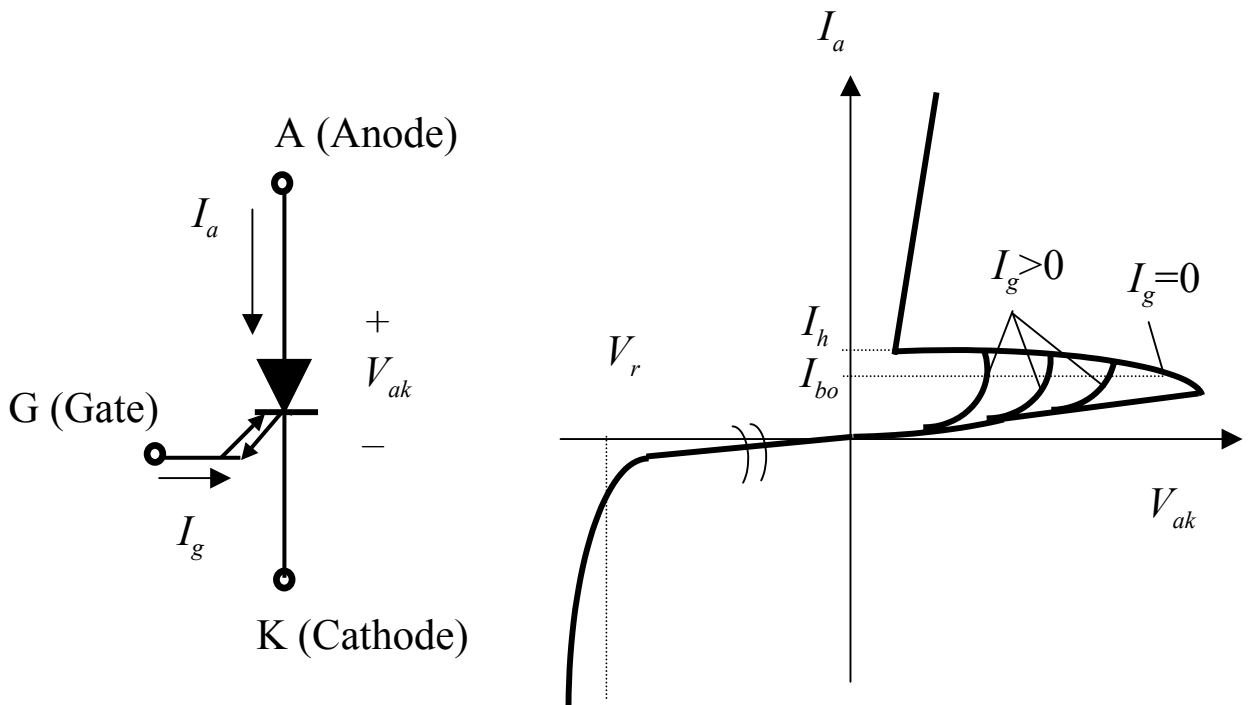
v-i characteristics

- Combination of BJT and MOSFET characteristics. Compromises include:
 - Gate behaviour similar to MOSFET - easy to turn on and off.
 - Low losses like BJT due to low on-state Collector-Emitter voltage (2-3V).

IGBT

- Ratings: Voltage: $V_{CE} < 3.3\text{kV}$, Current, : $I_C < 1.2\text{kA}$ currently available. Work in under progress for 4.5kV/1.2kA device. Constant improvement in voltage and current ratings
- Good switching capability (up to 100KHz) for newer devices. Typical application, IGBT is used at 20-50KHz.
- For very high power devices and applications, frequency is limited to several KHz.
- Very popular in new products; practically replacing BJT in most new applications.
- “Snubberless” operation is possible. Most new IGBTs do not require snubbers.

Gate turn-off thyristor (GTO)



GTO: Symbol

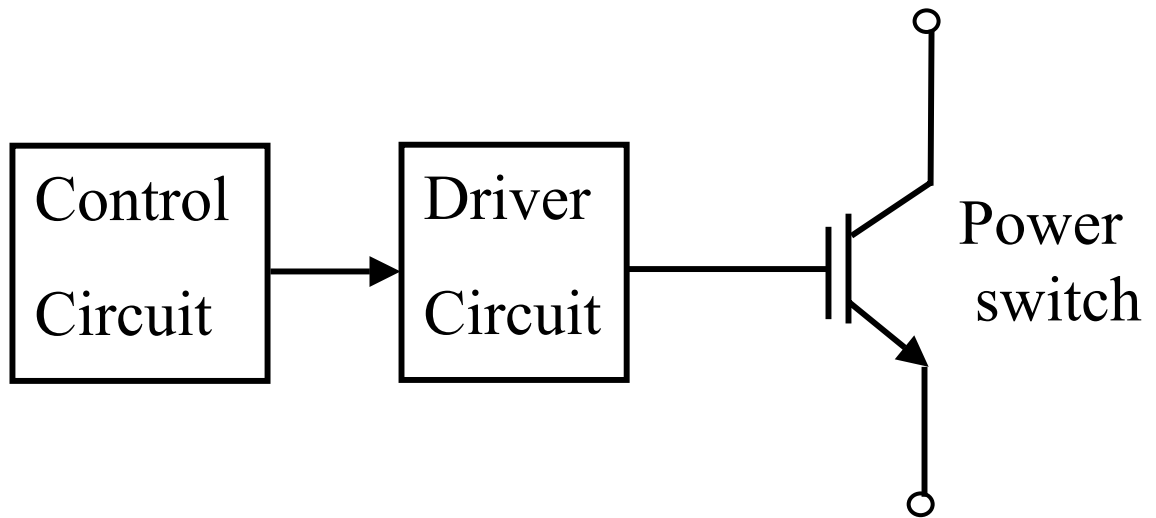
v - i characteristics

- Behave like normal thyristor, but can be turned off using gate signal
- However turning off is difficult. Need very large reverse gate current (normally 1/5 of anode current)

GTO

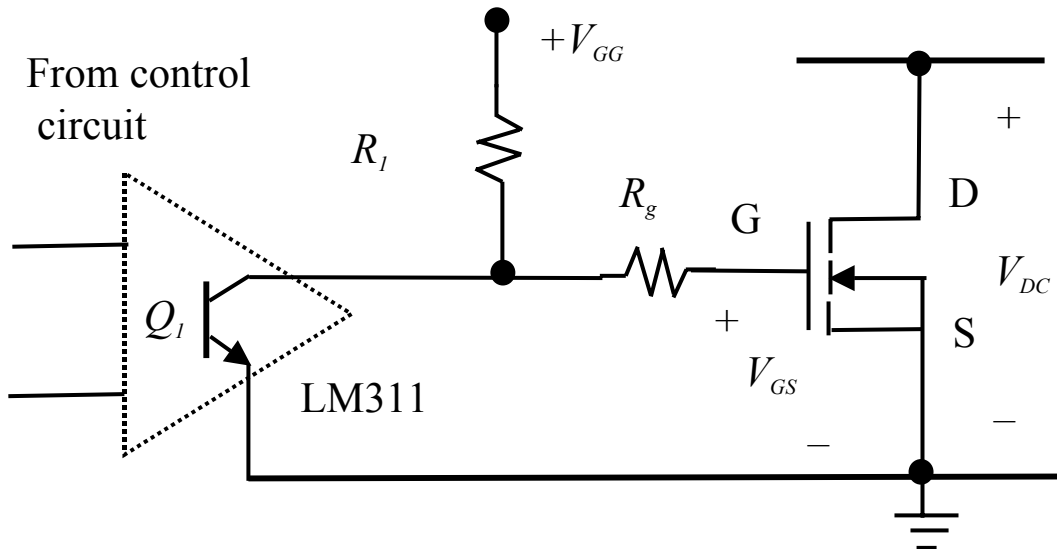
- Ratings: Voltage: $V_{ak} < 5\text{kV}$; Current: $I_a < 5\text{kA}$. Highest power ratings switch. Frequency $< 5\text{KHz}$.
- Gate drive design is very difficult. Need very large reverse gate current to turn off. Often custom-tailored to specific application.
- Currently getting very stiff competition from high power IGBT. The latter has much simpler and cheaper drivers.
- GTO normally requires snubbers. High power snubbers are expensive.
- In very high power region ($> 5\text{kV}$, $> 5\text{kA}$), development in gate-controlled thyristor (GCT) may effectively end the future of GTO

(Base/gate) Driver circuit



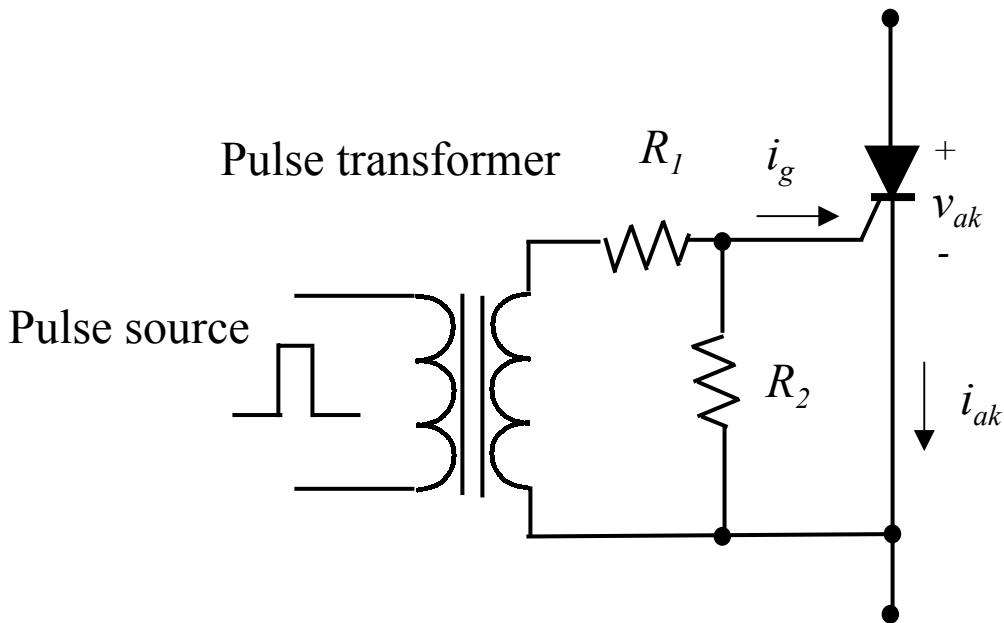
- Interface between control (low power electronics) and (high power) switch.
Functions:
 - amplifies control signal to a level required to drive power switch
 - provides electrical isolation between power switch and logic level
- Complexity of driver varies markedly among switches. MOSFET/IGBT drivers are simple but GTO drivers are very complicated and expensive.

Example: simple MOSFET gate driver



- Note: MOSFET requires $V_{GS} = +15V$ for turn on and $0V$ to turn off. LM311 is a simple amp with open collector output Q_1 .
- When B_1 is high, Q_1 conducts. V_{GS} is pulled to ground. MOSFET is off.
- When B_1 is low, Q_1 will be off. V_{GS} is pulled to V_{GG} . If V_{GG} is set to $+15V$, the MOSFET turns on.

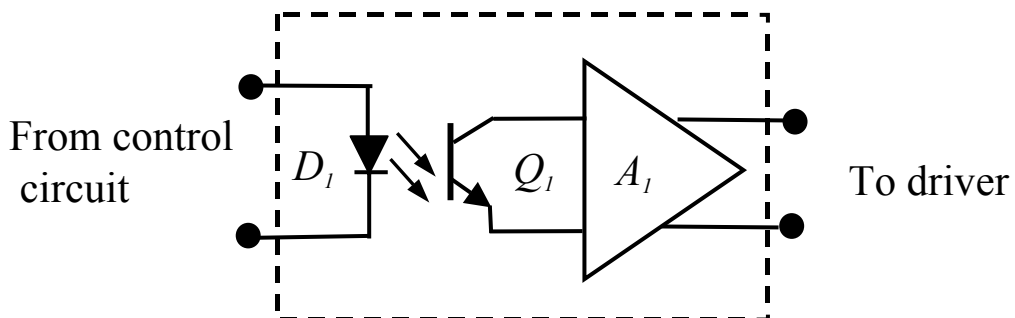
Gate drive for thyristors



- Pulse transformer is used for isolation. R_1 is to limit the gate current
- Normally a pulse with length 10 μ s with amplitude of 50mA is sufficient to turn-on the thyristors. It is quite common to fire the thyristors with successive pulses to ensure proper turn-on.
- It is not possible to *turn-off* a thyristor with the above circuit

Electrical isolation for drivers

- Isolation is required to prevent damages on the high power switch to propagate back to low power electronics.
- Normally opto-coupler (shown below) or high frequency magnetic materials (as shown in the thyristor case) are used.



Opto-coupler isolation

- Many standard driver chips have built-in isolation. For example TLP 250 from Toshiba, HP 3150 from Hewlett-Packard uses opto-coupling isolation.

Switches comparisons (2000)

	Thy	BJT	FET	GTO	IGBT
Avail- abilty	Early 60s	Late 70s	Early 80s	Mid 80s	Late 80s
State of Tech.	Mature	Mature	Mature/ improve	Mature	Rapid improve
Voltage ratings	5kV	1kV	500V	5kV	3.3kV
Current ratings	4kA	400A	200A	5kA	1.2kA
Switch Freq.	na	5kHz	1MHz	2kHz	100kHz
On- state Voltage	2V	1-2V	$I^* R_{ds}$ (on)	2-3V	2-3V
Drive Circuit	Simple	Difficult	Very simple	Very difficult	Very simple
Comm- ents	Cannot turn off using gate signals	Phasing out in new product	Good perform ance in high freq.	King in very high power	Best overall perform ance.

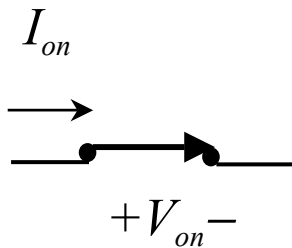
Application examples

- For each of the following application, choose the best power switches and reason out why.
 - An inverter for the light-rail train (LRT) locomotive operating from a DC supply of 750 V. The locomotive is rated at 150 kW. The induction motor is to run from standstill up to 200 Hz, with power switches frequencies up to 10KHz.
 - A switch-mode power supply (SMPS) for remote telecommunication equipment is to be developed. The input voltage is obtained from a photovoltaic array that produces a maximum output voltage of 100 V and a minimum current of 200 A. The switching frequency should be higher than 100kHz.
 - A HVDC transmission system transmitting power of 300 MW from one ac system to another ac system both operating at 50 Hz, 230 kV rms line to line and the DC link voltage operating at 200 kV.

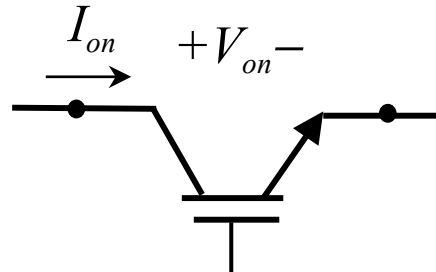
Power switch losses

- It is important to consider losses of power switches:
 - to ensure that the system operates reliably under prescribed ambient conditions
 - so that heat removal mechanism (e.g. heat sink, radiators, coolant) can be specified. Heat sinks and other heat removal systems are costly and bulky.
 - losses in switches affects the system efficiency
- If a power switch is not cooled to its specified junction temperature, the full power capability of the switch cannot be realised. *Derating* of the power switch ratings may be necessary.
- Main losses occurs in power switches are
 - forward conduction losses,
 - blocking state losses
 - switching losses

Forward conduction losses



Ideal switch



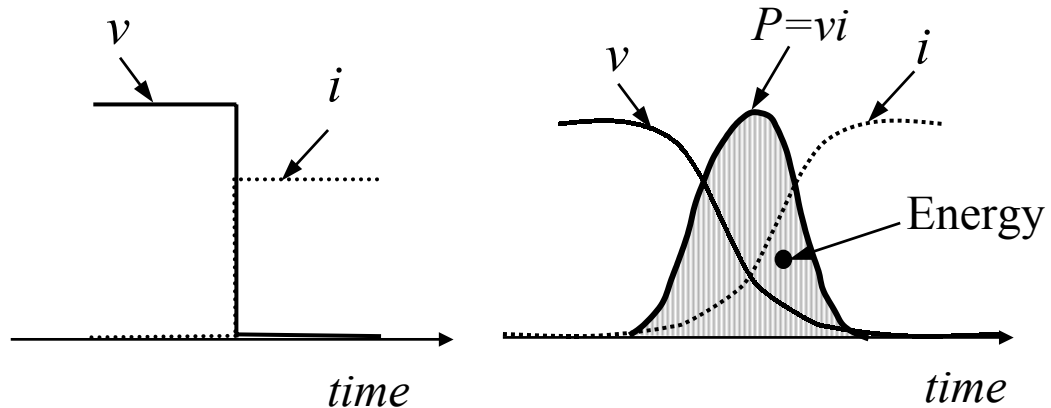
Real switch

- Ideal switch has zero voltage drop across it during turn-on (V_{on}). Although the forward current (I_{on}) may be large, the losses on the switch is zero.
- But for real switches, e.g. BJT, IGBT, GTO, SCR, GCT have forward conduction voltage (on state) between 1-3V. MOSFET has on state voltage which is characterised by the $R_{DS(ON)}$.

Forward conduction and blocking state losses

- Losses is measured by product of volt-drop across the device V_{on} with the current, I_{on} , averaged over the period.
- Forward conduction losses is the major source of loss at low frequency and DC operation.
- During turn-off, the switch blocks large voltage. Ideally no current should flow through the switch. But for real switch a small amount of leakage current may flow. This creates turn-off or blocking state losses
- The leakage current during turn-off is normally very small, Hence the turn-off losses are usually neglected.

Switching losses



Ideal switching profile
(turn on)

Real switching profile
(turn-on)

- During turn-on and turn off, ideal switch requires zero transition time. Voltage and current are switched instantaneously.
- In real switch, due to the non-idealities of power switches, the switching profile is as shown in above.
- The switching losses occurs as a result of both the voltage and current changing simultaneously during the switching period.

Switching losses

- The product of device voltage and current gives instantaneous power dissipated in the device.
- The heat energy that developed over the switching period is the integration (summation) of instantaneous power over time as shown by the shaded area under the power curve.
- The average power loss is the sum of the turn-on and turn off energies multiplied by the switching frequency.
- When frequency increase, switching losses increases. This limits the usable range of power switches unless proper heat removal mechanism is employed.

Losses estimation

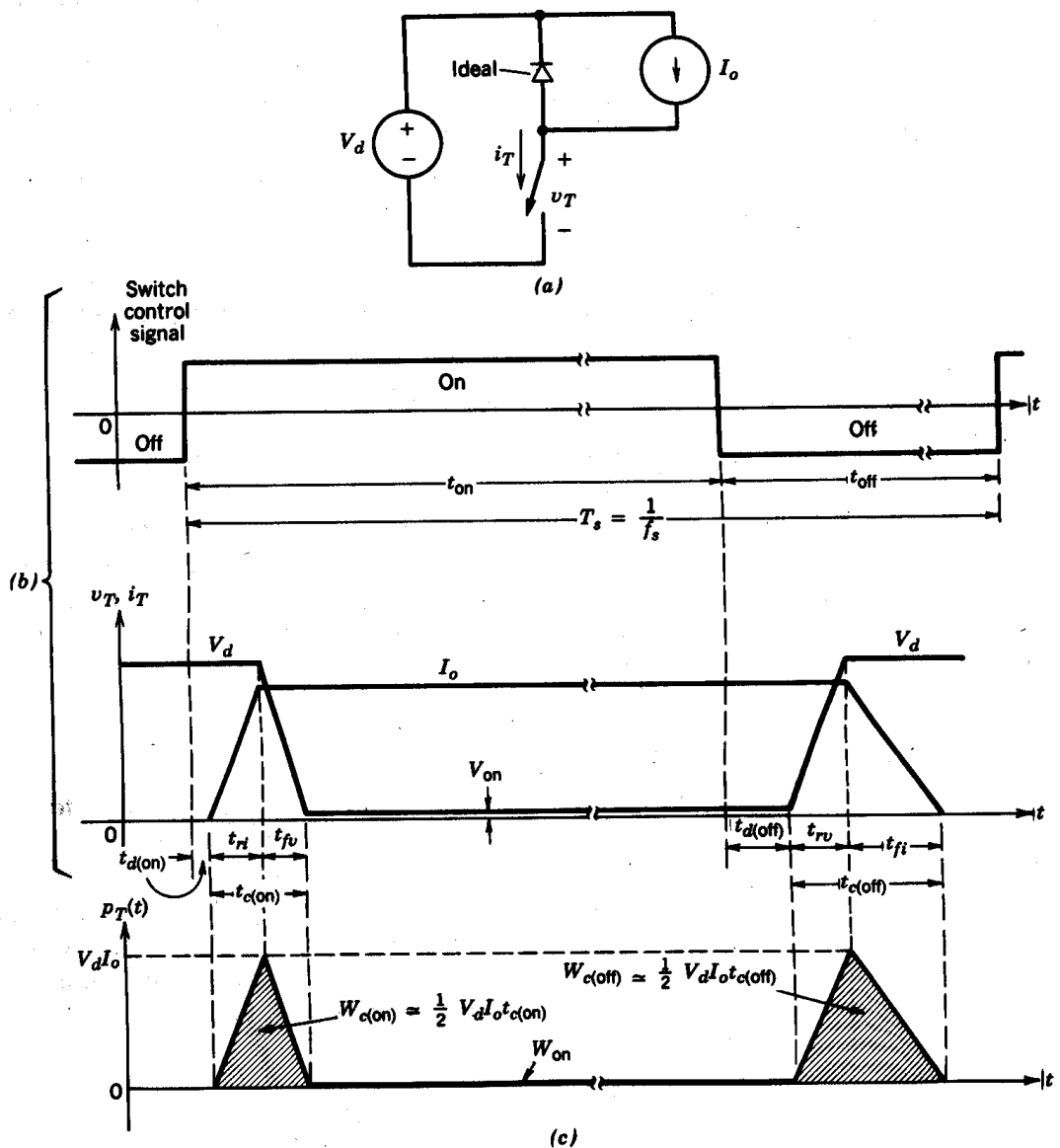


Figure 2-6 Generic-switch switching characteristics (linearized): (a) simplified clamped-inductive-switching circuit, (b) switch waveforms, (c) instantaneous switch power loss.

Losses estimation

Large values of switch voltage and current present simultaneously during turn - on crossover time,

$$t_{c(on)} = t_{ri} + t_{fv}$$

The energy dissipated in the device during this time :

$$W_{c(on)} = \frac{1}{2} V_d I_o t_{c(on)}$$

Once the switch is fully on, the on - state losses is approx :

$$W_{on} = V_d I_o t_{on}$$

Note that $t_{on} \gg t_{c(on)}, t_{c(off)}$

During turn - off transition,

$$t_{c(off)} = t_{rv} + t_{fi}$$

$$W_{c(off)} = \frac{1}{2} V_d I_o t_{c(off)}$$

The instataneous power dissipation,

$$p_T = v_T i_T$$

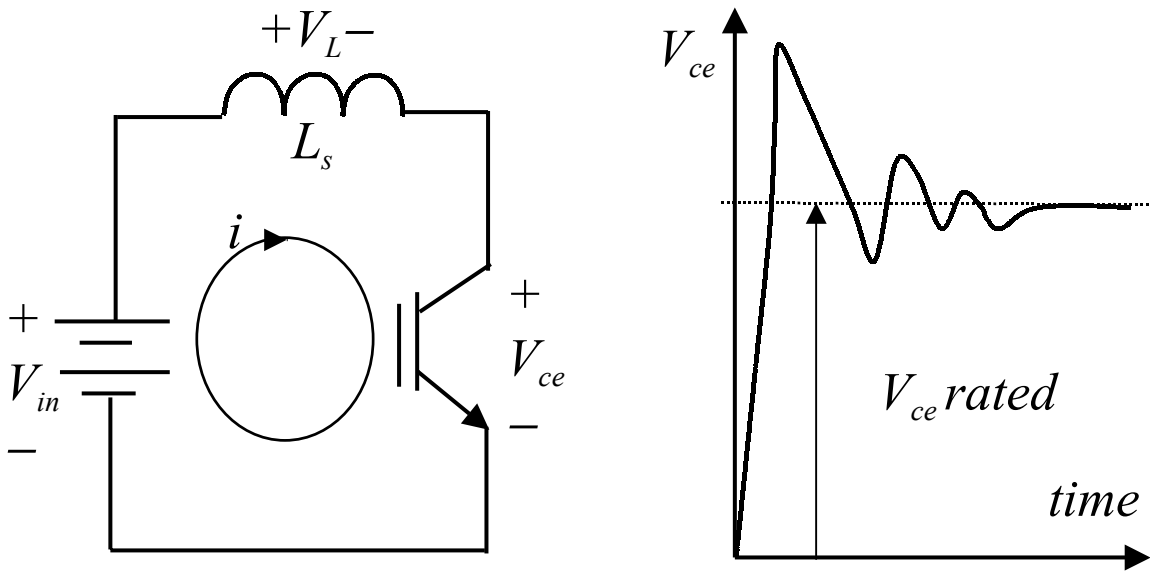
Since there are f_s turn - off and turn off per second,

$$P_s = \frac{1}{2} V_d I_o f_s (t_{c(on)} + t_{c(off)})$$

During on state :

$$P_{on} = V_{on} I_o \frac{t_{on}}{T_s}$$

Snubbers



Simple switch at turn off

- PCB construction, wire loops creates stray inductance, L_s .
- Using KVL,

$$v_{in} = v_s + v_{ce} = L_s \frac{di}{dt} + v_{ce}$$

$$v_{ce} = v_{in} - L_s \frac{di}{dt}$$

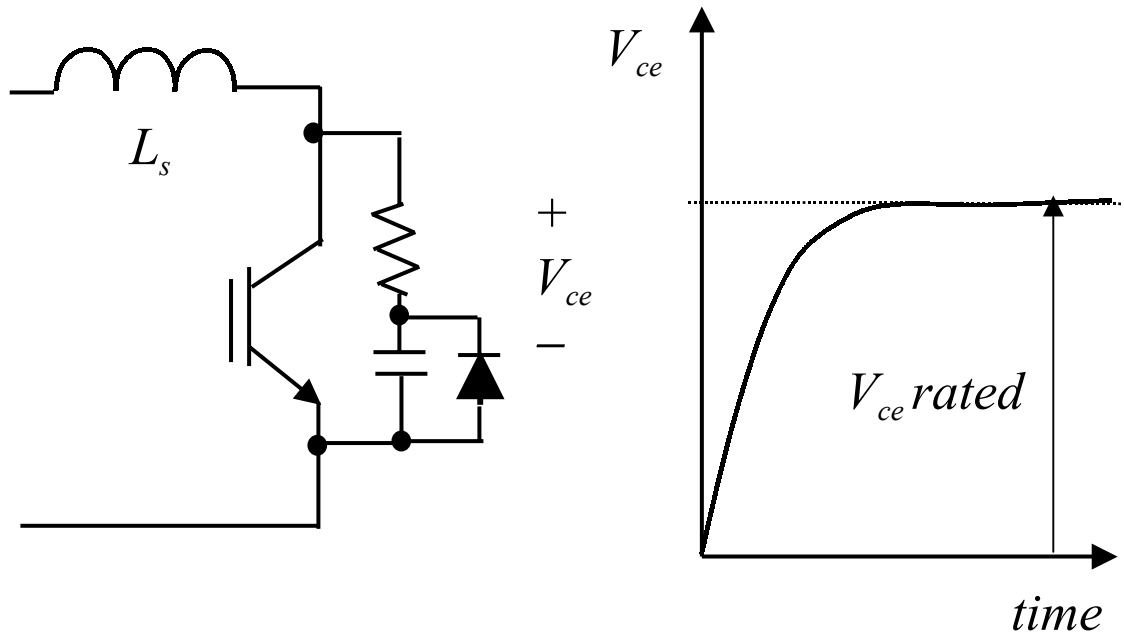
since di/dt is negative (turning off)

$$v_{ce} = v_{in} + L_s \frac{di}{dt}$$

Snubbers

- From previous equation, the voltage across the switch is bigger than the supply (for a short moment).
- The spike may exceed the switch rated blocking voltage and causes damage due to overvoltage.
- To prevent such occurrence, a snubber is put across the switch. An example of a snubber is an RCD circuit shown below.
- Snubber circuit “smoothened” the transition and make the switch voltage rise more “slowly”. In effect it dampens the high voltage spike to a safe value.
- Switches and diodes requires snubbers. However, new generation of IGBT, MOSFET and GCT do not require it.

RCD Snubbers



- In general, snubbers are used for:
 - turn-on: to minimise large overcurrents through the device at turn-on
 - turn-off: to minimise large overvoltages across the device during turn-off.
 - Stress reduction: to shape the device switching waveform such that the voltage and current associated with the device are not high simultaneously.

Ideal vs. Practical power switch

Ideal switch	Practical switch
Block arbitrarily large forward and reverse voltage with zero current flow when off	Finite blocking voltage with small current flow during turn-off
Conduct arbitrarily large currents with zero voltage drop when on	Finite current flow and appreciable voltage drop during turn-on (e.g. 2-3V for IGBT)
Switch from on to off or vice versa instantaneously when triggered	Requires finite time to reach maximum voltage and current. Requires time to turn on and off.
Very small power required from control source to trigger the switch	In general voltage driven devices (IGBT, MOSFET) requires small power for triggering. GTO requires substantial amount of current to turn off.

PE system simulations

- Challenges in PE system simulations
 - Non-linearity of power switches and diodes
 - Simulation takes a long time because time constants of various parts of the system may differ several orders of magnitude
 - Accurate models are not always available
 - Feedback and controller need to be modeled along with power converters
- Mechanics of simulation
 - Circuit-oriented simulators
 - User needs to supply the circuit topology and component values. The simulator internally generates the circuit equations that are totally transparent to the user
 - Pspice, MATLAB-Simulink with toolboxes
 - Equation solvers
 - The circuit is described by user by means of differential or algebraic equations. Equation must be developed for all possible switching states.
 - Then the equations is solved using high-level language such as C or Fortran