Module 1 INTRODUCTION

Structure

1.0 INTRODUCTION TO POWER ELECTRONICS

Power Electronics is a field which combines Power (electric power), Electronics and Control systems.

Power engineering deals with the static and rotating power equipment for the generation, transmission and distribution of electric power.

Electronics deals with the study of solid state semiconductor power devices and circuits for Power conversion to meet the desired control objectives (to control the output voltage and output power).

Power electronics may be defined as the subject of applications of solid state power semiconductor devices (Thyristors) for the control and conversion of electric power.

1.1 Objectives:

- To give an overview of applications power electronics, different types of power semiconductor devices, their switching characteristics.
- To explain power diode characteristics, types, their operation and the effects of power diodes on RL circuits.
- To explain the techniques for design and analysis of single phase diode rectifier circuits.

1.2 Power Electronic Applications

1. COMMERCIAL APPLICATIONS

Heating Systems Ventilating, Air Conditioners, Central Refrigeration, Lighting, Computers and Office equipments, Uninterruptible Power Supplies (UPS), Elevators, and

2. AEROSPACE APPLICATIONS

Space shuttle power supply systems, satellite power systems, aircraft power systems.

3. TELECOMMUNICATIONS

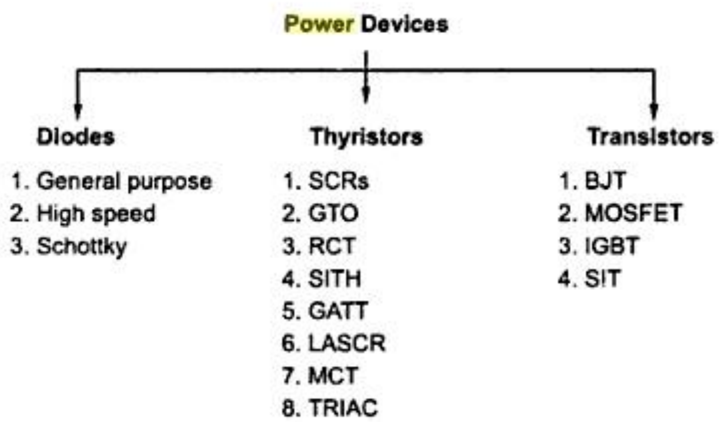
Battery chargers, power supplies (DC and UPS), mobile cell phone battery chargers.

4. TRANSPORTATION

Traction control of electric vehicles, battery chargers for electric vehicles, electric locomotives, street cars, trolley buses, automobile electronics including engine controls.

1.3 POWER SEMICONDUCTOR DEVICES

The power semiconductor devices are used as on/off switches in power control circuit. These devices are classified as follows.



A. **POWER DIODES**

Power diodes are made of silicon p-n junction with two terminals, anode and cathode. Diode is forward biased when anode is made positive with respect to the cathode. Diode conducts fully when the diode voltage is more than the cut-in voltage (0.7 V for Si). Conducting diode will have a small voltage drop across it.

Diode is reverse biased when cathode is made positive with respect to anode. When reverse biased, a small reverse current known as leakage current flows. This leakage current increases with increase in magnitude of reverse voltage until avalanche voltage is reached (breakdown voltage).

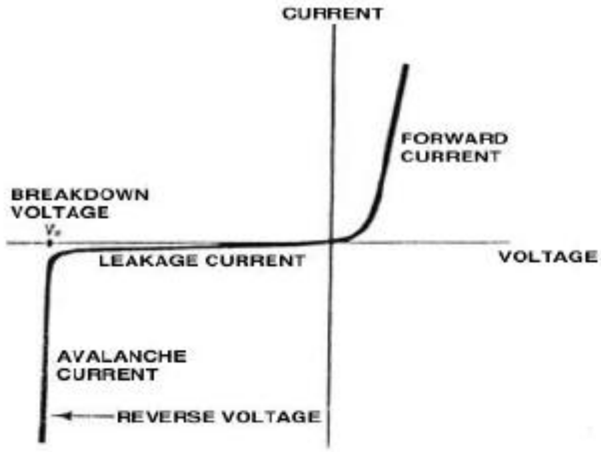


Fig.1.1 V-I Characteristics of diode.

POWER DIODES TYPES

Power diodes can be classified as

1. General purpose diodes.
2. High speed (fast recovery) diodes.
3. Schottky diode.

General Purpose Diodes

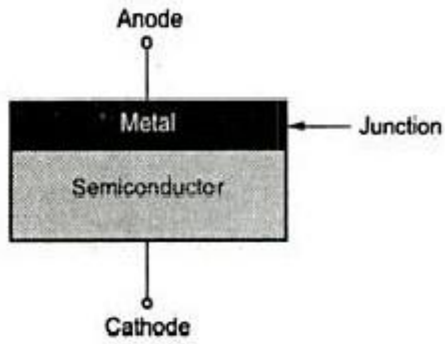
The diodes have high reverse recovery time of about 25 microsecs (μsec). They are used in low speed (frequency) applications. e.g., line commutated converters, diode rectifiers and converters for a low input frequency upto 1 KHz. Diode ratings cover a very wide range with current ratings less than 1 A to several thousand amps (2000 A) and with voltage ratings from 50 V to 5 KV. These diodes are generally manufactured by diffusion process. Alloyed type rectifier diodes are used in welding power supplies. They are most cost effective and rugged and their ratings can go upto 300A and 1KV.

Fast Recovery Diodes

The diodes have low recovery time, generally less than 5 μs. The major field of applications is in electrical power conversion i.e., in free-wheeling ac-dc and dc-ac converter circuits. Their current ratings is from less than 1 A to hundreds of amperes with voltage ratings from 50 V to about 3 KV. Use of fast recovery diodes are preferable for free-wheeling in SCR circuits because of low recovery loss, lower junction temperature and reduced di/dt. For high voltage ratings greater than 400 V they are manufactured by diffusion process and the recovery time is controlled by platinum or gold diffusion. For less than 400 V rating epitaxial diodes provide faster switching speeds than diffused diodes. Epitaxial diodes have a very narrow base width resulting in a fast recovery time of about 50 ns.

Schottky Diodes

A Schottky diode has metal (aluminium) and semi-conductor junction. A layer of metal is deposited on a thin epitaxial layer of the n-type silicon. In Schottky diode there is a larger barrier for electron flow from metal to semi-conductor. Figure shows the schotty diode.



When Schottky diode is forward biased free electrons on n-side gain enough energy to flow into the metal causing forward current. Since the metal does not have any holes there is no charge storage, decreasing the recovery time. Therefore a Schottky diode can switch-off faster than an ordinary p-n junction diode. A Schottky diode has a relatively low forward voltage drop and reverse recovery losses. The leakage current is higher than a p-n junction diode. The maximum allowable voltage is about 100 V. Current ratings vary from about 1 to 300 A. They are mostly used in low voltage and high current dc power supplies. The operating frequency may be as high 100-300 kHz as the device is suitable for high frequency application.

Comparison Between Different Types Of Diodes

General Purpose Diodes	**Fast Recovery Diodes**	**Schottky Diodes**
Upto 5000V & 3500A	Upto 3000V and 1000A	Upto 100V and 300A
Reverse recovery time – High	Reverse recovery time – Low	Reverse recovery time – Extremely low.
Turn off time - High	Turn off time - Low	Turn off time – Extremely Low
Switching frequency – Low	Switching frequency – High	Switching frequency – Very high.
V_F = 0.7V to 1.2V	V_F = 0.8V to 1.5V	V_F ≈0.4V to 0.6V

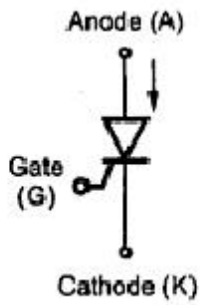
B. Thyristors

Silicon Controlled Rectifiers (SCR):

The SCR has 3- terminals namely:

Anode (A), Cathode (k) and Gate(G).

Internally it is having 4-layers p-n-p-n as shown in figure (b).



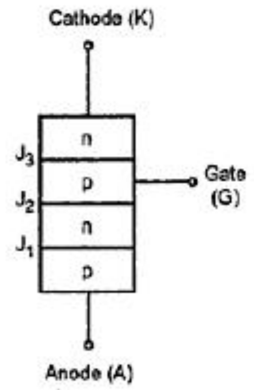


Fig.1.2 (a). Symbol Fig.1.2 (b). Structure of SCR

The word thyristor is coined from thyratron and transistor. It was invented in the year 1957 at Bell Labs.

The Thyristors can be subdivided into different types

- Forced-commutated Thyristors (Inverter grade Thyristors)
- Line-commutated Thyristors (converter-grade Thyristors)
- Gate-turn off Thyristors (GTO).
- Reverse conducting Thyristors (RCT's).
- Static Induction Thyristors (SITH).
- Gate assisted turn-off Thyristors (GATT).
- Light activated silicon controlled rectifier (LASCR) or Photo SCR's.
- MOS-Controlled Thyristors (MCT's).

C. POWER TRANSISTORS

Transistors which have high voltage and high current rating are called power transistors. Power transistors used as switching elements, are operated in saturation region resulting in a low - on state voltage drop. Switching speed of transistors is much higher than the thyristors. And they are extensively used in dc-dc and dc-ac converters with inverse parallel connected diodes to provide bi-directional current flow. However, voltage and current ratings of power transistor are much lower than the thyristors. Transistors are used in low to medium power applications. Transistors are current controlled device and to keep it in the conducting state, a continuous base current is required.

Power transistors are classified as follows

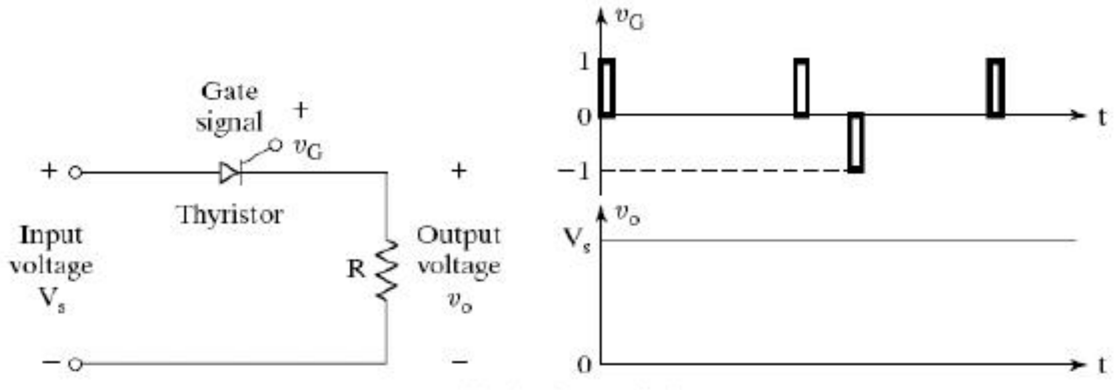
- Bi-Polar Junction Transistors (BJTs)
- Metal-Oxide Semi-Conductor Field Effect Transistors (MOSFETs)
- Insulated Gate Bi-Polar Transistors (IGBTs)

- Static Induction Transistors (SITs)

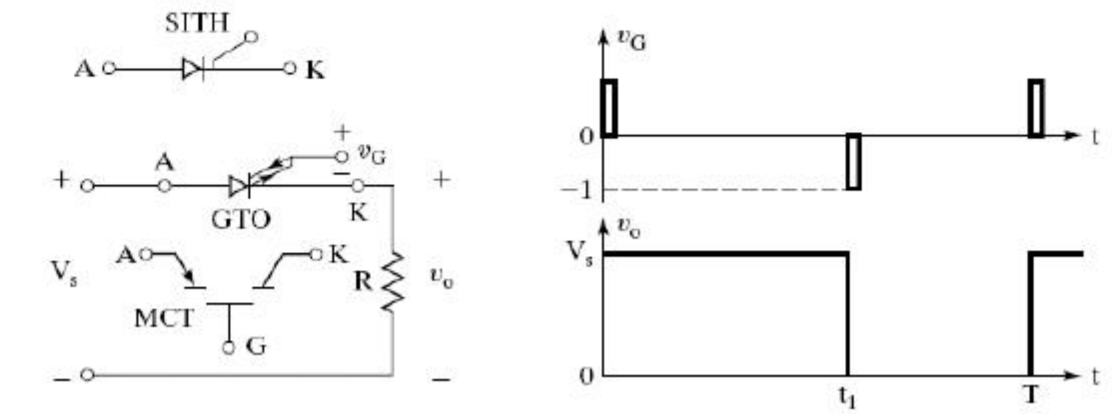
1.4 CONTROL CHARACTERISTICS OF POWER DEVICES

The power semiconductor devices are used as switches. Depending on power requirements, ratings, fastness & control circuits for different devices can be selected. The required output is obtained by varying conduction time of these switching devices.

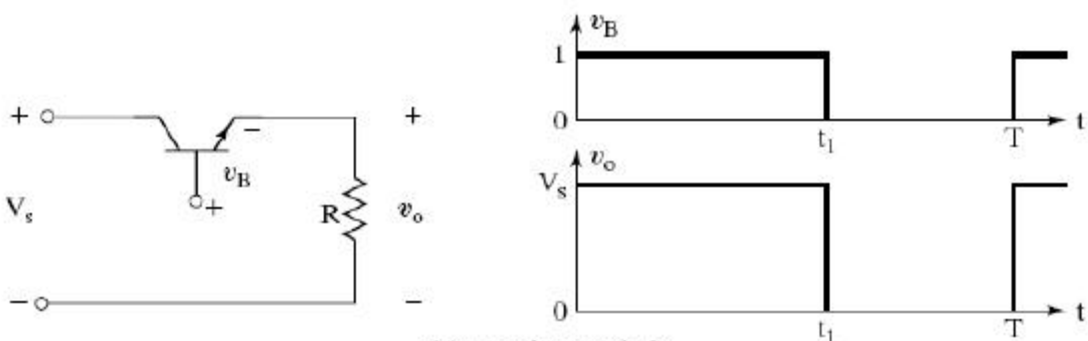
Control characteristics of Thyristors:



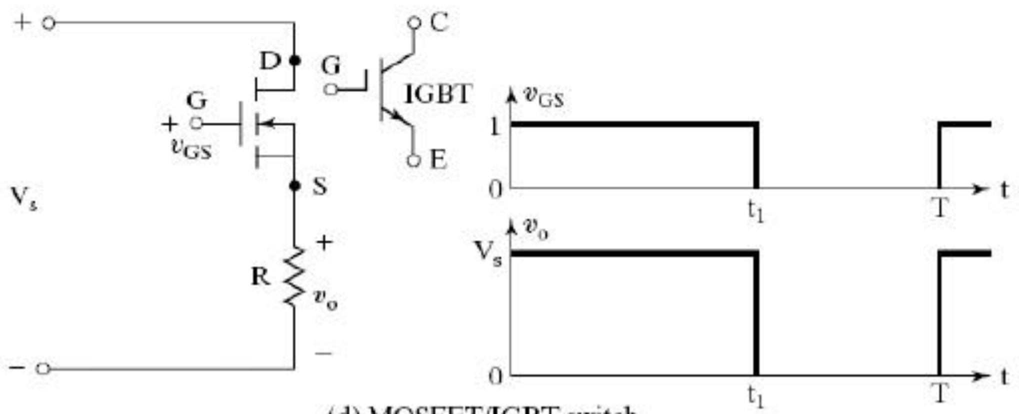
(a) Thyristor switch



(b) GTO/MTO/ETO/IGCT/MCT/SITH switch (For MCT, the polarity of V_G is reversed as shown)



(c) Transistor switch



(d) MOSFET/IGBT switch

Fig1.3: Control Characteristics of Power Switching Devices

Classification of power semiconductor devices:

- Uncontrolled turn on and turn off (e.g.: diode).
- Controlled turn on and uncontrolled turn off (e.g. SCR)
- Controlled turn on and off characteristics (e.g. BJT, MOSFET, GTO, SITH, IGBT, SIT, MCT).
- Continuous gate signal requirement (e.g. BJT, MOSFET, IGBT, SIT).
- Pulse gate requirement (e.g. SCR, GTO, MCT).
- Bipolar voltage withstanding capability (e.g. SCR, GTO).
- Unipolar voltage withstanding capability (e.g. BJT, MOSFET, GTO, IGBT, MCT).
- Bidirectional current capability (e.g.: Triac, RCT).
- Unidirectional current capability (e.g. SCR, GTO, BJT, MOSFET, MCT, IGBT, SITH, SIT & Diode).

1.5 Types of Power Converters or Types of Power Electronic Circuits

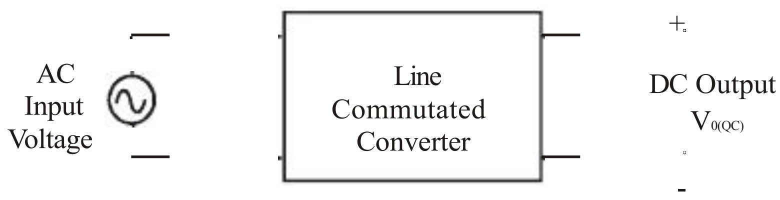
For the control of electric power supplied to the load or the equipment/machinery or for power conditioning the conversion of electric power from one form to other is necessary and the switching characteristic of power semiconductor devices (Thyristors) facilitate these conversions.

The thyristorised power converters are referred to as the static power converters and they perform the function of power conversion by converting the available input power supply in to output power of desired form.

The different types of thyristor power converters are

- Diode rectifiers (uncontrolled rectifiers).
- Line commutated converters or AC to DC converters (controlled rectifiers)
- AC voltage (RMS voltage) controllers (AC to AC converters).
- Cyclo converters (AC to AC converters at low output frequency).
- DC choppers (DC to DC converters).
- Inverters (DC to AC converters).

1. AC TO DC Converters (Rectifiers)



These are AC to DC converters. The line commutated converters are AC to DC power converters. These are also referred to as controlled rectifiers. The line commutated converters (controlled rectifiers) are used to convert a fixed voltage, fixed frequency AC power supply to obtain a variable DC output voltage. They use natural or AC line commutation of the Thyristors.

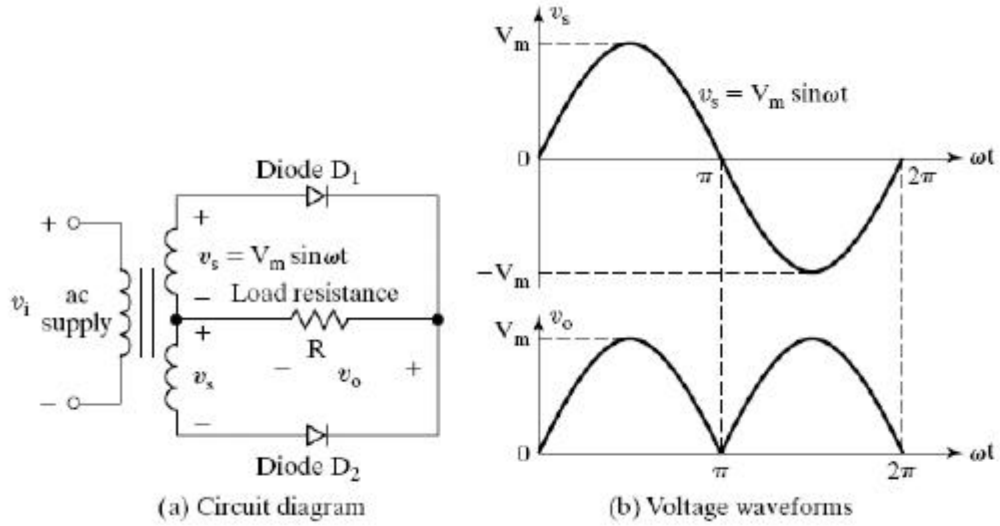


Fig1.4: A Single Phase Full Wave Uncontrolled Rectifier Circuit (Diode Full Wave Rectifier) using a Center Tapped Transformer

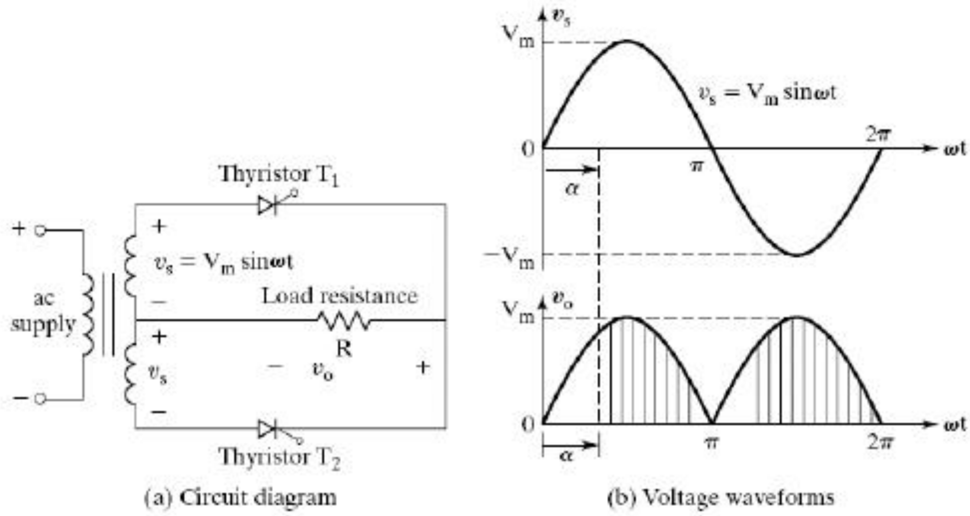


Fig: 1.5 A Single Phase Full Wave Controlled Rectifier Circuit (using SCRs) using a Center Tapped Transformer

Different types of line commutated AC to DC converters circuits are

- Diode rectifiers – Uncontrolled Rectifiers
- Controlled rectifiers using SCR's.
  - Single phase controlled rectifier.
  - Three phase controlled rectifiers.

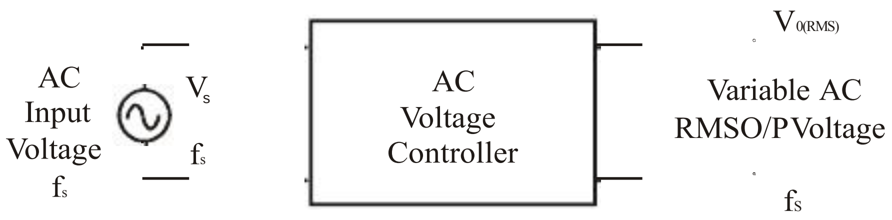
Applications of Ac To Dc Converters

AC to DC power converters are widely used in

- Speed control of DC motor in DC drives.

- UPS.
- HVDC transmission.
- Battery Chargers.

2. a. AC TO AC Converters or AC regulators.



The AC voltage controllers convert the constant frequency, fixed voltage AC supply into variable AC voltage at the same frequency using line commutation.

AC regulators (RMS voltage controllers) are mainly used for

- Speed control of AC motor.
- Speed control of fans (domestic and industrial fans).
- AC pumps.

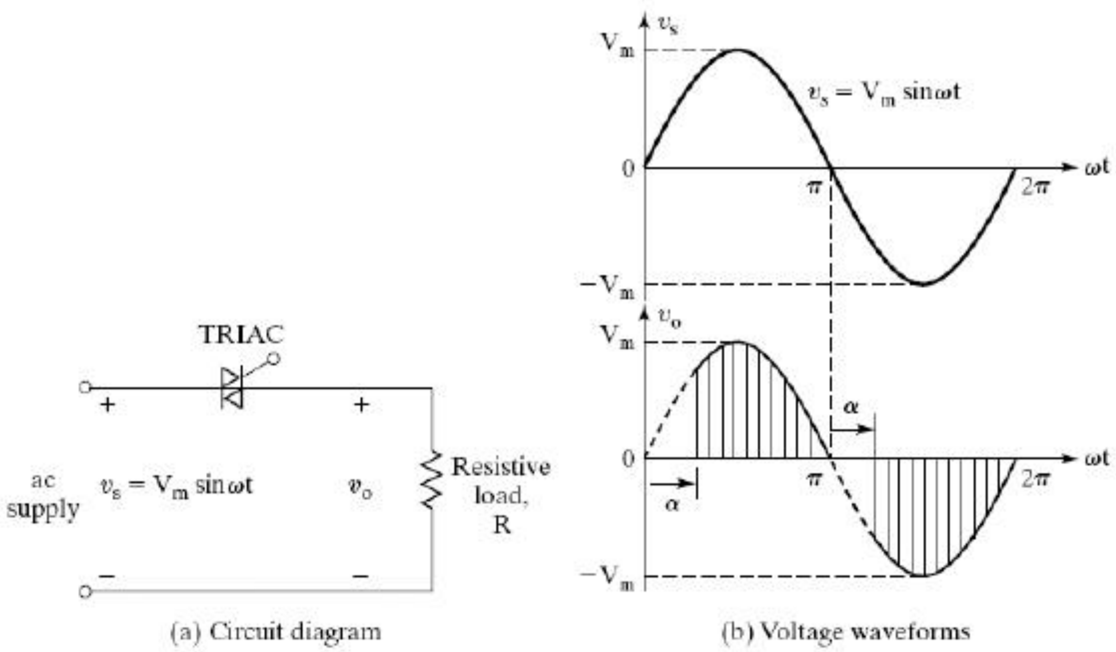
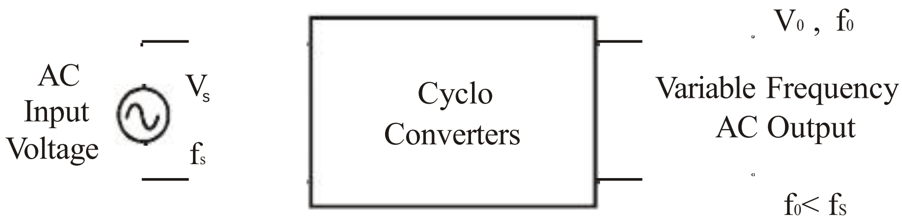


Fig.1.6: A Single Phase AC voltage Controller Circuit (AC-AC Converter using a TRIAC)

2. b. AC TO AC Converters with Low Output Frequency or CYCLO CONVERTERS

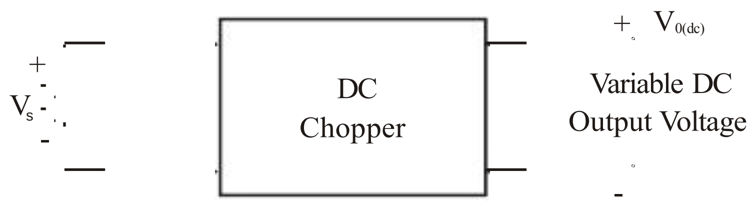


The cyclo converters convert power from a fixed voltage fixed frequency AC supply to a variable frequency and variable AC voltage at the output.

The cyclo converters generally produce output AC voltage at a lower output frequency. That is output frequency of the AC output is less than input AC supply frequency.

Applications of cyclo converters are traction vehicles and gearless rotary kilns.

3. CHOPPERS or DC TO DC Converters



The choppers are power circuits which obtain power from a fixed voltage DC supply and convert it into a variable DC voltage. They are also called as DC choppers or DC to DC converters. Choppers employ forced commutation to turn off the Thyristors. DC choppers are further classified into several types depending on the direction of power flow and the type of commutation. DC choppers are widely used in

- Speed control of DC motors from a DC supply.
- DC drives for sub-urban traction.
- Switching power supplies.

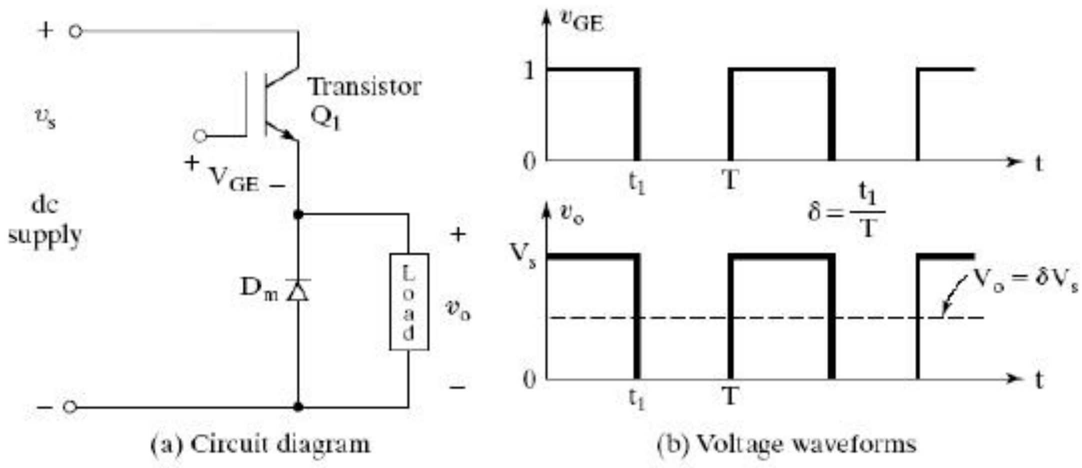
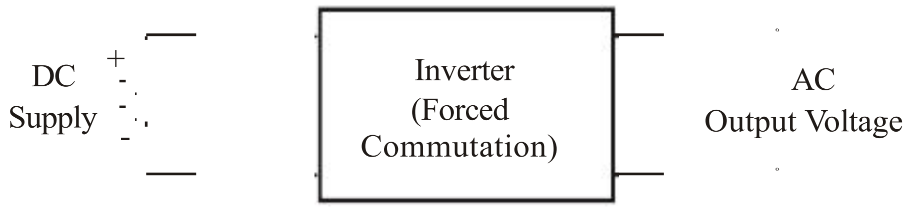


Fig.1.7: A DC Chopper Circuit (DC-DC Converter) using IGBT

4. INVERTERS or DC TO AC Converters



The inverters are used for converting DC power from a fixed voltage DC supply into an AC output voltage of variable frequency and fixed or variable output AC voltage. The inverters also employ force commutation method to turn off the Thyristors.

Applications of inverters are in

- Industrial AC drives using induction and synchronous motors.
- Uninterrupted power supplies (UPS system) used for computers, computer labs.

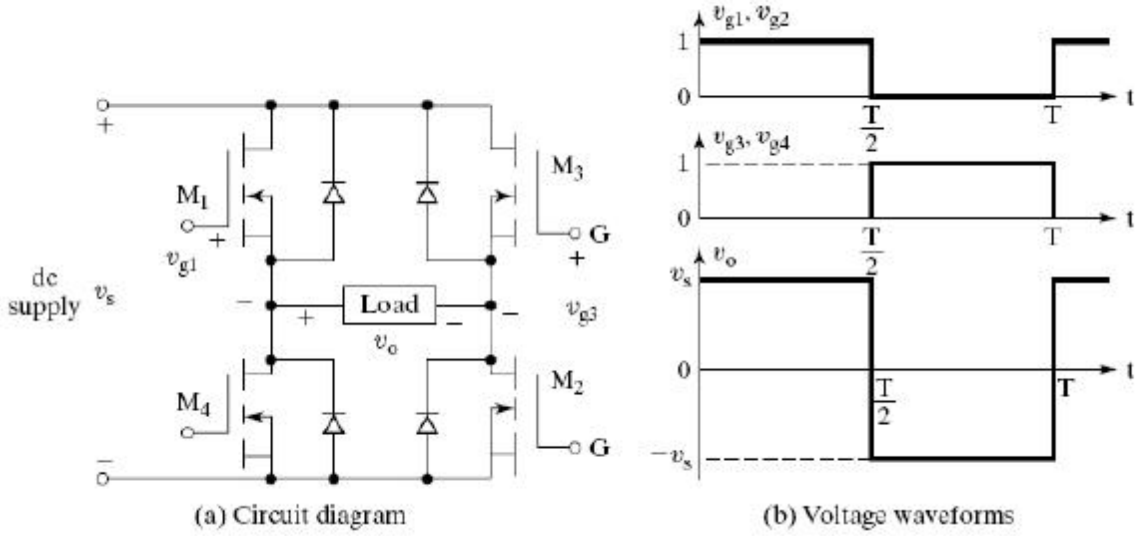


Fig.1.8: Single Phase DC-AC Converter (Inverter) using MOSFETS

1.6 Peripheral Effects

The power converter operations are based mainly on the switching of power semiconductor devices and as a result the power converters introduce current and voltage harmonics (unwanted AC signal components) into the supply system and on the output of the converters.

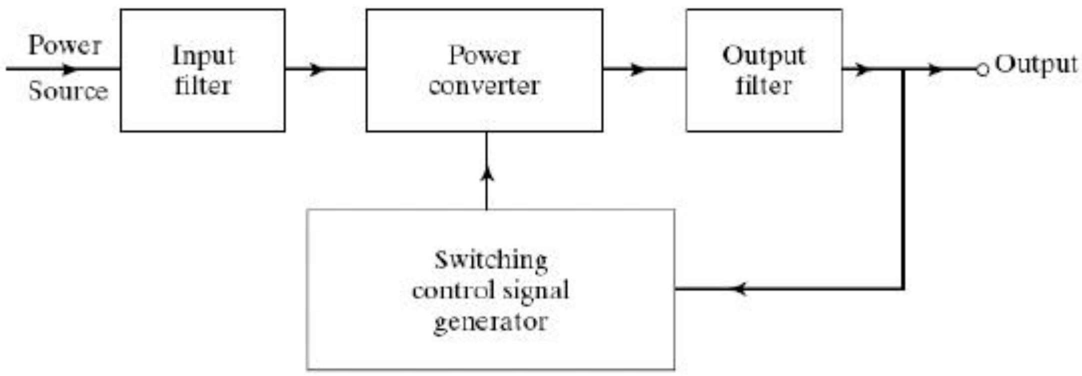


Fig.1.9: A General Power Converter System

These induced harmonics can cause problems of distortion of the output voltage, harmonic generation into the supply system, and interference with the communication and signaling circuits. It is normally necessary to introduce filters on the input side and output side of a power converter system so as to reduce the harmonic level to an acceptable magnitude. The figure below shows the block diagram of a generalized power converter with filters added. The application of power electronics to supply the sensitive electronic loads poses a challenge on the power quality issues and raises the problems and concerns to be resolved by the researchers. The input and output quantities of power converters could be either AC or DC. Factors such as total harmonic distortion (THD), displacement factor or harmonic factor

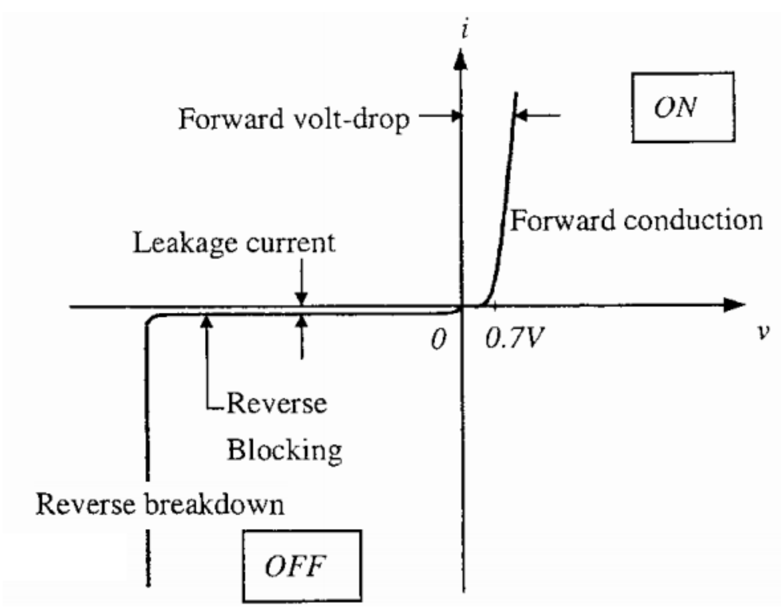
(HF), and input power factor (IPF), are measures of the quality of the waveforms. To determine these factors it is required to find the harmonic content of the waveforms. To evaluate the performance of a converter, the input and output voltages/currents of a converter are expressed in Fourier series. The quality of a power converter is judged by the quality of its voltage and current waveforms.

The control strategy for the power converters plays an important part on the harmonic generation and the output waveform distortion and can be aimed to minimize or reduce these problems. The power converters can cause radio frequency interference due to electromagnetic radiation and the gating circuits may generate erroneous signals. This interference can be avoided by proper grounding and shielding.

1.7POWER DIODES

Introduction : Power diodes are made of silicon p-n junction with two terminals, anode and cathode. Diode is forward biased when anode is made positive with respect to the cathode. Diode conducts fully when the diode voltage is more than the cut-in voltage (0.7 V for Si). Conducting diode will have a small voltage drop across it. Diode is reverse biased when cathode is made positive with respect to anode. When reverse biased, a small reverse current known as leakage current flows. This leakage current increases with increase in magnitude of reverse voltage until avalanche voltage is reached (breakdown voltage).

Fig shows V-I Characteristics of diode.



Forward Voltage Drop:

- Is the forward-conducting junction level
- The forward voltage drop is due to the forward resistance of the junction.
- forward volt drop is across the junction
-

Reverse Leakage Current:

Thermal agitation does break some of the bonds in the crystal, resulting in minority carriers, Which permit a small reverse current flow, i.e. leakage current.

1.8 Reverse Recovery Characteristics

When a diode is in forward conduction mode, a sudden reversal of the polarity of the applied voltage would not stop the diode current at once. But the diode continues to conduct in the opposite direction due to minority carriers that remain stored in pn-junction and the bulk semiconductor material. Fig.2 shows the effect of minority carriers on the turn off characteristics of the power diode.

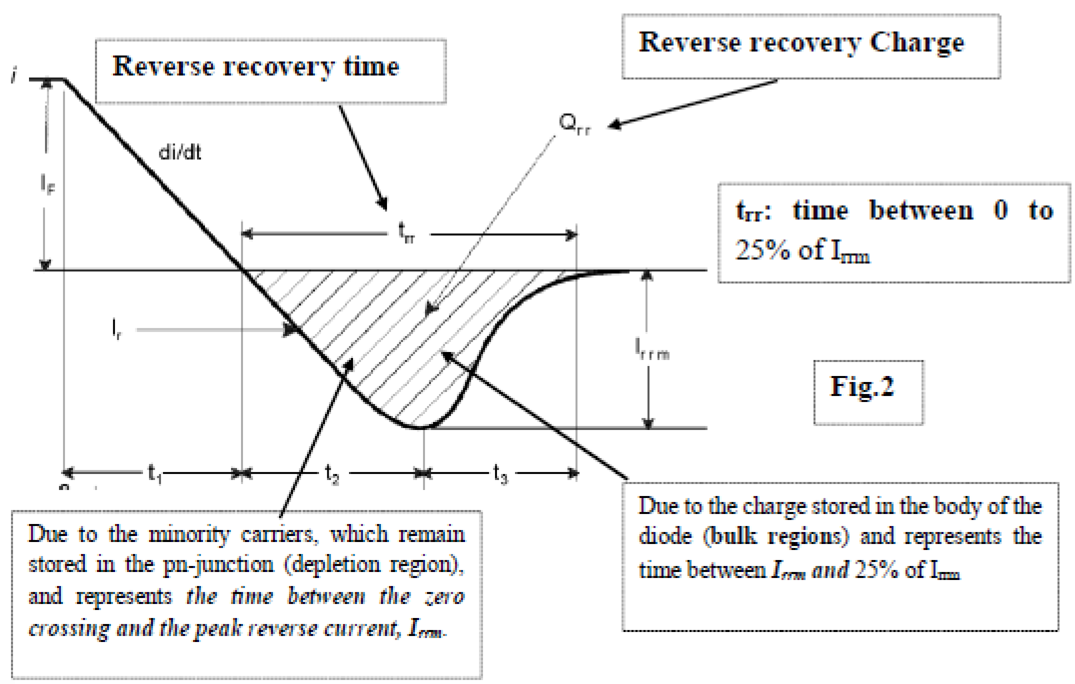


Fig.2

The charge carriers (holes & electrons) require a certain time to recombine with opposite n charges and to be neutralized; this time is called the **reverse recovery time trr o**f the diode. From Fig.2, one can found the following relationships:

$$t_{rr} = t_2 + t_3 \quad I_{rr} = t_2 \frac{di}{dt} \quad \text{then} \quad Q_{rr} = \frac{1}{2} I_{rrm} t_2 + \frac{1}{2} I_{rrm} t_3 = \frac{1}{2} I_{rrm} t_{rr}$$

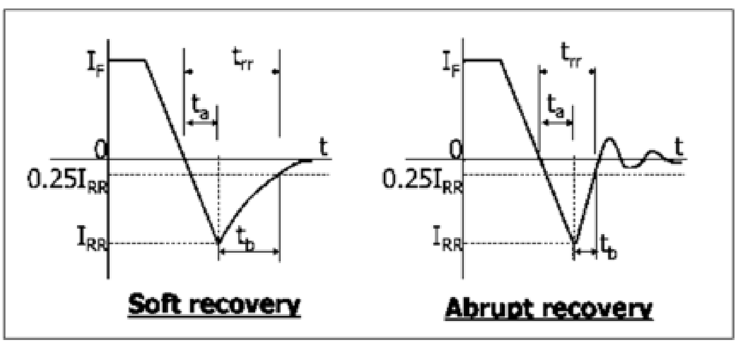
$$I_{rrm} \cong \frac{2Q_{rr}}{t_{rr}} = t_2 \frac{di}{dt}$$

For Fast recovery :

$$t_3 \ll t_2 \rightarrow t_2 = t_{rr} \rightarrow t_{rr} = \sqrt{\frac{2Q_{rr}}{\frac{di}{dt}}}$$

Hence, $I_{rrm} = \sqrt{2Q_{rr} \frac{di}{dt}}$

The fast decay of negative current creates an inductive drop that adds with the reverse blocking voltage VR as illustrate in Fig.3.There are two types of reverse recovery characteristics of junction diodes: **Soft recovery and Fast recovery** where, the **softness factor, SF** is the ratio of t2/t3.



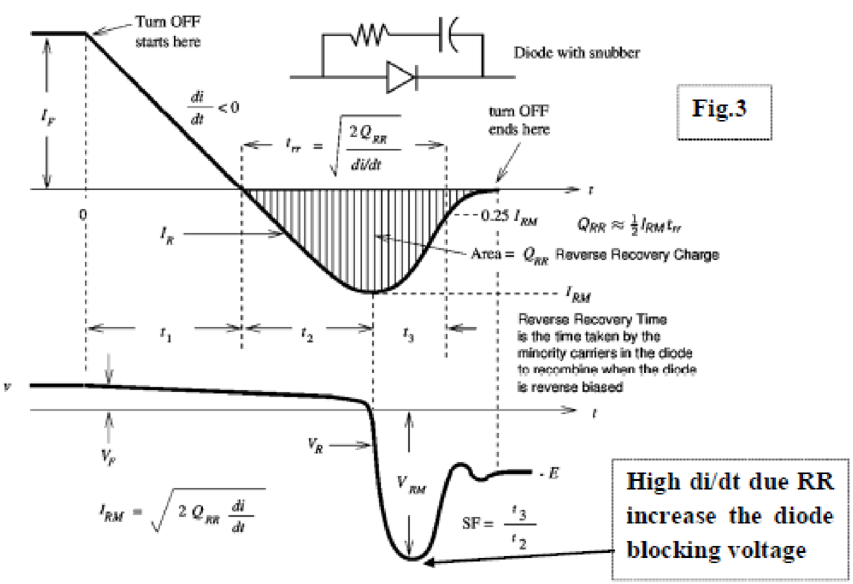


Fig.3

Hence, the blocking voltage across the diode increases to: $V_{rrm} = V_{rr} + V_R$ where, Vrr is reverse recovery voltage due to the fast decay in the negativecurrent and equal to: $V_{rr} = L\frac{di}{dt}$

Based on the diode reverse recovery characteristics power diode are classified into:

- Standard Recovery (General) Diodes
- Fast Recovery Diodes
- Schottky Diodes
- Silicon Carbide Diodes.

For high frequency rectifier applications, Fast recovery and Schottky Diodes are generally used because of their short reverse recovery time and low voltage drop in their forward bias condition

General Purpose Diodes

The diodes have high reverse recovery time of about 25 microsecs (μsec). They are used in low speed (frequency) applications. e.g., line commutated converters, diode rectifiers and converters for a low input frequency upto 1 KHz. Diode ratings cover a very wide range with current ratings less than 1 A to several thousand amps (2000 A) and with voltage ratings from 50 V to 5 KV. These diodes are generally manufactured by diffusion process. Alloyed type rectifier diodes are used in welding power supplies. They are most cost effective and rugged and their ratings can go up to 300A and 1KV.

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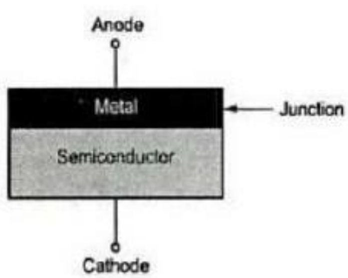

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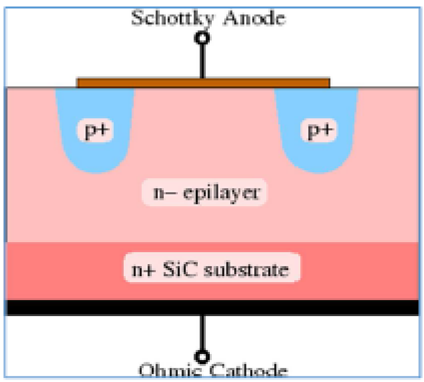
Silicon Carbide SiC Schottky Barrier Diode (SBD)

SiC (Silicon Carbide) is a compound semiconductor comprised of silicon (Si) and carbon (C). Compared to Si, SiC has

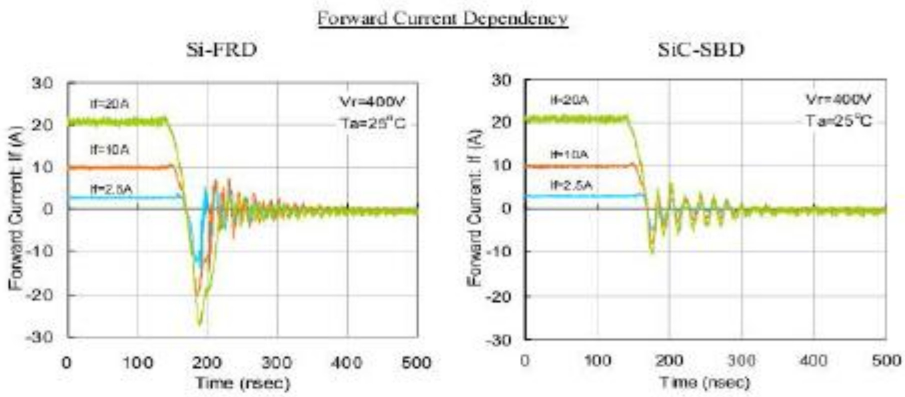
- ✓ Ten times the dielectric breakdown field strength.
- ✓ Three times the bandgap.
- ✓ Three times the thermal conductivity.



Both p-type and n-type regions, which are necessary to fashion device structures in a semiconductor materials, can be formed in SiC. These properties make SiC an attractive material from which to manufacture power devices that can far exceed the performance of their Si counterparts. SiC devices can withstand ***higher breakdown voltage, have lower resistivity, and can operate at higher temperature***. SiC SBDs (Schottky barrier diodes) with breakdown voltage from 600V (which far exceeds the upper limit for silicon SBDs) and up are readily available. Compared to silicon FRDs (fast recovery diodes),

- ✓ SiC SBDs have much lower reverse recovery current and recovery time, hence dramatically lower recovery loss and noise emission. Furthermore, unlike silicon FRDs, these characteristics do not change significantly over current and operating temperature ranges.
- ✓ SiC SBDs allow system designers to improve efficiency, lower cost and size of heat sink, increasing switching frequency to reduce size of magnetics and its cost, etc.

SiC-SBDs have similar threshold voltage as Si- FRDs, i.e., a little less than 1V.



Reverse recovery characteristics of SiC-SBD

Si fast P-N junction diodes (e.g. FRDs: fast recovery diodes) have high transient current at the moment the junction voltage switches from the forward to the reverse direction, resulting in significant switching loss. This is due to minority carriers stored in the drift layer during conduction phase when forward voltage is applied. The higher the forward current (or temperature), the longer the recovery time and the larger the recovery current.

In contrast, since SiC-SBDs are majority carrier (unipolar) devices that use no minority carriers for electrical conduction, they do not store minority carrier s. The reverse recovery current in SiC SBDs is only to discharge junction capacitance. Thus the switching loss is substantially lower compared to that in Si-FRDs. The transient current is nearly independent of temperatures and forward currents, and thereby achieves stable fast recovery in any environment. This also means SiC-SBDs generate less noise from the recovery current.

A typical comparison between different types of diodes is shown in the table below:

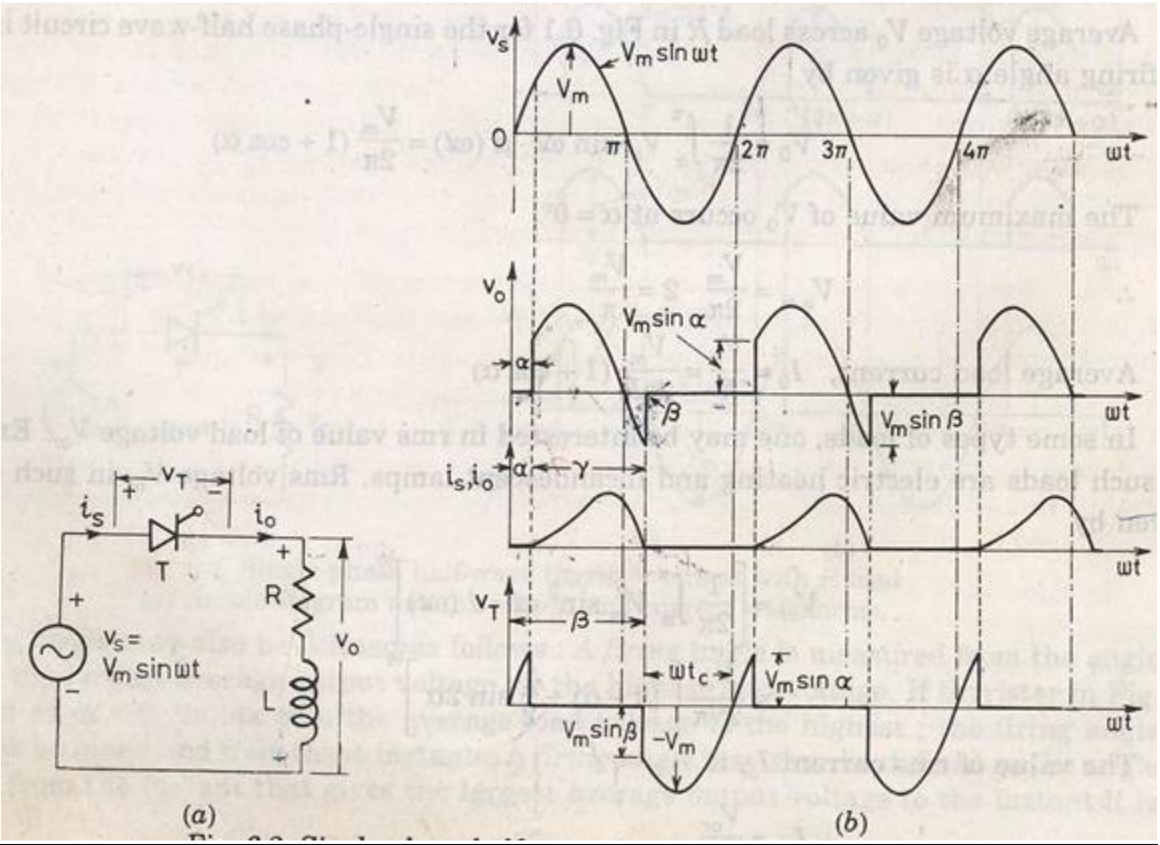
Standard Recovery Diodes	Fast Recovery Diodes	Schottky Diodes	Silicon Carbide Diodes.
Upto 5000V & 3500A	Upto 3000V and 1000A	Upto 100V and 300A	Upto 600V and 200A
Reverse recovery time –High t_{rr} ~=25µs.	Reverse recovery time – Low $t_{rr} \leq 5$µs.	Reverse recovery time – Extremely low. trr is typically around few ns	have extremely fast switching behaviour with ultra-low trr
Typically used in rectifiers at power frequencies i.e., at 50Hz or 60 Hz.	Typically operating at higher frequencies as freewheeling diodes.	Typically operating at higher frequencies as freewheeling diodes.	Typically operating at higher frequencies as freewheeling diodes.
V_F = 0.7V to 1.2V	V_F = 0.8V to 1.5V	V_F = 0.4V to 0.6V	V_F <0.5V

1.10 DIODE RECTIFIER

Rectifier are used to convert A.C to D.C supply.

Rectifiers can be classified as single phase rectifier and three phase rectifier. Single phase rectifier are classified as 1-Φ half wave and 1-Φ full wave rectifier. Three phase rectifier are classified as 3-Φ half wave rectifier and 3-Φ full wave rectifier. 1-Φ Full wave rectifier are classified as1-Φ mid point type and 1-Φ bridge type rectifier. 1-Φ bridge type rectifier are classified as 1-Φ half controlled and 1-Φ full controlled rectifier. 3-Φ full wave rectifier are again classified as 3-Φ mid point type and 3-Φ bridge type rectifier. 3-Φ bridge type rectifier are again divided as 3-Φ half controlled rectifier and 3-Φ full controlled rectifier.

Single phase half wave circuit with R-L load



Output current $i_o$rises gradually. After some time i_o reaches a maximum value and then begins to decrease.

At π, v_o=0 but i_o is not zero because of the load inductance L. After π interval SCR is reverse biased but load current is not less then the holding current.

At β>π, i_o reduces to zero and SCR is turned off.

At 2π+β SCR triggers again

α is the firing angle.

β is the extinction angle.

$v = \beta - \alpha = conduction\ angle$

Analysis for V_T.

At $\omega t = \square, V_T = V_m sin\square$

During $= \square\ to\ \square$, $V_T = 0;$

When $= \square$, $V_T = V_m sin\square;$

$$V_m \sin \omega t = Ri_0 + L\frac{di_0}{dt}$$

$$i_s = \frac{V_m}{\sqrt{R^2 + X^2}} \sin(\omega \mathrm{t} - \phi)$$

Where,

$$\phi = \tan^{-1}\frac{X}{R}$$

$$X = \omega L$$

Where $\square$ is the angle by which I_s lags V_s.

The transient component can be obtained as

$$Ri_t + L\frac{di_0}{dt} = 0$$

So $i_t = Ae^{-(Rt/L)}$

$i_0 = i_s + i_t$

$$\frac{V_m}{z}\sin(\omega t - \square) + Ae^{-(Rt/L)}$$

Where $z = \sqrt{R^2 + X^2}$

At $\alpha = \omega t, i_o = 0;$

$0 = \frac{V_m}{z}\sin(\alpha - \square) + Ae^{-(R\alpha/L\omega)};$

$$A = \frac{-V_m}{z}\sin(\alpha - \square)e^{(R\alpha/L\omega)}$$

$$i_o = \frac{V_m}{z}\sin(\omega t - \square) - \frac{V_m}{z}\sin(\alpha - \square)e^{-R(\omega t - \alpha)/L\omega}$$

Therefore,

$\omega t = \beta, i_0 = 0;$

So $\sin(\beta - \alpha) = \sin(\alpha - \Box) e^{-(\beta-\alpha)/(\omega L)}$

β can obtained from the above equation.

The average load voltage can be given by

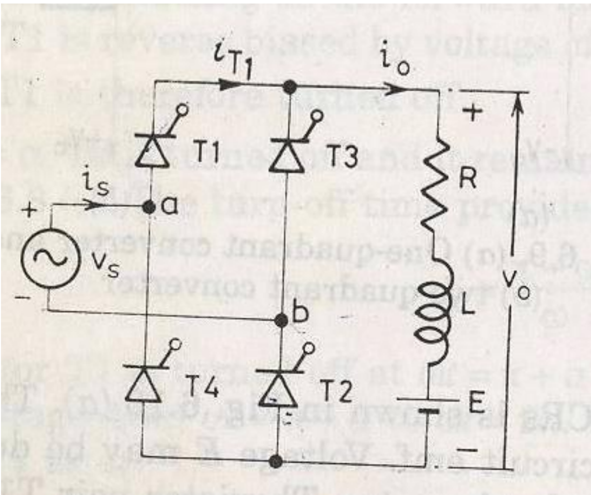
$$V_0 = \frac{1}{2\pi}\int_{\alpha}^{\beta} V_m \sin \omega t d(\omega t)$$

$$\frac{V_m}{2\pi}(\cos(\alpha) - \cos(\beta))$$

Average load current

$$I_0 = \frac{V_m}{2\pi R}(\cos\alpha - \cos\beta)$$

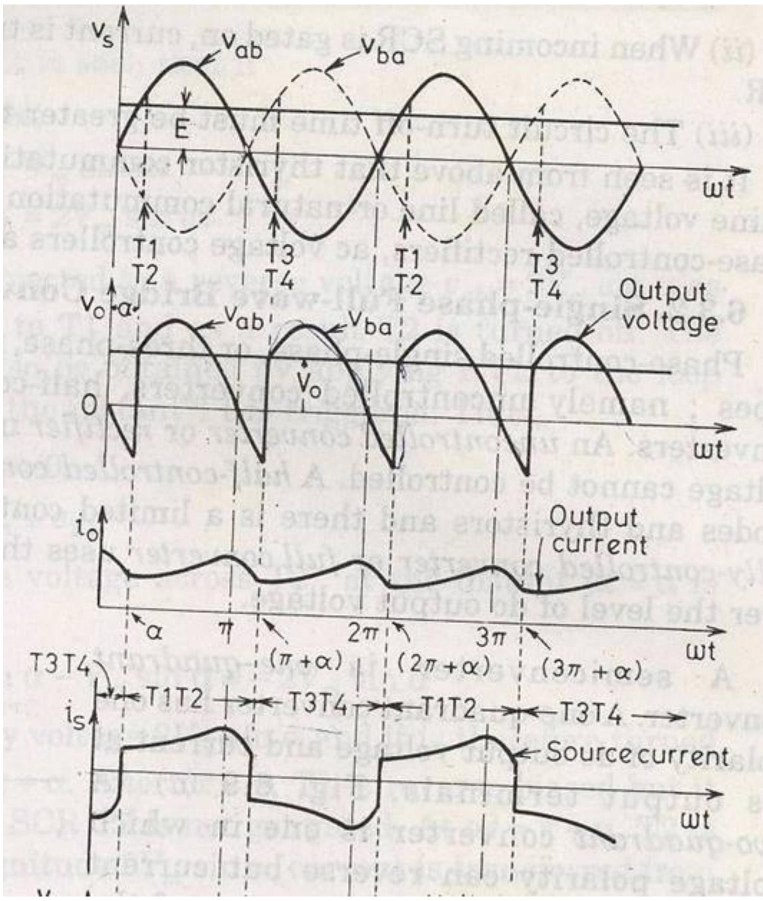
Single phase full converter



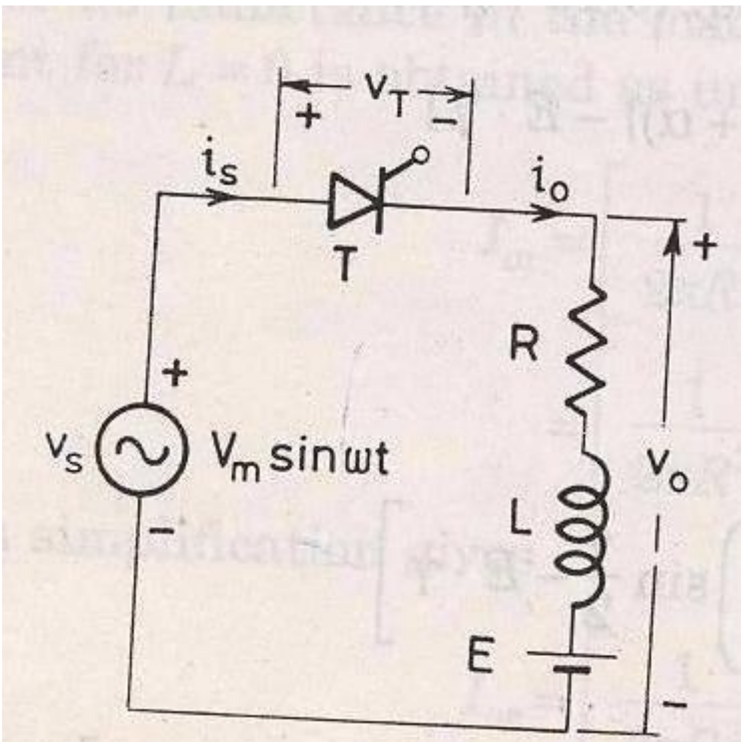
$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi+\beta} V_m \sin(\omega t) d(\omega t)$$

$$= \frac{2V_m}{\pi}\cos\alpha$$

T_1,T_2 triggered at α and π radian latter T_3, T_4 are triggered.



Single phase half wave circuit with RLE load



The minimum value of firing angle is

$$V_m \sin(\omega t) = E$$

So,

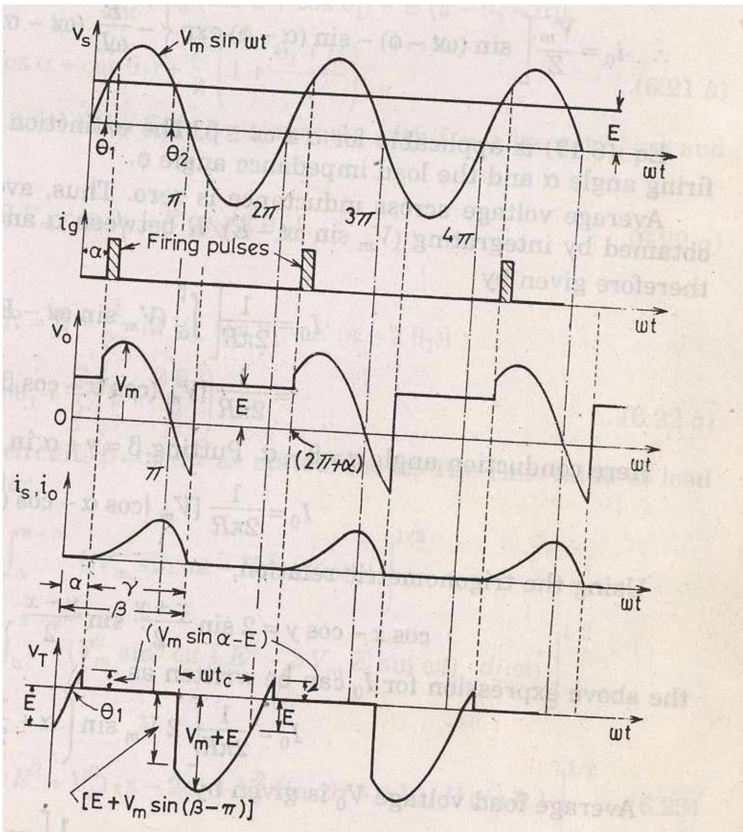
$$\theta_1 = \sin^{-1} \frac{E}{V_m}$$

Maximum value of firing angle

$$\theta_2 = \pi - \theta_2$$

The voltage differential equation is

$$V_m \sin(\omega t) = Ri_0 + L\frac{di_0}{dt} + E$$



$$i_s = i_{s1} + i_{s2}$$

Due to source volt

$$i_{s1} = \frac{V_m}{Z}\sin(\omega t - \phi)$$

Due to DC counter emf

$i_{s2} = -(E/R)$

$i_t = Ae^{-(R/L)t}$

Thus the total current is given by

$i_{s1} + i_{s2} + i_t$

$$= \frac{V_m}{Z}\sin(\omega t - \phi) - \frac{E}{R} + Ae^{-(\mathrm{R/L})\mathrm{t}}$$

$$i_{s0} = \frac{V_m}{Z}\sin(\omega t - \phi) - \frac{E}{R} + Ae^{-(\mathrm{R/L})\mathrm{t}}$$

$At\,\omega t = \alpha, i_0 = 0$

$$A = [\frac{E}{R} - \frac{V_m}{Z}\sin(\alpha - \phi)]\mathrm{e}^{-R\alpha/L\omega}$$

So

$$i_0 = \frac{V_m}{Z}[\sin(\omega t - \phi) - \sin(\alpha - \phi)e^{\{\frac{-R}{\omega L}(\omega t - \alpha)\}} - \frac{E}{R}[1 - e^{\{\frac{-R}{\omega L}(\omega t - \alpha)\}}]$$

Average voltage across the inductance is zero. Average value of load current is

$$\mathrm{I}_0 = \frac{1}{2\pi R}\int_\alpha^\beta (V_m \sin\omega t - E)\,\mathrm{d}(\omega t)$$

$$= \frac{1}{2\pi R}[V_m(\cos\alpha - \cos\beta) - \mathrm{E}(\beta - \alpha)]$$

Conduction angle $v = \beta - \alpha$

$\Rightarrow \beta = \alpha + v$

$$\mathrm{I}_0 = \frac{1}{2\pi R}[V_m(\cos\alpha - \cos(\alpha + v)) - \mathrm{E}(v)]$$

$$\cos A - \cos\mathrm{B} = 2\sin\frac{A+B}{2}\sin\frac{A-B}{2}$$

So

$$\mathrm{I}_0 = \frac{1}{2\pi R}[2V_m \sin(\alpha + \frac{v}{2})\sin\frac{v}{2} - E.v]$$

$$v = E + I_0 R$$

$$= \mathrm{E} + \frac{1}{2\pi}[2V_m \sin(\alpha + \frac{v}{2})\sin\frac{v}{2} - E.v]$$

$$= \mathrm{E}(1 - \frac{v}{2\pi}) + [\frac{V_m}{\pi}\sin(\alpha + \frac{v}{2})\sin\frac{v}{2}]$$

If load inductance L is zero then

$$\beta = \theta_2$$

And $v = \beta - \alpha = \theta_2 - \alpha$

But $\theta_2 = \pi - \theta_1$

So $\beta = \theta_2 = \pi - \theta_1$

And $v = \pi - \theta_1 - \alpha$

So average current will be

$$\mathrm{I}_0 = \frac{1}{2\pi R}[V_m(\cos\alpha - \cos(\pi - \theta_1)) - E(\pi - \theta_1 - \alpha)]$$

So $V_0 = E + I_0 R$

$$= \frac{V_m}{2\pi}(\cos\alpha + \cos\theta_1) + \frac{E}{2}(1 + \frac{\theta_1 + \alpha}{\pi})$$

For no inductance rms value of load current

$$\mathrm{I}_0 = [\frac{1}{2\pi R^2}\int_{\alpha}^{\pi-\alpha} (\mathrm{V}_m \sin(\omega t) - E)^2 d\left(\omega t\right)]^{1/2}$$

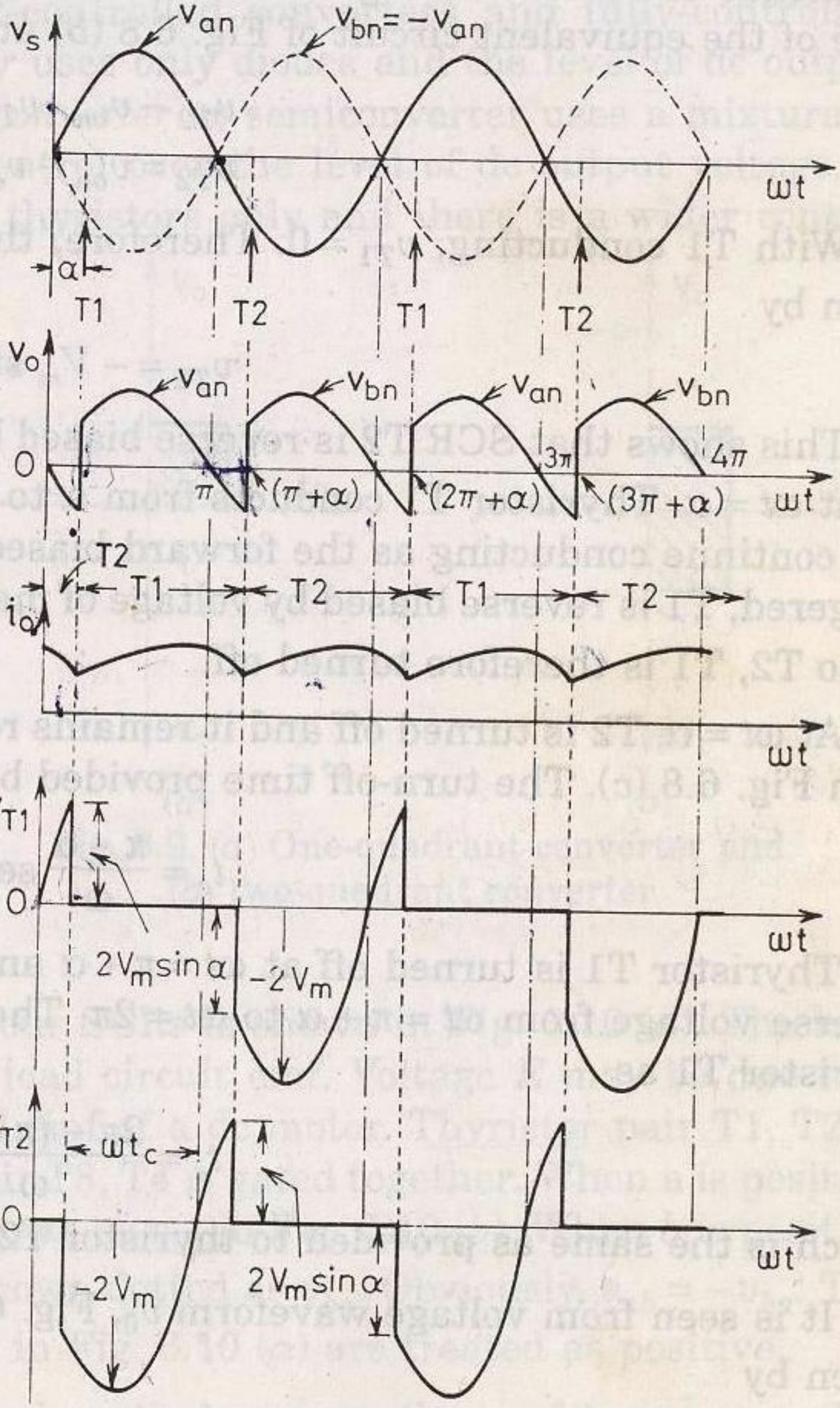
Power delivered to load

$$P = I_{or}^2 R + I_0 E$$

Supply power factor

$$Pf = \frac{I_{or}^2 R + I_0 E}{V_s I_{or}}$$

Single phase full wave converter:



vs
van
vbn = −van
ωt
α
T1
T2
T1
T2
vo
van
vbn
van
vbn
O
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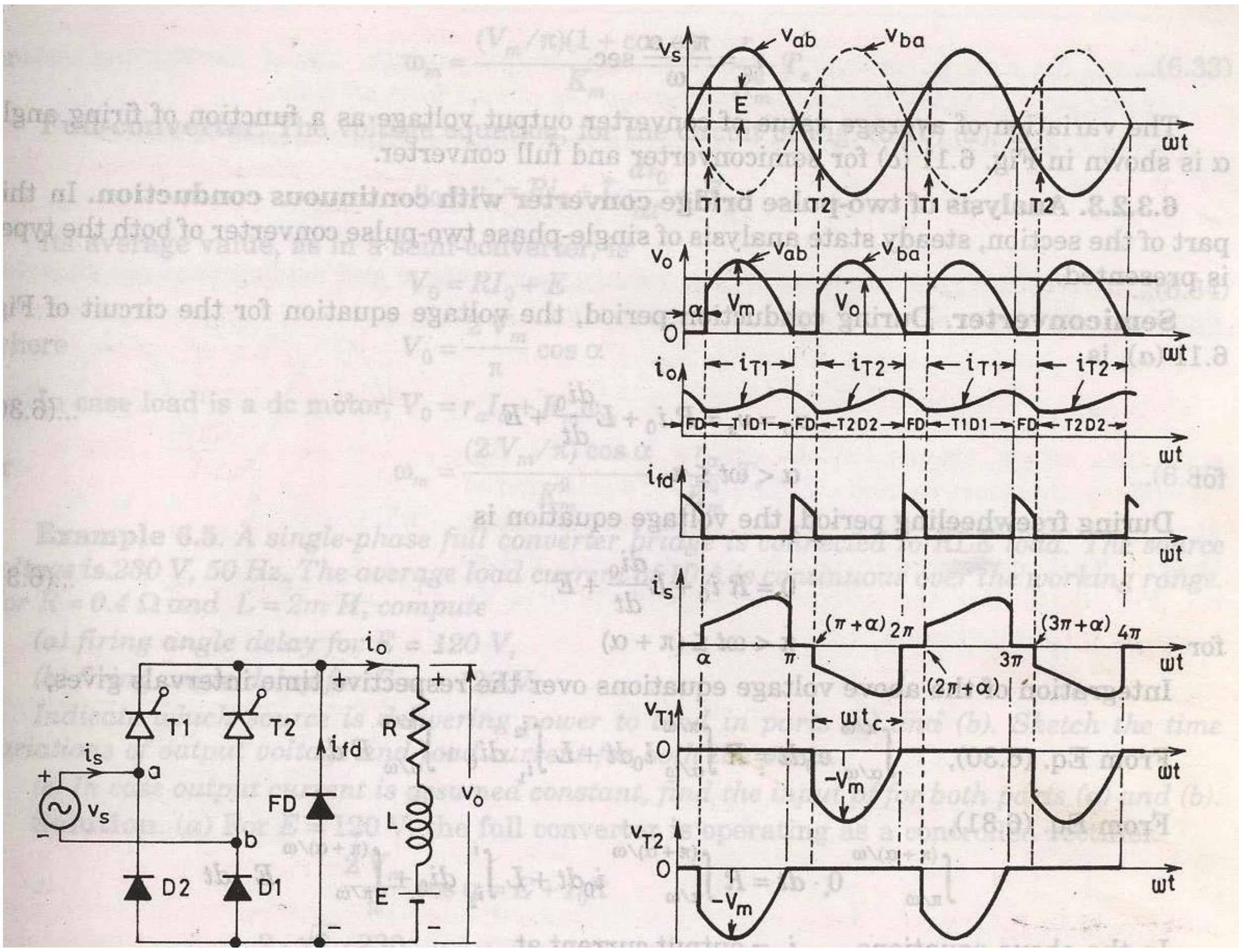
(π + α)
(2π + α)
3π
(3π + α)
4π
ωt
T2
T1
T2
T1
T2
io
ωt
vT1
O
2Vm sin α
−2Vm
ωt
vT2
ωtc
O
−2Vm
2Vm sin α
ωt

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin(\omega t)d(\omega t)$$

$$= \frac{2V_m}{\pi}\sin\alpha$$

Single phase semi converter:



$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin(\omega t)d(\omega t)$$

$$= \frac{V_m}{\pi}\cos\alpha$$

full converter:

steady state analysis

$$V_s = Ri_o + L\frac{di_0}{dt} + E$$

$$V_0 = RI_0 + E$$

$$V_0 = \frac{2V_m}{\pi}\cos\alpha$$

So in case of DC motor load

$$V_0 = r_a I_a + \alpha_m \omega_m$$

So $$\omega_m = \frac{\frac{2V_m}{\pi}\cos\alpha - r_a I_a}{\alpha_m}$$

$$T = \alpha_m I_a$$

$$\Rightarrow I_a = \frac{T_e}{\alpha_m}$$

Put $$I_a = \frac{T_e}{\alpha_m}$$

So $$\omega_m = \frac{(\frac{2V_m}{\pi})\cos\alpha}{\alpha_m} - \frac{r_a T_e}{\alpha_m^2}$$

1.7 Recommended questions:

1. State important applications of power electronics
2. What is a static power converter? Name the different types of power converters and mention their functions.
3. Give the list of power electronic circuits of different input / output requirements.
4. What are the peripheral effects of power electronic equipments? What are the remedies for them?
5. What are the peripheral effects of power electronic equipments? What are the remedies for them?

1.8 Generic Skills / Outcomes:

- To get an overview of power electronics and its history of development.
- Various applications of power converters such as UPS, Inverters, DC motor control.

1.9 Further Redaing

1. http://books.google.co.in/books/about/Power_Electronics.html?id=-WqvjxMXClAC
2. http://www.flipkart.com/power-electronic-2ed/p/itmczynuyqnbvzzj
3. http://www.scribd.com/doc/36550374/Power-Electronics-Notes
4. http://elearning.vtu.ac.in/EC42.html
5. http://www.onlinevideolecture.com/electrical-engineering/nptel-iit-bombay/power-electronics/?course_id=510