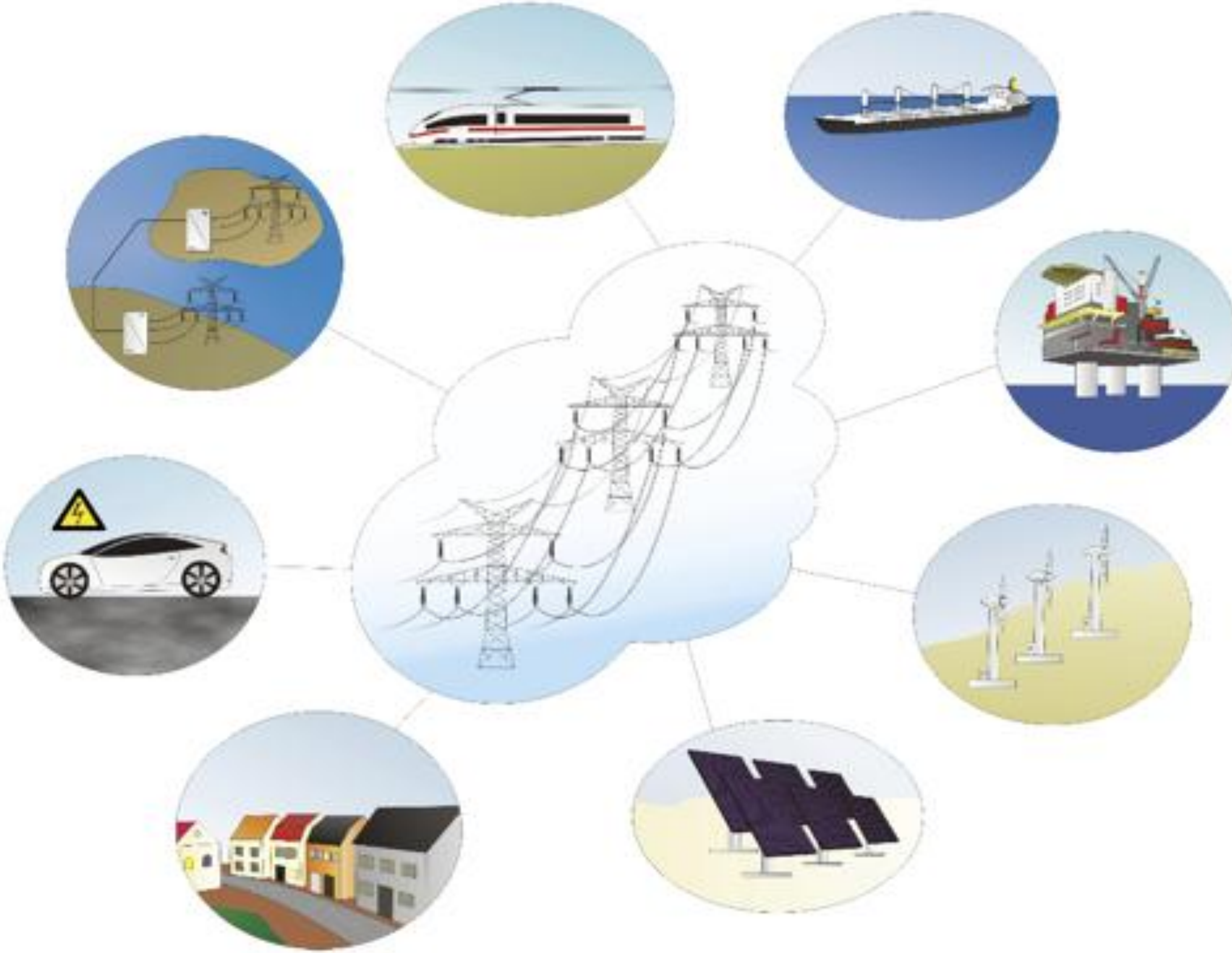
Department of Electronics & Communication Engg.

Course: Power Electronics (15EC73). **Sem.: 7th (2017-18)**

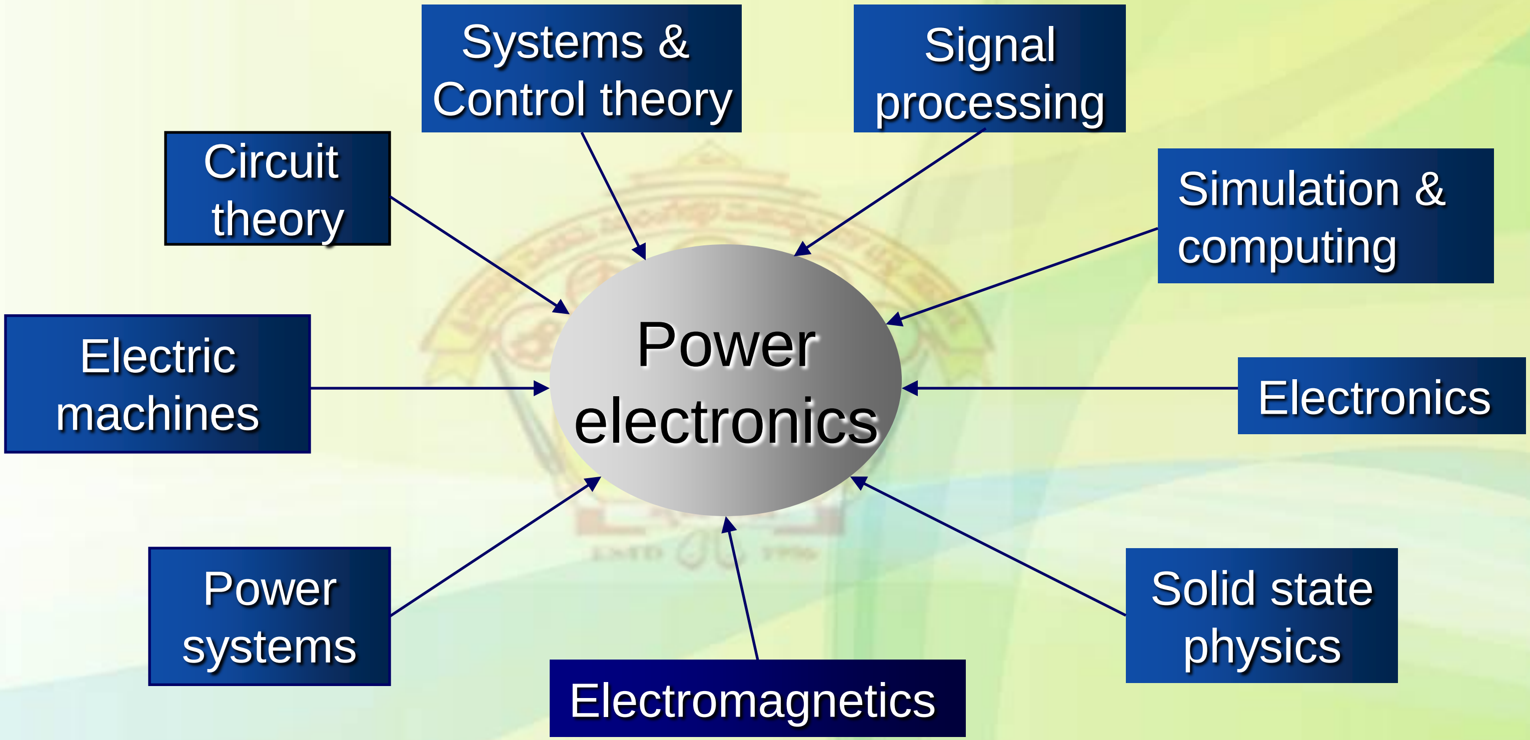
Course Coordinator:

Prof. D. M. Kumbhar

INTRODUCTION TO POWER ELECTRONICS



Relation with multiple disciplines



Power electronics is currently the most active discipline in electric power engineering worldwide.

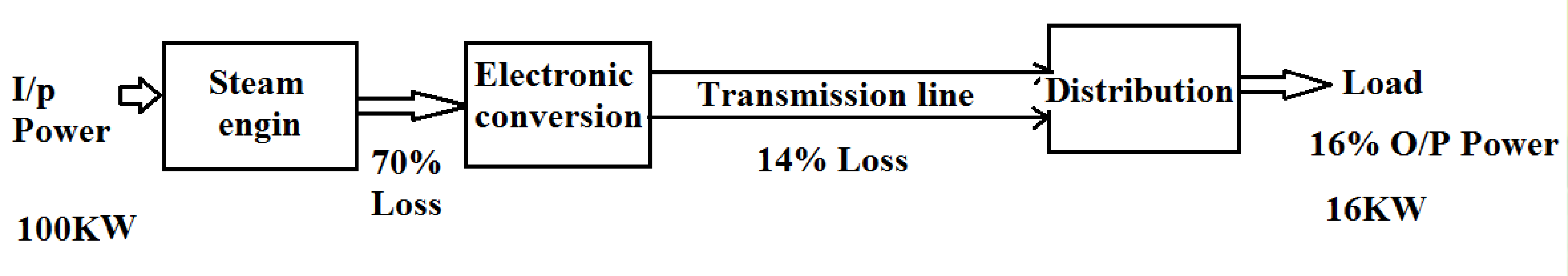
Quotes

- “We now live in truly globally society, in the highly automated industrial front with economic competitiveness of nation, in future the two technologies will dominate – Computer and Power Electronics.”
- “Modern computers, communication and electronic systems get their blood from Power Electronics.”
- “Solid state electronics brought the first revolution where as solid state power electronics brought second revolution.”

Energy scenario

- 87 % Electrical energy – coal, oil and wood,
- 6% Electrical energy – nuclear,
- 7 % Electrical energy – renewable resources.
- In India 70 % Electrical energy – thermal energy.
- Limited fuel – 200 years.
- Will civilization ends after 200 years?
- Responsibility
- Solution – efficient use, improve conversion efficiency and use renewable energy resources.

Power conversion cycle



Issues

- Pollution – Is it decreased?
- Bulk load – induction motors & lighting
- Motor load – constant or variable speed
  Is variable voltage / frequency can be given?
- Fan speed regulator – electrical and electronic
  Is size, heat and power loss reduced?
- Air conditioner – On/Off problem
  voltage deep and stress on cable reduced?
- DC Power Supply and SMPS Can we eliminate TFR?
- Speed Computer How to minimize switching losses?
- Transmission line loss – Can we reduce it?
- Lighting load – Can we increase illumination with minimum size, noise and cost.

Outline of Subject

- Module 1- Introduction & Power Transistors
- Module 2- Thyristors
- Module 3 - Controlled Rectifiers & AC Voltage Controllers
- Module 4 - DC-DC Converters
- Module 5 - Pulse Width Modulated Inverters

Books

- "Power Electronics" - M. H. Rashid 3rd edition, PHI/Pearson publisher 2004.
- “Power Electronics” – M. D. Singh & Kanchandani K. B. TMH, Publisher, 2007.
- “Power Electronics, Essentials and Applications”, L Umanand, John Wiley India Pvt. Ltd,2009.
- "Power Electronics" Daniel W. Hart, McGraw Hill,2010.
- "Power Electronics" V Nattarasu and R.S. Anandamurthty, Pearson/Sanguine Pub.2006.

Internal Reputed National Journals

- IEEE Journal of Power Electronics
- IEEE Journal of Industrial Applications
- IEEE Journal of Industrial Electronics
- IEEE Journal of Power Delivery

What is power electronics?

- Power Electronics – Interesting
  Important
  Easy to understand
- Definition
- Goal of Power Electronics

Definition

Power electronics is the electronics applied to conversion and control of electric power.

Goal

Control the flow of energy from source to load.

What is power electronics?

- Power Electronics – G-T-D.
- Definition

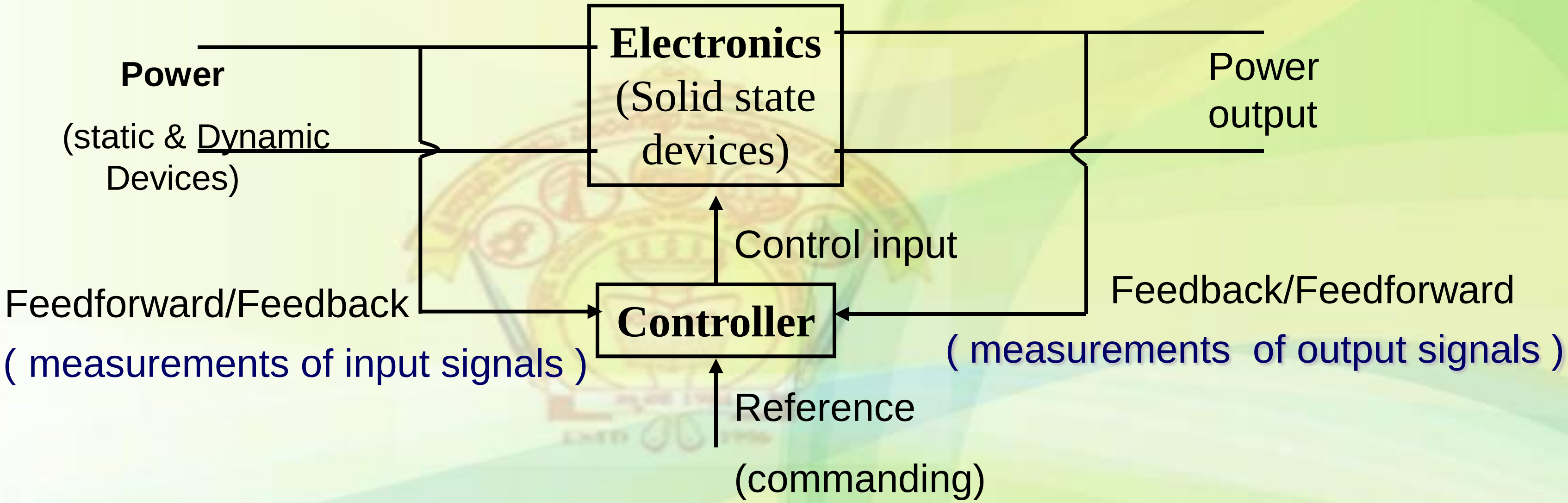
  Application of Power Electronics circuit for conversion of energy is known as power electronics.

  Use of electronics for large power control is known as Power Electronics.

  Application of semiconductor devices to control and conversion of electric power is known as Power Electronics.
- Electric power is the major form of energy source used in modern human society.
- The objective of power electronics is exactly about how to use electric power, and how to use it effectively and efficiently, and how to improve the quality and utilization of electric power.

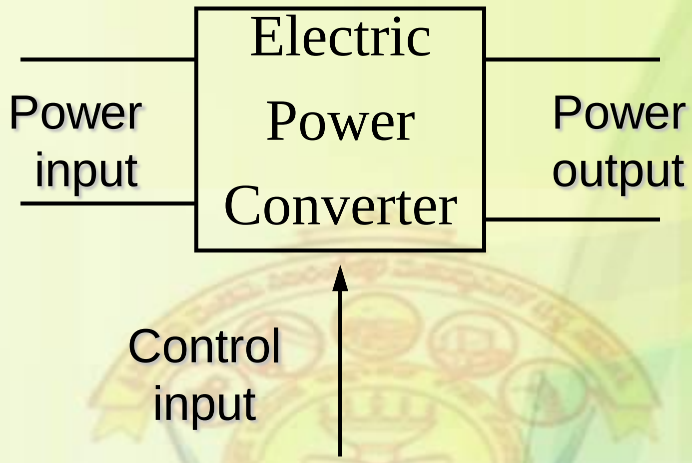
Power electronic system

Generic structure of a power electronic system



Power electronics – brain and muscle.

Conversion of electric power

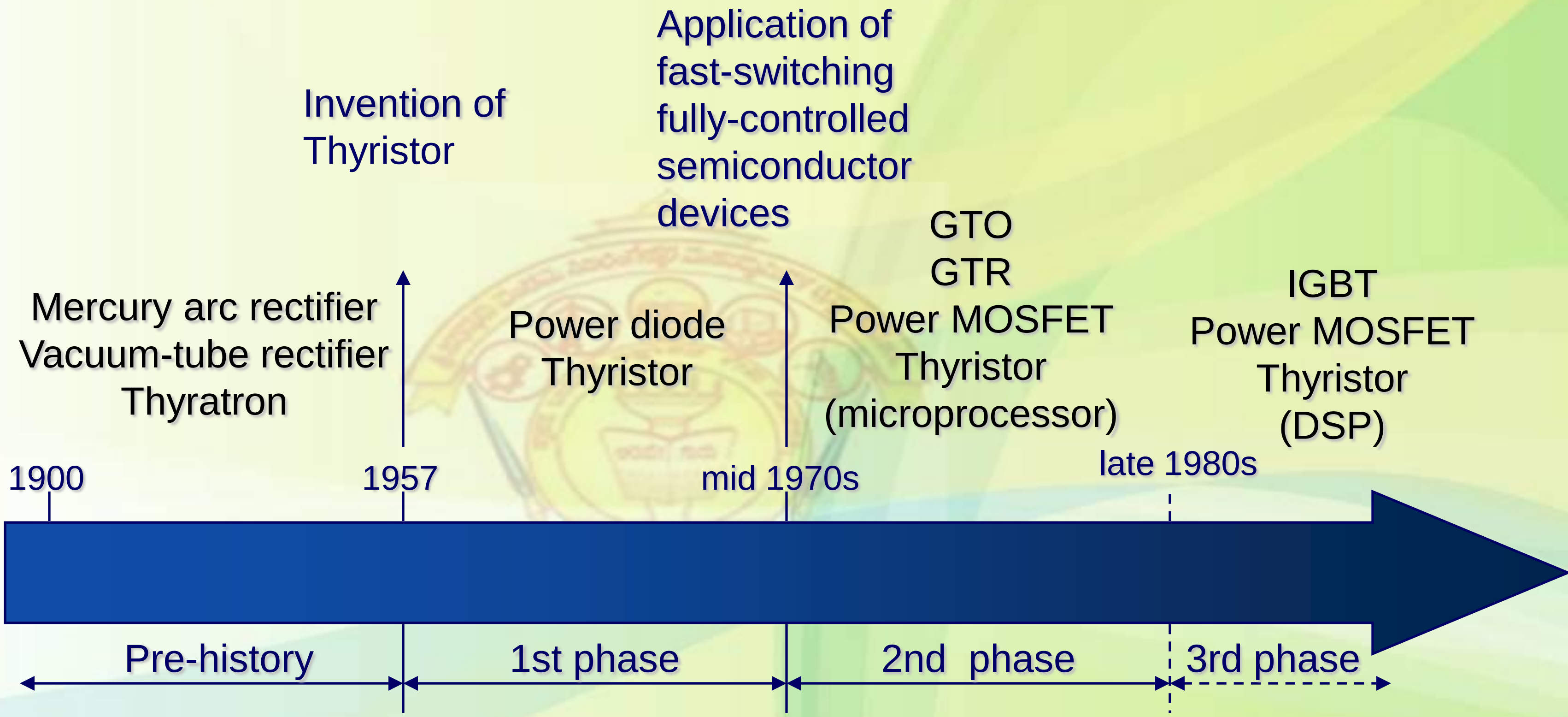


Types of electric power	Changeable properties in conversion
DC(Direct Current)	Magnitude
AC (Alternating Current)	Frequency, magnitude, number of phases

Applications

- Heat control
- Light control
- Speed control
- Power supplies
- Audio and video applications
- Other

The history



The thread of the power electronics history precisely follows and matches the break-through and evolution of power electronic devices

Power semiconductor devices

- Diodes
- Transistors – BJT, MOSFET, IGBT, SIT.
- Thyristors – SCR, LASCR, TRIAC, GTO, SITH, MCT.
- Silicon, Germanium.

Power diode

- P-I-N structure.
- Symbol and characteristics.
- Types - 1. General purpose (6000V/4500A)

trr-25µs, speed-50-60Hz,

Applications – battery chargers, power supplies, m/c control.

2. High speed (6000V/1100A)

trr-0.1 to 5µs, (50ns) high speed in GHz,

Applications – choppers, inverters,

Higher voltage drop.

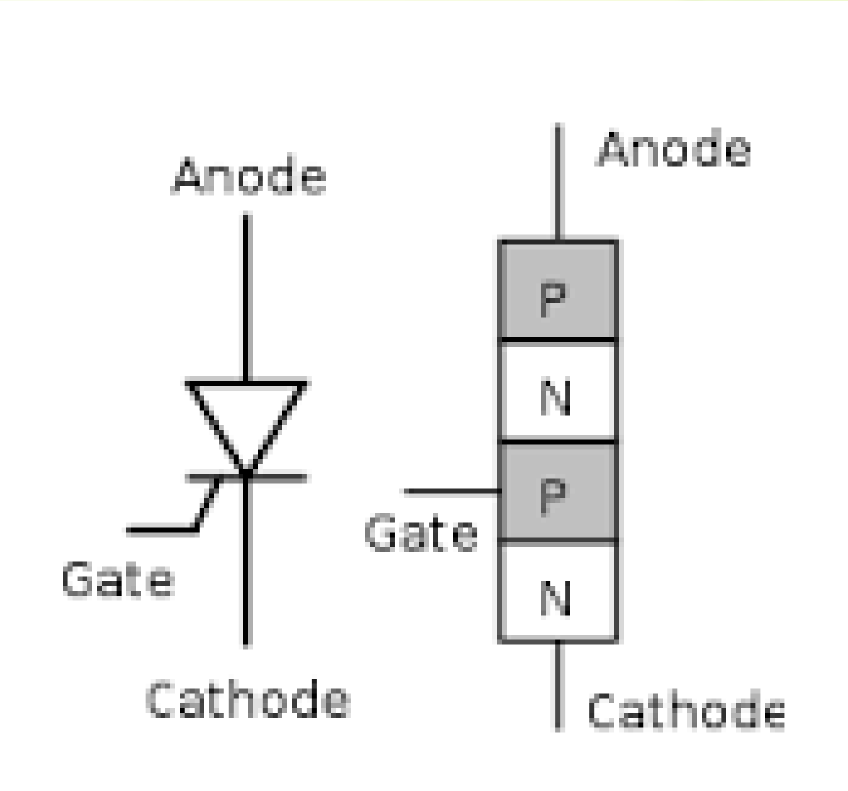
3.Schottky (100V/30A)

trr- 5µs, high speed in GHz

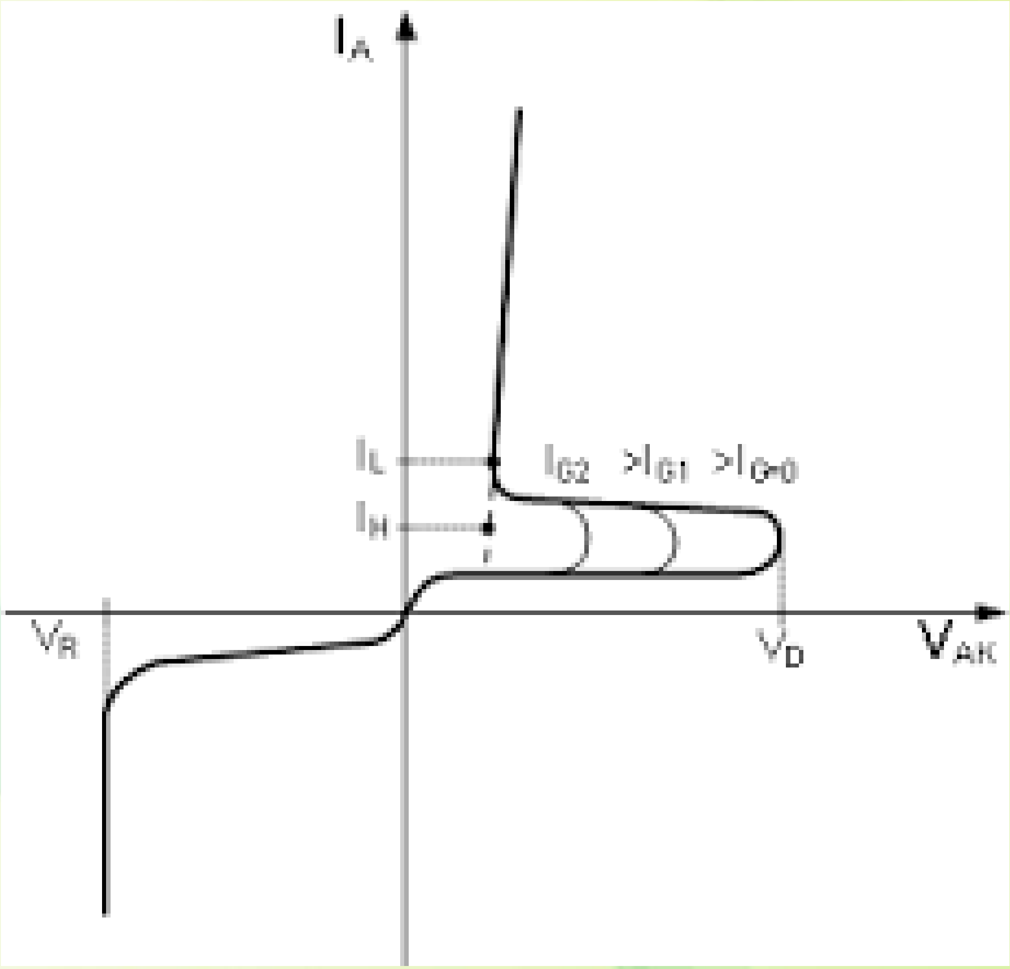
Low voltage drop –o.5 to 1.5V.

Power semiconductor devices

Thyristors



Thyristors Characteristics



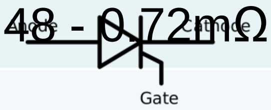
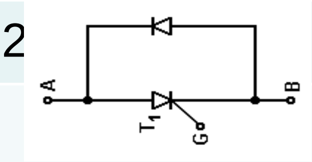
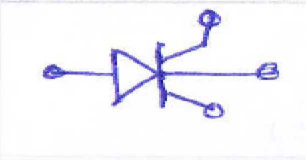
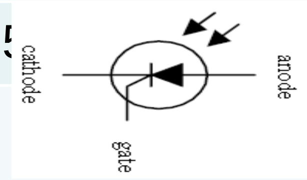
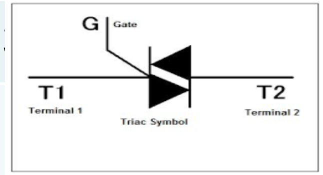
Thyristors

- Commutation circuit
- Line commutation
- Turn off time
- Holding current
- Latching current

Types of Thyristors

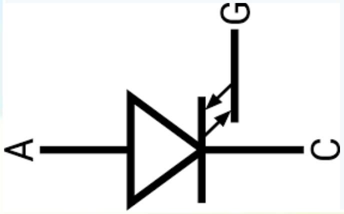
- Line commutated Thyristors
- Forced commutated Thyristors
- Gate Turn Off Thyristors (GTO)
- Reverse Conducting Thyristors (RCT)
- Static Induction Thyristors (SITH)
- Gate Assisted Turn Off Thyristors (GATT)
- MOS Controlled Thyristors (MCT)
- Emitter Controlled Thyristors (ECT)
- Integrated Gate Commutated Thyristors (IGCT)
- MOS Turn Off Thyristors (MTO)
- Light Activated Silicon Controlled Rectifier (LASCR)

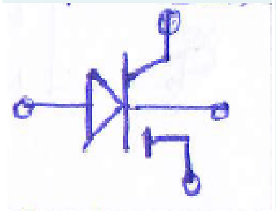
Thyristors types

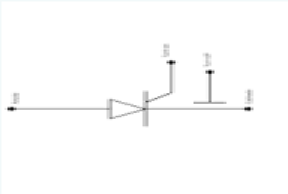
Natural /Line commutated Thyristor	RCTs (Reverse Conduction Thyristor)	GATT (Gate Assisted Turn off Thyristor)	LASCR (Light Activated SCR)	TRIAC
General purpose	High speed switching Ex. Traction	High speed switching Ex. Traction	HVDC System	Low power applications AC, heat, light, motor control, washing m/c
6000V	4000V	1200V	6000V	1200V
4500A	2000A R 800A	400A	1500A	300A
100-400µs	22-100µs	10-50µs	200-400µs	200-400µs
0.48 - 0.72mΩ 	2 		5 	

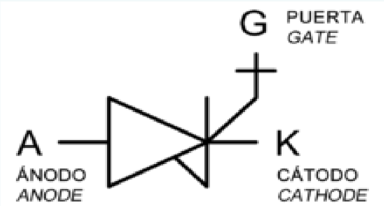
Thyristors

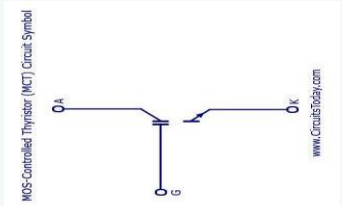
GTO (Gate turn off thyristor)	MTO (Moss turn off thyristor)	ETO(Emitter turn off thyristor)	IGCT (Integrated gate commuted thyristor)	MCT (Moss controlled thyristor)
Medium power application- UPS, Electric car, motor control	High power application	High power application	Medium power converter	Medium power converter
6000V	10kv	6kv	4500V	1400 – 4500V
6000A	4000A	4000A	250A	65 – 250A
50 – 110µs	80 - 110µs	80 - 110µs	80 - 110µs	50 - 110µs
1.07mΩ	10.2mΩ	0.5mΩ	0.8mΩ	10mΩ







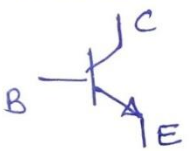
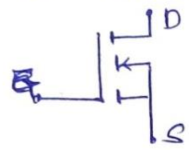
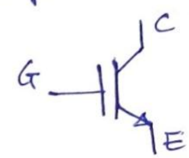
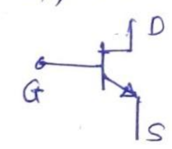




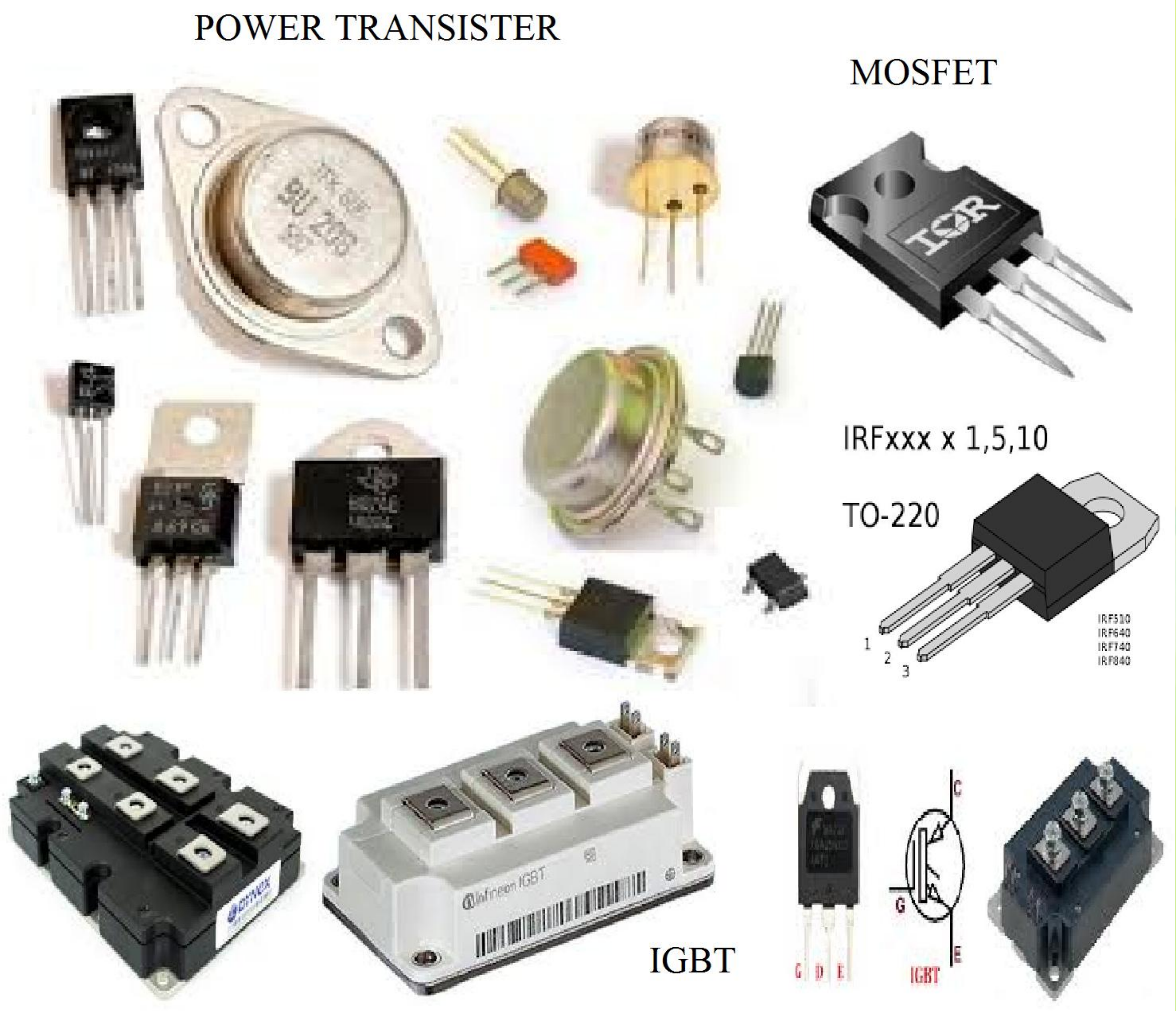
Thyristors

Power Transistors

POWER TRANSISTORS.

	Power BJT	MOSFET.	COOLMOS.	IGBT	SIT
	Bipolar Junction Transistor	Metal oxide semiconductor Field effect transistor.		Insulated gate bipolar transistor	- Static Induction transistor - 1987, Tokin croporation
Symbol			* New techonology for High power voltage		
	• Current controlled • Fully controlled unidirectional. • Used in CE configuration.	• Voltage controlled • Fully controlled unidirectional • Used in common source configuration.	voltage controlled. • compensation in vertical drift region to improve on state resistance. • Less on state resistance • Conduction loss 5 times less • Power handling capacity 2-3 times more • Active chip are 5 times smaller.	• Voltage controlled. • 4 layer, 3 terminal, unidirectional, fully controlled device. • Combines advantage of quality MOSFET & transistor.	• Normally ON device • -ve voltage to turn off it. • like JFET but it is vertical device • low channel resistance & have low voltage drop. • It has low noise, low distortion, high freqn capability. • Not used for general purpose.
Applications	Power converters below 10 KHz Washing m/c, AC, refrigerators, Robot, motor control.	Power converter upto several KHz freqn. Microwave oven, Audio power supplies, VCR, Electric cars.	High voltage applications	High voltage & high current application -UPS Robots	High power, high freqn audio amplifiers, eg. Audio amplr in VHF & UHF Microwave amplr.
voltage	1200V	1000V	1500V	1700V	1200V
current	400A	100 A	400 A	2400 A	300 A
on state resistance	0.4-30 mΩ	1Ω/100V, 5Ω/500V,	0.12mΩ - 2Ω	2.3mΩ -	1.2Ω
frequency	20-30 KHz	100 KHz	125 KHz	100 KHz	100 KHz
Switching Time	2 to 9 μs.	1.6 μs.	1 to 2 μs.	5-10 μs.	0.5 μs. typically 0.25μ

Power Transistors



- Symbol & VI Characteristics of commonly used semiconductor devices
- Control Characteristics of semiconductor devices

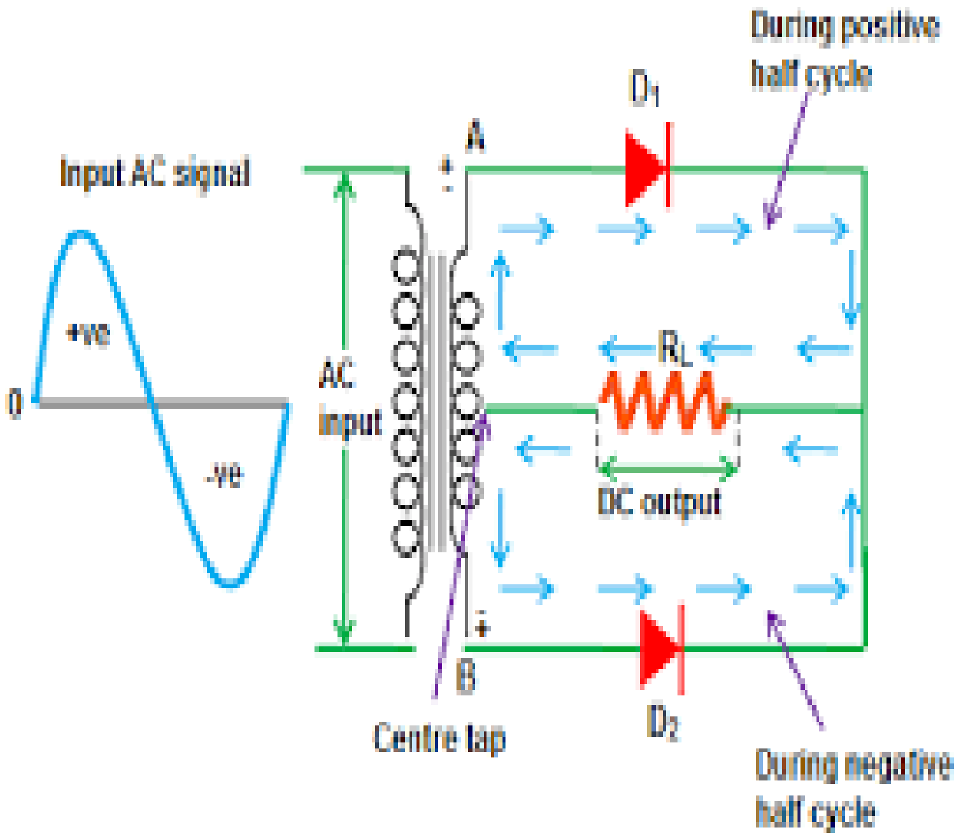
Types of Power Electronic Circuits

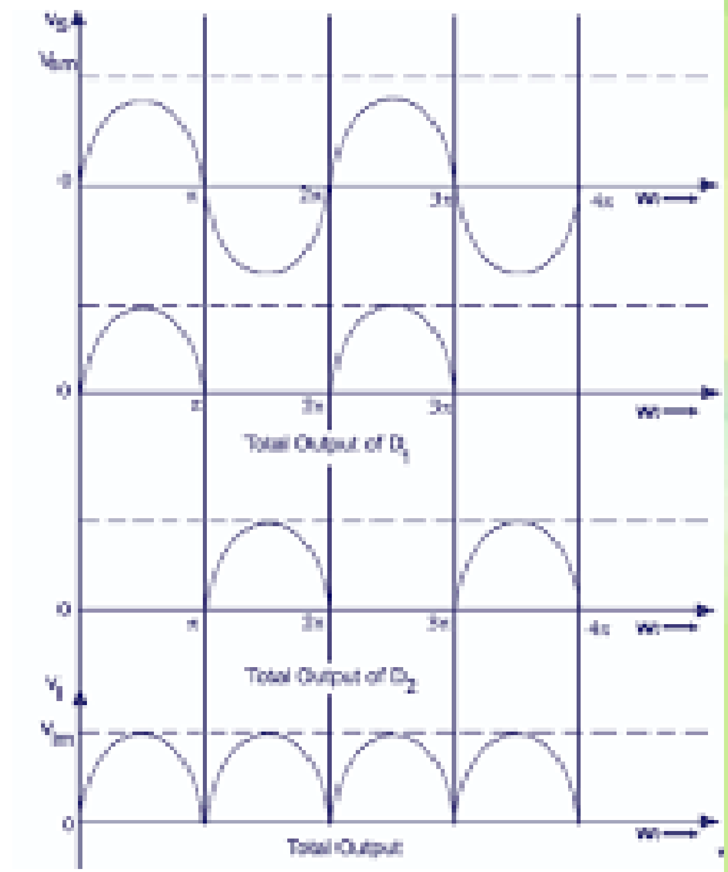
- AC-DC Converters- a) Uncontrolled Rectifiers

  b) Controlled Rectifiers
- AC-AC Converters- a) AC voltage controllers (ACVC)

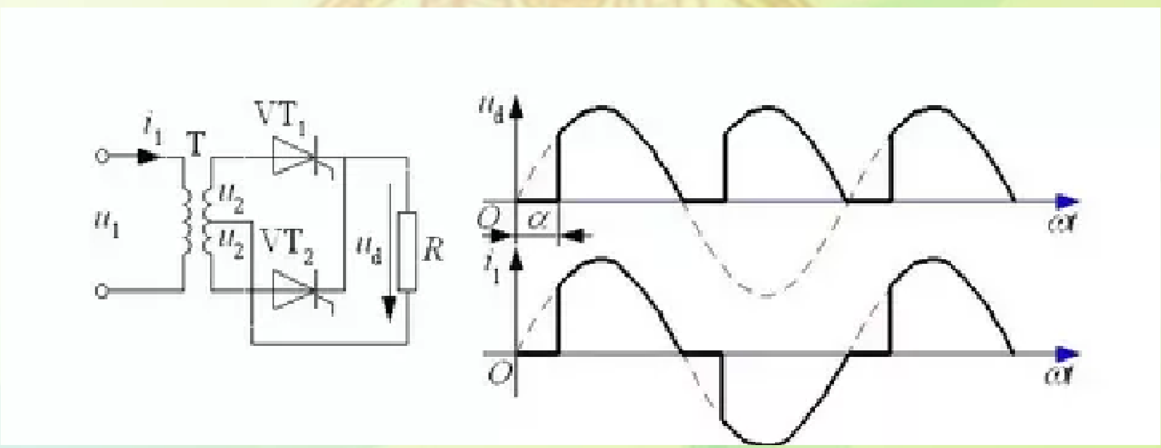
  b) Cycloconverters
- DC-DC Converters
- DC-AC Converters
- Static switches

AC-DC Converters - Uncontrolled Rectifiers





AC-DC Converters – Controlled Rectifiers

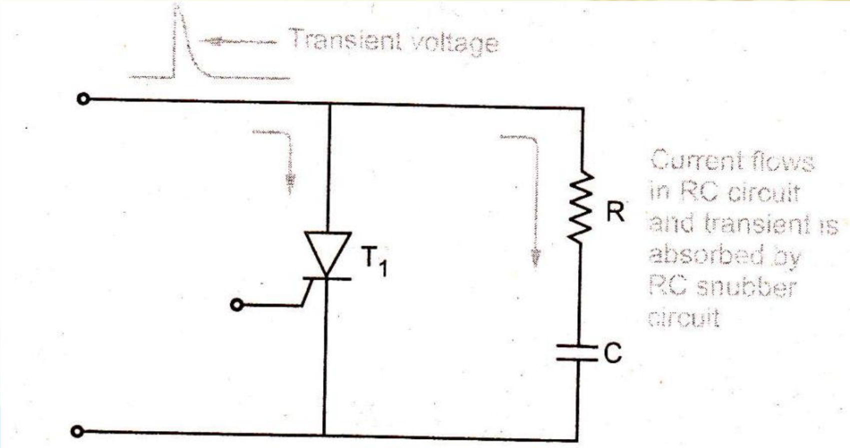


dv/dt and di/dt protection

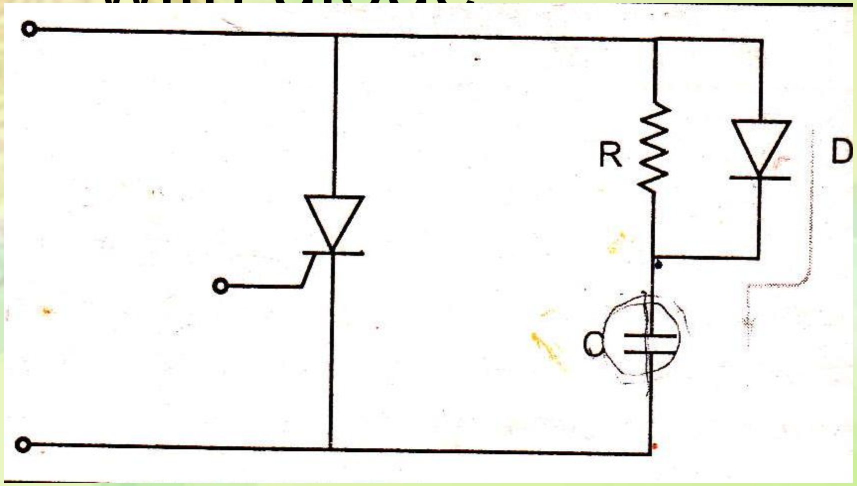
- Voltage surge
- Current surge
- Over current
- Over voltage

dv/dt and di/dt protection

- Snubber for dv/dt protection



- Snubber for dv/dt protection
- with diode



dv/dt and di/dt protection

Design of snubber

The value of capacitor is given as,

$$C = \frac{1}{2L}\left(\frac{0.564\ V_m}{\frac{dv}{dt}}\right)^2$$

Here V_m is the peak value of supply voltage

$\frac{dv}{dt}$ is the permissible $\frac{dv}{dt}$

L is the source inductance.

And resistance is given as,

$$R = 2\sigma\sqrt{\frac{L}{C}}$$

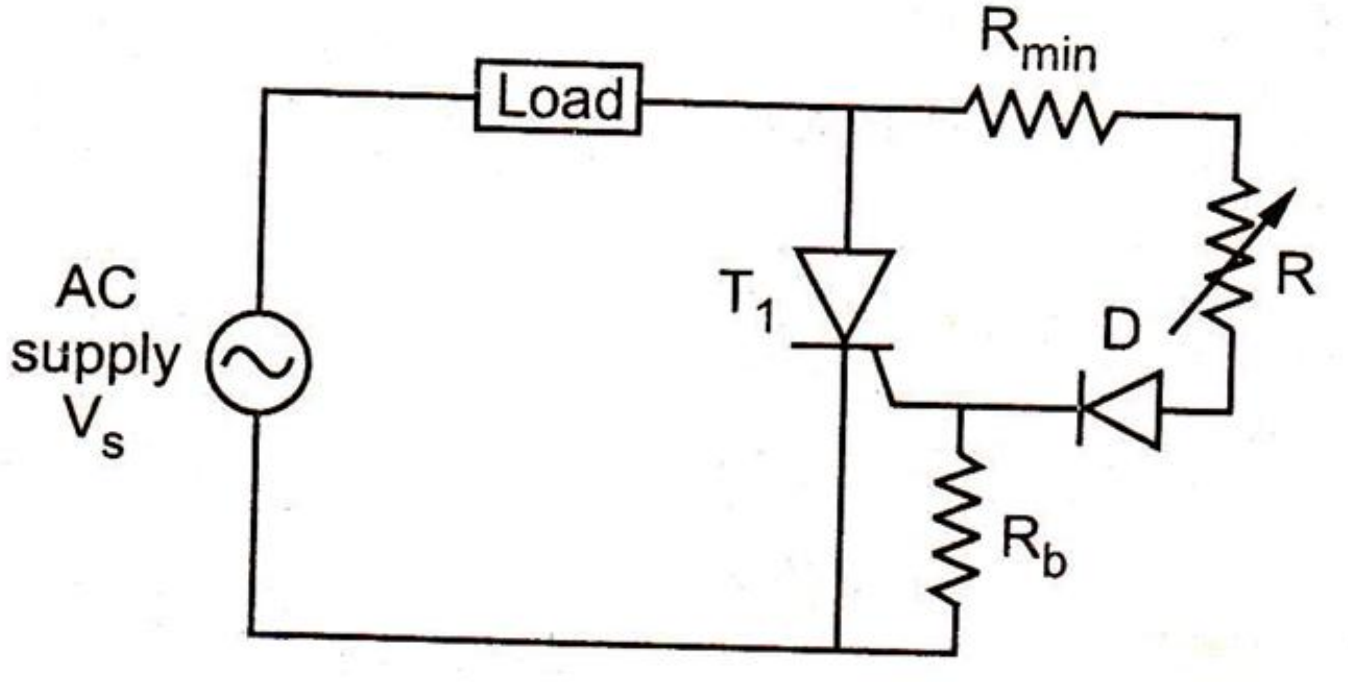
Here σ is the damping factor. It's value is normally taken as 0.65.

Gate Firing / Triggering Circuits

Requirements of triggering circuit

- Ensure triggering
- Prevent false triggering
- Provide isolation
- Power loss – low
- Should not sink current
- Sufficient pulse width
- Voltage / current applied within limit

R Firing circuit



$$Rgmin = \frac{Vsmax}{Igmin} \qquad Rb = \frac{Vgmax(Rmin+Rv)}{Vsmax - Vgmax}$$

R Firing circuit

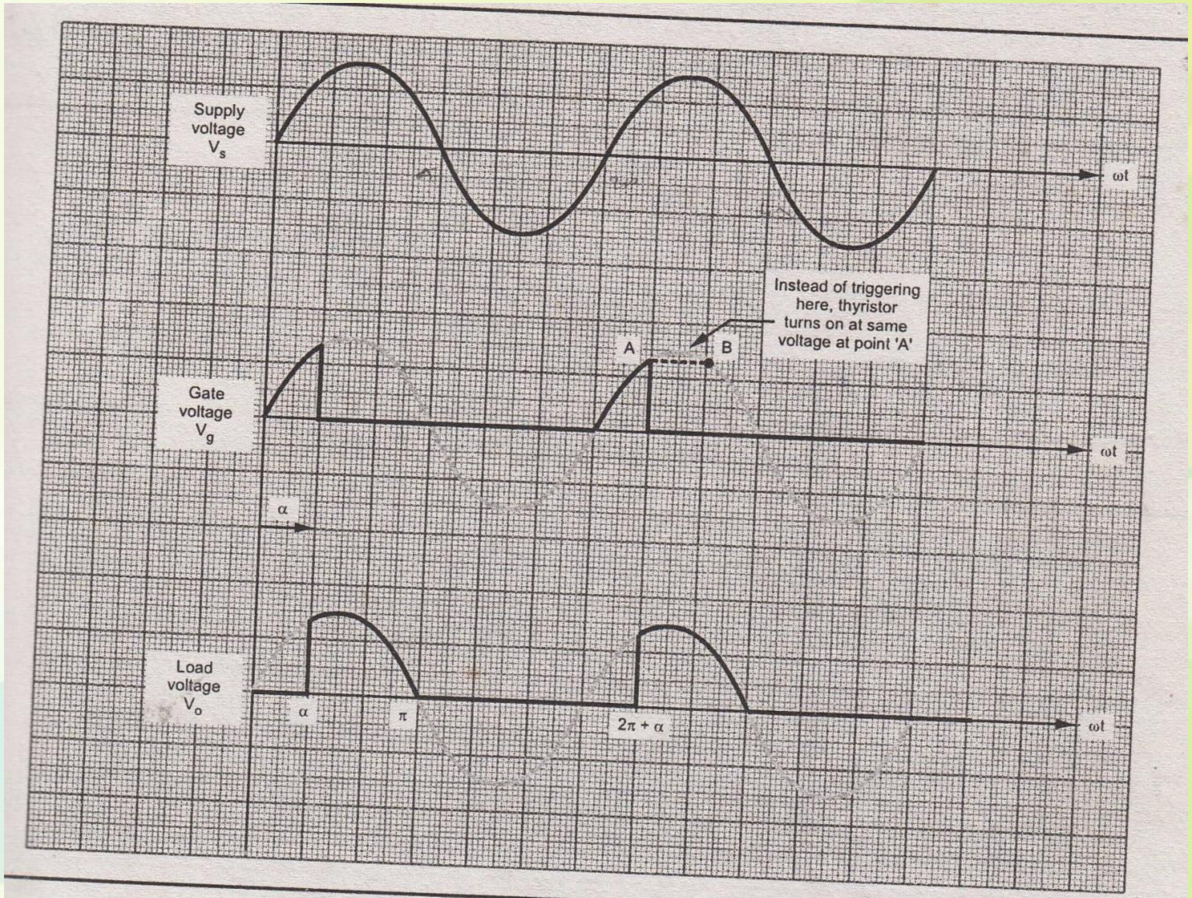
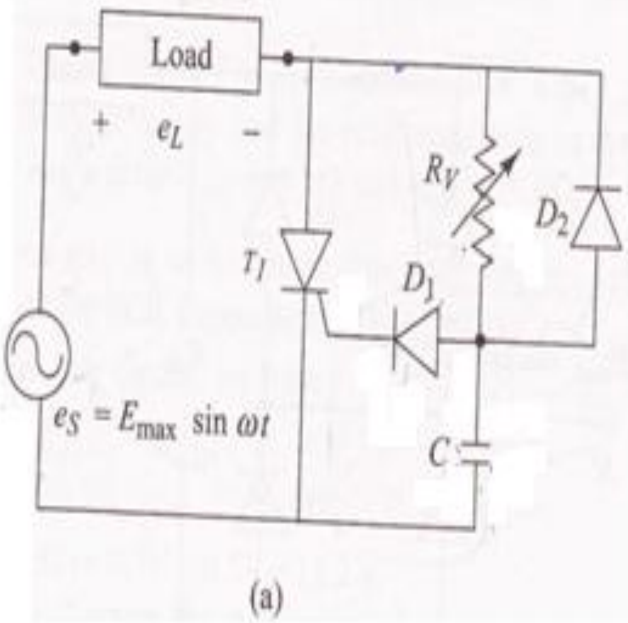


Fig. 3.7.3 Waveforms of R-firing circuit

RC Firing circuit



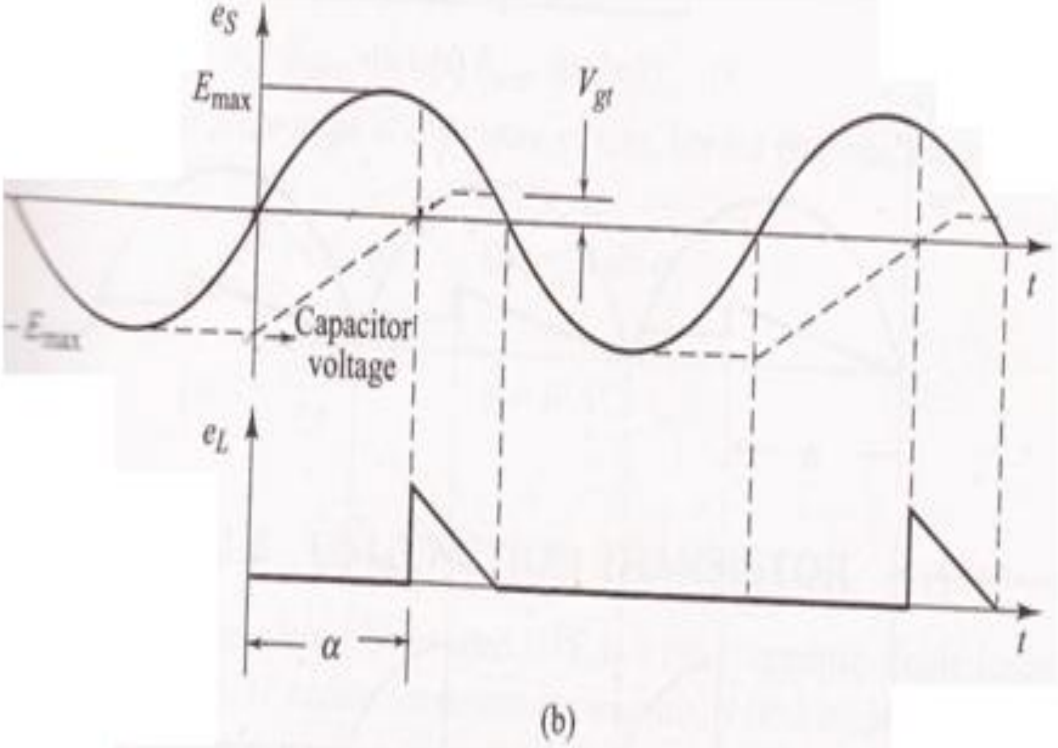


Fig. 3.12 ***(a)*** *RC firing circuit,* ***(b)*** *voltage-waveform*

$$R_vC \geq \frac{1.3T}{2} = \frac{4}{w}$$

R C Triggering

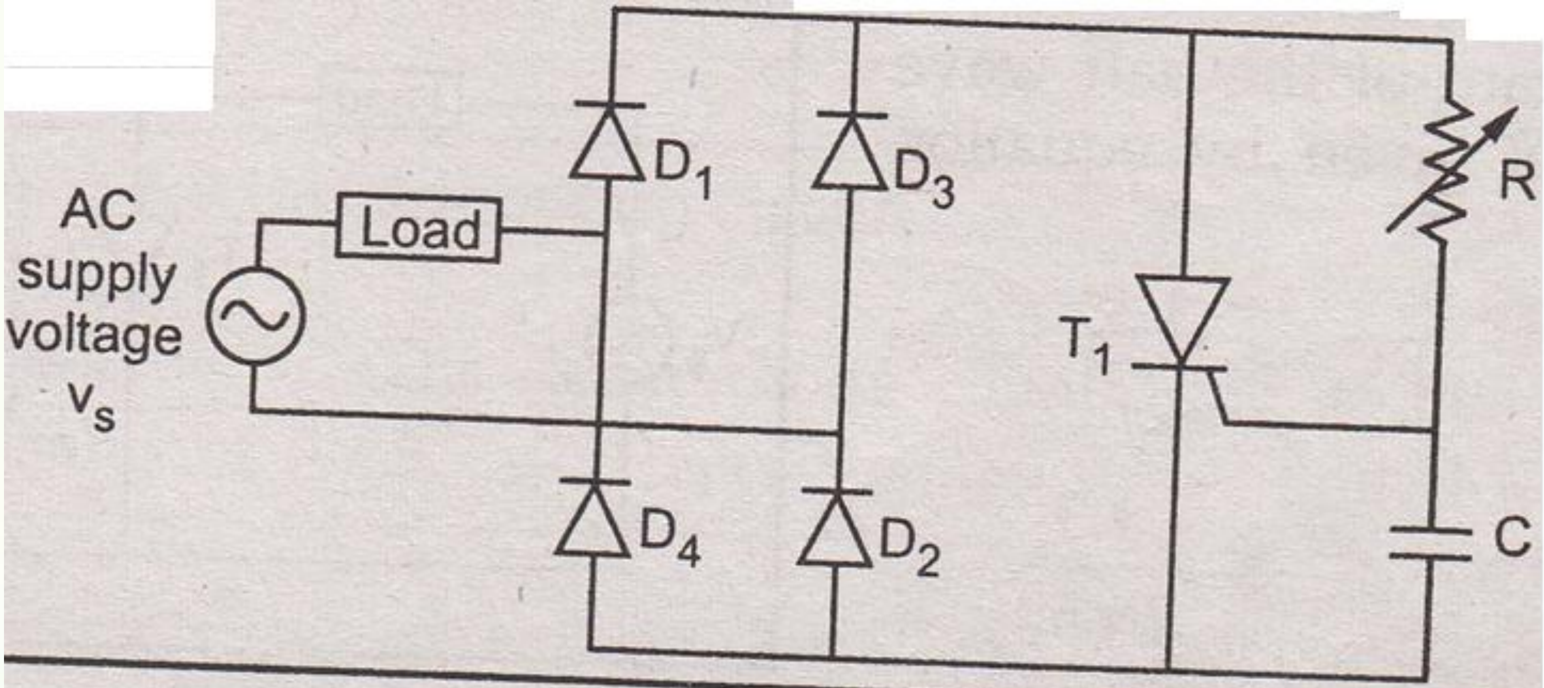


Fig. 3.7.6 Full wave RC firing circuit

$$R_vC \geq \frac{50T}{2} = \frac{157}{w}$$

$$R_v = (V_s - V_{gmin})/I_{gmin}$$

R C Triggering

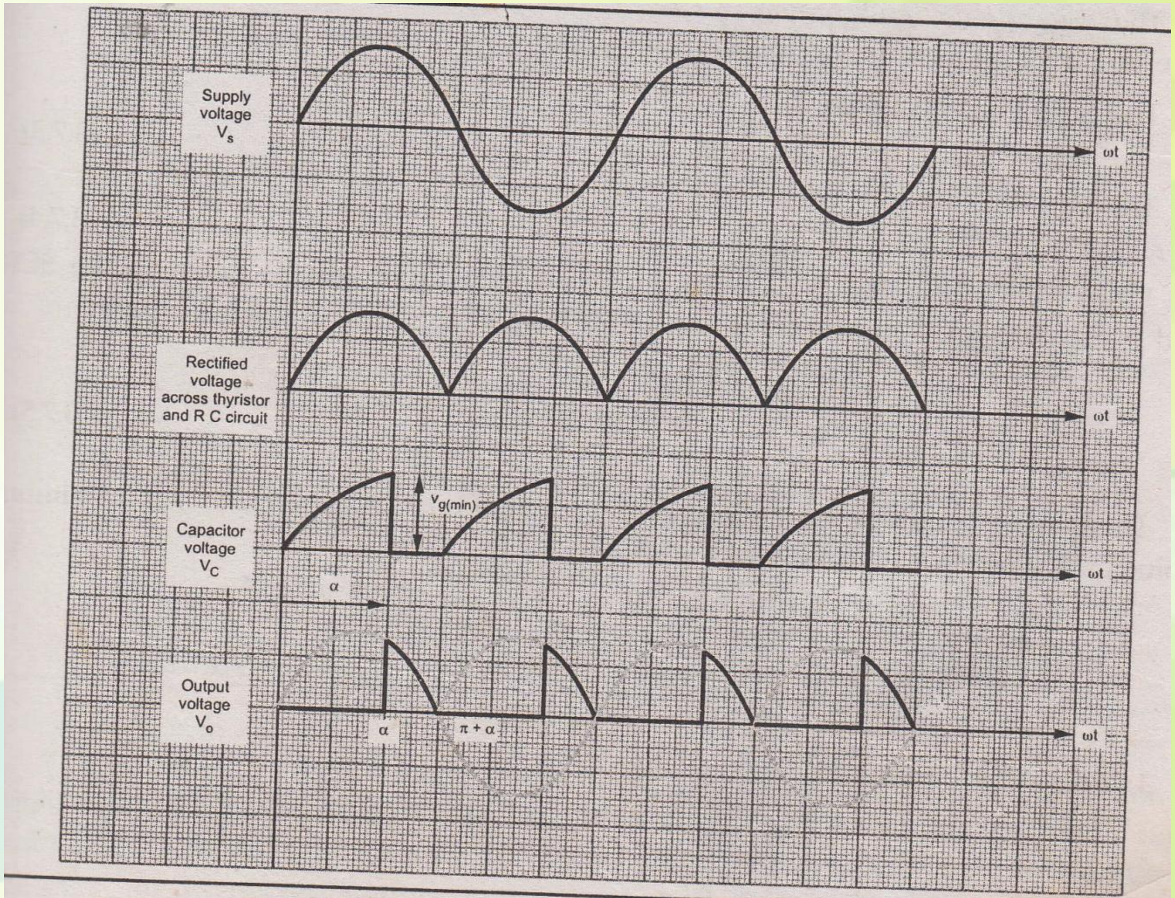


Fig. 3.7.7 Waveforms of full wave RC firing circuit

Synchronized UJT Triggering

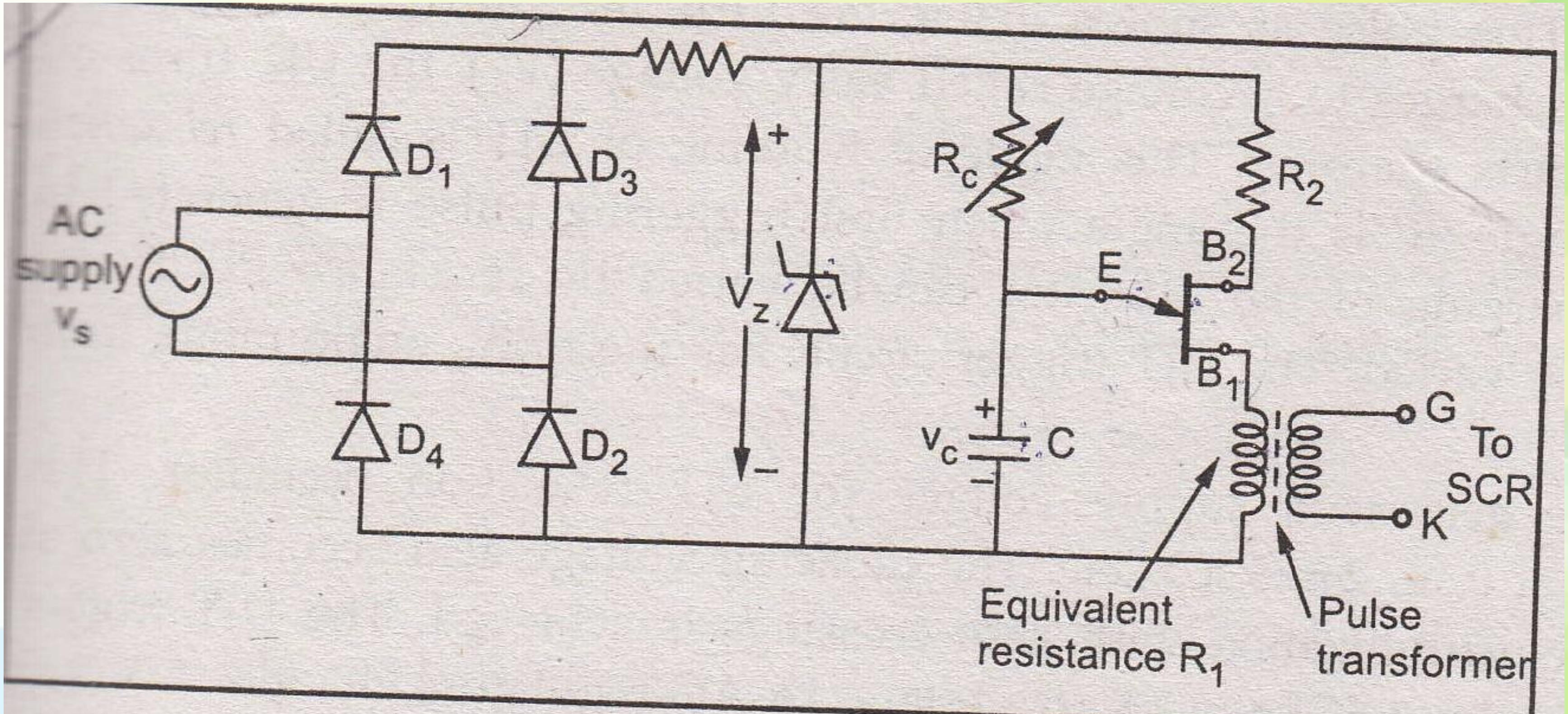


Fig. 3.7.9 UJT triggering circuit

Synchronized UJT Triggering

Mathematical analysis

The peak voltage at which UJT turns on is given as,

$$V_p = \eta V_{BB} + V_D$$

Here V_p is the peak voltage

V_{BB} is the supply voltage of UJT circuit

V_D is forward drop of UJT

η is intrinsic standoff ratio.

The period of oscillation $$T = R_c C \ln\left(\frac{1}{1-\eta}\right)$$

triggering angle will be, $$\alpha = \omega T$$

$$\alpha = \omega R_c C \ln\left(\frac{1}{1-\eta}\right)$$

Synchronized UJT Triggering

Design: The resistance R_2 should be selected as follows :

$$R_2 = \frac{0.7\left(R_{B2} + R_{B1}\right)}{\eta V_{BB}} \quad \textbf{OR} \quad R_2 = \frac{10^4}{\eta V_{BB}}$$

Width of triggering pulse, $\tau_2 = R_1 C$

More accurately this pulse width will be,

$$\tau_2 = (R_1 + R_{B_1})C$$

R_1 can be calculated using following equation,

$$V_{BB} = I_{leakage}(R_1 + R_2 + R_{B_1} + R_{B_2})$$

$$R_{c\,(\max)} = \frac{V_{BB} - V_p}{I_p}$$

$$R_{c(\min)} = \frac{V_{BB} - V_v}{I_v}$$

Microprocessor based training

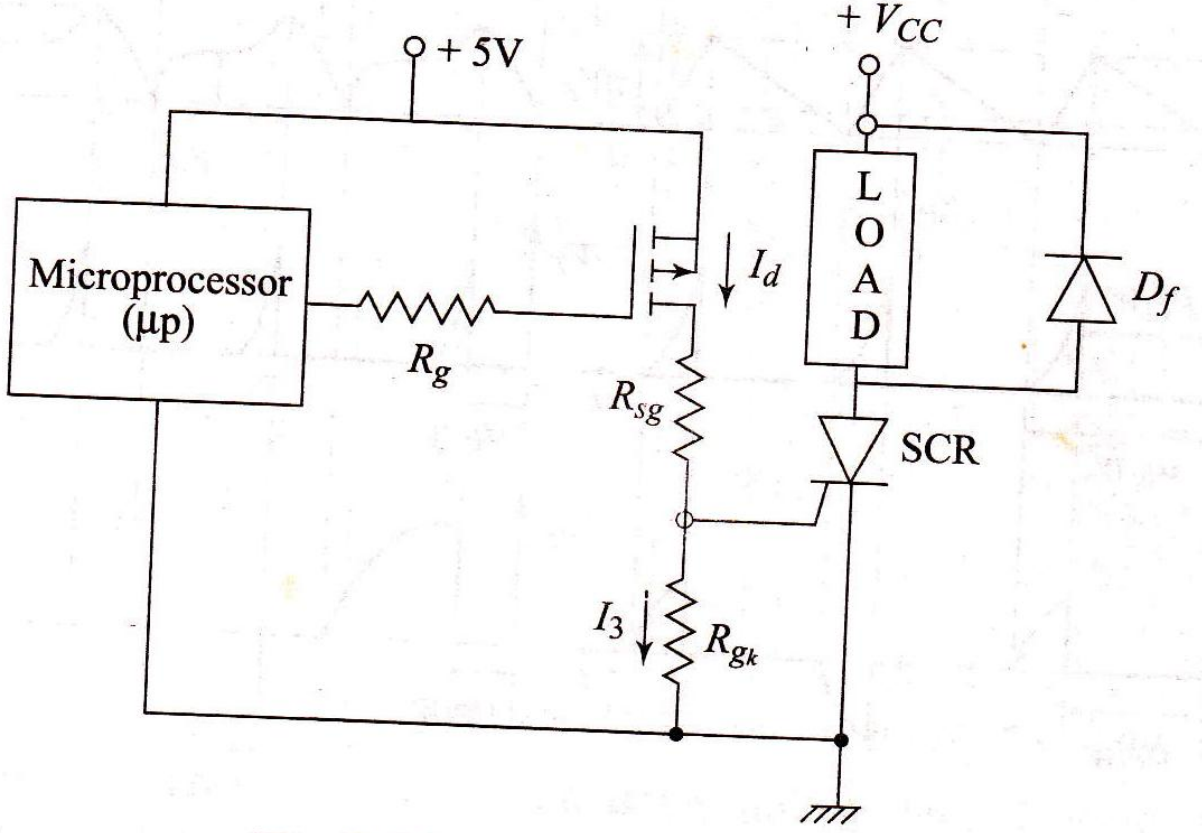
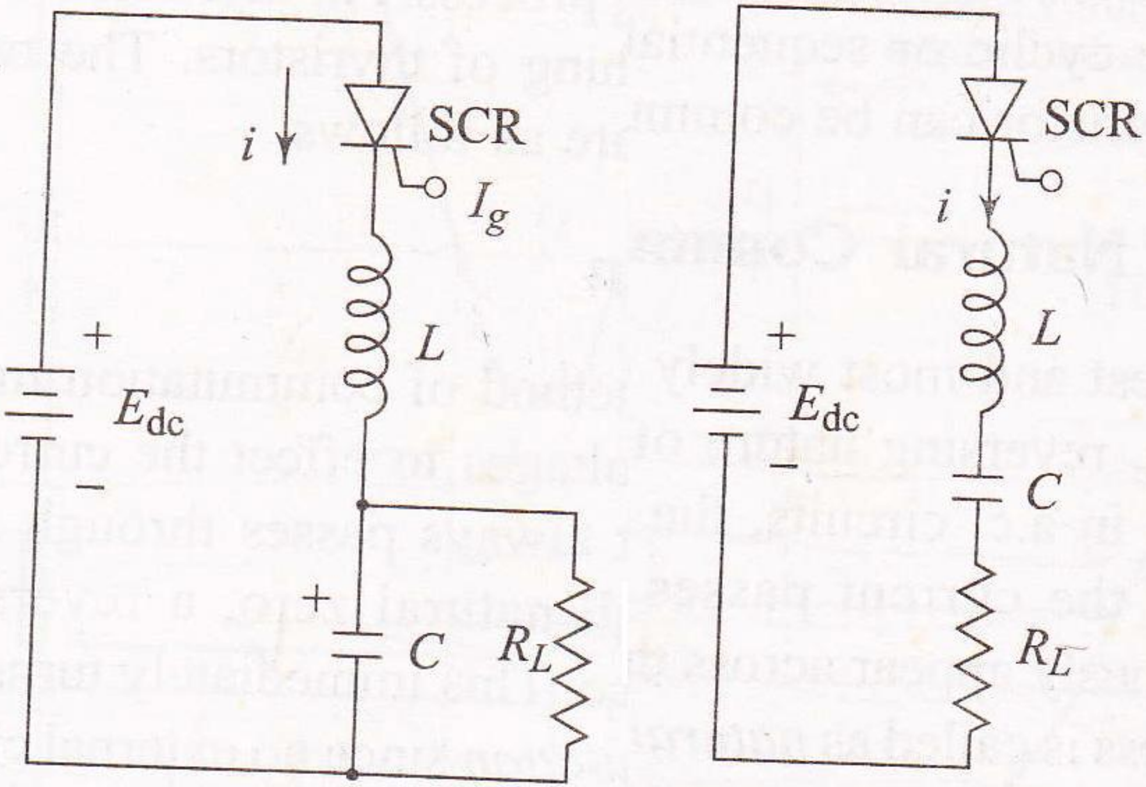


Fig. 3.31 *μp interfacing to SCR*

Thyristor Turn Off Methods

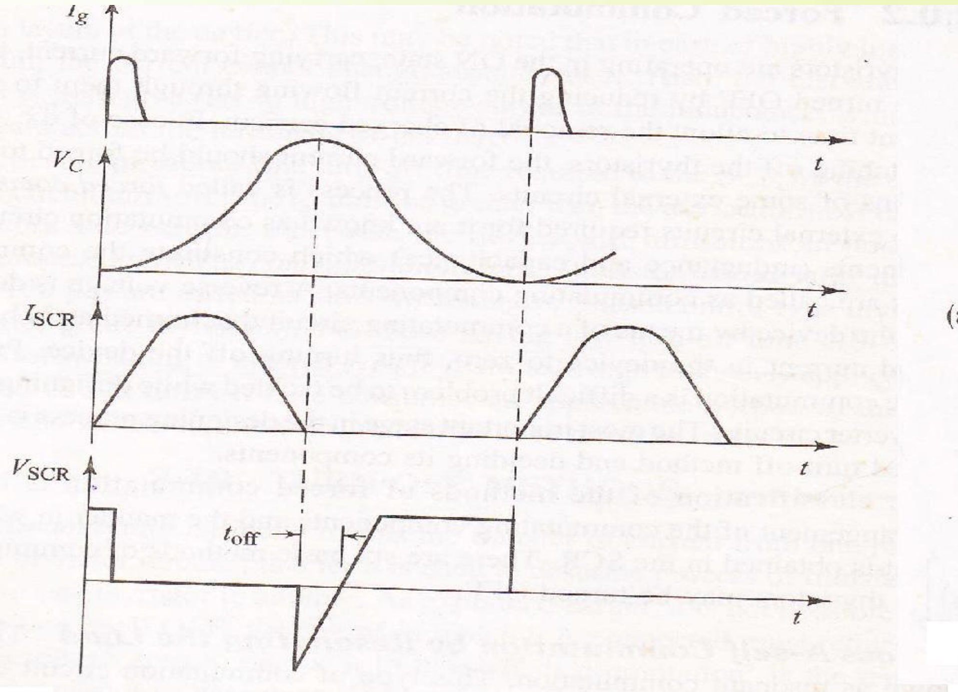
- Natural commutation
- Forced commutation
- Class A – self commutation by resonating load
- Class B – self commutation by LC circuit
- Class C – complimentary commutation
- Class D – auxillary commutation (Impulse)
- Class E – external pulse commutation
- Class F – line commutation

Class A – self commutation

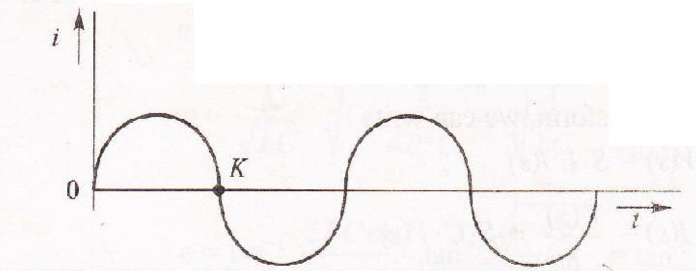


(a) Load in parallel with capacitor (b) Load in series with capacitor

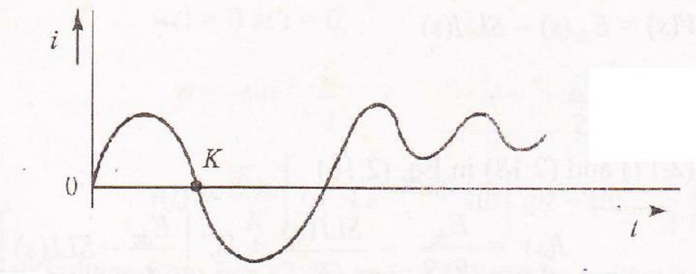
Class A – self commutation



Voltages and currents in Class A (load is parallel with capacitor)



(a) Waveforms of the current produced in Fig. 2.12(b) (series capacitor)



Waveforms of the current produced in Fig. 2.12(a) (parallel capacitor)

Design Considerations

(a) Load in parallel with capacitor C Let us consider the resonant circuit of Fig. 2.12 (a). Let E_{dc} be the applied d.c. voltage, V be the load voltage, and i be the load current.

The circuit equation is

$$E_{dc} = L\frac{di}{dt} + V$$

and

$$i = C\frac{dV}{dt} + \frac{V}{R}$$

By using Laplace transform, we can write

$$E_{dc}(s) - V(s) = S \cdot L\ I(s) \tag{2.15}$$

and

$$I(s) = \frac{V(s)}{R} + S \cdot C \cdot V(s) \tag{2.16}$$

From Eq. (2.15), we can write

$$V(s) = E_{dc}(s) - SL\ I(s) \tag{2.17}$$

But

$$E_{dc}(s) = \frac{E_{dc}}{S} \tag{2.18}$$

Substitute Eqs (2.17) and (2.18) in Eq. (2.16)

$$\therefore \quad I(s) = \frac{E_{dc}}{R \cdot S} - \frac{SLI(s)}{R} + SC\left[\frac{E_{dc}}{s} - SLI(s)\right]$$

$$I(s) + SL\frac{I(s)}{R} + S^2\,CLI(s) = \frac{E_{dc}}{R \cdot S} + \frac{E_{dc}SC}{S}$$

$$\therefore \quad I(s)\left[1 + \frac{SL}{R} + S^2CL\right] = \frac{E_{dc}}{S}\left[\frac{1}{R} + SC\right]$$

$$I(s)\left[\frac{R + LS + RCLS^2}{R}\right] = \frac{E_{dc}}{s}\left[\frac{1 + RCS}{R}\right]$$

$$I(s) = \frac{E_{dc}}{s}\left[\frac{1 + RCS}{R + LS + RCLS^2}\right]$$

$$I(s) = \frac{E_{dc}}{RLCS}\left[\frac{1 + RCS}{S^2 + \frac{1}{RC}S + \frac{1}{LC}}\right] \tag{2.19}$$

Taking inverse Laplace transform of Eq. (2.19), we get

$$i(t) = \frac{E_{dc}}{R}\left[1 + \frac{1}{\sqrt{1-\varepsilon^2}}\frac{W_n^2}{\varepsilon}e^{-t/RC}\sin(\omega t + \phi)\right]$$

where

$$\varepsilon = \frac{1}{2R}\sqrt{\frac{L}{C}} = \text{damping ratio}$$

$$W_n = \frac{1}{\sqrt{LC}} = \text{undamped natural angular frequency.}$$

$$\omega = \omega_n \sqrt{1-\varepsilon^2}$$

or,
$$\omega = \frac{1}{\sqrt{LC}} \sqrt{1 - \frac{L}{4R^2C}} = \sqrt{\frac{1}{LC} - \frac{1}{4R^2C^2}}$$

$$\phi = \tan^{-1} \frac{2RC\omega}{-\varepsilon} - \tan^{-1} \frac{\sqrt{1-\varepsilon^2}}{-\varepsilon} = \tan^{-1} 2RC\omega$$

If $i(t) = 0$ at $t = 0$,

$$\phi = -\sin^{-1} \frac{1}{A}$$

$$\therefore \quad i(t) = \frac{E_{dc}}{R}\left[1 + A\, e^{-t/2RC} \sin\left(\omega t - \sin^{-1}\frac{1}{A}\right)\right] \tag{2.20}$$

Now, load voltage from Eqs (2.15) and (2.16) can be written as

$$V(s) = \frac{E_{dc}}{LC\left(S^2 + \frac{1}{RC}S + \frac{1}{LC}\right)} \tag{2.21}$$

Taking inverse Laplace transform of Eq. (2.21), we get

$$V(t) = E_{dc} \frac{W_n}{\sqrt{1-\varepsilon^2}} e^{-t/2RC} \sin \omega t + E_{dc} \tag{2.22}$$

In this case, the triggering frequency of the thyristor must be less than W_n, so that the conduction cycle is completed.

(b) *Load in series with capacitor C* Let us consider the series resonant circuit of Fig. 2.12 (b). Let the thyristor be turned ON at $t = 0$ with the initial capacitor voltage zero.

The circuit equation is

$$E_{dc} = iR + L\frac{di}{dt} + \frac{1}{C}\int i\, dt \tag{2.23}$$

On differentiating and dividing by L, we get

$$\frac{d^2i}{dt^2} + \frac{R}{L}\frac{di}{dt} + \frac{i}{LC} = \frac{1}{L}\frac{d}{dt}E_{dc} \tag{2.24}$$

The corresponding homogeneous equation is of the second order and is as below.

$$\frac{d^2i}{dt^2} + \frac{R}{L}\cdot\frac{di}{dt} + \frac{1}{LC}i = 0 \tag{2.25}$$

The solution of this well known second order equation for under damped case is

$$i = e^{-\varepsilon t}\left[A_1 \cos \omega t + A_2 \sin \omega t\right] \tag{2.26}$$

where

$$\varepsilon = \frac{R}{2l} \tag{2.27}$$

and

$$\omega_o = \frac{1}{\sqrt{LC}} \tag{2.28}$$

$$\omega = \omega_o \sqrt{1-\varepsilon^2} = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \tag{2.29}$$

When $i(0+) = i(0-) = 0$

$$A_1 = 0, \qquad A_2 = \frac{E_{dc}}{L}$$

This gives

$$i(t) = e^{-\frac{R}{2L}t}\left[\frac{E_{dc}}{\omega L} \sin \omega t\right] \tag{2.30}$$

This equation shows that the thyristor-current i goes to zero at

$$\omega t = \pi$$

or

$$t = \frac{\pi}{\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}} \tag{2.31}$$

Now,

$$\frac{di}{dt} = -e^{\frac{\pi R}{2\omega L}}\left(\frac{E_{dc}}{l}\right)$$

Therefore, the capacitor voltage at the end of conduction, $V_c = E_{dc} - V_L$

where $V_L = L\,di/dt$

$$\therefore \quad V_c = E_{dc}\left[1 + e^{-\pi R/2\omega L}\right] \tag{2.32}$$

Now, if V_0 is the initial-state voltage of the capacitor then Eq. (2.30) becomes

$$i(t) = e^{-(R/2L)t}\left[\frac{E_{dc} - V_0}{\omega L} \sin \omega t\right] \tag{2.33}$$

and

$$V_c = E_{dc} + e^{\pi R/2\omega t}(E_{dc} - V_0) \tag{2.34}$$

For $\omega > 0$, we now calculate the condition for underdamped.

$$\therefore \quad \frac{1}{LC} - \frac{R^2}{4L^2} > 0 \qquad \text{i.e.,} \quad \frac{1}{LC} > \frac{R^2}{4L^2}$$

or

$$R < \sqrt{\frac{4L}{C}} \tag{2.35}$$

Class B – self commutation

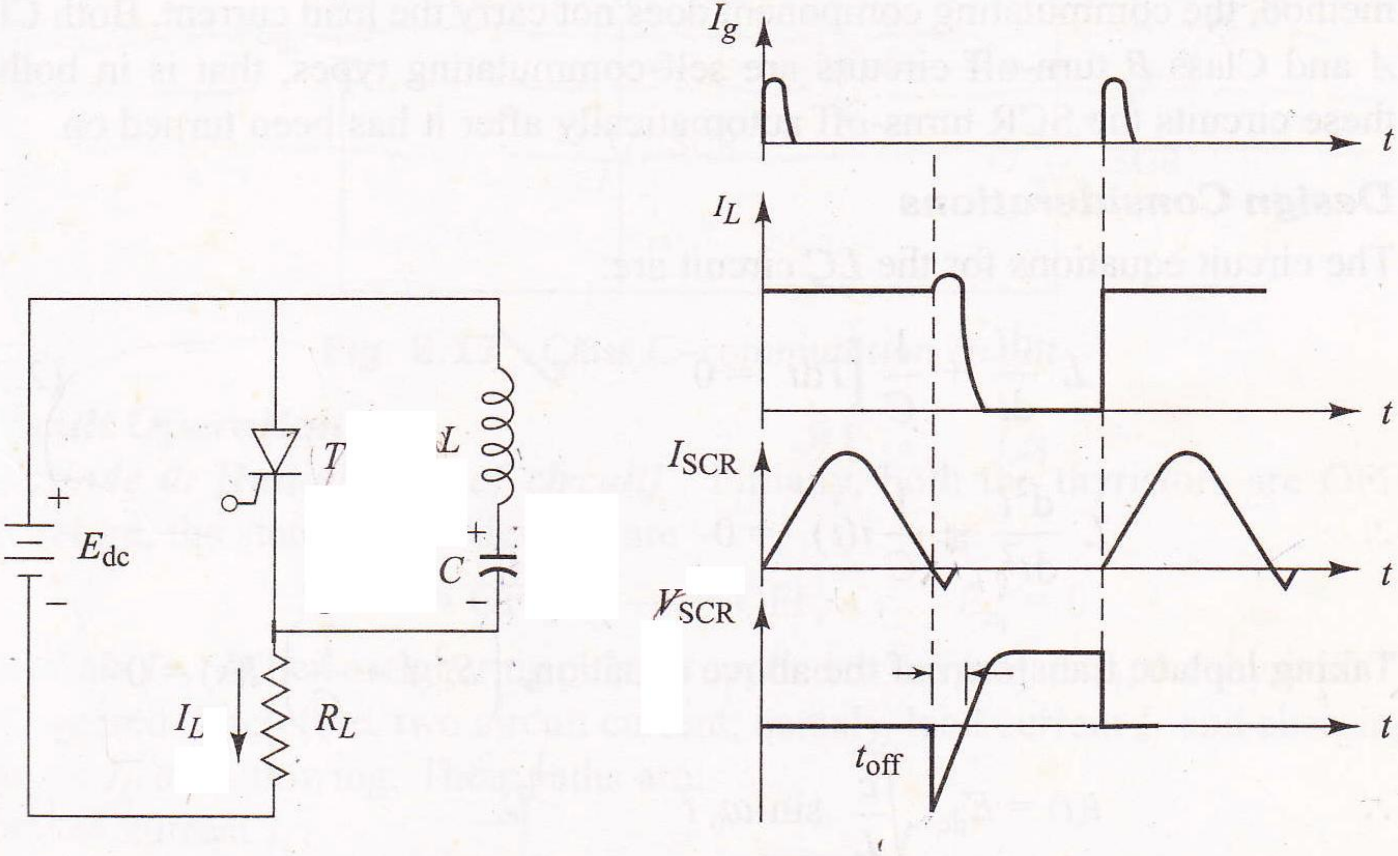


Fig. 2.15 *Class B commutation circuit* **Fig. 2.16** *Associated waveforms*

Design Considerations

The circuit equations for the LC circuit are:

$$L\frac{di}{dt} + \frac{1}{C}\int i\,dt = 0 \tag{2.36}$$

$$\therefore \quad L\frac{d^2 i}{dt^2} + \frac{1}{C}i(t) = 0$$

Taking laplace transform of the above equation, $\left(S^2 L + \frac{1}{C}\right) I(s) = 0$

$$\therefore \quad i(t) = E_{dc}\sqrt{\frac{C}{L}}\sin \omega_0 t \tag{2.37}$$

where $$\omega_0 = \sqrt{\frac{1}{LC}} \tag{2.38}$$

Therefore, the peak commutation current is

$$I_{C(peak)} = E_{dc}\cdot\sqrt{C/L} \tag{2.39}$$

For this Class B commutation method, the peak discharge current of the capacitor is assumed to be twice the load-current I_L, and the time for which the SCR is reverse biased is approximately equal to one-quarter period of the resonant circuit.

Therefore, $$I_{C(peak)} = 2\,I_L = E_{dc}\sqrt{C/L} \tag{2.40}$$

And $$t_{off} = \frac{\pi}{2}\sqrt{LC} \tag{2.41}$$

Class C – complimentary commutation

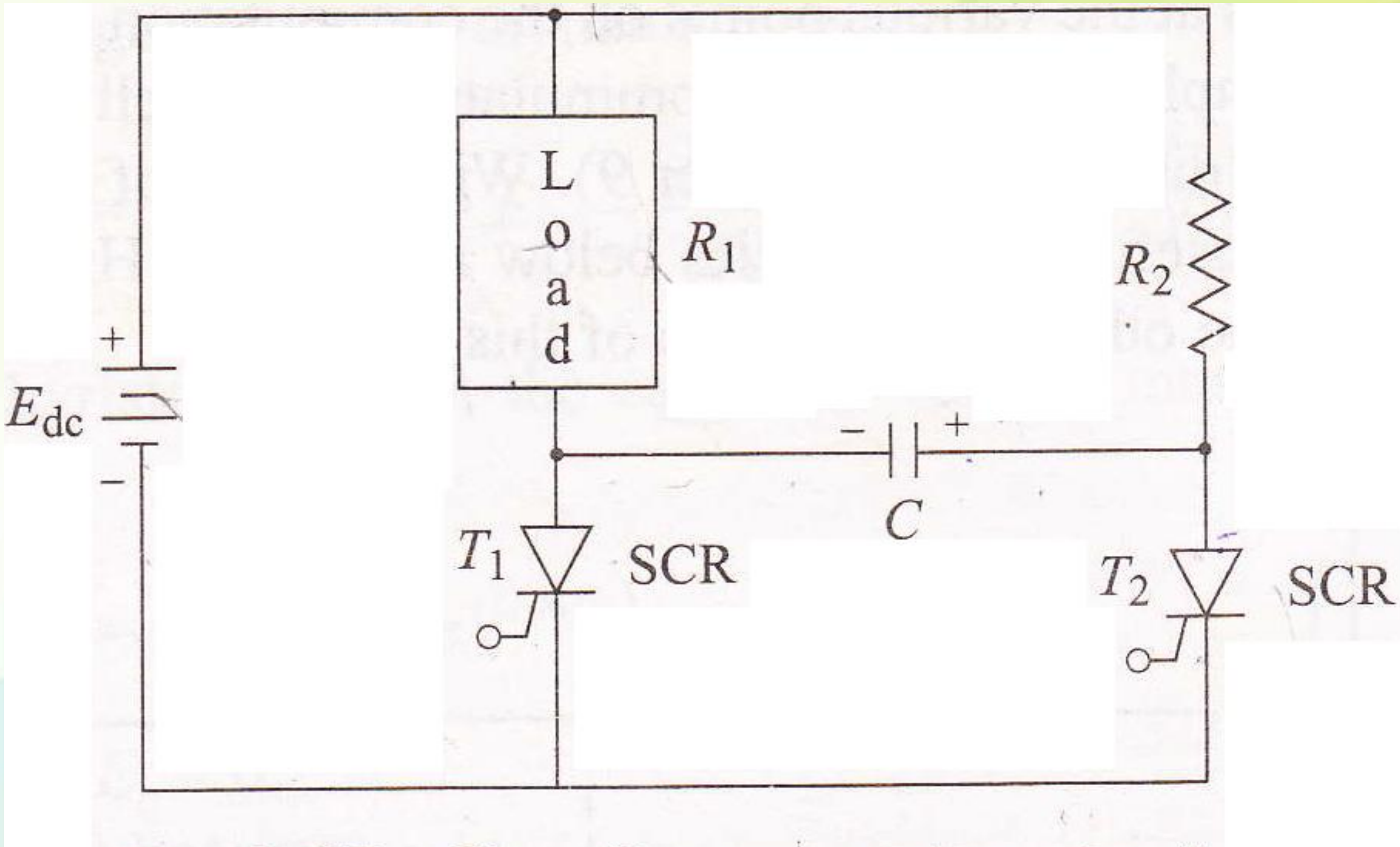
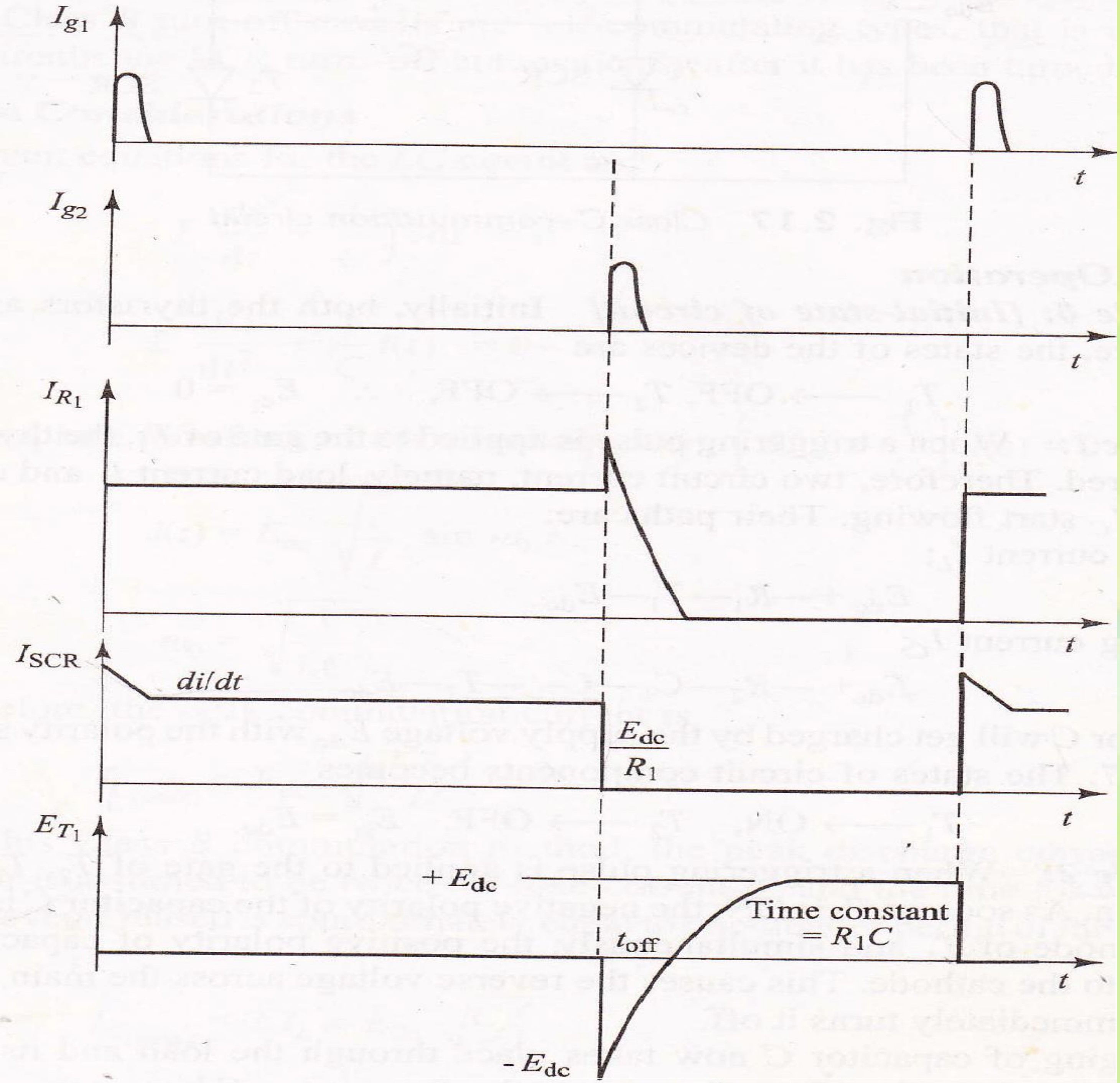


Fig. 2.17 *Class C–commutation circuit*


I_{g1}
t
I_{g2}
t
I_{R_1}
t
I_{SCR}
di/dt
$\frac{E_{dc}}{R_1}$
t
E_{T_1}
$+E_{dc}$
Time constant
$= R_1C$
t_{off}
t
$-E_{dc}$

Class C – complimentary commutation

Design:

$$i = \frac{2E_{dc}}{R_1} e^{-t/R_1C}$$

$$E_{T_1} = E_{dc} - i R_1 = E_{dc} - \frac{2E_{dc}}{R_1} e^{-t/R_1C} \cdot R_1 = E_{dc} \left(1 - 2e^{-t/R_1C}\right)$$

$$E_c = E_{dc} \left(1 - 2e^{-t/R_1C}\right)$$

Let $t = t_{off}$ when $E_c = 0$.

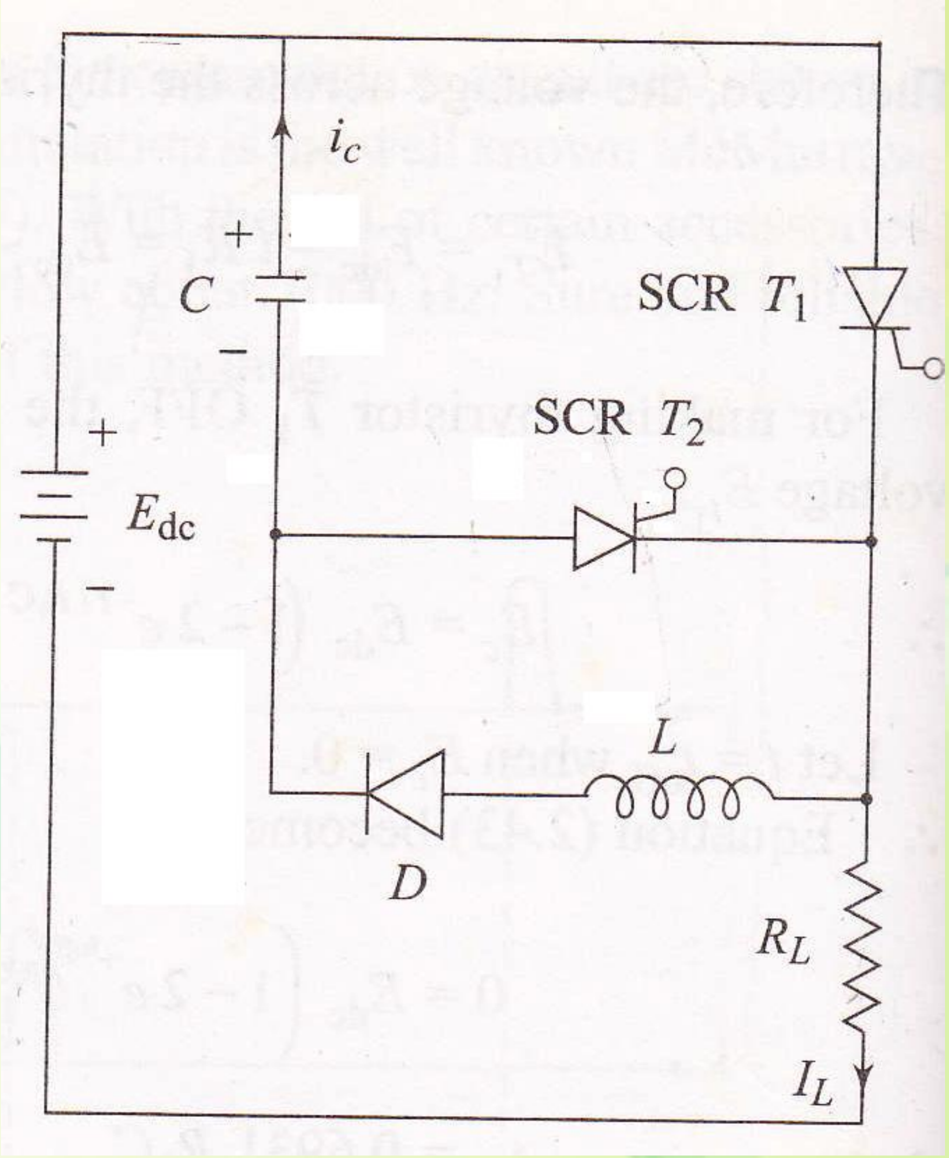
$$0 = E_{dc} \left(1 - 2e^{-t_{off}/R_1C}\right) \quad \text{or} \quad 0 = 1 - 2e^{-t_{off}/R_1C}$$

$$t_{off} = 0.6931\, R_1C$$

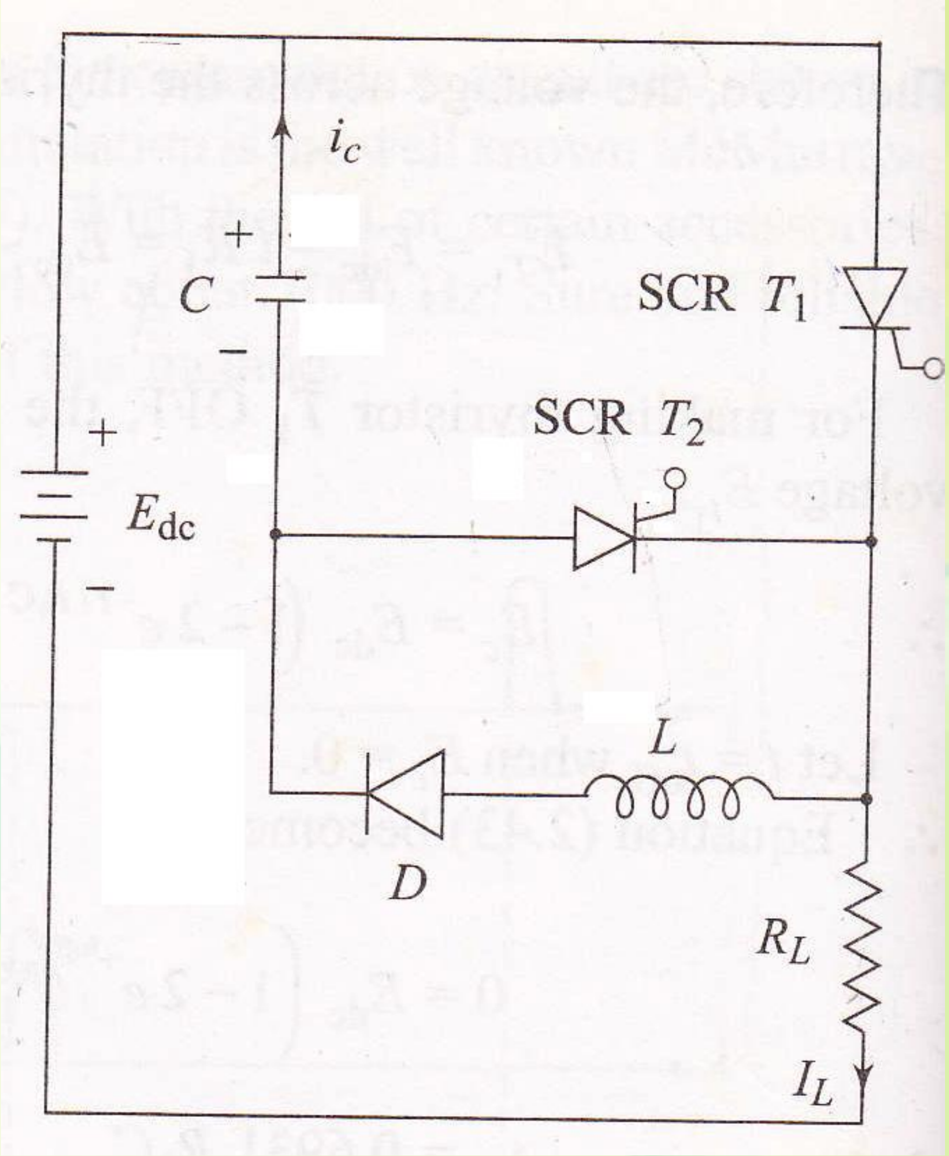
$$C = 1.44 \frac{t_{off}}{R_1}$$

$$\frac{dV}{dt}_{(max)} > \frac{2E_{dc}}{R_1C}$$

Class D – Auxiliary commutation



Class D – Auxiliary commutation



Class D – Auxiliary commutation

Design: Capacitor -- I_L, t_{off}, E_{dc}

$$C\,E_{dc} = I_L\, t_{off} \quad \therefore\; C = \frac{I_L\, t_{off}}{E_{dc}}$$

Inductor -- Ic discharge, time (t_2-t_1)

$$I_{C_{(peak)}} = \frac{E_{dc}}{W_r L}$$

where W_r = oscillating frequency = $\frac{1}{\sqrt{LC}}$ rad/sec

$$I_{C_{(peak)}} = E_{dc}\sqrt{\frac{C}{L}}$$

Also, periodic time during oscillation T_r, is given by

$$T_r = \frac{2\pi}{W_r} = 2\,(t_1 - t_2)$$

Now, let $I_{L_{(max)}}$ be the maximum current through SCR

$$E_{dc}\sqrt{\frac{C}{L}} \le I_{L_{(max)}}$$

or $$L \ge C.\left(\frac{E_{dc}}{I_{L_{(max)}}}\right)^2$$

Class E – External pulse commutation

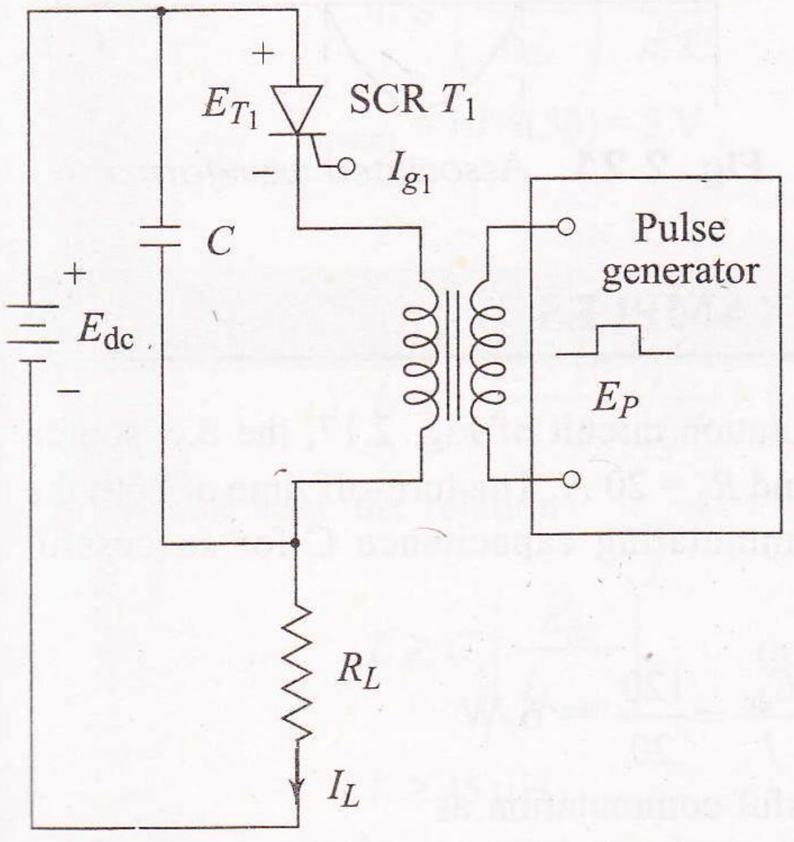


Fig. 2.21 *Class E commutation circuit*

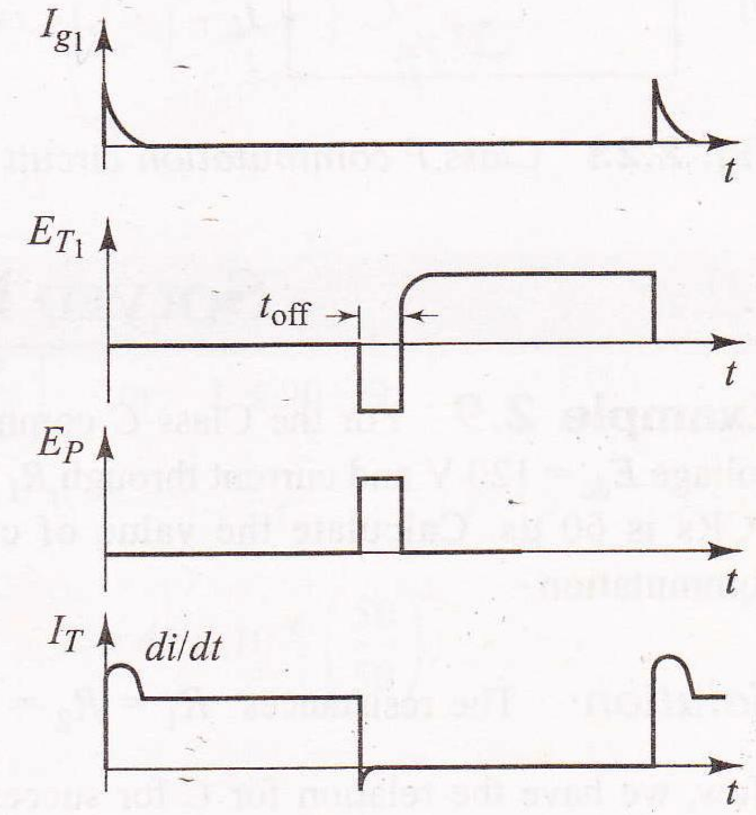


Fig. 2.22 *Associated waveforms*

Class F – AC Line commutation

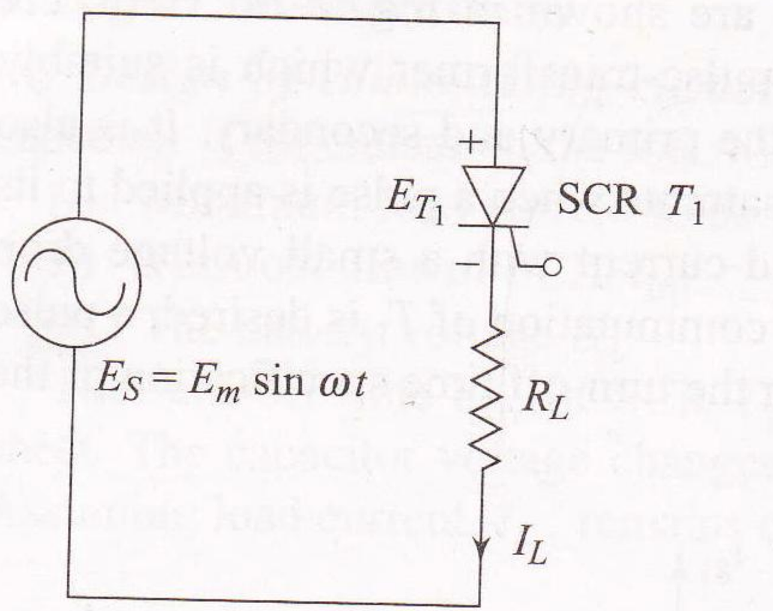


Fig. 2.23 *Class F commutation circuit*

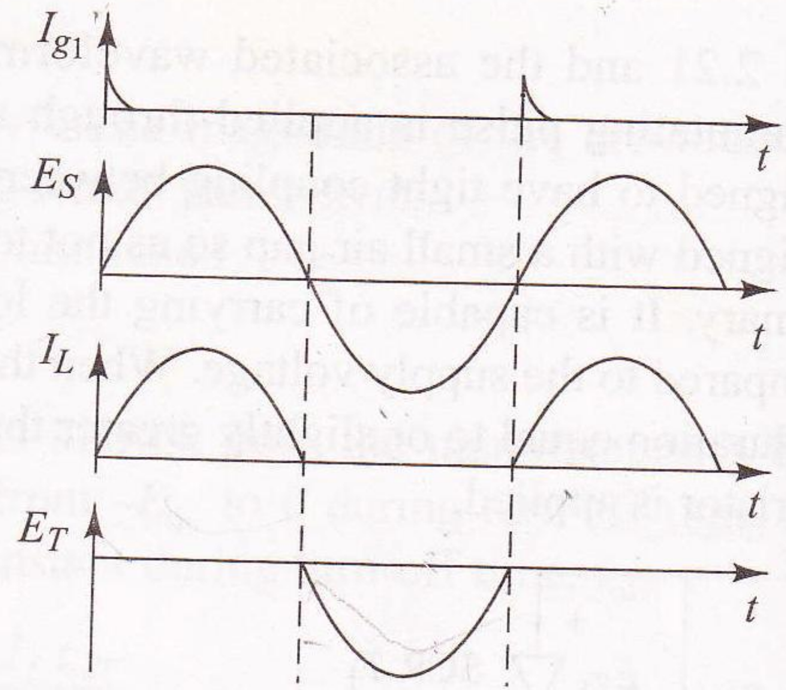


Fig. 2.24 *Associated waveforms*

Queries ...?