Power Converters
Introduction and Scope

Lecture-1
Prof. Dr. Tahir Izhar

Main Areas in Electronics

Signal Electronics

- Electronic circuits process signals
- Electronic circuits contain electronic-devices
- Dominant application of Electronics is to process information.
- The biggest user of semiconductor Electronic devices is the computer industry.
- Next user is the consumer electronics.
- The primary function is to process information.

Main Areas in Electronics

Power Electronics

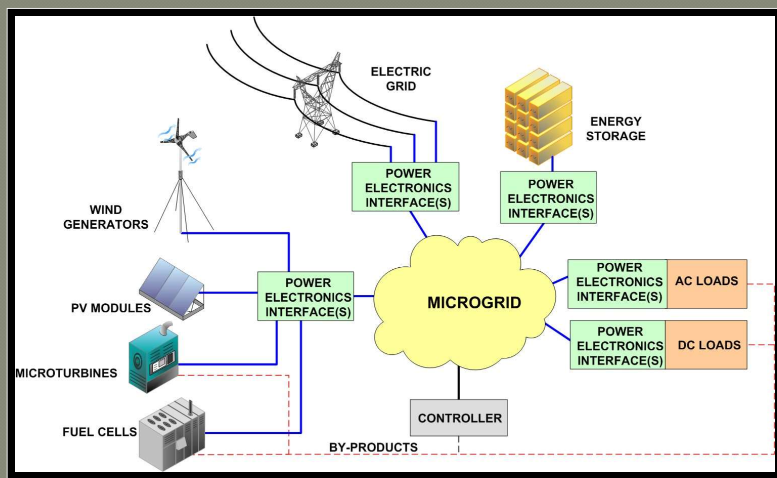
- Process electric power.
- Uses power devices handling large power.
- Electric Power Processing is "Power Conditioning".
- Power devices operated in switch-mode for higher efficiencies.

Scope of Power Converters

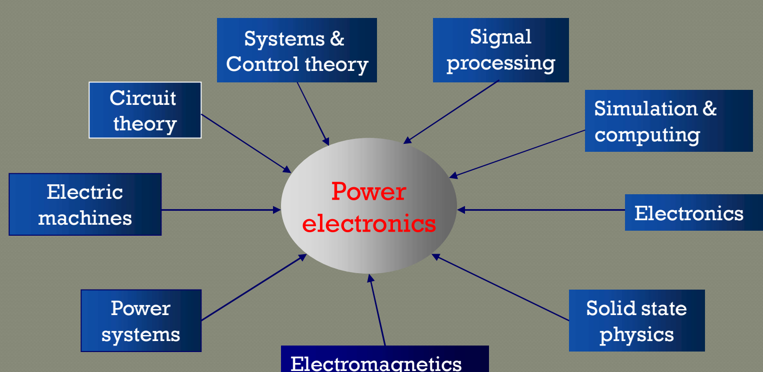
- All electronic systems are operated by power from a wall plug or battery
- It is needed to convert electrical energy from the form supplied by the source to the form required by the load.
- In some cases the power circuit converts electric energy to the form required by the electromechanical system, such as an electric motor.

Power Converters in Micro-grid

- Power electronic converters provide the necessary adaptation functions to integrate all different micro-grid components into a common system.



Relation with multiple disciplines

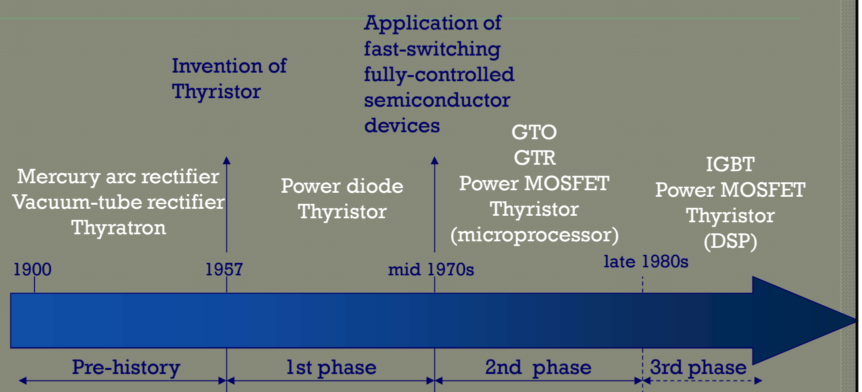


- Power electronics is currently the most active discipline in electric power engineering worldwide.

Position and significance in the human society

- Electric power is used in almost every aspect and everywhere of modern human society.
- 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 electronics and information electronics make two poles of modern technology and human society—— information electronics is the brain, and power electronics is the muscle.

The history



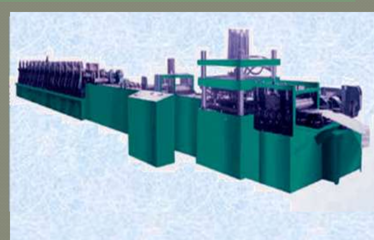
- The thread of the power electronics history precisely follows and matches the break-through and evolution of power electronic devices

Applications

- Industrial
- Transportation
- Utility systems
- Power supplies
- Residential and home appliances
- Space technology
- Other applications

Industrial applications

- Motor drives
- Electrolysis
- Electroplating
- Induction heating
- Welding
- Arc furnaces and ovens
- Lighting



Transportation applications

- Trains & locomotives
- Subways
- Trolley buses
- Magnetic levitation
- Electric vehicles
- Automotive electronics
- Ship power systems
- Aircraft power systems



Utility systems applications

- High-voltage dc transmission(HVDC)
- Flexible ac transmission(FACTS)
- Static var compensation & harmonics suppression: TCR, TSC, SVG, APF
- Custom power & power quality control
- Supplemental energy sources : wind, photovoltaic, fuel cells
- Energy storage systems



Power supplies for electronic equipment

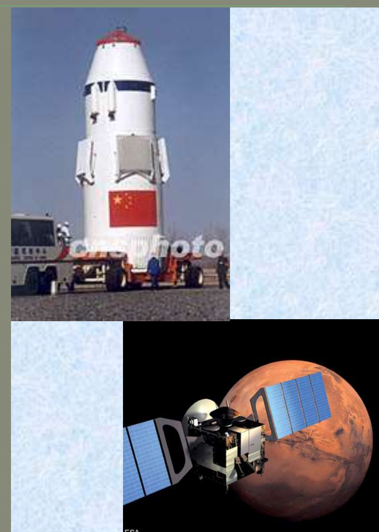
- Telecommunications
- Computers
- Office equipment
- Instruments
- Mobile electronics

Residential and home appliances

- Lighting
- Heating
- Air conditioning
- Refrigeration & freezers
- Cooking
- Cleaning
- Entertaining

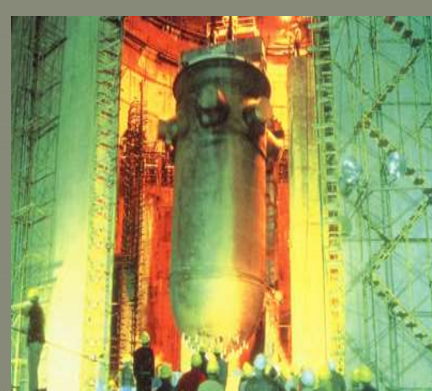
Applications in space technology

- Spaceship power systems
- Satellite power systems
- Space vehicle power systems



Other applications

- Nuclear reactor control
- Power systems for particle accelerators
- Environmental engineering



Trends

- It is estimated that in developed countries now 60% of the electric energy goes through some kind of power electronics converters before it is finally used.
- Power electronics has been making major contributions to:
  --better performance of power supplies and better control of electric equipment
  --energy saving
  --environment protection
  - reduction of energy consumption leads to less pollution
  - reduction of pollution produced by power converters
  - direct applications to environment protection technology

Power Conditioners

- Power Converters
  - AC/DC converters
  - DC/DC converters
  - DC/AC converters
  - AC/AC converters

AC to DC Converters

- Uncontrolled AC to DC converters- Rectifiers
- Semi-Controlled AC to DC converters
- Fully controlled AC to DC converters
- Three-Phase, 6-step AC to DC converters
- 12-step and 24-step AC to DC converters
- Pulse Width Modulation AC to DC converters

DC to DC converters

- **Linear**
  - *Series type*
  - *Shunt type*
- **Switch mode**
  - *Non Isolated converters*
    - Buck converters
    - Boost converters
    - Polarity inverting Converters
  - *Isolated converters*
    - Forward converters
    - Fly back converters

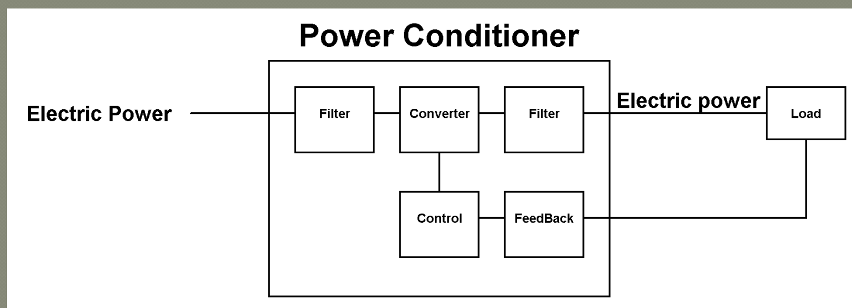
DC to AC converters

- Square wave DC to AC converter
- Quasi-Square wave DC to AC converters
- Multi-step DC to AC converters
- Pulse Width Modulation DC to AC converters
  - *Natural Sampling PWM*
  - *Regular Sampling PWM*
  - *Selective Harmonic Reduction PWM*

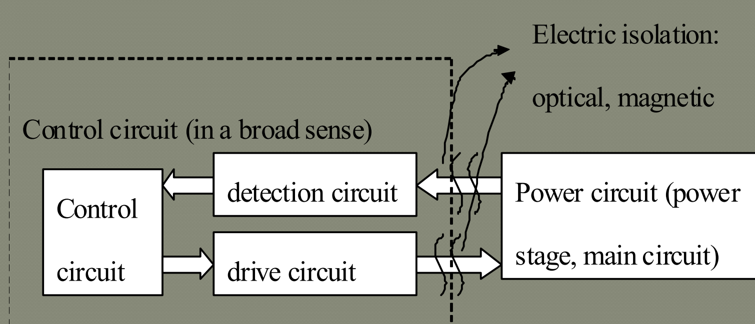
AC to AC converters

- Input is AC with fixed voltage and frequency
- Output is AC with variable voltage and variable frequency.
- Cycle-Converters
- Matrix Converters

Power Conditioner



Configuration of systems



Protection circuit is also very often used in power electronic system especially for the expensive power semiconductors.

Conclusions

- The scope of power converters design is discussed to process Electric Power under high voltage -high current Scenario.
- All four types of power converters are introduced.
- The use of Power converters are increasing and main concern is the power quality.
- The research in this area is mainly addressing these power quality issues

Thank you

For your attention

Power Converters

Power Semiconductor Devices

Power Diodes

Dr. Tahir Izhar
UET-Lahore

Electronic History

- 1892-Mercury arc vacuum tube invented
- 1902-Mercury arc rectifier patented.
- 1906-Vacuum Diode invented.
- 1906~1950 electronics based on vacuum tubes.

- 1947-germanium BJT invented
- 1952-germanium diode manufactured
- 1954-Silicon transistor produced by TI .
- 1950~1960 vacuum tube to transistor migration.

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Power Semiconductors

- 1957 SCR developed
- 1960~1970 SCR in power control.

Since 1970, various types of power semiconductor devices were developed and become commercially available.

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Power Devices

Power Devices can be divided into following major types.

- Power Diodes
- Power BJTs
- Power MOSFETs
- IGBTs
- Thyristors:
  - ***SCR***
  - ***GTO***
  - ***DIAC***
  - ***TRIAC***

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Power Diode

- High current densities when ***'on'***
- Withstand high voltage when ***'off'.***
- When ***'on'*** the device drop is 2-3 volts.
- With large conducting current, the power dissipation is large.
- The power diode are much bigger in size and encapsulated in metal body to be mounted on metal heat sink for proper thermal design.

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Bipolar Diode

Reverse Biased

- The reverse bias voltage across a bipolar diode is limited because of high leakage current and avalanche breakdown.
- The *v-j* relation of a diode is given as

$$j = j_s(e^{qV_A/kT} - 1) \text{-------}(1)$$

- Under reverse biased, VA <<0, J=Js

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Bipolar Diode

- J_s is called the leakage current density.
- At room temperature (25^OC) and under forward bias, J_s is very small compared to J.
- If V_A = 0.6 V, J is $2.6X10^{10}$ times greater than J_s.
- Such a small leakage current results in negligible power dissipation.

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Bipolar Diode

n_i^2 is a strong function of temperature as shown in following relation.

$$n_i^2 \propto T^3 e^{-E_g/kT} \qquad \text{---------------- (2)}$$

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Bipolar Diode

$$n_i^{\ 2} = 2X10^{20} / cm^3 \ @\ 25^o C$$
$$n_i^{\ 2} = 2X10^{27} / cm^3 \ @\ 175^o C$$

7th order of magnitude increase gives a leakage current whose effect is no longer negligible.

Bipolar Diode

- The diode equation (1) given above does not account for all the current under reverse bias,
- As we know, under thermal equilibrium

$$n_o \times p_o = n_i^{\ 2}$$

Bipolar Diode

- However, under reverse bias, the device is no longer in thermal equilibrium.
- The excess carrier concentration in SCL and adjacent regions is substantially below than n_o and p_o.
- Therefore the thermal generation rate exceeds the recombination rate.

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Bipolar Diode

- The carrier concentrations do not built us because thermally generated carriers are swept out of SCL.
- These carrier flow give a component of measured leakage current that is not accounted for by equation (1)

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Conclusions

- Generation in wide SCL & adjacent regions of a power diode will yield substantially more leakage current at 25^{O}C than predicted by diode equation.
- To keep the leakage current in acceptably small, the minority carriers life time in the SCL should be as long as possible.

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Conclusions

- The component of leakage current resulting from thermal generation in the SCL, grows as n_i, which approximately doubles for every 11^{O}C increase in T between -50^{O}C to 200^{O}C. But J_s grows as n_i^2, so it eventually dominates at high temperature.
- This increase in reverse leakage current limits the maximum operating junction temperature of a power diode.

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PIN-Diode

PIN Diode

- The transient performance of diodes tends to deteriorate as the thickness of silicon wafer is increased in attaining higher reverse voltage.
- The asymmetric doping concentration is preferred in Power Diodes fabrication.

PIN Diode

- Under reverse bias, nearly all the voltage is supported by the SCL in the lightly doped region.
- Power diode are vertical in structure and fabricated by simply diffusing P^+ region into n^- substrate.

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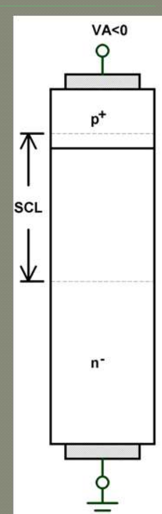
PIN Diode

- The substrate thickness is usually about 500um to maintain mechanical strength.
- A long n^- region results in a large resistive component of the diode drop under forward bias.



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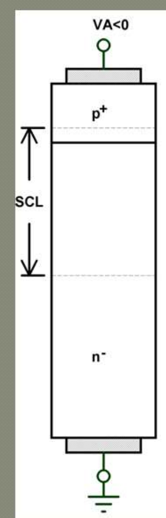
PIN Diode

- The SCL width is approximately between 10 to 200um and most of it is in the n^- region.



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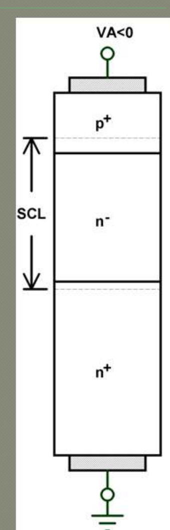
PIN Diode

- The lower part of the substrate can be heavily doped to lower the resistive component of the forward voltage drop as shown in the diagram.
- Performance can be further improved by doping the n^- region so lightly that is nearly intrinsic.



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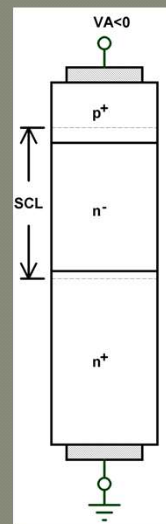
PIN Diode

- Resulting diode is called a ***PIN*** diode.
- Almost all power diodes have ***PIN*** type of structure.



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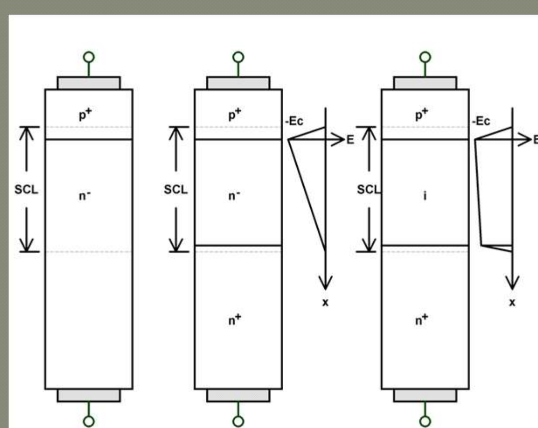
PIN Diode



Evolution of PIN structure

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PIN Diode
under Forward Bias

- Analysis of ***PN*** diode is based on the assumption that both sides are in low-level injection.
- Low level injection means minority carrier concentration remains small compared to majority carrier concentration even if the diode may not be in thermal equilibrium.

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PIN Diode
under Forward Bias

- This is not valid for the i-region of ***PIN*** diode.
- i-region is in high level injection.
- Consequently ***n*** is nearly equal to ***p*** in the neutral region.

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PIN Diode
under Forward Bias

- High level injection is also called
  "Conductivity Modulation".
- Under conductivity modulation, the conductivity of the material is no longer determined by the majority doping level.
- It is now a function of injection level.

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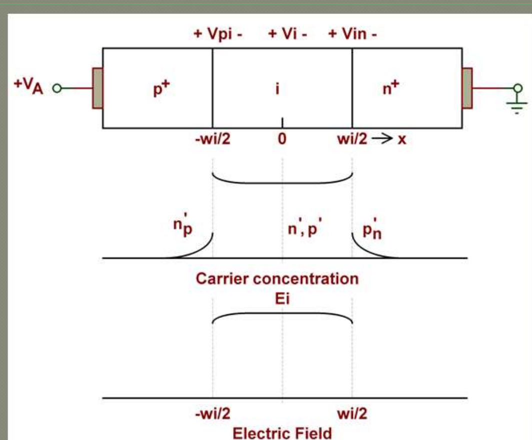
PIN Diode
under Forward Bias



One dimensional PIN structure

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PIN Diode *under Forward Bias*

- In PN diode, the minority current flows only by diffusion.
- There is also a drift component of current in the intrinsic region and drift field gives rise to a voltage drop V_i which adds to the on state voltage drop of the diode.

PIN Diode *under Forward Bias*

- All the current flowing through the diode results from recombination within the i-region therefore, E_i & V_i are dependent only on physical parameters and length of i-region.
- Because n_i increases rapidly with increasing temperature, J increases with temperature and the forward drop decreases with temperature if the forward current is fixed.

PIN Diode
Transient Operation

- For simplicity, let us ignore the SCL capacitance and focus on the excess stored charge in the neutral regions outside the SCL.

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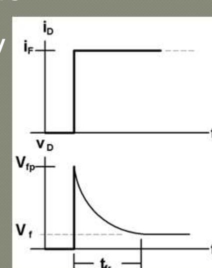
PIN Diode
Transient Operation

Forward Recovery

- Let us consider turn-on transient, The diode current steps from zero to I_f, the terminal voltage first rises to V_{fp} and then decay to steady state value of V_f.
- This process is called forward recovery of the diode. V_{fp} is known as the Forward recovery voltage
- The duration of forward recovery is called Forward recovery time t_{fr}.



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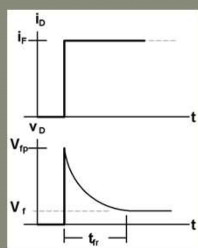
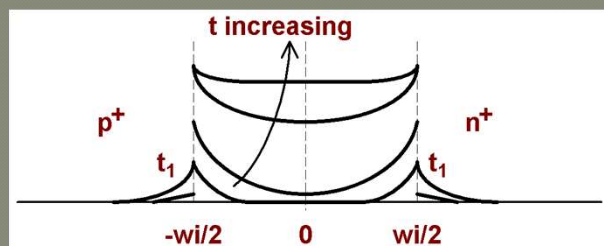
PIN Diode
Transient Operation

- As forward current I_F flows, holes drift through p^+ region and injected into i-region. Similarly electrons drift through n^+ region and injected into i-region.
- The carrier concentration builds up with time as indicated below





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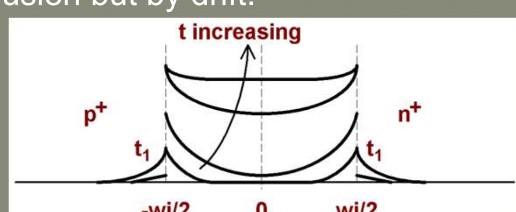
PIN Diode
Transient Operation

- At t_1 just after the forward current starts, the carrier builds up near the junctions but not in the middle of the i-region.
- In most of the i-region at t_1, there is no gradient to the carrier profile.
- Therefore, the injected carriers flows across the i-region not by diffusion but by drift.



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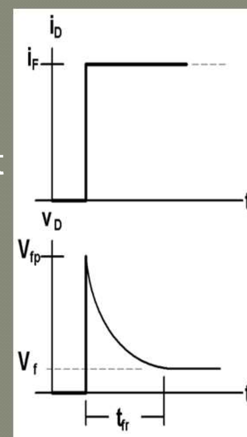
PIN Diode
Transient Operation

- The voltage that results from this drift is very large.
- i-region is not in high level injection at this time so that conductivity is very low and the region is carrying the full current I_F.



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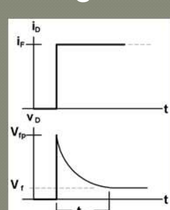
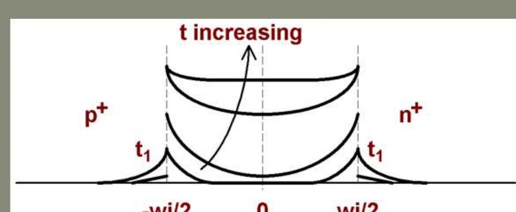
PIN Diode
Transient Operation

- The high resistance is the source of the peak transient voltage V_{fp}.
- As time passes, the carrier concentration grows in the middle of the i-region modulating the conductivity and reducing the resistance.





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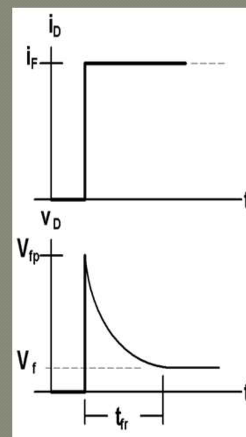
PIN Diode
Transient Operation

- As a result, the voltage across the middle region drops.
- The change in the middle region at steady state is proportional to the forward current I_f.
- The duration of forward recovery transient is called "Forward Recovery Time", t_{fr}.



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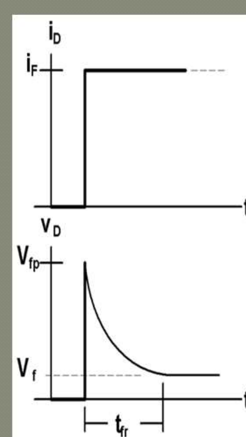
PIN Diode
Transient Operation

Reverse Recovery

- Consider that that PIN diode is carrying a forward current of I_F.
- At t = 0, the diode is connected to reverse voltage V_R.
- Because the excess charge in the i-region and diffusion regions of the diode can not change instantaneously, the p^+-i and i-n^+ junctions remain forward biased for some time even after t = 0.
- As the diode voltage is zero during this time, the diode current is negative.



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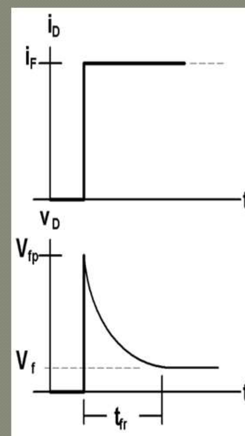
PIN Diode
Transient Operation

Reverse Recovery

- This reverse current adds the removal of excess charge, until the concentrations at the SCL edges become negative and the junction can begin to support a reverse voltage.
- This process is called reverse recovery.



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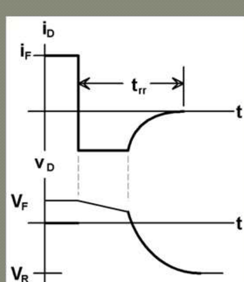
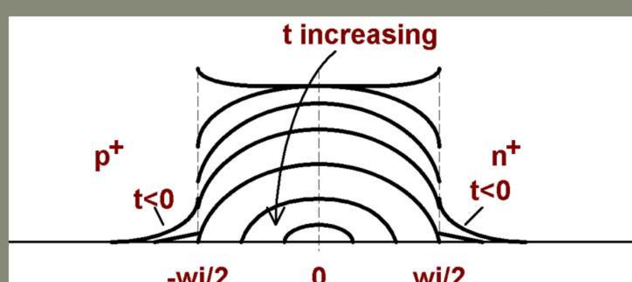
PIN Diode
Transient Operation

- Following figure shows the carrier profile in the i-region as the reverse recovery current flows.
- Just after t = 0, the excess carrier concentrations at the junction edges are still positive, therefore the junction voltages are also positive.





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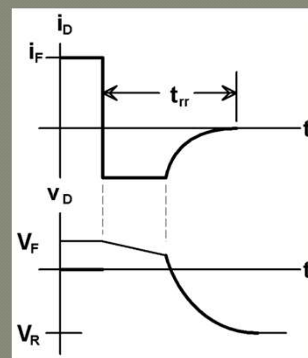
PIN Diode
Transient Operation

- To support the negative current, the excess carrier distribution develop a negative slope near the junction edges.
- Continuing recover current flow eliminates the excess carrier concentrations in the i-region.



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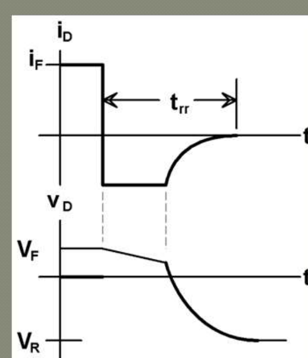
PIN Diode
Transient Operation

- When the excess carrier concentrations at the junction edges reach zero, the concentration gradients decreases and the diode current can no longer be maintained.



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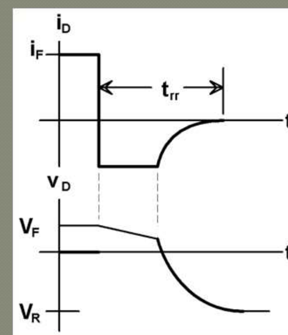
PIN Diode
Transient Operation

- The dynamics of this process produce an exponential rise of i_D to zero and fall of V_D to $-V_R$ as shown in the Figure.
- During the initial phase of reverse recovery, the diode voltage changes only slightly this is due to the change in sign of vi.



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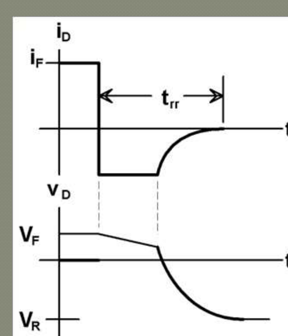
PIN Diode
Transient Operation

- The duration of reverse current flow in the diode is t_{rr}, the *reverse recovery time*.
- Based on the above discussion, t_{rr} is directly proportional to the reverse current I_R and initial stored charge in i-region.



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Conclusions

A. If less charge is stored for a given forward current, the diode will recover quicker from the transient and switch faster.

B. To store less charge, the carrier lifetime should be shortened in the i-region.

C. However, doing so will result in less conductivity modulation of the i-region and higher voltage drop across it.

D. Therefore the forward drop of a fast diode is typically greater than that of a slower diode.

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Thank you

For your attention

Questions?

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Power Converters

Power Transistors

Dr. Tahir Izhar
UET-Lahore

Power BJT

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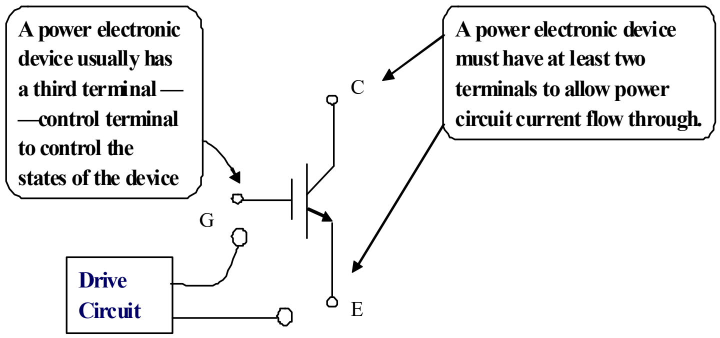
Power Transistor

- Power Transistor is a controlled Device



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Power Transistor

- Two types of transistor are extensively used in power switching circuits: bipolar junction transistor (BJT) and Metal Oxide Semiconductor Field Effect Transistor (MOSFET).
- The BJT consists of a *pnp* or *npn* single-crystal silicon structure.
- It operates by the injection and collection of minority carriers, both electrons and holes, and is therefore termed a '*Bipolar Transistor'.*

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Power Transistor

- The MOSFET depends on the voltage control of a depletion width, it is therefore a *Uni-polar Transistor.*
- Unlike the BJT, the MOSFET is a majority carrier device and therefore does not exhibit minority carrier storage delays, so switching times of the MOSFETs are ultra fast.

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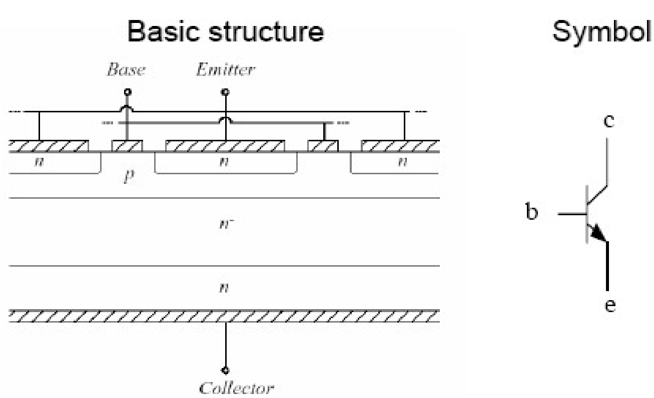
Power BJT Structure

- Power BJT can handle high voltage and large current.



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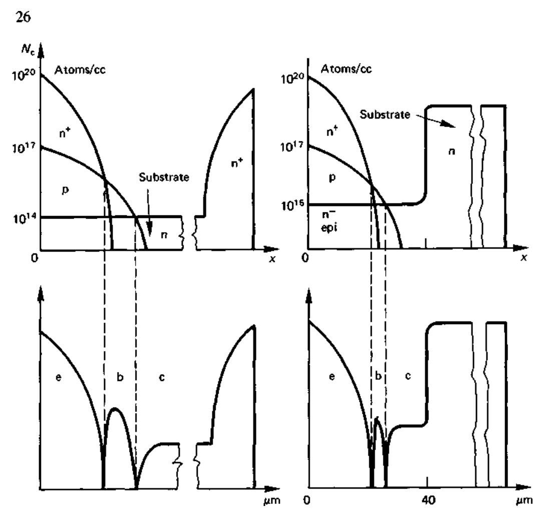
Power BJT doping

A typical high-voltage triple-diffused transistor doping profile is shown below

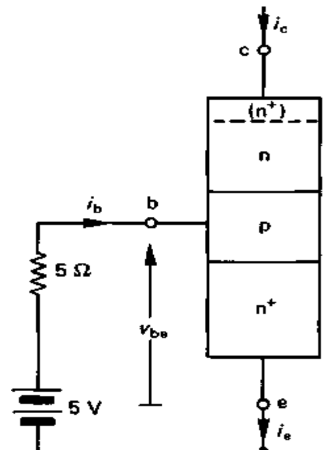


Power BJT

- The n-collector region is the initial high-resistivity silicon material and the collector n^+ diffusion is performed first, usually into both sides.
- One n^+ diffusion is lapped off and the p-base and n^+ emitter diffusions are sequentially performed.

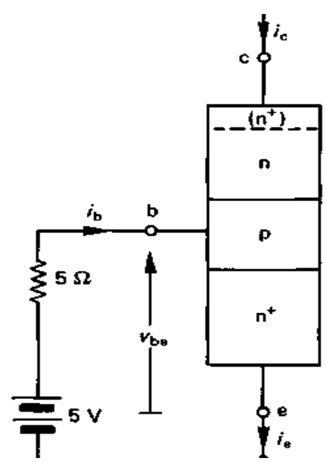
Power BJT Operation

- A simple and qualitative view of the bipolar power switching transistor.
- ***npn*** bipolar transistor connected in the common *emitter* configuration.



Power BJT Operation

- In this configuration, injection of electrons from the lower n^+p junction into the centre p-region supplies minority carrier electrons to participate in the reverse current through the upper np junction.



Power BJT Operation

- The n^+ region which serves as the source of injected electrons is called the *emitter* and forms the emitter junction with the p^-*base,* while the n-region into which electrons are swept by the reverse bias np junction is called the *collector* and, with the p-base, forms the collector junction

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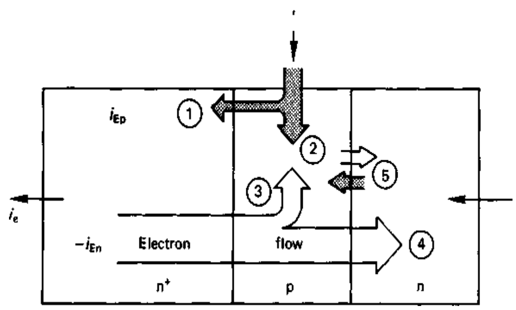
Power BJT Operation

- To have a 'good' npn transistor almost all the electrons injected by the emitter into the base should be collected.
- Thus the p-base region should be narrow and the electron minority carrier lifetime should be long to ensure that the average electron injected at the emitter will diffuse to the collector ***scl*** without recombining in the base.
- The average lifetime of electrons in the p-base increases as the p-base concentration decreases, that is as the hole concentration decreases.

12

Power BJT Operation

- The fraction of electrons which make it across to the collector is called the *base transport factor*, b_t.
- If we neglect the saturation current at the collector, component 5 in figure below, and such effects as space charge layer recombination, then $i_c = b_t i_{En}$ where i_{En} is the electron component of the total emitter current i_e.



Power BJT Operation

- Electrons lost to recombination in the p-base must be re-supplied through the base contact.
- It is also required that the emitter junction carrier flow should be composed almost entirely of electrons injected into the base, rather than holes crossing from the base region to the emitter.
- Any such holes must be provided by the base current, which is minimised by doping the base region lightly compared with the emitter such that an n^+p emitter results.

Power BJT Operation

- Such a junction is said to have a high *injection efficiency.*
- Holes swept into the base at the reverse-biased collector junction because of thermal generation in the collector must also be accounted for by the base current.
- This base current component is generally very small in high-voltage transistors when in the on-state since the collector scl electric field is small.

15

Power BJT Operation

- In the common emitter configuration, the ratio between the base current I_b and the collector current I_c is of practical importance.
- Since the base current is the difference between the emitter and the collector current.
- The factor β, relating the collector current to the base current, is defined as the base-to-collector *current amplification factor.*
- If α is near unity, β is very large, implying the base current is very small compared with the collector current.

16

Power BJT Operation

- In power switching applications a transistor is controlled in two states: the *off-state and the on-state.*
- Ideally the transistor should appear as a short circuit when on and an open circuit when in the off-state.
- Furthermore the transition time between these two states is ideally zero. In reality, transistors only approximate these requirements.

17

Power BJT Operation

- The two operational states for the power switching transistor are defined as follows.
- ***Cut-off region:*** In this region the emitter junction is not injecting; hence only leakage current flows.
- ***The saturation:*** In traversing from the off-state to the saturated state the transistor passes through the linear operating region, where the collector junction voltage changes from a large reverse bias to a forward bias state.

18

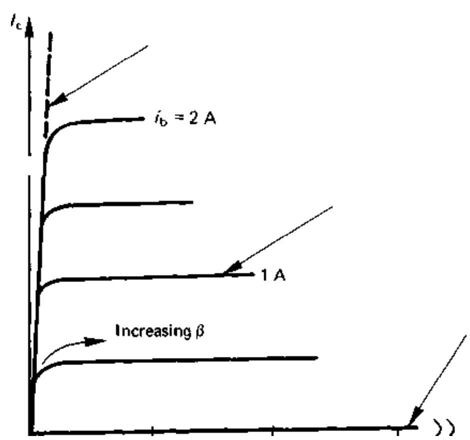
Power BJT Operation

- Both junctions are forward-biased, termed *saturated,* and the collector-to-emitter voltage is almost zero, high current is able to flow.
- This saturated situation represents the switched-on hard mode, and over-saturation exists.
- The gain ***β*** is a minimum in the saturated mode since the neutral base width between the two forward-biased ***scl's*** is at a maximum.

19

Power BJT Characteristics

The typical BJT collector output characteristics are shown below which illustrates the various BJT operating regions.



20

Power BJT

Current Gain

- A number of electrical phenomena are of particular importance to the high-voltage, power switching ***BJT***.
- The characteristics to be considered are as a result of the device structure and geometry.
- The gain of a power transistor falls off at both very low and very high current levels.
- At low currents the gain decreases as a result of generation recombination.

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Conductivity Modulation

- At high currents, as the concentration of excess electrons in the base becomes large, the matching excess hole concentration can become greater than the base doped level.
- A balance of holes and electrons must occur in order to maintain a neutral base region.
- Thus holes in the base are injected into the emitter, countering the conversely injected electrons, and thus effectively decreasing the emitter injection efficiency.
- This effect is called *conductivity modulation.*

22

First Breakdown

- The collector junction supports the off-state voltage and in so doing develops a wide ***scl***.
- This ***scl*** increases in width with increased reverse bias, penetrating into the base.
- It is unusual that a correctly designed high-voltage power switching ***BJT*** would break down as a result of punch-through of the collector ***scl*** through the base to the emitter ***scl***.

First Breakdown

- Because of the profile of the diffused base, collector junction voltage breakdown is usually due to the avalanche multiplication mechanism, created by the high electric field at the collector junction.
- In the common emitter configuration, the transistor usually breaks down gradually, but before the collector junction avalanches.
- This occurs because the avalanche-generated holes in the collector ***scl*** are swept by the high-field into the base.

First Breakdown

- The emitter injects electrons in order to maintain base neutrality.
- This emitter junction in turn causes more collector current, creating more avalanche pairs and causing a regenerative action.
- Thus the gain mechanisms of the transistor cause collector emitter breakdown- *first breakdown*

25

Second Breakdown

- First breakdown need not be catastrophic provided junction temperature limits are not exceeded.
- If local hot spots occur because of non-uniform current density distribution as a result of crystal faults, doping fluctuation etc., *second breakdown* occurs.
- Silicon crystal melting and irrepairable damage results, the collector voltage falls and the current increases rapidly as shown in figure below

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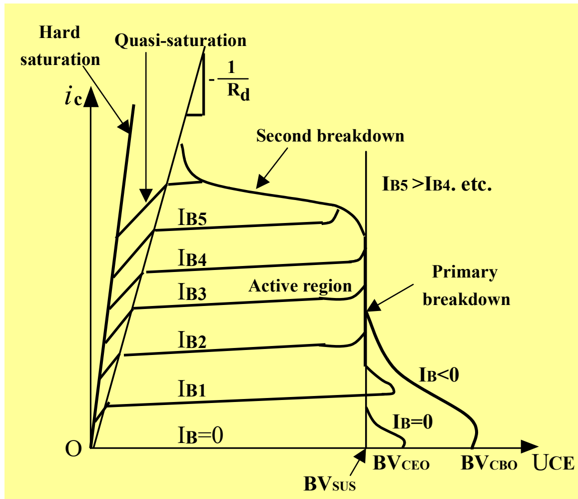
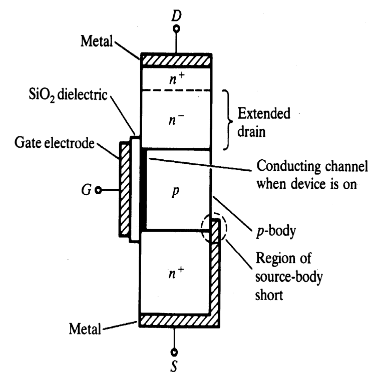
Second Breakdown

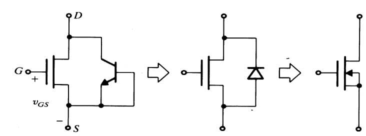


Power MOS

Power MOS

- When positive V_{GS} is applied, a conducting n-channel is formed beneath the gate in the p-region (body).
- MOSFET turns 'on' when V_{GS} exceeds V_T.
- The gate acts like a capacitor.
- The gate power is zero.
- The gate-drive circuit is very simple as compared to BJT.





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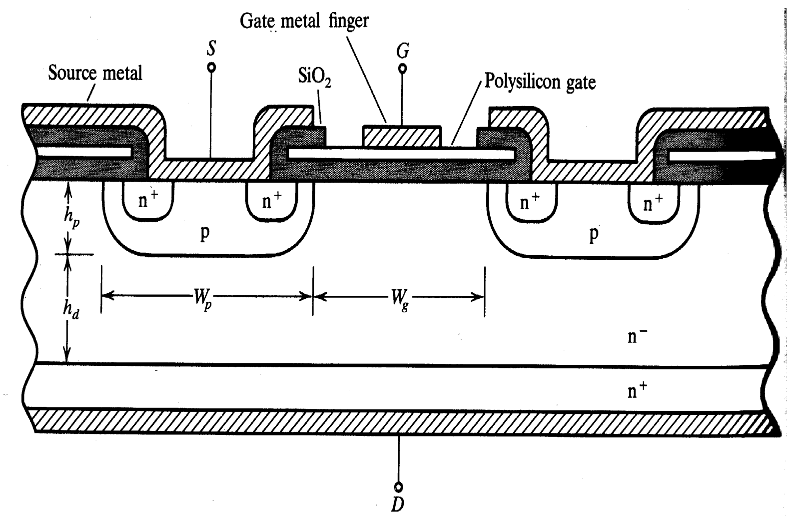
Power MOS

- If the MOSFET has to operate at high frequencies, the gate capacitance must be charged and discharged quickly, therefore, the gate drive circuit should have low source impedance.
- When MOSFET is 'on' it acts like a resistor of Value '$R_{DS(on)}$'.
- $R_{DS(on)}$ consists of two parts:
  a) Conducting channel resistance
  b) Resistance of the extended drain region. Which is unique to Power MOS due to its vertical structure.

30

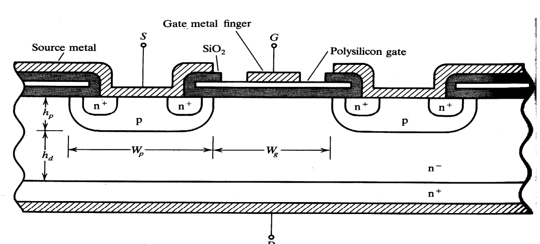
Power MOS Physical Structure



31

Power MOS Structure

- The drain contact is on the bottom of the die, rather than on the top as in signal MOSFET.
- This vertical structure gives maximum area to both drain and source contacts.



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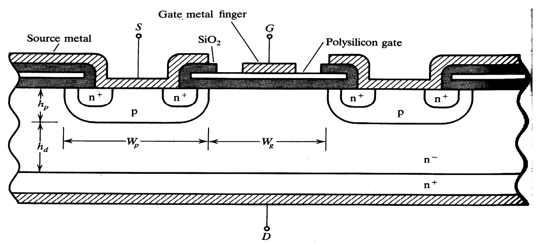
Power MOS Structure

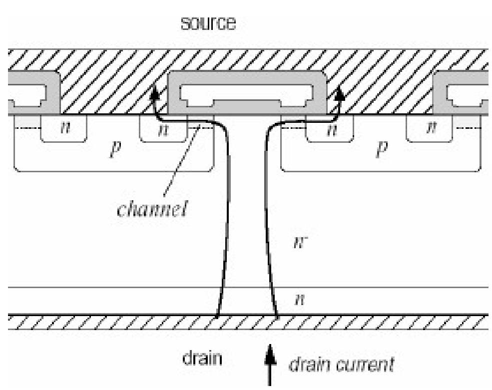
- There are P-wells between drain and source. These wells are the body regions of the device.
- The channel is formed on the surface of the p-wells just beneath the gate-oxide.
- The p-type wells are shorted to the source electrode.



33

Power MOS

Creation of channel beneath the gate in the p-regions.



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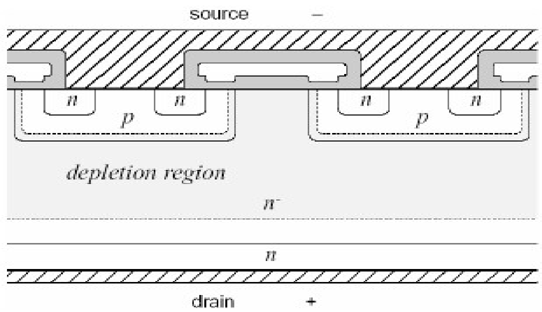
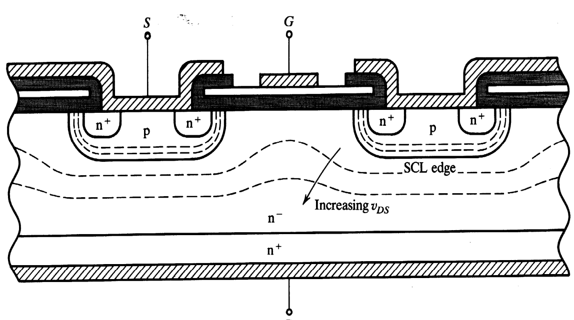
Power MOS

- The lightly doped n-type drain region is unique to Power MOS.
- It will allow the growth of long SCL to block high voltage when the device is 'off'.



Power MOS
Under Reverse Biased

Following figure illustrate how the SCL grows with increasing V_{DS} , pinching off the n- region between the p-wells.



Power MOS

- The lightly doped drain region is also referred as extended drain region.
- When the device is off, SCL grows and pinches off the region between P-wells.
- The gate electrode acts as a field plate to promote the depletion of the region between p-wells.
- The voltage just beneath the gate oxide is only 5-10 volts w.r.t. gate even though the drain voltage is 200-400V, as a result the gate oxide can be made relatively thin keeping V_T low.

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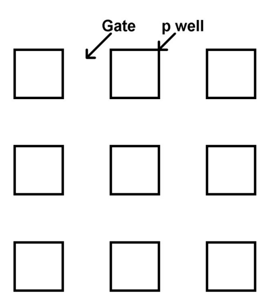
Power MOS

- If viewed from the top, the gate and source contacts look like interleaved pattern of cells as shown in the figure.
- These cells can be arranged in a square pattern.
- For a large power device, the cells can be increased over a large area of the die.
- This is similar to connecting the Power MOS transistors in parallel on a single die to increase the conduction region and power.



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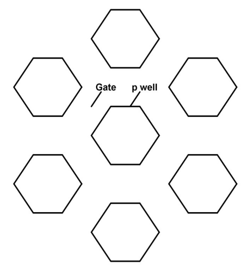
Power MOS

- The p-type wells can also be arranged in hexagonal cell pattern to increase the gate perimeter for a given die area as shown in the diagram.
- This hexagonal structure is a patent of ‘International Rectifiers (IR)’ for its trademark “HEXFET”



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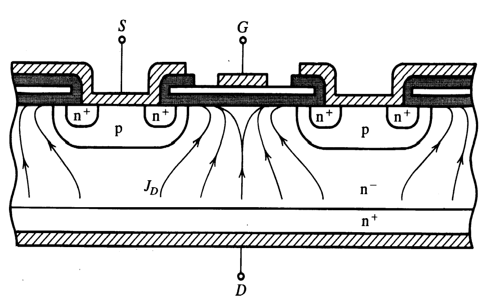
On state Resistance

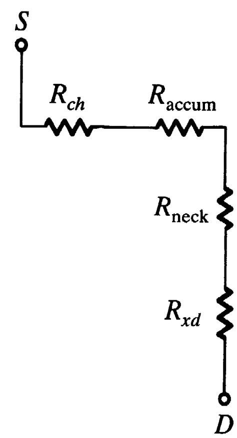
- The drain current distribution when the device is ‘on’, is shown below.
- The current flows from drain to source when ‘on’.
- The current focuses in the area between the p-wells called the neck region.



40

On state Resistance

- The current further focuses in the thin entrance to the p-well channels on either sides of the neck regions.
- The n-region just beneath gate is accumulated which makes it much more conductive than rest of the n-region.



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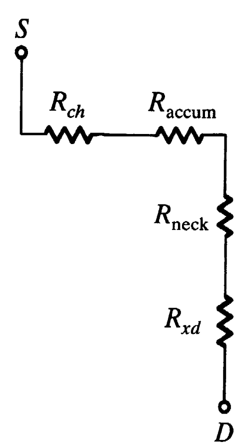
On state Resistance

- The total R_{DS}(on) can be divided into four components as shown in the diagram.
- For high voltage device, R_{xd} and R_{neck} are much larger than R_{accum} and R_{ch}.
- For low voltage devices, R_{ch} is ⅓ to ½ of total R_{DS}(on).



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Temperature Effect

- For high voltage device, $R_{DS(ON)}$ is dominated by extended drain resistance.
- This on resistance is temperature dependent.
- $R_{DS(ON)}$ increases with temperature.
- A 100 degree rise produces an increase of approximately 90%.

43

Body Diode

- The connection of the p-wells to the source metal gives the MOSFET an anti-parallel body diode.
- This body diode is a PIN diode as discussed earlier.
- It displays the static and dynamic characteristics of a PIN diode.

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Body Diode

- The cross sectional area of
- MOSFET is approximately same as the body diode.
- The body diode displays a reverse recovery phenomenon in the order of 100nS but this is not as short as possible in separate diode.

Switching Characteristics

Turn- on transient

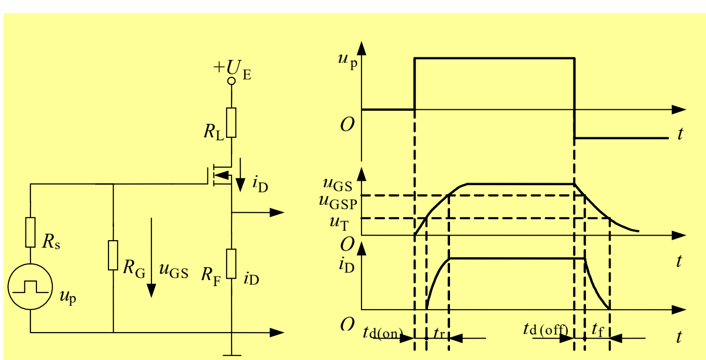
–Turn- on delay time $t_{d(on)}$

–Rise time t_r

Turn- off transient

–Turn- off delay time $t_{d(off)}$

–Falling time t_f



Switching Performance

- The speed at which a Power MOS turns on or off is determined by the rate at which its parasitic capacitance can be charged or discharged.
- The more current the gate drive circuit can deliver or sink, the faster the device switch.

Switching Performance

- The gate-drive circuit determines the rise and fall times of the drain current and voltage.
- For instant, if the gate drive is capable to source 1A, and the gate charge is 40nC then;

$$t_f = \frac{40nC}{1A} = 40nS$$

IGBT

Insulated Gate Bipolar Transistor

IGBT

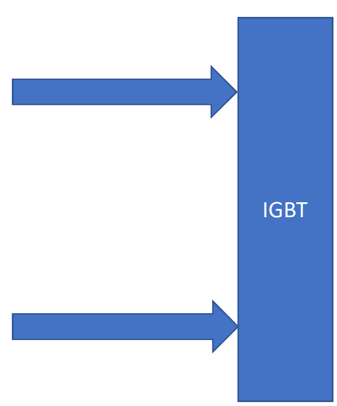
Combination of MOSFET and Power BJT

BJT:

Low conduction losses
(especially at larger blocking voltages)
Longer switching times
Current driven

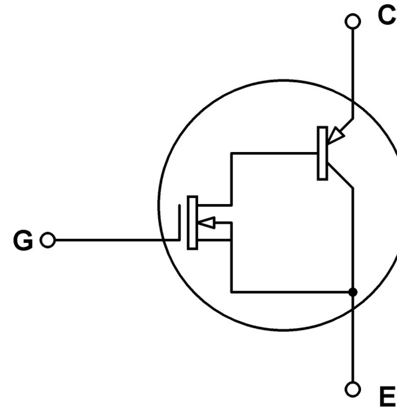
MOSFET

Faster switching speed
Easy to drive(voltage driven)
Large conduction losses
(especially for higher blocking Voltage)



IGBT

IGBT is an integrated Darlington like connection of MOSFET and BJT.



51

IGBT

- The driving is simple like Power MOS.
- Low forward drop per unit area of BJT.
- Much smaller area results compared to same power MOSFET.

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IGBT

- The two transistors are of opposite polarity (n-channel and PNP).
- The gate is driven with respect to collector of BJT.
- Therefore, the collector of BJT is designated as Emitter of IGBT and Emitter of BJT as collector of IGBT.

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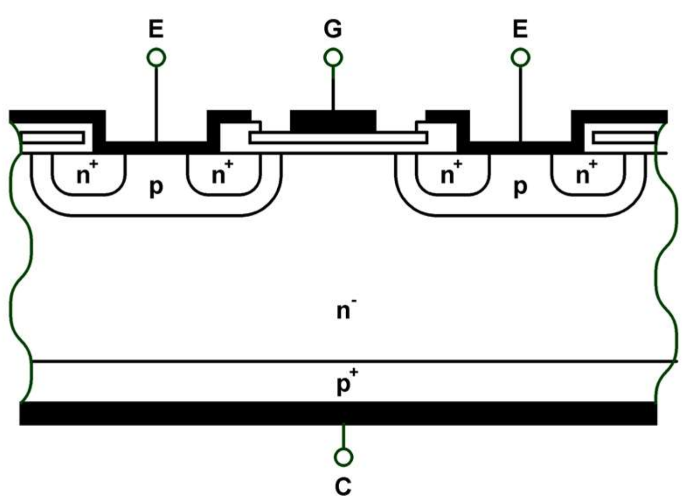
IGBT Physical Structure



54

Structure of IGBT

- The structure of IGBT is very much like vertical MOSFET, except that the substrate is heavily doped p-type rather than n-type.
- Integration of two devices rather than discrete connection has an advantage: when the IGBT is on, the BJT is also on conductivity modulating the drift region and greatly reducing the drain resistance of MOSFET.

Structure of IGBT

- If the two devices are connected discretely, the FET un-modulated resistive drop would result in a higher collector-base drop resulting higher V_{CE} for the Bipolar Transistor.
- One disadvantage of integration is that the structure forces the BJT with wide base.

Structure of IGBT

- Another disadvantage is that the BJT has PNP configuration rather than superior NPN transistor.
- A further problem of integration of the two devices eliminates access to the base terminal of the BJT, preventing the use of negative base current to improve turn-off.

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Structure of IGBT

- Turn-off can be improved by reducing the transistor gain but at the expense of on-state drop.
- The integration of two devices produces a parasitic SCR as a regenerative connection of PNP and NPN transistors.

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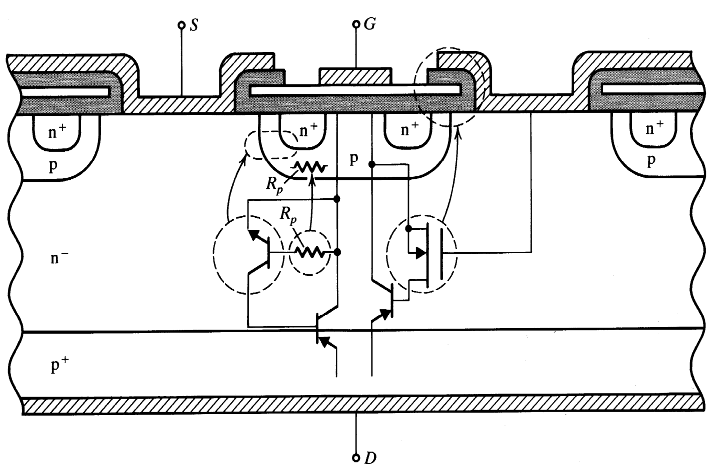
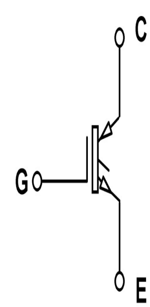
Structure of IGBT

- Although the base of NPN transistor is shorted to emitter which should keep this transistor off, however, there is some resistance in this connection.

Structure and Symbol of IGBT





Structure of IGBT

- If during operation, the current through this region becomes high, the NPN transistor might be turned on, and SCR may latch.
- Once latched, nothing can be done to turn off the device.

61

Structure of IGBT

- If the rate of rise of voltage at turn off is high enough, the capacitive charging current could trigger the SCR.
- Even with these problems IGBT has much to offer.
- This device is well suited to high voltage with moderate frequencies

  (1200 V, up to 50KHz.)

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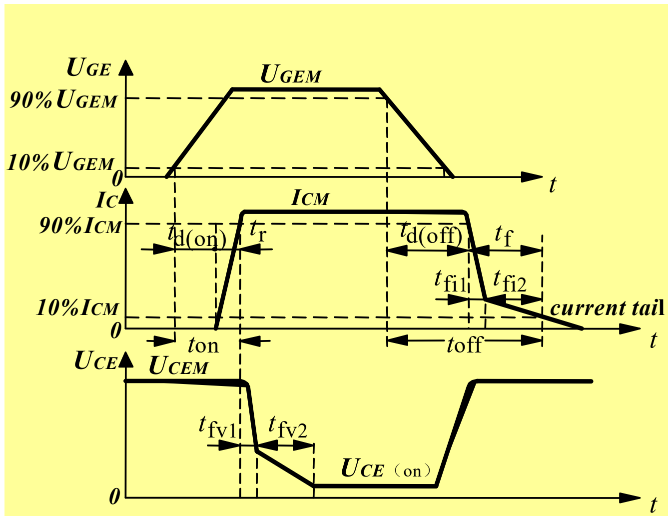
IGBT-Switching characteristics



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Commercial IGBTs

part number	Rated max voltage	Rated avg current	V_F(typical	t_f(typical)
Single-chip devices				
HGTG32N60E2	600V	32A	2.4V	0.62 μs
HGTG30N120D2	1200V	30A	3.2V	0.58 μs
multiple-chip power modules_				
CM400HA-12E	600V	400A	2.7V	0.3 μs
CM300HA-24E	1200V	300A	2.7V	0.3 μs

Thank you

For your attention

Power Converters

Power Transistors

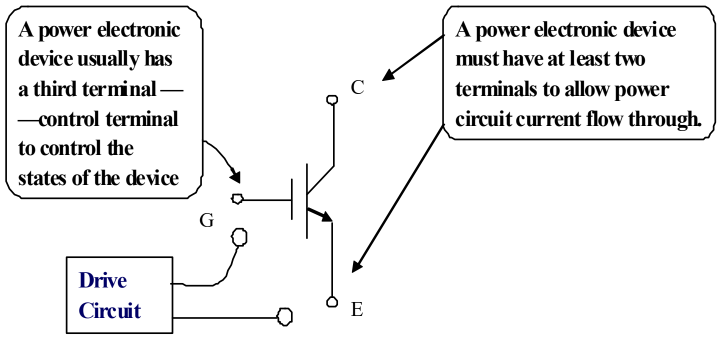
Dr. Tahir Izhar
UET-Lahore

Power BJT

2

Power Transistor

- Power Transistor is a controlled Device



Power Transistor

- Two types of transistor are extensively used in power switching circuits: bipolar junction transistor (BJT) and Metal Oxide Semiconductor Field Effect Transistor (MOSFET).
- The BJT consists of a ***pnp*** or ***npn*** single-crystal silicon structure.
- It operates by the injection and collection of minority carriers, both electrons and holes, and is therefore termed a '*Bipolar Transistor'.*

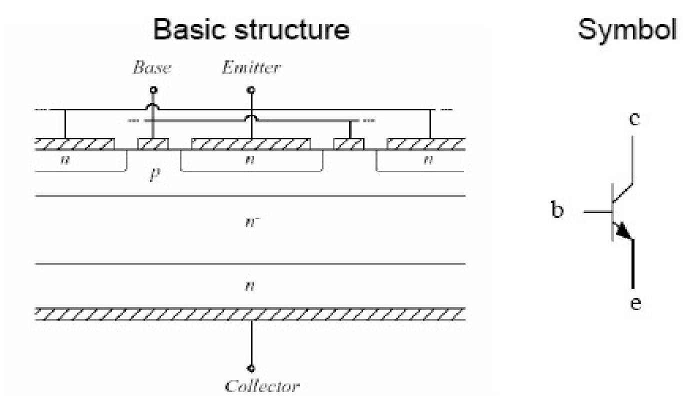
Power Transistor

- The MOSFET depends on the voltage control of a depletion width, it is therefore a *Uni-polar Transistor.*
- Unlike the BJT, the MOSFET is a majority carrier device and therefore does not exhibit minority carrier storage delays, so switching times of the MOSFETs are ultra fast.

5

Power BJT Structure

- Power BJT can handle high voltage and large current.

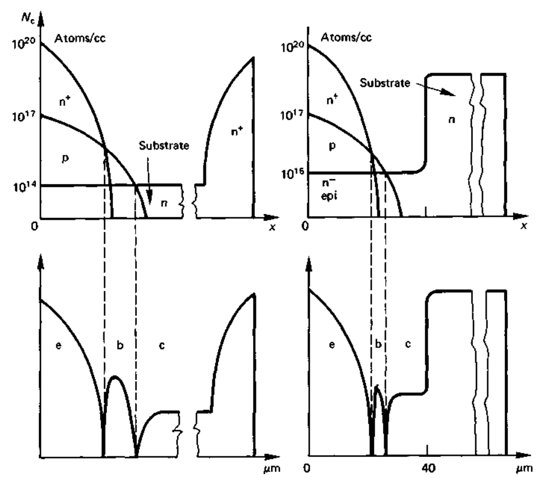


6

Power BJT doping

A typical high-voltage triple-diffused transistor doping profile is shown below

26



7

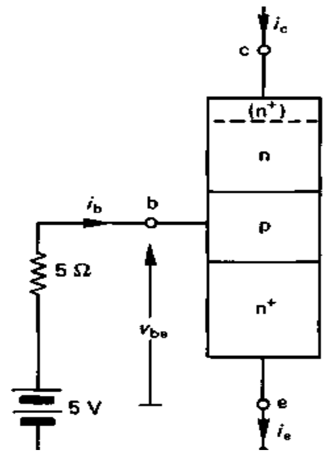
Power BJT

- The n-collector region is the initial high-resistivity silicon material and the collector n^+ diffusion is performed first, usually into both sides.
- One n^+ diffusion is lapped off and the p-base and n^+ emitter diffusions are sequentially performed.

8

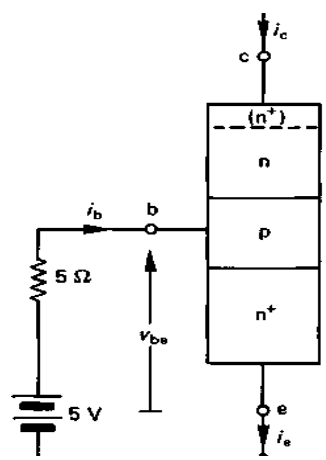
Power BJT Operation

- A simple and qualitative view of the bipolar power switching transistor.
- *npn* bipolar transistor connected in the common *emitter* configuration.



Power BJT Operation

- In this configuration, injection of electrons from the lower n^+p junction into the centre p-region supplies minority carrier electrons to participate in the reverse current through the upper np junction.



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- The n^+ region which serves as the source of injected electrons is called the *emitter* and forms the emitter junction with the p^-*base,* while the n-region into which electrons are swept by the reverse bias np junction is called the *collector* and, with the p-base, forms the collector junction

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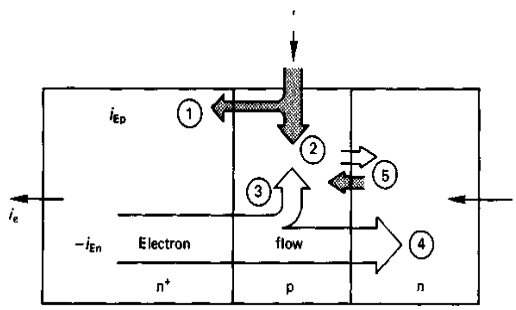

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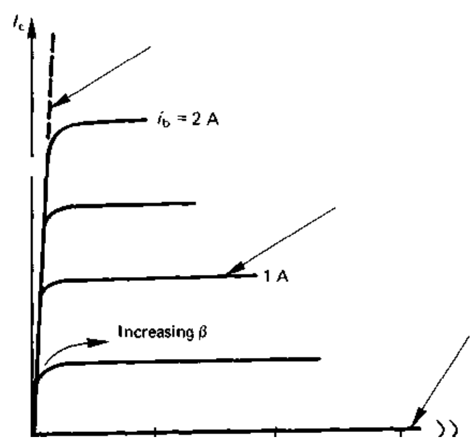
Power BJT Characteristics

The typical BJT collector output characteristics are shown below which illustrates the various BJT operating regions.



20

Power BJT
Current Gain

- A number of electrical phenomena are of particular importance to the high-voltage, power switching ***BJT***.
- The characteristics to be considered are as a result of the device structure and geometry.
- The gain of a power transistor falls off at both very low and very high current levels.
- At low currents the gain decreases as a result of generation recombination.

21

Conductivity Modulation

- At high currents, as the concentration of excess electrons in the base becomes large, the matching excess hole concentration can become greater than the base doped level.
- A balance of holes and electrons must occur in order to maintain a neutral base region.
- Thus holes in the base are injected into the emitter, countering the conversely injected electrons, and thus effectively decreasing the emitter injection efficiency.
- This effect is called *conductivity modulation.*

22

First Breakdown

- The collector junction supports the off-state voltage and in so doing develops a wide ***scl***.
- This ***scl*** increases in width with increased reverse bias, penetrating into the base.
- It is unusual that a correctly designed high-voltage power switching ***BJT*** would break down as a result of punch-through of the collector ***scl*** through the base to the emitter ***scl***.

First Breakdown

- Because of the profile of the diffused base, collector junction voltage breakdown is usually due to the avalanche multiplication mechanism, created by the high electric field at the collector junction.
- In the common emitter configuration, the transistor usually breaks down gradually, but before the collector junction avalanches.
- This occurs because the avalanche-generated holes in the collector ***scl*** are swept by the high-field into the base.

First Breakdown

- The emitter injects electrons in order to maintain base neutrality.
- This emitter junction in turn causes more collector current, creating more avalanche pairs and causing a regenerative action.
- Thus the gain mechanisms of the transistor cause collector emitter breakdown- *first breakdown*

25

Second Breakdown

- First breakdown need not be catastrophic provided junction temperature limits are not exceeded.
- If local hot spots occur because of non-uniform current density distribution as a result of crystal faults, doping fluctuation etc., *second breakdown* occurs.
- Silicon crystal melting and irrepairable damage results, the collector voltage falls and the current increases rapidly as shown in figure below

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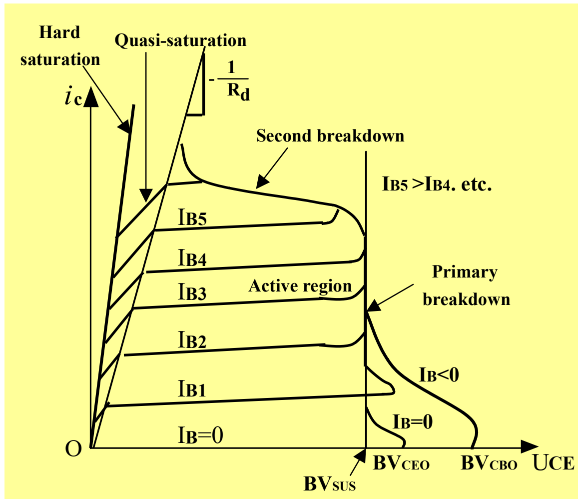
Second Breakdown



Power MOS

Power Converters

Lecture-4

The Thyristor

Dr. Tahir Izhar

1

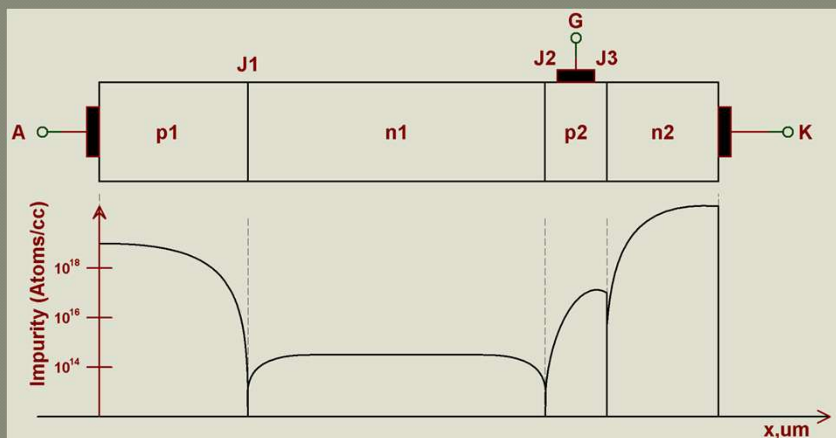
Thyristor

- The name Thyristor is a generic term for bipolar device consisting of four layers and operate as a switch.
- Numerous members of thyristor family exists i.e. SCR, GTO, TRIAC etc.
- As far as structure is concerned the simplest is the SCR and most complicated is TRIAC.

2

SCR
Basic Structure

The basic structure of an SCR with doping profile.



3

SCR
Basic Structure

- The SCR is a four layer ($p^+ n^- p\ n^+$) device.
- Low rating (10-100A), device is built on a small die of silicon wafer.
- High rating (100-4000A), the SCR is built on an entire wafer.

4

SCR
Basic Structure

- The *Cathode* is the heavily doped
- n-region on the top of the device.

- The *Anode* is heavily doped p-region on the bottom of the device.

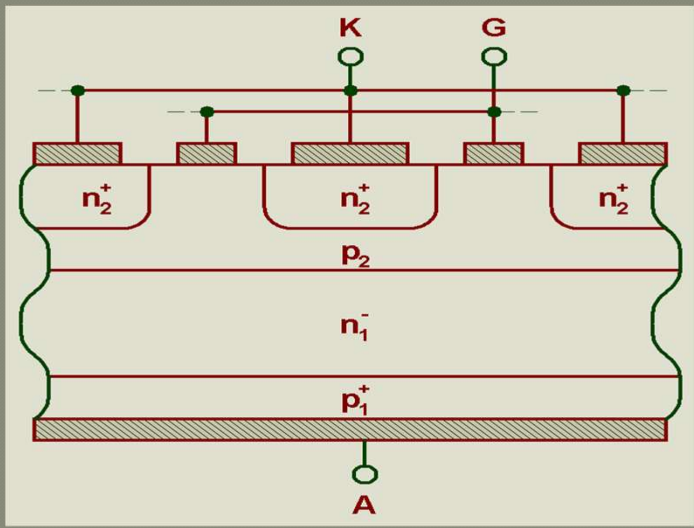
SCR
Physical Structure

- The P-region (p_2) under the cathode is the gate.

- The gate of the device is connected to the metal contact on the top of the die.

SCR

Physical Structure



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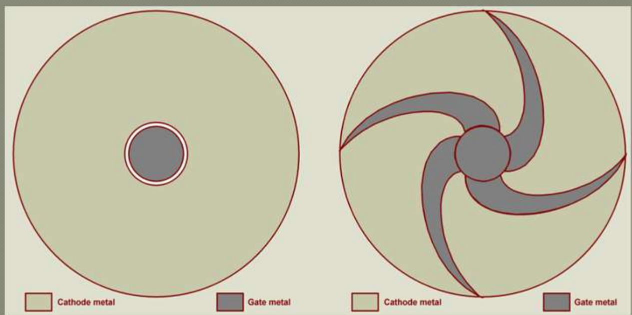
Top View of the Structure

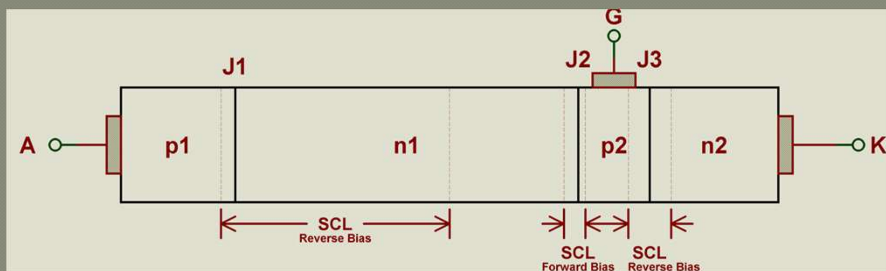
- This is the top view of two different gate geometries.
- The center-gate type is for low frequency SCRs.
- The involute-gate is used for high frequency SCRs.



8

SCR Operation

- The SCR junctions are labeled as J_1, J_2, J_3, and each of the four layers as p_1, n_1, p_2, n_2.

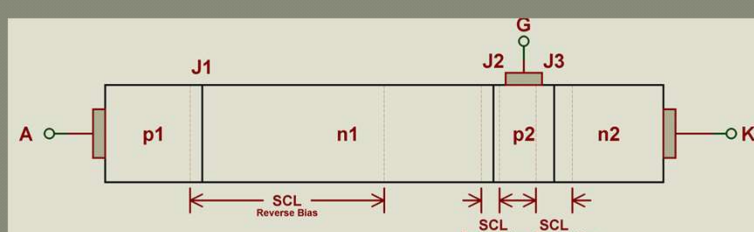


9

SCR Operation

The Off State

- When the SCR is off, it can block a reverse voltage or a forward voltage.
- when SCR is blocking Reverse voltage. V_{AK} is negative, J_1 & J_3 are reverse biased.

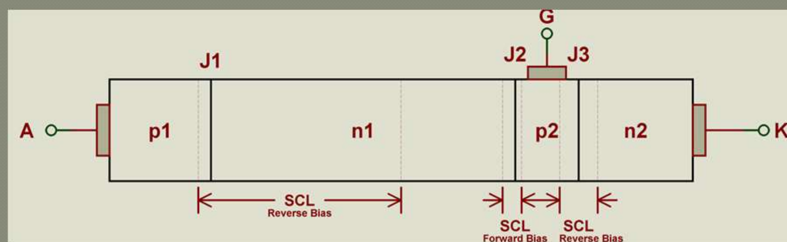


10

SCR Operation

The Off State

- The doping on each side of J_3 is very heavy, so breakdown voltage of J_3 is relatively low.

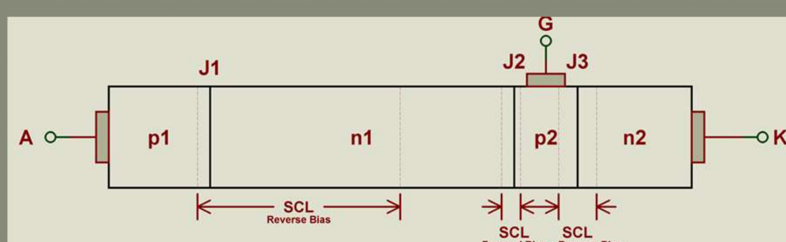


11

SCR Operation

The Off State

- n_1 region is long and lightly doped, therefore, J_1 can block large reverse voltage.
- The SCL at J_1 grows mostly into n_1 region.

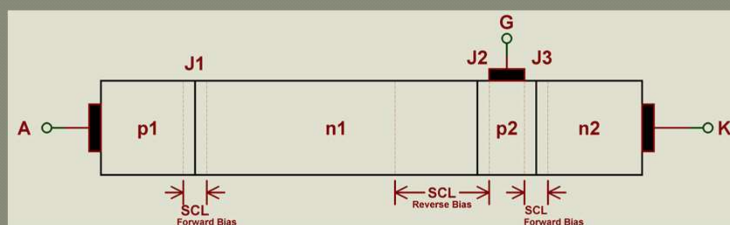


12

SCR Operation

The Off State

- When V_{AK} is positive, J_1& J_3 are forward biased and J_2 is reverse biased.

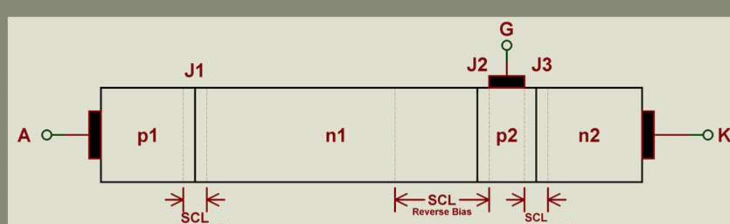


13

SCR Operation

The Off State

- J_2 withstands all the applied voltage.
- As the n_1 region is more lightly doped than p_2 region, the SCL again grows into the n_1 region.



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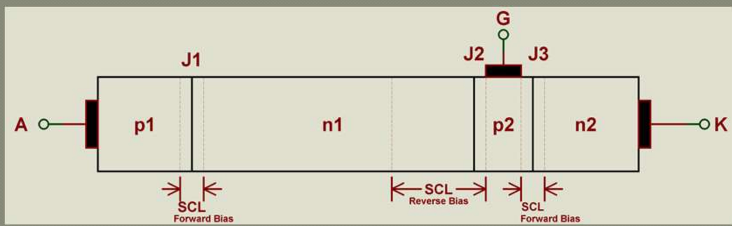
SCR Operation

The Off State

- The n_1 region is used to block both polarities of voltage when SCR is off.
- The doping level & length of n_1 region must be chosen to give the desired breakdown voltage.



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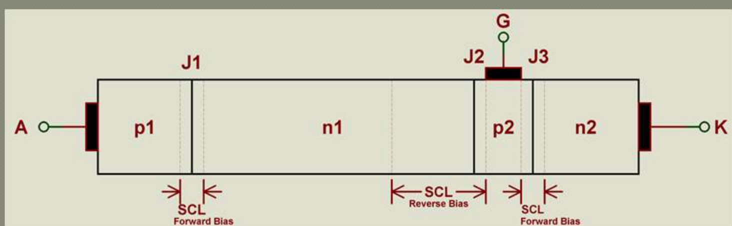
SCR Operation

The Off State

- The breakdown of n_1 can be either due to punch through or due to avalanche.
- Most SCRs are designed with n_1 long enough to cause the avalanche to be the breakdown mechanism.



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Turn 'on' Process

- If V_{AK} is positive, the SCR will block the voltage when the gate is open.
- A momentary gate current can turn 'on' the SCR and it will remain 'on' even if the gate current is made zero.
- This latching of the SCR can be understood from the two transistor model.

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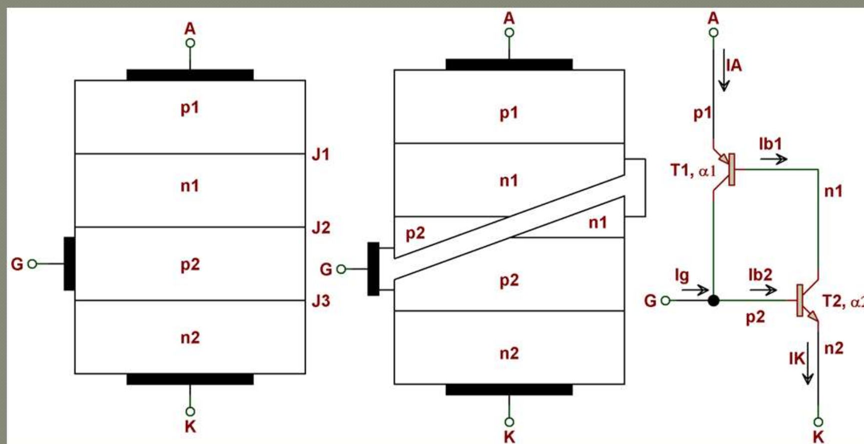
Two Transistor Model

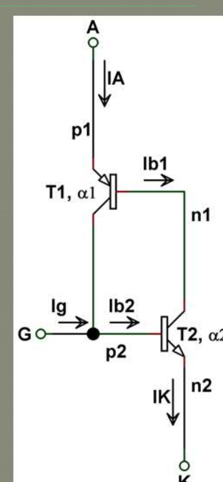


Cross-section of the SCR showing its two transistor model derivation.

18

Regenerative Process

- The application of a positive voltage at Anode can not turn on the SCR, because the junction J_2 is reverse biased and Blocking.
- Base-Collector junctions of both the transistors are reverse biased and both transistors are off.



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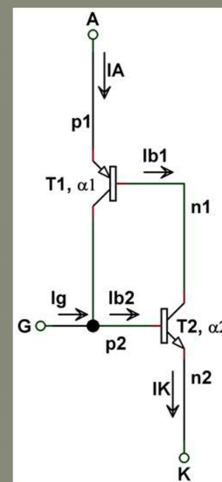
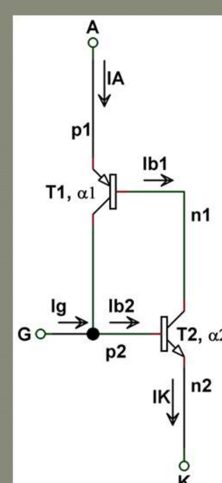
Regenerative Process

- The collector current of T_2 provides the base current for T_1.
- The collector current of T_1 along with gate current supplies the base drive for T_2.



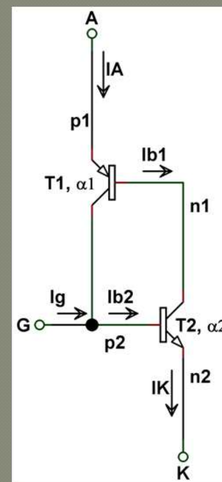
The On State

- As the two transistor drive each other into saturation, the excess carrier concentrations in their base regions reach high level injection.
- At this point doping concentrations in the base regions are no longer relevant, and the SCR behaves as a three layer PIN diode.



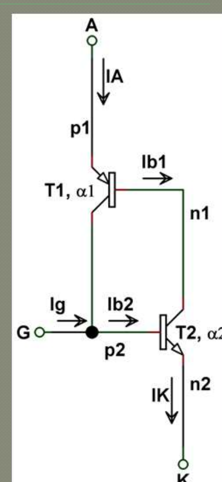
The On State

- The two middle layers corresponds to the i-region.
- The forward voltage across the i-region is inversely proportional to the recombination rate.



Regenerative Process

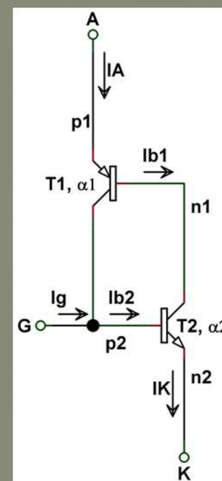
- Base current of each transistor is β times its collector current.
- The regenerative turn on process can be initiated, if a short pulse of current is applied at the gate terminal



Regenerative Process

- As long as the product
  $\beta_1 \beta_2 > 1$

the two transistors will drive each other harder and harder until they saturate.



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Break Over Voltage

- The SCR does not breakdown in the forward direction, instead it turns on.
- This process is known as Breaking over and the voltage at which it occurs is called the break over voltage V_{BO}.
- The breaking over process starts due to forward leakage current, I_A of the SCR which must be kept small to save it from Beak over.

25

Break Over Voltage

- It can be shown that the SCR leakage current is

$$I_A = \frac{I_{CO1} + I_{CO2}}{1 - (\alpha_1 + \alpha_2)} \quad \text{---------------} \ (1)$$

- To keep the I_A small, the loop gain,

$$(\alpha_1 + \alpha_2) << 1$$

- If $(\alpha_1 + \alpha_2) = 1$, the equation (1) shows that SCR will enter into sustained breakdown.

26

Break Over Voltage

- The leakage current of the SCR increases with temperature.
- Therefore at elevated temperature, the thermally generated leakage current can be sufficient to increase the SCR loop gain such that turn on occur.
- If α_2 is made smaller than α_1, the reverse and forward breakdown voltages are nearly same.

27

SCR *dv/dt* Rating

- The SCR can also turn on by means of high ***dv/dt*** across anode and cathode.
- The increasing voltage is supported by J_2.
- The associated SCL width increases and a charging current flows across the anode and cathode junctions, causing hole and electron injection respectively.

28

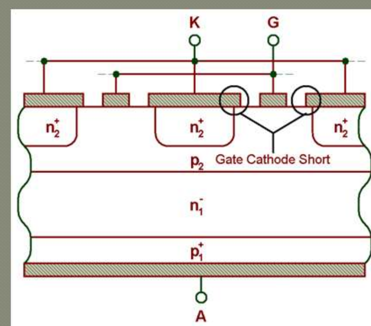
SCR *dv/dt* Rating

- The same mechanism occurs at the cathode when gate current is applied; hence if the terminal ***dv/dt*** is large enough, SCR turns on.

29

Gate Cathode Short

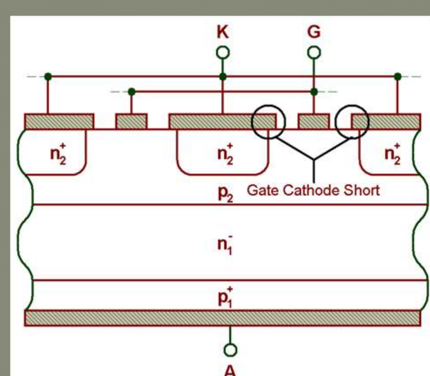
- A structural modification is used to reduce temperature sensitivity of the device and to increase the rating by introducing gate cathode shorts.



30

Gate Cathode Short

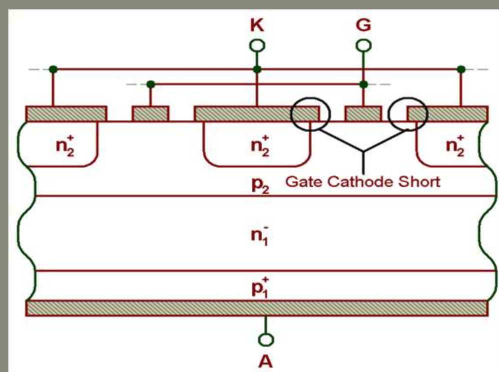
- The effect of this short is like placing a resistor across the base-emitter junction of T_2.



31

Gate Cathode Short

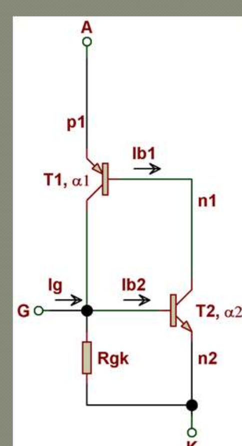
- The cathode electron injection efficiency is effectively reduced thereby decreasing α_2 which results in V_{BO} and ***dv/dt*** rating.



32

Function of Cathode Short

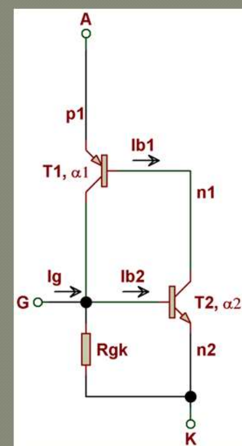
- In the forward blocking state, J_2 leakage current will forward bias base-emitter of T_2.
- As this junction voltage rises, the cathode short diverts some of the leakage current of p_2 base reducing the current that is multiplied by the transistor action, in effect the gain of T_2 is reduced.



33

Function of Cathode Short

- The designer will make $0.7/R_{gk}$ larger than the maximum leakage current expected when SCR is in forward blocking state.



34

Latching Current

- To turn on the SCR, we need T_2 to contribute to the regenerative process.
- This contribution will not occur until the current flowing through the SCR is $0.7/R_{gk}$.
- Because this value of current is usually exceeded by I_g, the SCR will turn on by the gate drive.

35

Latching Current

- But if the gate drive is removed, the regenerative process stops and the SCR returns to its off state.

- The Anode current level required for the SCR to remain on when the gate drive is removed is called the latching current I_L.

36

Holding Current

- Similarly, if the SCR is on and the gate drive has been removed, the anode current must fall below than a critical level to turn off the SCR because of the failure of the regenerative process.
- The anode current at which this occurs is called the holding current, I_H.
- Our simple description here suggests that

$$I_L=I_H=0.7/R_{gk}.$$

37

Holding Current

- However, R_{gk} is slightly different for the turn-on and turn-off processes owing to the differences in excess charge concentrations in the p_2 region.
- For a 100A device, I_L and I_H are typically in the range of 100 to 300mA , with $I_H < I_L$.

38

Latched SCR

- An important property of the SCR is that once latched on, the gate control is lost.
- The SCR can not turned off through gate.
- SCR turn off can only be achieved by reducing the anode current externally to a level below which the loop gain is significantly less than unity.

39

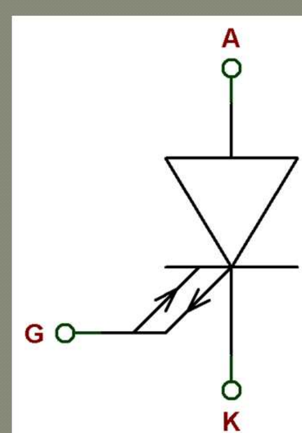
GTO

The Gate Turn of Tyristor

GTO

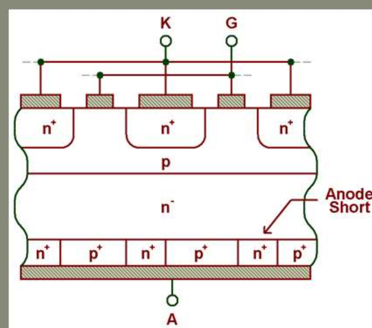
The Gate Turn Off Thyristor

- GTO, is one of the new power semiconductor device.
- Introduced in the 1970's but was not established until the 1980's.



GTO
The Gate Turn Off Thyristor

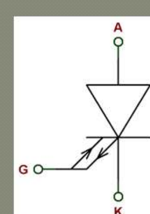
- Research and development has led to the present day range of devices, with peak turn-off current in the range of 300A to 4000A and rated forward blocking voltages of between 1300V and 6000V.

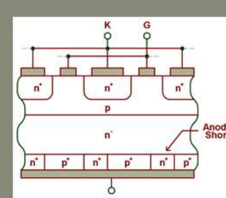


42

GTO

- The gate terminal has two arrowheads, on the circuit symbol of GTO indicating current flow in both directions, since the GTO can also be turned off with a negative gate current signal.

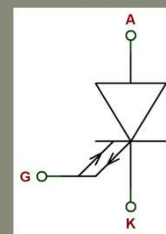




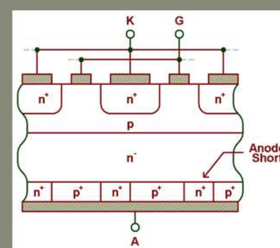
43

GTO

- The difference in the structure of GTO from the SCR is the Anode short which helps to stop the regeneration process with negative gate pulse.



- However, Anode short gives rise to an asymmetrical voltage blocking characteristics.



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Thank you

For your attention

45

Power converters
AC/DC Converters

Dr. Tahir Izhar
UET-Lahore

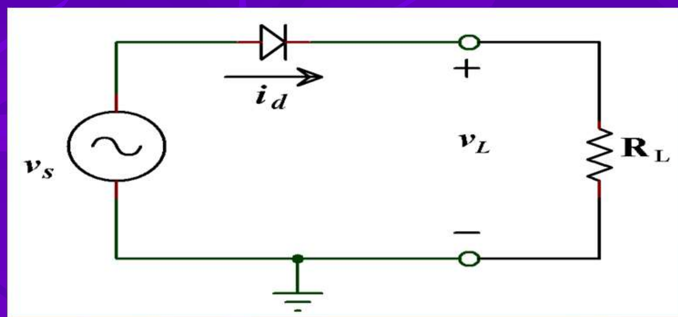
1

Single Phase Converters

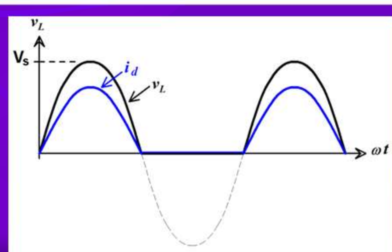
- The basic rectifier principles are understood from the operation of single phase circuits.
- The emphasis will be on physical understanding not on the detailed analysis.
- First consider a simple half wave rectifier circuit with resistive load.

2

Half-Wave Rectifier



Resistive Load



3

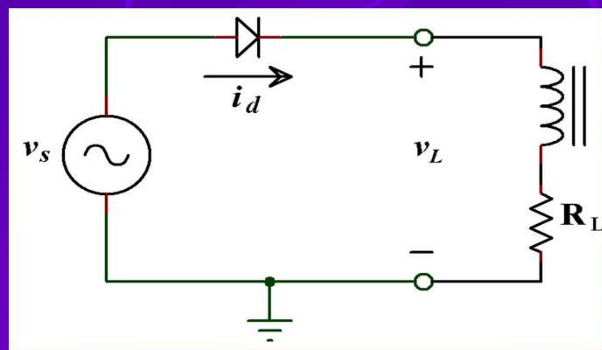
Half-Wave Rectifier

Resistive Load

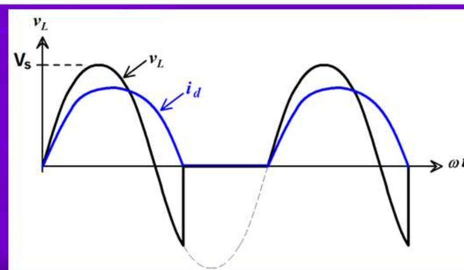
- The load voltage is nearly same as the source voltage during positive half cycle.
- The current is also sinusoidal during positive half cycle.
- During negative half cycle, the diode is reverse biased the load current is zero, source current is zero and the load voltage is also zero.

4

Half wave Rectifier



Inductive Load



5

Half wave Rectifier

Inductive Load

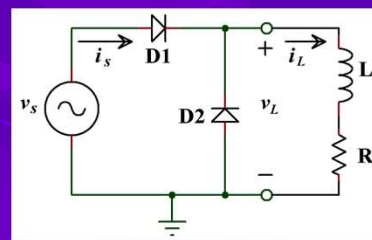
- For inductive load, the current will keep on flowing even if the source voltage is negative.
- This is due to the stored energy in the inductor.
- When the source voltage reverses its polarity, the inductor becomes a source and the polariyty of this source is so that it will keep the current flowing in the same direction.
- When the stored energy is release the diode current will reduced to zero and the diode is reverse biased.
- During a part of the negative cycle, the load voltage will follow the source voltage.

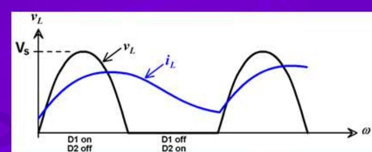
6

Half wave Rectifier

Inductive Load with Freewheeling Diode

- The addition of diode D_2 permits the load current to be continuous and prevents v_L from going negative.
- When D_1 is off, D_2 allows the energy in the circuit to maintain continuity by providing a path through which the inductor current can free wheel.
- Diode D_2 is known as free-wheel diode, by-pass, fly-back, catch diode or commutation diode.

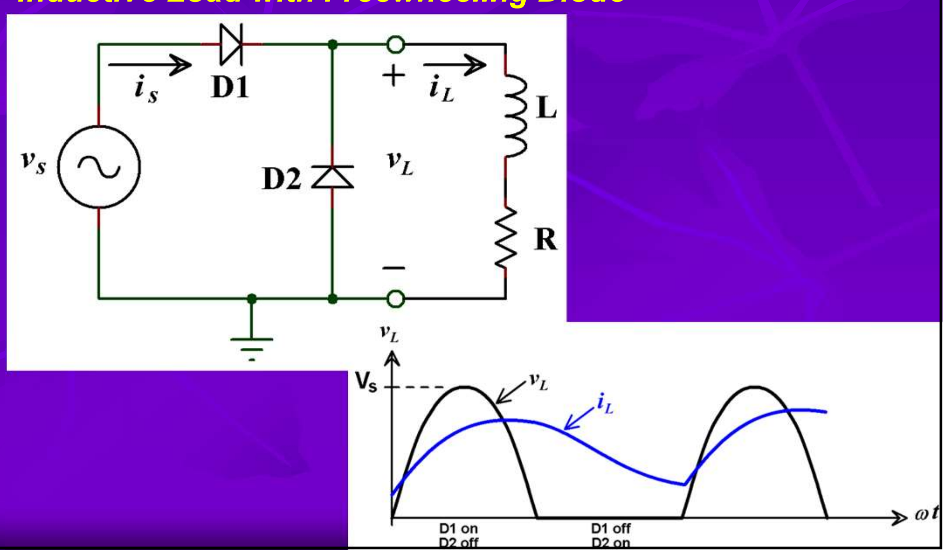




7

Half wave Rectifier

Inductive Load with Freewheeling Diode



Half wave Rectifier

Inductive Load with Freewheeling Diode

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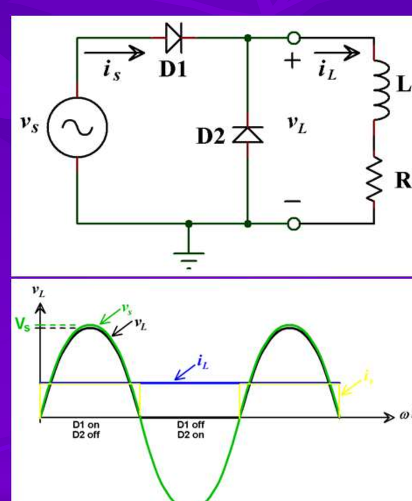
- Diode D_2 is known as free-wheel diode, by-pass, fly-back, catch diode or commutation diode.

9

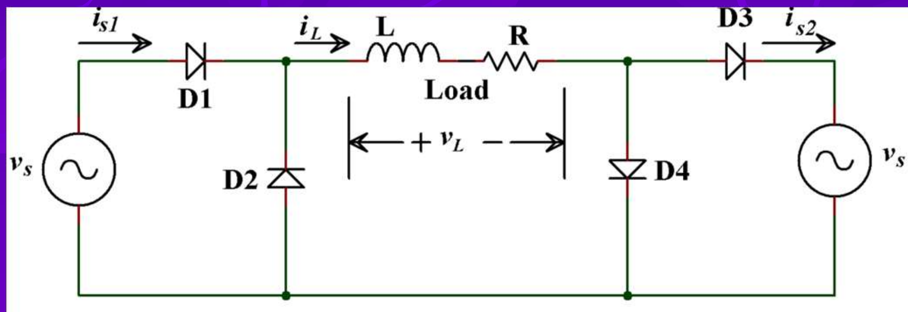
Half wave Rectifier

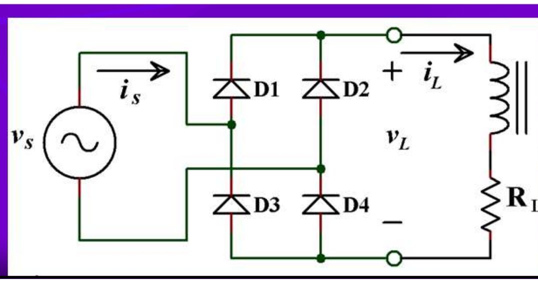
Highly Inductive Load with Freewheeling Diode

- If we assume that the inductor is very large approaching infinity, the load current will become constant without any fluctuations.
- The Green line shows v_s, Black is the load voltage, blue is the load current and yellow is the source current.
- It can be observed that the source current is unidirectional step waveform.



1-Φ Bridge Rectifier

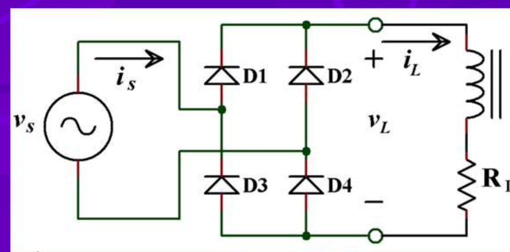


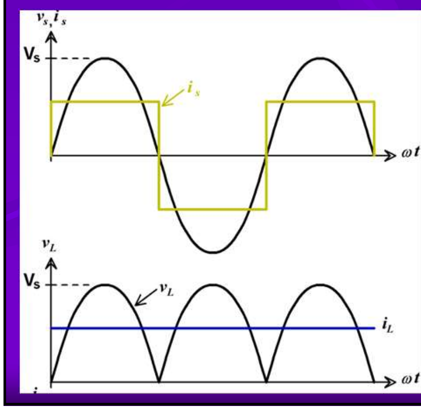


1-Φ Bridge Rectifier

- AC source current contain no DC component.
- For same AC source voltage, the full wave rectifier produces an average output voltage twice that of the half-wave circuit with free-wheeling diode.
- The half-wave rectifier with free wheeling diode serves as the basic building block for the bridge circuit and in this context the circuit is sometimes called a half-bridge.

1-Φ Bridge Rectifier





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1-Φ Bridge Rectifier

- The source currents i_{s1} and i_{s2} contain DC components, however, the total source current for the full-bridge circuit does not contain any DC components.
- The reason is that the source current in the bridge is sum of the two source currents, which have DC components of equal magnitude but of opposite polarity.
- As the load is highly inductive, the load current i_L is constant.

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1-Φ Bridge Rectifier

- During positive half cycle, i_L is supplied by D1 and D4, therefore, $i_s = i_L$.
- During negative half cycle, i_L is supplied by D2 and D3, therefore, $i_s = - i_L$.
- Therefore the source current will have a square wave shape with zero DC component.

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Analysis of 1-Φ Converter

Power Transfer From Mains

Consider that a Single Phase Bridge rectifier is connected to the mains supply an it draws a non-sinusoidal current from the mains.

The average or mean output Voltage is

$$V_{mean} = \frac{1}{\pi}\int_0^{\pi} V_s \sin\omega t d\omega t \quad \textbf{(1)}$$

$$V_{mean} = \frac{2V_s}{\pi} \quad \textbf{(2)}$$

The average load current is

$$I_L = \frac{V_{mean}}{R} = \frac{2V_s}{\pi R} \quad \textbf{(3)}$$

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Analysis of 1-Φ Converter

Power Transfer From Mains

The average load Power is

$$P_{av} = V_{mean} I_L \qquad (4)$$

$$= \frac{2V_s}{\pi} \frac{2V_s}{\pi R} = \frac{4V_s^{\,2}}{\pi^2 R} \qquad (5)$$

Since $V_s = \sqrt{2} V_{rms}$

$$P_{av} = \frac{8V_{rms}^2}{\pi^2 R} \qquad (6)$$

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Analysis of 1-Φ Converter

Power Transfer From Mains

Since the AC current is a simple square wave, it has the well known spectrum of odd harmonics with amplitude inversely proportional to the order.

$$I_n = \frac{4I_L}{n\pi} \qquad (7)$$

For n=1,3,5…

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Analysis of 1-Φ Converter

We also know that in case of non-sinusoidal mains current, only the fundamental component of current contributes towards average power.

$$P_{av} = V_{mean} I_{1rms} \qquad \textbf{(8)}$$

Peak value of fundamental current is

$$I_1 = \frac{4I_L}{\pi} = \frac{4 \times 2 \times V_s}{\pi \times \pi \times R} = \frac{8V}{\pi^2 R} = \frac{8V_{rms} \times \sqrt{2}}{\pi^2 R}$$

$$I_{1rms} = \frac{I_1}{\sqrt{2}} = \frac{8V_{rms}}{\pi^2 R} \qquad \textbf{(9)}$$

Therefore

$$P_{av} = \frac{8V_{rms}^2}{\pi^2 R} \qquad \textbf{(10)}$$

Note that the results obtained in equations (6) and (10) is same

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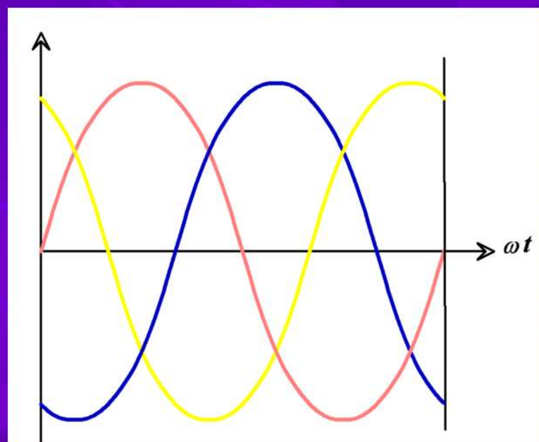
Poly-Phase Rectifiers

- Consider the 3-phase supply of sinusoidal waveforms.
- Phases are displaced by 120 degrees from each other.



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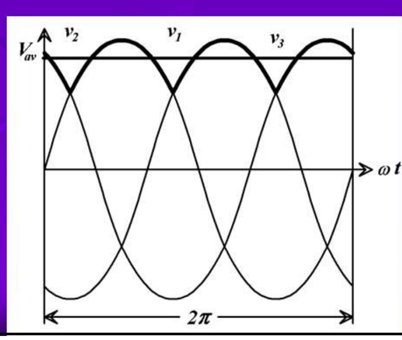
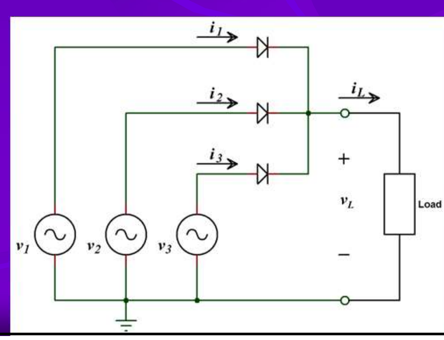
3-Pulse Rectifiers

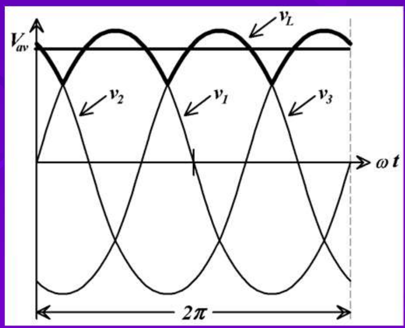
- The poly-phase rectifier operation is similar to diode or-gate operation.
- The output assumes the value of the highest input at any instant in time.
- Therefore there will be three pulses in the output voltage waveform.
- The output ripple frequency is therefore 150 Hz.
- In practice, the poly-phase AC sources are displaced symmetrically in phase, however, this condition is not necessary for the basic operation of the circuit below.

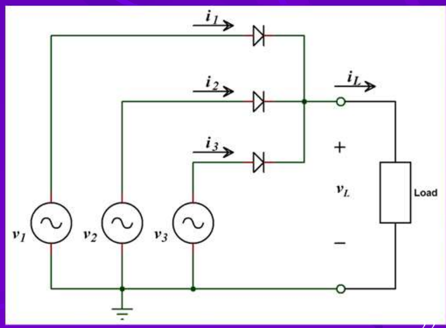




3-Pulse Rectifiers

- If it is assumed that the load is highly inductive and the inductance approaches infinity, the load current becomes constant.
- This circuit is known as 3-phase, half-wave, 3-pulse rectifier.





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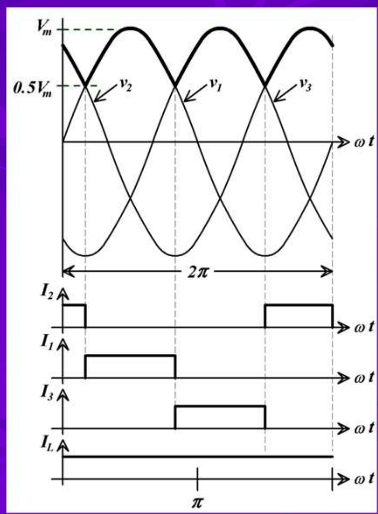
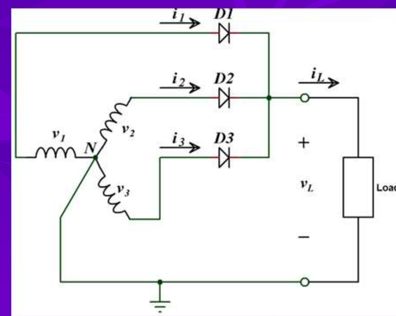
3-Pulse Rectifiers

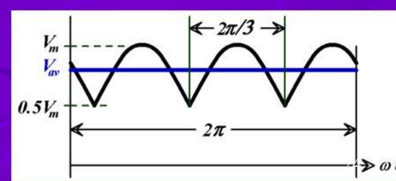
- The load current and phase current waveforms w.r.t. voltages are shown.
- It can be seen that the circuit draws unidirectional current from the sources.
- Therefore, this circuit is not used in practice for high power outputs.
- In practice, a full-wave circuit is used.
- The full-wave circuit draws AC current from the sources.



3-Φ, 3-Pulse Converter

- The connections of a 3-pulse converter using three diodes and a three phase transformer are shown.
- The secondary winding of the power transformer is Y-connected using the common N point as the negative of the load point.
- The output is has three pulses per cycle with a pulse width of $2\pi/3$ radians.
- Note that the pulses do not touch the zero level.
- The peak of the output DC is nearly the peak value of the AC.
- The minimum DC voltage is $V_m \sin(2\pi/6)=V_m/2$





3-Φ, 3-Pulse Converter

The average DC voltage can be calculated as

$$V_{av} = \frac{1}{(2\pi/3)} \int_{\pi/6}^{5\pi/6} V_m \sin\theta d\theta \qquad (14)$$

$$V_{av} = \frac{3\sqrt{3}}{2\pi} V_m \qquad (15)$$

The peak to peak ripple voltage is

$$V_{r(P-P)} = V_m - V_m \sin\left(\frac{\pi}{6}\right) = \frac{V_m}{2} = \frac{\sqrt{2}}{2} V_{rms} \qquad (16)$$

And rms value of the ripple voltage is

$$V_{r(rms)} = \frac{V_{r(p-p)}}{2\sqrt{2}} = \frac{\sqrt{2}}{2\times 2\times\sqrt{2}} V_{rms} = \frac{V_{rms}}{4} \qquad (17)$$

For phase voltage of 230 Volts, the rms ripple is 57.5 Volts @150Hz.

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3-Φ, 6-Pulse Converter

- 6-pulse, full-wave converter can be constructed by connecting two-half wave converters in series.
- The six pulses in the output are obtained by using two, 3-pulse converters connected in series.
- Two sets of three pulses, displaced by 60^{O} if added, results 6-pulses per cycle.

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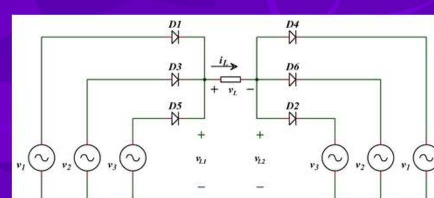
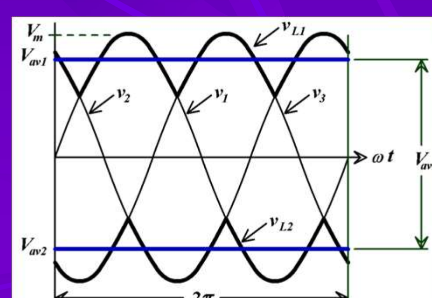
3-Φ, 6-Pulse Converter

- The evolution of 6-pulse converter from two 3-pulse converters is shown with input and output voltage waveforms.
- The average value of the voltage at positive terminal of load ***w.r.t.*** common point is v_{av1}.
- And the average voltage at negative terminal of the load ***w.r.t.*** common point is v_{av2}.
- The average voltage across the load can be calculated by adding the two 3-phase half-wave voltages.





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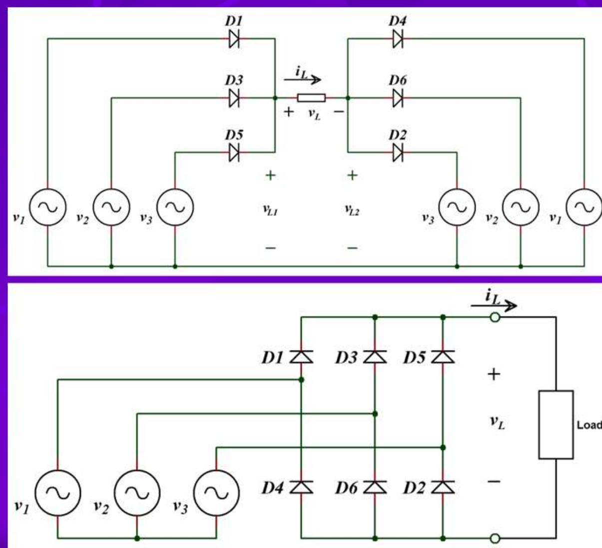
3-Φ, 6-Pulse Converter



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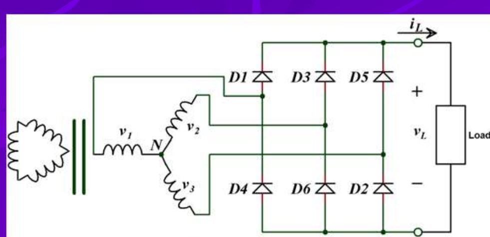
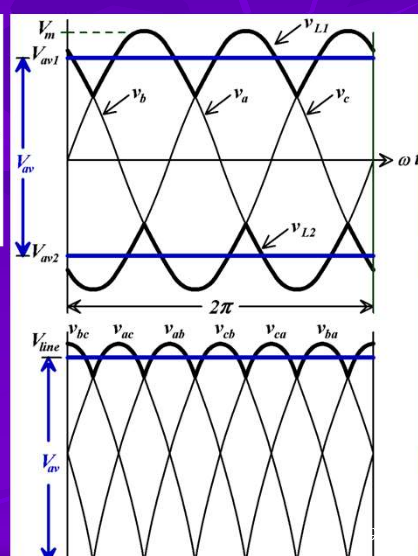
3-Φ, 6-Pulse Converter





- The practical circuit of the 6-pulse converter using a delta-star transformer is shown with output load voltage waveform.
- It can be seen that the output have six pulse per cycle.
- Therefore, the ripple will have a frequency of 300Hz.
- The ripple is small compared to 3-pulse converter.

Analysis of 6-Puse Converter

$$V_L = V_{L1} + V_{L2} \quad (17)$$

$$V_{av} = 2\left[\frac{3\sqrt{3}}{2\pi}V_m\right] \quad (18)$$

Where V_m is the peak value of the Phase to neutral voltage V_{ph}.

$$V_{av} = \left[\frac{3\sqrt{3}}{\pi}V_{ph}\right] = \frac{3}{\pi}V_{line} \quad (19)$$

The ripple in the output voltage can be calculated by calculating the voltage at cross-points of the output waveform

$$V_{line(60^o)} = 0.866V_{line(pk)} \quad (20)$$

$$V_{r(p-p)} = (1-0.866)V_{line} = (1-0.866)\sqrt{3}V_{ph} \quad (21)$$

$$V_{r(p-p)} = (1-0.866)\sqrt{3}\sqrt{2}V_{rms} \quad (22)$$

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Analysis of 6-Puse Converter

$$V_{r(rms)} = \frac{V_{r(p-p)}}{2\sqrt{2}} \quad (23)$$

$$V_{r(rms)} = \frac{(1-0.866)\sqrt{3}}{2}V_{rms} = 0.166V_{rms} \quad (24)$$

For V_{rms} of 230 volt, the rms ripple is

$$V_{r(rms)} = 26.8V \quad (25)$$

As there are six pulses per cycle, the frequency of the ripple is 300 Hz.

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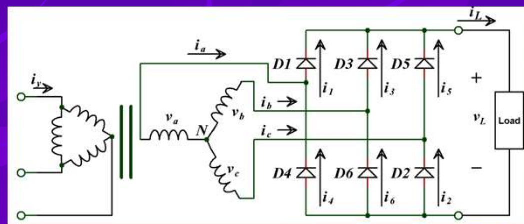
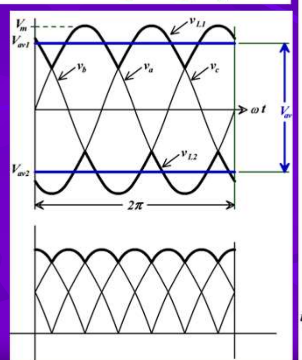
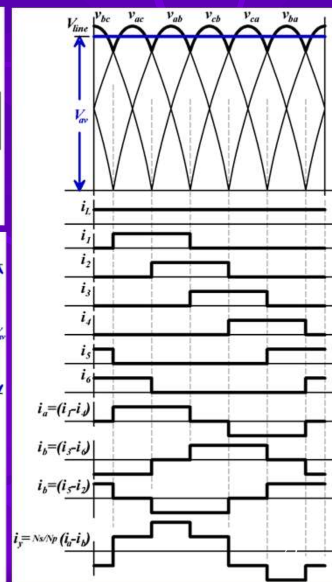
Currents Waveforms



Practical circuit of
6-puse converter with
Phase Voltage, Line Voltage,
and phase current and line
current waveforms





Analysis of Current Waveform

If we perform the Fourier analysis of the line current waveform, the following equation represents the nth harmonic of the current waveform.

$$\boxed{I_n = \frac{4I_d}{n\pi}\sin\left(\frac{n\pi}{2}\right)\bullet\cos\left(\frac{n\pi}{6}\right)} \qquad (26)$$

For n=1,2,3,4….∞

- ‘sin’ term in equation (26) indicates that the even harmonics are zero.
- ‘cos’ term indicates that the 3rd and its multiple (triplen) harmonics are zero.
- However, all other odd harmonics are present in the spectrum.
- The distortion factor will be more closer to 1 as compared to square wave.
- The distortion factor can be improved by increasing the number of steps in the current wave and making is more closer to sinusoidal wave.
- This technique to improve the quality of current waveform is known as
- “***Selective Harmonic Cancellation Technique***”.

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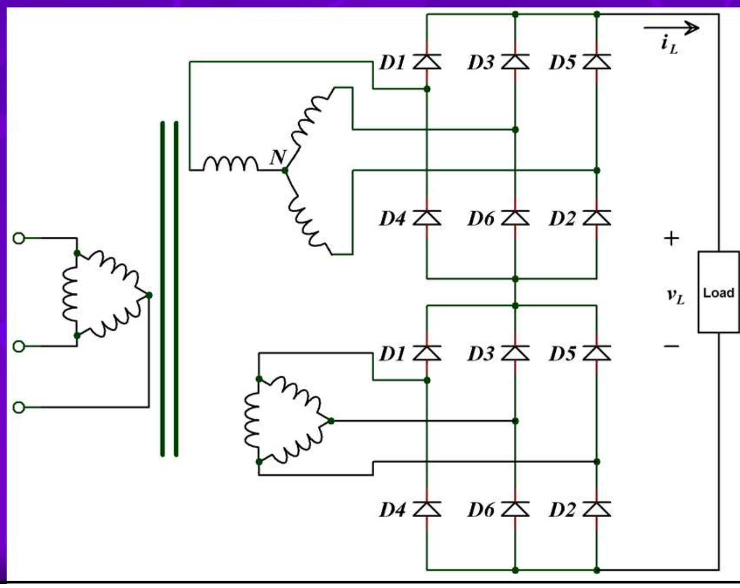
12-pulse Converter



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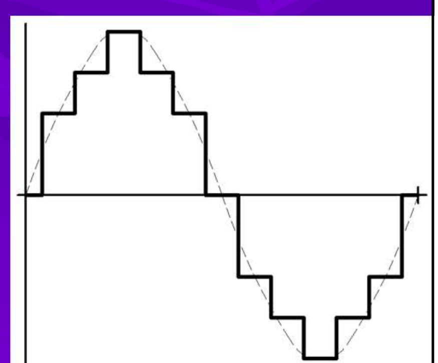
12-Step Current Waveform

- The 12-step converter can be realised by using two 6-step converters.
- The 3-phase input to these converters is displaced by 30 degrees using dual secondary windings one is delta connected and the other is star connected.
- The outputs of the 6-step converters can be connected in series to the load to get the 12-step output across the load.
- If the load is highly inductive the load current will be nearly constant and the input line current will have step sine waveform as shown in the diagram.
- It can be seen that the waveform is much closer to sine wave.



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12-pulse Converter

- The outputs of the 6-step converters can also be connected in parallel, however, there will be an instantaneous voltage difference due to the ripple on each converter output which prevents direct connection.
- The differential ripple voltage can be be accounted for by a center-tapped iron cored inductor.

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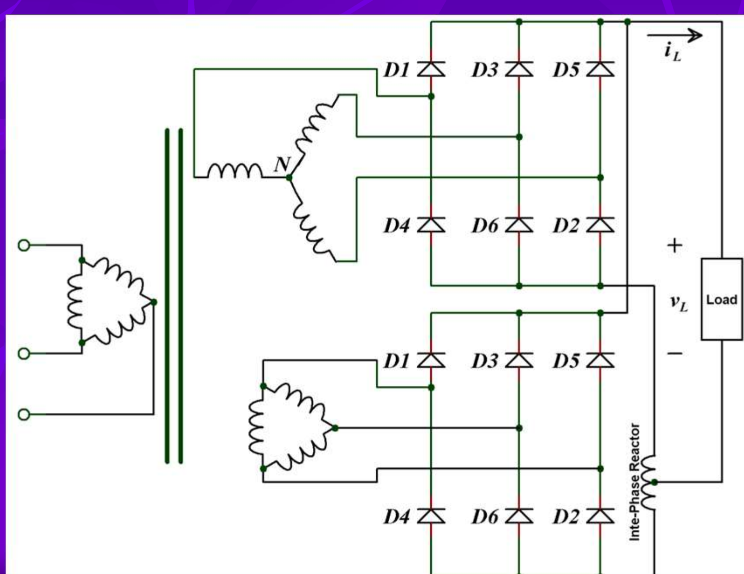
Parallel Converter Connections



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12-pulse Converter

- The DC current in the inductor produces equal and opposite mmfs in each half but the AC voltage is divided across the inductance and causes some AC circulating current .
- This Device is known as an " Inter-phase Reactor" and has to be carefully designed to satisfy both AC and DC conditions.

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Parallel Converter Connections

- The parallel connection allows good device utilization and increase current capability.
- In parallel connection total number of diode in series are less resulting less drop, therefore suitable for low voltage high current loads
- The cost is higher due to the requirement of inter-phase reactor.
- In Railway traction applications, the series connection is used for 1500 volts DC systems.
- The parallel connection is preferred for 750V DC systems.

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24-pusle Converter

Introduction

- 24-pulse converter can be realized by connecting 4 bridges in series and displacing the inputs by 15^o.
- The advantage is clear that the current waveform is very close to sine wave.
- The mains power utilization is very good with distortion factor nearly unity.
- However, the cost will be high due to the use of large number of power diodes.

40

Thank you

For your attention

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Half Controlled Bridge Converter

- 3-phase half controlled converter is cheaper than fully controlled converter.
- There is no starting problem in half controlled converter.
- The output is 3-pulse per cycle therefore high harmonics in voltage waveforms.
- Single quadrant operation only the output load voltage is always positive.
- The range of α is from zero to 180°.

$$V_{mean} = \frac{3\sqrt{3}}{2\pi} V_m (1 + \cos\alpha) \qquad (11)$$

$$V_{mean} = \frac{3}{2\pi} V_{m(line)} (1 + \cos\alpha) \qquad (12)$$

1

Phase Controlled Converters

Lecture-6

Dr. Tahir Izhar

Introduction

- The **All Diode** Rectifier circuits discussed so for are uncontrolled converters.
- The converter can be made controllable if diodes are replaced with SCR's.
- Converters containing one or more SCR's are known as phase controlled converters.

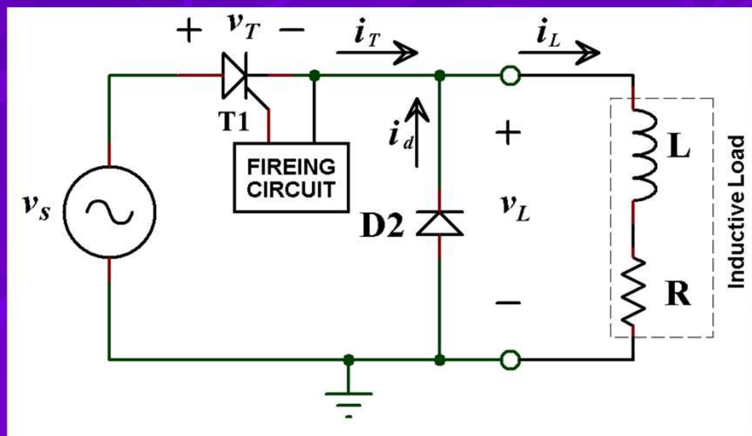
3

Introduction

- The output voltage can be controlled in these converters by controlling the phase angle.
- These converters can also be designed to permit power flow from DC side to AC side as well.
- Can operate in more than single quadrant.

4

Half-wave Phase Controlled



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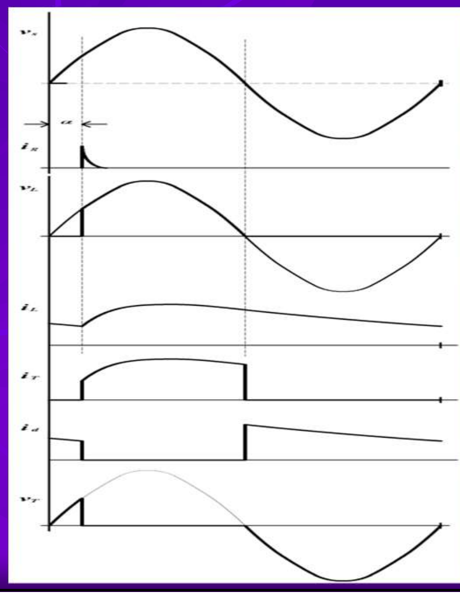
Half-wave Phase Controlled

- The SCR will only conduct when its voltage v_T is positive and it has received a gate pulse i_g.
- The output voltage can be controlled by changing the firing angel ***'α'***.

6

Half-wave Phase Controlled



7

Analysis

The average or mean output Voltage is

$$V_{mean} = \frac{1}{2\pi}\int_{\alpha}^{\pi} V_s \sin\omega t d\omega t \quad (1)$$

$$V_{mean} = \frac{V_s}{2\pi}\left(1+\cos\alpha\right) \quad (2)$$

8

Analysis

- The average DC output will be maximum i.e. V_s/π for α=0 and will be zero for α=π.
- Without the commutation diode the output goes negative for a short time.
- The commutating diode prevents negative load voltage.
- The commutating diode allows the SCR to regain its blocking state at the voltage zero by transferring the load current away from the SCR.

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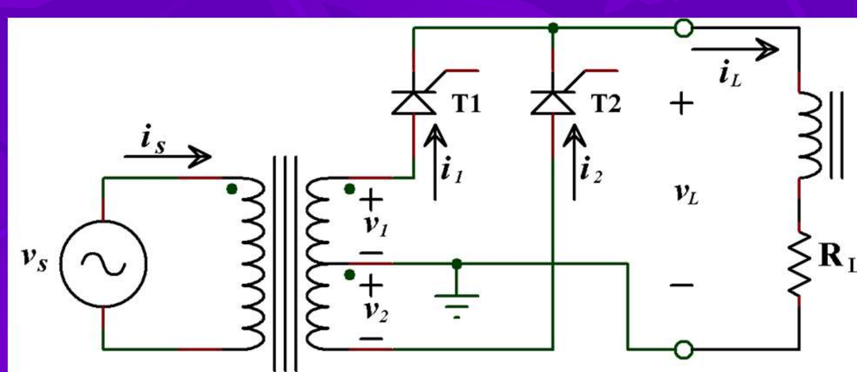
Bi-Phase Half-Wave Converter

- The bi-phase connection provides two voltages v_1 & v_2 in anti-phase relative to the mid-point 'N'



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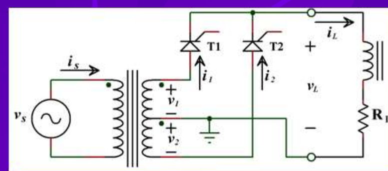
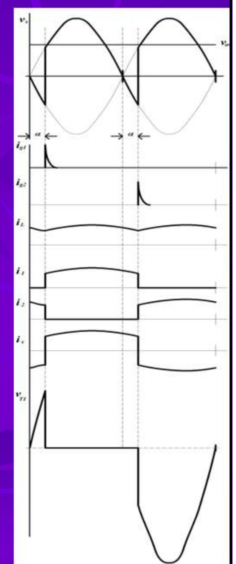
Bi-phase Converter Waveforms





- T1 can be fired at any time after v1 goes positive.
- Once T1 turns on, current builds up in the inductive load maintaining T1 in on state into the period when v1 goes negative.
- However, once v_1 goes negative, v_2 becomes positive and firing of T2 immediately turns on T2 which takes up the load current, placing a reverse voltage on T1.
- The current of T1 will be commutated to T2.
- The SCR can be fired at anytime when v_T is positive.

Bi-phase Converter

The peak inverse voltage across SCR is 2Vs

The load mean voltage is

$$V_{mean} = \frac{1}{\pi} \int_{\alpha}^{\pi+\alpha} V_s \sin\theta d\theta \qquad (3)$$

$$V_{mean} = \frac{2V_s}{\pi} \cos\alpha \qquad (4)$$

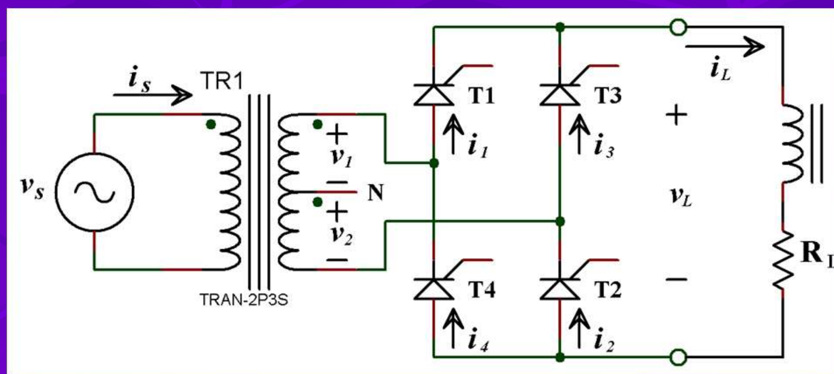
Bi-phase Converter

- ‘α’ can be varied from 0 to 180 degrees.
- Output is maximum at $\alpha = 0$ i.e. $2V_s/\pi$.
- Output is zero at $\alpha = 90$ degrees.
- Output is negative for a greater than 90 up to 180.

Bi-phase Converter

- The load current is continuous, however, ripple will increase as the mean voltage is reduced.
- The SCR currents are of half cycle duration and are nearly square shaped for continuous load current.
- Supply current is non sinusoidal, square wave and delayed w.r.t. voltage.

Fully Controlled Bridge Converter



15

Fully Controlled Bridge Converter

- Fully controlled bridge converter can be realized by connecting four SCR's in bridge configuration.
- The conduction starts when T1 and T2 are fired simultaneously during positive and negative half cycles.
- To ensure simultaneous firing both T1 and T2 are fired from the same firing circuit using a pulse transformer with single primary and dual isolated secondary's.
- Isolated secondary's are required because the cathodes of T1 and T2 are at different potentials in the main circuit.

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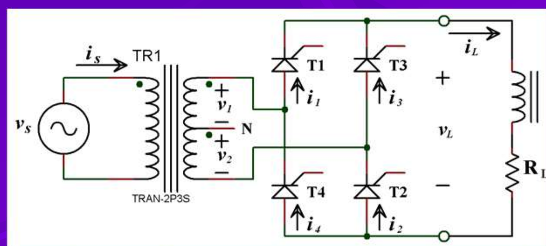
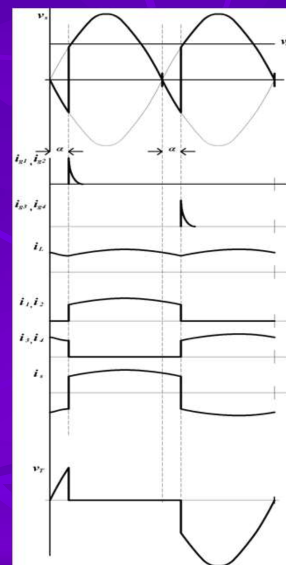
Fully Controlled Bridge Converter

Wave Forms





Fully Controlled Bridge Converter

The mean load voltage is

$$V_{mean} = \frac{1}{\pi} \int_{\alpha}^{\pi+\alpha} V_s \sin\theta d\theta \qquad (5)$$

$$V_{mean} = \frac{2V_s}{\pi} \cos\alpha \qquad (6)$$

The converter operates in two quadrants. If α = 0 to 90, the power flows from AC to DC and if α = 90 to 180, the power flows form DC to AC.

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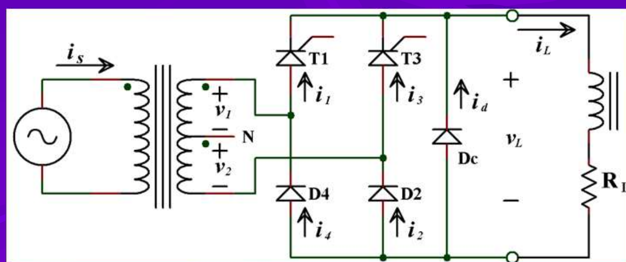
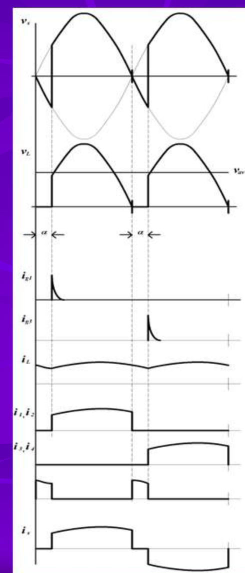
Half Controlled Bridge Converter

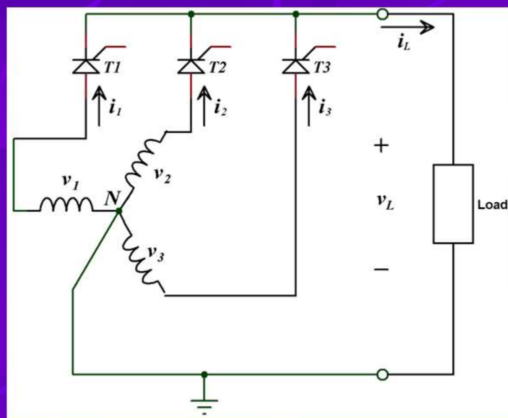
Half controlled bridge converter with free wheeling diode is shown below.

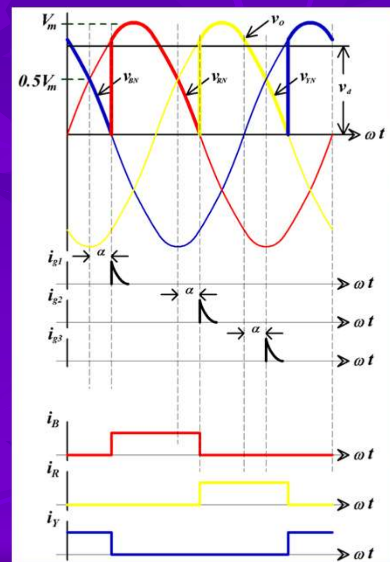




3-Phase Controlled Converters

Fully Controlled 3-pulse converter





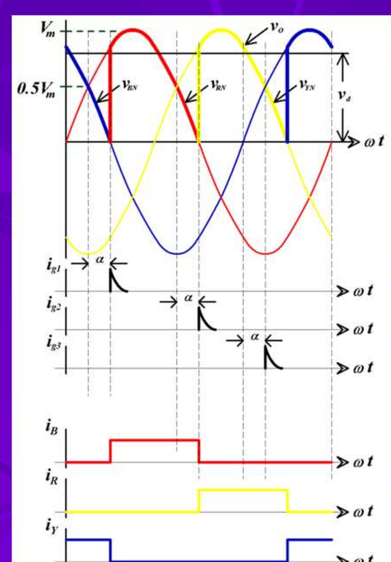
The diodes are replaced with SCRs. The SCR's are fired after a delay angle of ***α***.

Fully Controlled 3-pulse converter

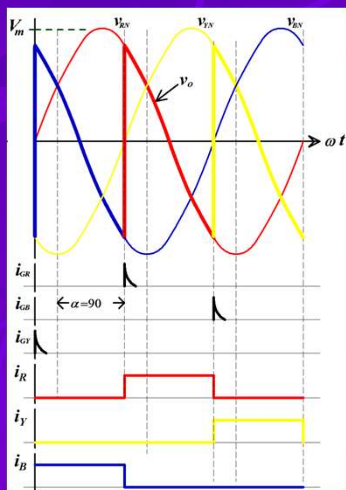
- The SCR will not take up conduction until turned on by the gate pulse, thereby allowing the previous phase voltage to continue at the load.
- This gives an overall lower mean load voltage compared to uncontrolled converter.
- The ripple is increased but still have three pulses per cycle.
- The mean load voltage is

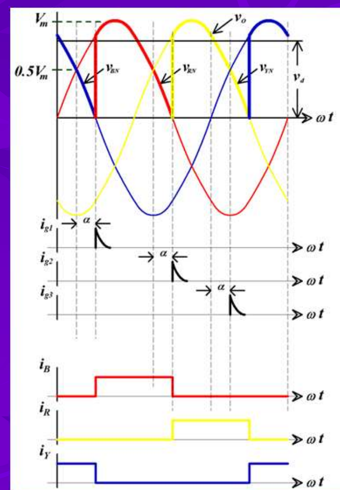
$$V_{mean} = \frac{1}{2\pi/3}\int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} V_s \sin\theta d\theta \qquad (7)$$

$$V_{mean} = \frac{3\sqrt{3}}{2\pi} V_s \cos\alpha \qquad (8)$$



Fully Controlled 3-pulse converter

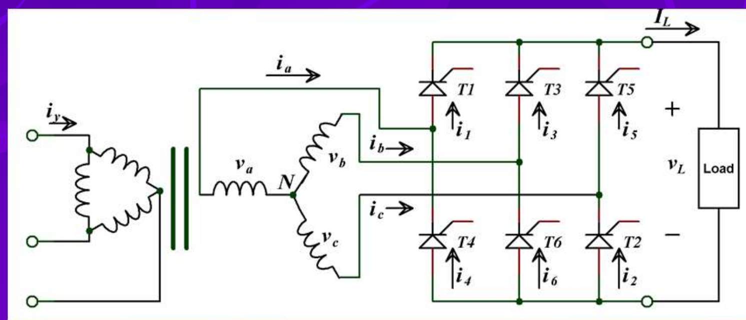




Fully Controlled 3-pulse converter

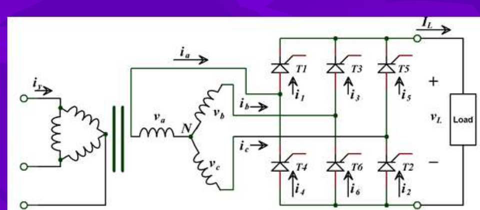
- The range of α is form zero to $2\pi/3$ radians (90^o).
- The mean load voltage is proportional to the cosine of α as in 2 pulse controlled converter.
- The output voltage will be positive for α from zero to 90^o.
- The output will be zero for α equal to 90^o.
- The output voltage is negative for $120^o > \alpha > 90^o$.

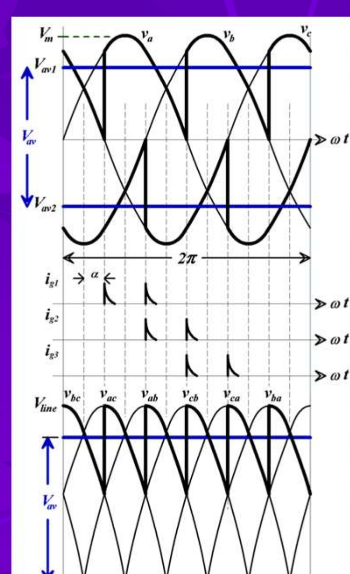
Fully Controlled 6-pulse Converter



- Fully controlled 6-pulse AC/DC converter is shown in the above diagram.
- It uses 6 SCRs connected in bridge configuration.
- The output voltage waveform will have six pulses in one cycle.

6-pulse Converter Waveforms





6-pulse Converter Waveforms

- Two 3-pulse waveforms add to give the 6-pulse load voltage waveform.
- Phase current have positive step pulse as will as negative step pulse of 120° flat top, same as diode converter.
- The current pulse is delayed by the firing angle α as compared to diode converter.

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6-pulse Converter Waveforms

- Therefore, the displacement factor will be $\cos\alpha$. i.e. decreases with firing angle α.
- There is a starting problem with this circuit.
- In order to start the circuit, two SCRs must be fired at the same time.
- If the supply is connected at an instant when V_a is at its peak, the next pulse will be to T_2.

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6-pulse Converter Starting

- However, T_2 will not conduct unless T_1 is also fired at the same time.
- Hence for starting purpose, the firing circuit must produce a firing pulse 60^o after its first pulse.
- Once the circuit is running, the second pulse have no effect, as the SCR is already on.
- The firing angle α is measured from the crossing points of the input voltage waveforms.

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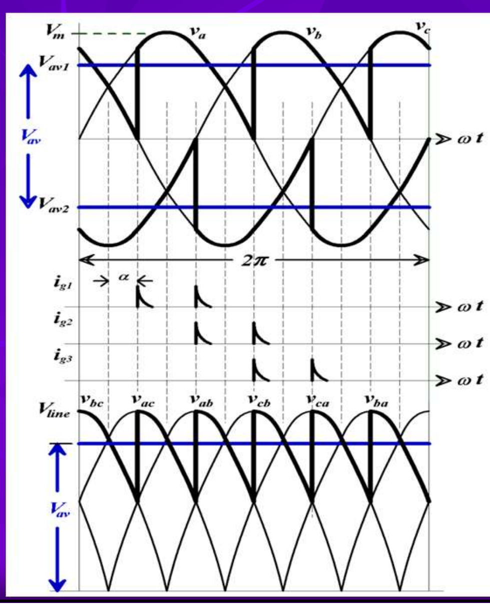
6-pulse Converter Starting



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6-pulse Converter V_{mean}

$$V_{mean} = \frac{6}{2\pi} \int_{\frac{\pi}{3}+\alpha}^{\frac{\pi}{3}+\alpha} V_{m(line)} \sin\theta d\theta \qquad (9)$$

$$V_{mean} = \frac{3}{\pi} V_{m(line)} \cos\alpha \qquad (10)$$

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Half Controlled Bridge Converter

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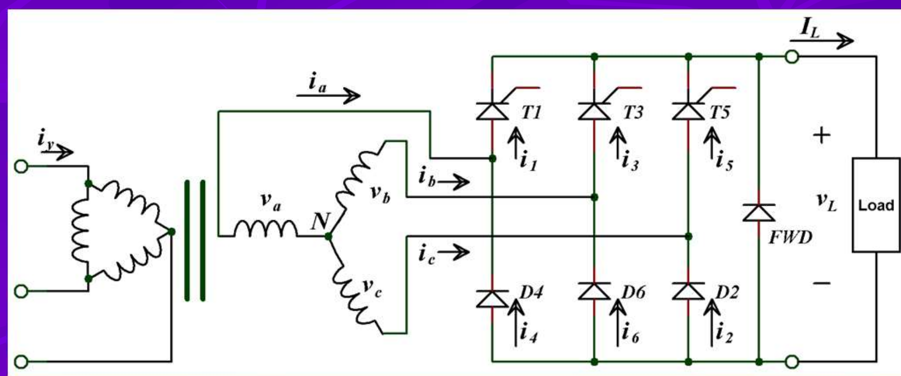
Half Controlled Bridge Converter



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Half Controlled Bridge Converter

- The lower 3 SCRs can be replaced with diodes to realized the Half controlled Bridge.
- The free-wheeling current path is through the lower diode and the conducting SCR.
- However, additional free wheeling diode is usually used to improve the blocking state of SCR.

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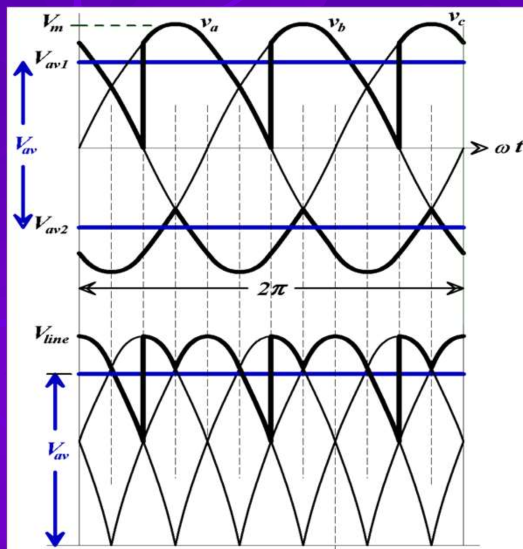
Waveforms



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Waveforms

- The voltage waveform has 3-pulses with higher harmonic ripple than fully controlled converter.
- As the firing delay angle is above 60^o making the upper waveform more negative than positive, the load voltage has periods of zero voltage.
- The commutation diode taking the free-wheeling load current in preference to the series arm.
- The zero mean load voltage is reached when firing angle is 180^o.

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Half Controlled Bridge Converter

- 3-phase half controlled converter is cheaper than fully controlled converter.
- There is no starting problem in half controlled converter.
- The output is 3-pulse per cycle therefore high harmonics in voltage waveforms.

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Half Controlled Bridge Converter

- Single quadrant operation only the output load voltage is always positive.
- The range of ***α*** is from zero to 180°.

$$V_{mean} = \frac{3\sqrt{3}}{2\pi} V_m (1 + \cos\alpha) \quad (11)$$

$$V_{mean} = \frac{3}{2\pi} V_{m(line)} (1 + \cos\alpha) \quad (12)$$

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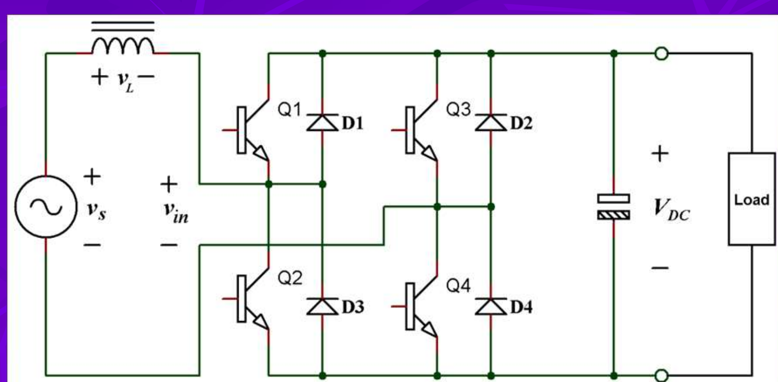
PWM
AC/DC Converters

PWM AC to DC Converter



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PWM AC to DC Converter

- It is called a PWM converter because the pulse width of switch driving signals are varied according to the value of the modulating wave.
- PWM techniques were initially introduced in communication but now these techniques are extensively used in power electronics due to the availability of high power high switching frequency efficient devices.

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PWM AC to DC Converter

PWM vs Phase Controlled Converter

- *Good harmonic performance.*
- *Ability to draw current at unity power factor.*
- *The PWM converter circuit was evolved from PWM inverter topology.*

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PWM AC to DC Converter

- PWM AC to DC converter was first proposed for German Railway (1974).
- PWM converters are used in applications which fall into the middle power range(1KW to 2MW)
  - *Variable speed drives for fans and pumps.*
  - *Small distribution systems with DC backups: ships, aircrafts, electric cars.*
  - *Traction drives.*

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PWM Converter Operation

To understand the operation-note following:

- V_s is a sinusoidal supply voltage.
- Supply inductor is used to minimize current ripple. It is essential for successful operation.
- Four BJTs (or IGBTs, GTOs, etc) each with ant parallel diode are used as a bridge.
- The V_{in} is defined as voltage just after source inductor.
- Capacitor is used as a filter and energy storing reservoir.

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PWM Converter Operation

- The circuit can be thought of as an ordinary diode bridge, with anti-parallel switches added so that V_{in} can be chopped.
- This in turn requires the supply inductor to support the voltage difference between V_{in} and Vs.
- The converter is capable to transmit power in both direction. i. e. AC to DC (rectifying) or DC to AC (inverting).
- The converter can operate in all the four quadrants of Is and V_s.
- V_{in} can take two values $+V_{DC}$ and $-V_{DC}$.
- It is also possible to get V_{in} Zero.

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Modes of Operation

- The converter is capable to transmit power in both direction:
  - *AC to DC*
  - *DC to AC*
- The converter can operate in all the four quadrants of I_s-V_s plan.
- V_{in} can take two values V_{DC} and $-V_{DC}$.
- It is also possible to get $V_{in} = 0$ if devices 1&3 are 'on' or devices 2&4 are 'on'.

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Four Quadrant Operation

Quadrant	Vs	Is	Power Flow	Vin	Conducting Device
1	>0	>0	Rectifying	$+V_{DC}$	D1&D4
2	>0	<0	Inverting	$+V_{DC}$	T1&DT
3	<0	<0	Rectifying	$-V_{DC}$	D2&D3
4	<0	>0	Inverting	$-V_{DC}$	T2&T3

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Phasor Analysis

- We have seen that V_{in} can take three values, ***Zero***, $+V_{DC}$, $-V_{DC}$.
- If V_{in} is PWM sinusoidal waveform.
- The switching is arranged so that the fundamental of V_{in} has the same frequency as V_s.
- Then the current I_s is also close to fundamental frequency compared with small harmonics.

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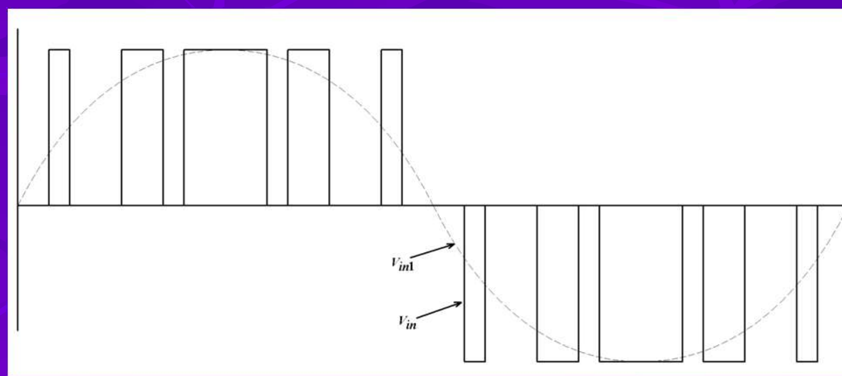
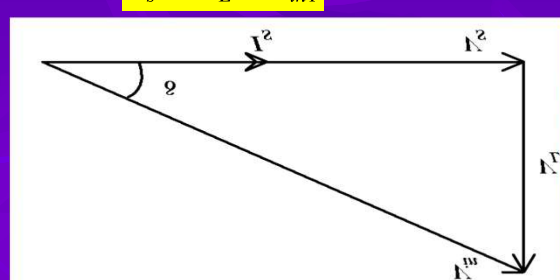
Phasor Analysis



Phasor Analysis

The input circuit can be modeled at fundamental frequency. The phasor diagram can be used to analyze the circuit.

$$\vec{V}_s = \vec{V}_L + \vec{V}_{in1} \qquad (1)$$



It is assumed that V_s and I_s are in-phase V_{in} lags V_s by an angle *'δ'*.

Phasor Analysis

$$Power = V_s I_s \quad (2)$$

$$V_L = XI_s = V_{in}\sin\delta \quad (3)$$

$$I_s = \frac{V_{in}\sin\delta}{X} \quad (4)$$

$$Power = \frac{V_s V_{in}}{X}\sin\delta \quad (5)$$

Where 'δ' is known as the Power Angle.

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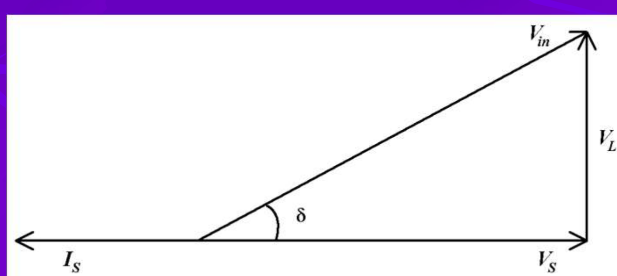
Phasor Analysis

- If V_{in} lags V_s then the power flow is from AC to DC. i.e. Rectifying mode.
- If V_{in} leads V_s then the power flow is reversed. i.e. Inverting mode, as shown below.



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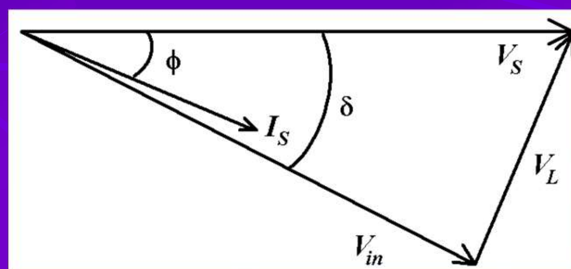
Leading & Lagging PF

- Earlier examples are for Unity Power Factor.
- However, this converter can be operated at lagging or leading power factor by changing the magnitude of V_{in} and retaining the power angle 'δ'.



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Thank you

For your attention

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DC to AC Converters

Dr. Tahir Izhar

DC to AC Converter

- DC to AC converter is a circuit that converter DC power into AC power.
- If the power flow is only in one direction the converter is operating as an inverter.
- However, it is possible to operate the converter in two or four quadrants.

2

Inverter Waveforms

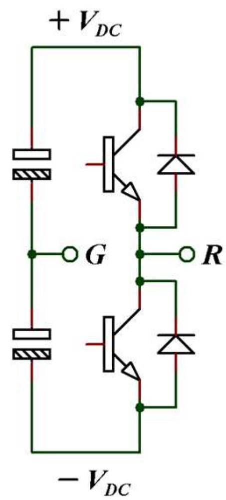
- The output voltage waveforms of inverters are seldom ideal.
- The ideal waveform is usually a sinusoidal because it ensures constant and continuous flow of power.
- The actual inverter waveforms are more commonly, square, quasi-square, PWM or some other train of pulses.

Inverter Waveforms

- The behavior of the power system can easily be understood if waveforms are represented in terms of ideal sinusoidal fundamental component at power frequency, plus a series of harmonics.

Inverter Building Block

- The power semiconductor building block for inverter is referred as inverter leg.
- Two switching devices are connected in series across the DC power supply as shown.



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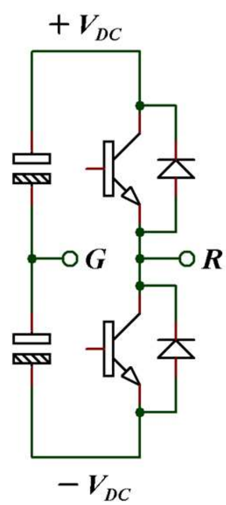
Inverter Building Block

- Two anti-parallel diodes are connected across the semiconductor switching devices.
- The output terminal ***R*** can be connected to the positive or negative rail by switching ***on*** either the upper or lower device.



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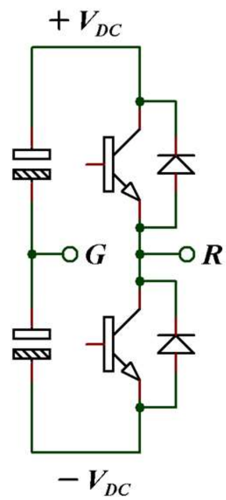
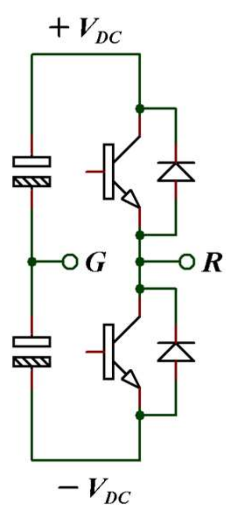
Inverter Building Block

- It is a four quadrant switch due to the bidirectional current capability.
- For low power, 1-phase applications, a mid point ***G*** is provided by means of two capacitors and the load is connected between ***R*** and ***G***.

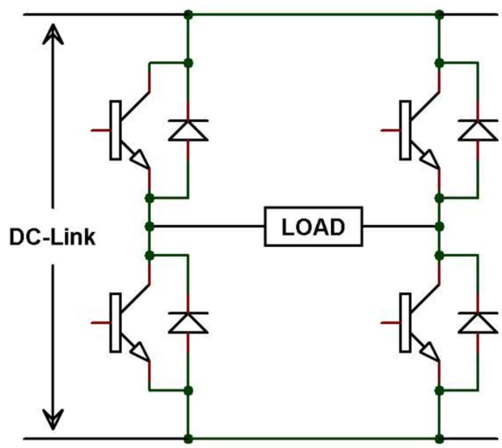


Inverter Building Block

- This circuit is known as half bridge inverter.
- For high power single phase or poly phase applications, more than one inverter leg is used.



H-Bridge Inverter



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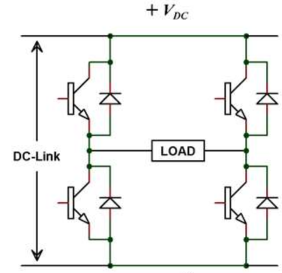
H-Bridge Inverter

- In single phase full bridge configuration, two inverter legs are used and the load is connected across the middle points of the series connected switches.



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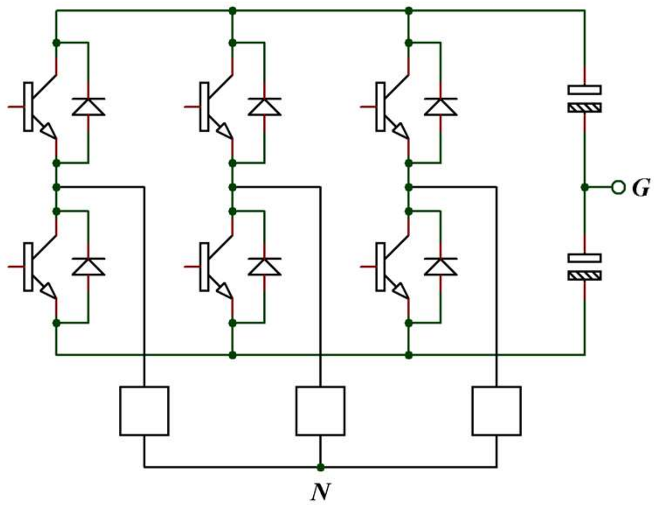
3-Phase Inverter Bridge

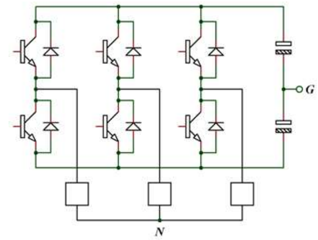
For three phase inverter, three inverter legs are used.



3-Phase Inverter Bridge

- For most high power multi-leg inverter, the point ***G*** is not a physical point but only a notational point of reference.
- The waveforms at output points of inverter legs w.r.t. point ***G*** are known as ***pole*** waveforms.
- ***Pole*** waveforms are different form load voltage waveforms.

3-Phase Inverter Bridge



- The most common application of ***DC/AC*** inverter is to drive AC motors at variable speed i.e. ***VFDs***.
- ***VFDs*** can be used for: Traction, Pumps, Compressors, Servo, wire-draw lines, Steel re-rolling, paper-rolling, conveyor drive, textile, and machine tools.

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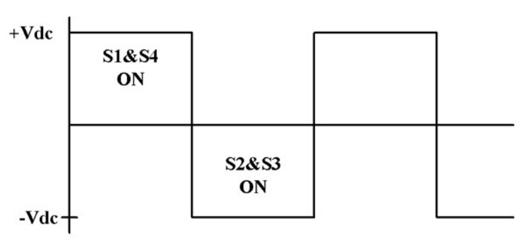
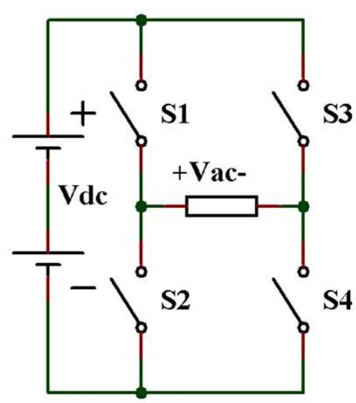
Analysis of Basic H-Bridge





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Analysis of Basic H-Bridge

- When diagonal switches open and closes simultaneously, the ac voltage is produced across the load resistor.
- The output AC is a square wave consisting of fundamental component plus harmonics.

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Analysis of Basic H-Bridge

- Sometimes a variable AC output is required form the inverter.
- The amplitude of the fundamental component can be controlled by changing the input DC voltage source.
- This scheme requires a complicated system consisting of phase controlled AC/DC converter or switch-mode DC/DC converter.

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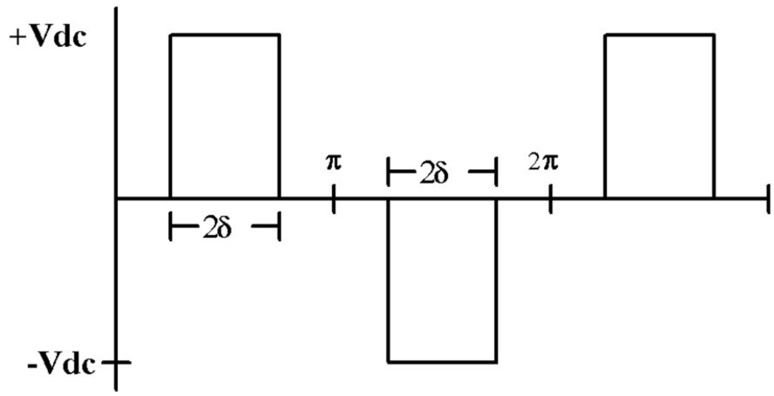
Analysis of Basic H-Bridge

- The output amplitude of fundamental can also be changed by changing the pulse.



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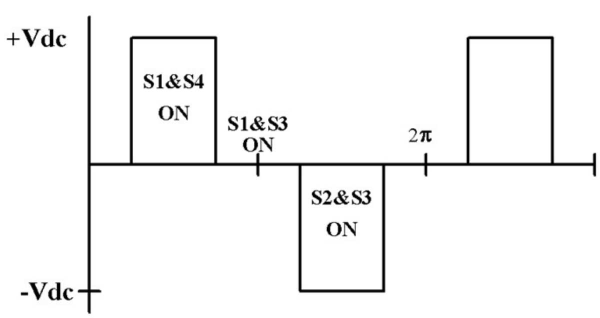
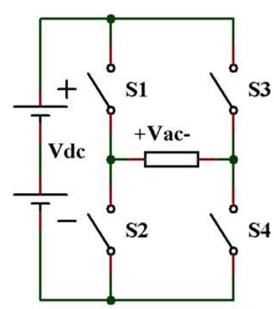
Analysis of Basic H-Bridge





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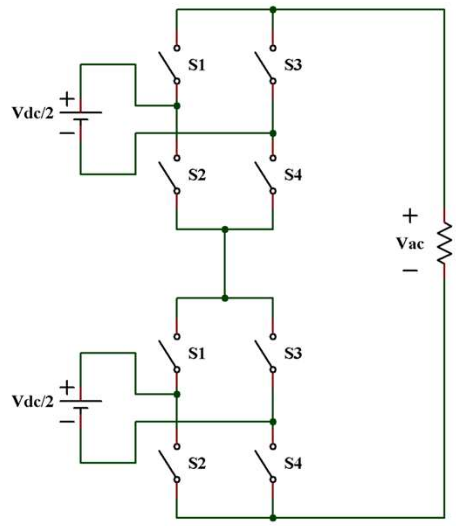
Analysis of Basic H-Bridge

- We can see that the amplitude of fundamental component decreases as the pulse width decreases.
- However, the percentage harmonics increases as the pulse width decreases.

Analysis of Basic H-Bridge

- This type of inverter is known as tri-state inverter because the output can be ***+V_{DC}***, ***-V_{DC}***, or ***Zero***.
- The third state can be obtained either by closing the upper two switches or lower two switches of the H-Bridge.

Harmonic Cancellation



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Harmonic Cancellation

- If two square waves having a phase shift of 60^o are added, the resulting wave is a quasi-square wave.
- The triplen harmonics are absent from the spectrum of quasi-square wave.
- This can be achieved practically by connecting two inverter bridges in series.

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Harmonic Cancellation

- Cancellation of 3rd and 5th harmonics simultaneously is possible by operating the bridges in tri-state.
- 7th and 11th harmonics can be cancelled by using four bridges in series.
- However, generation of stepped voltage waveform requires complex power circuit with large number of power switching devices.

Harmonic Cancellation

- The overall cost increases due to increased number of switching devices and their associated drive circuitry.
- However, cheap low voltage low frequency power semiconductor devices can be employed.

Harmonic Cancellation

- Pulse Width Modulation Technique can also be used to generate near sinusoidal voltage waveform.
- In PWM inverter, the number of switches are minimum but they are operated at high switching frequencies.

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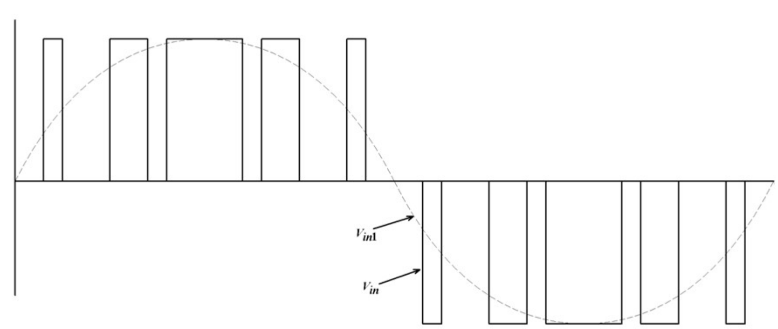
Pulse Width Modulation PWM

- In voltage source inverters, the sinusoidal output can also be produced through PWM.



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Modulation Strategies in PWM

- The PWM strategies can be classified as :
  - **Natural Sampling**
  - **Regular Sampling**
  - **Optimized PWM**
  - **Space Vector Modulation**

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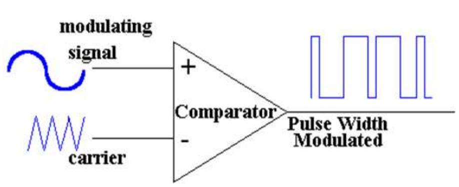
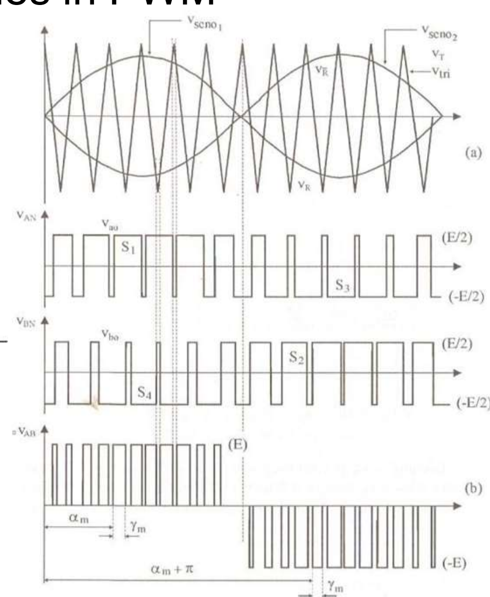
Modulation Strategies in PWM

Natural Sampling:
widely used with analog electronics.

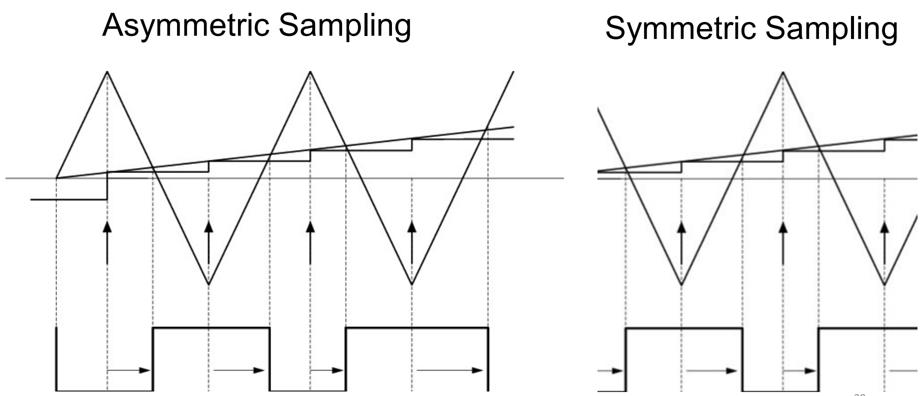




Modulation Strategies in PWM

Regular Sampling:

simplified version of PWM that gives easier implementation when micro-controllers are used.



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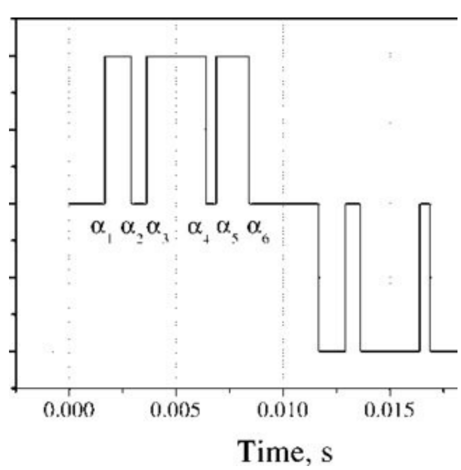
Modulation Strategies in PWM

Optimized PWM:

based on minimization of certain performance criteria. Example is Selective harmonic reduction.



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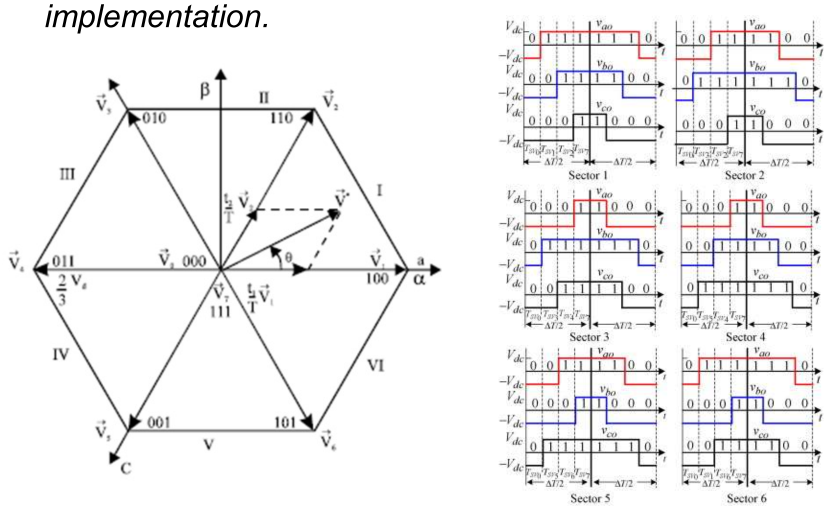
Modulation Strategies in PWM

Space Vector Modulation:

another simplified technique ideal for micro processor implementation.



Thank you

For your attention

Overlap in Rectifiers

Dr. Tahir Izhar

Overlap

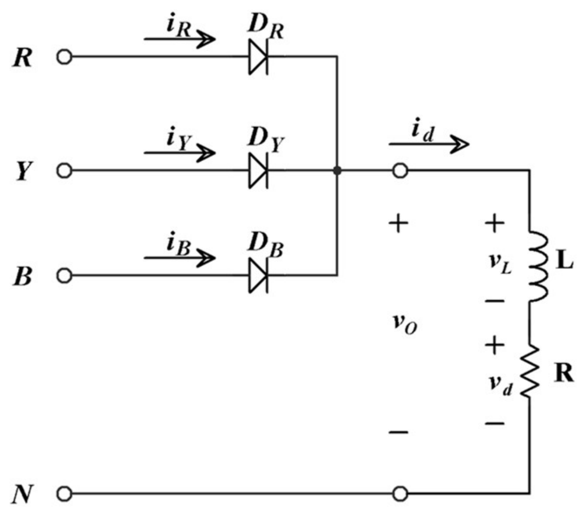
Introduction

❖Source impedance on rectifier characteristics.

❖The half wave three phase rectifier is considered to explain the effect.

❖Not a practical circuit, but convenient to use it as a vehicle to explain the ***"overlap" .***

Ideal 3-Pulse Converter

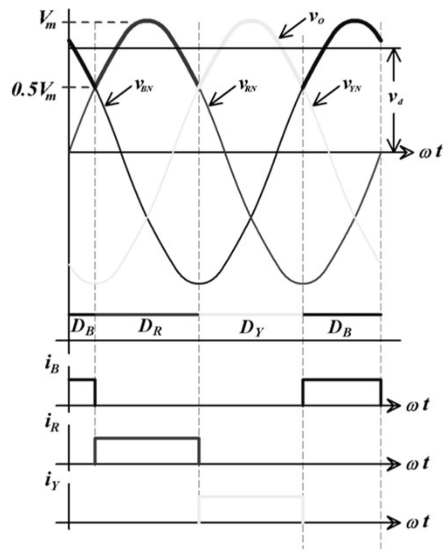


Overlap

Introduction

- ❖Let us review the ideal behavior of this circuit
- ❖If the load inductance is infinite, the load current will be constant.
- ❖Without source impedance, the current commutation is instantaneous.

Ideal 3-Pulse Converter



Overlap

Introduction

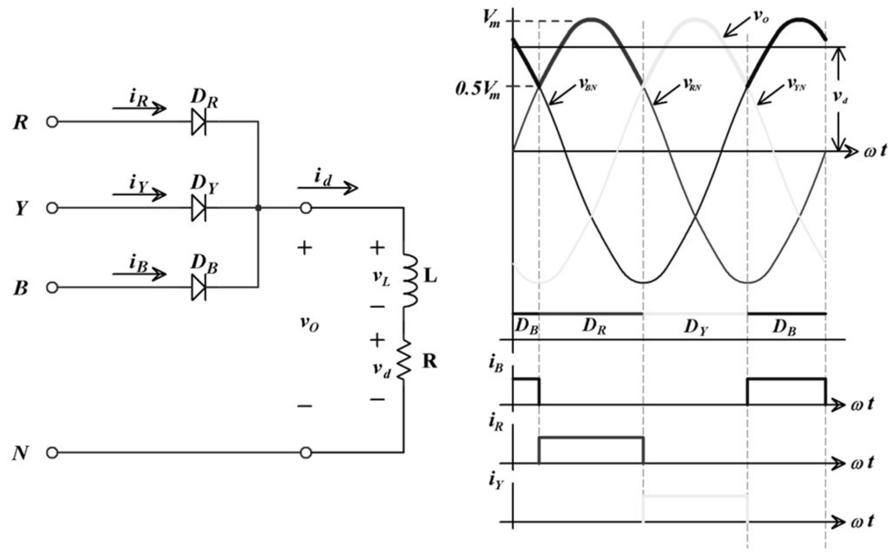
❖The diode with the highest anode voltage will conduct.

❖The three diodes conduct for 120^O each.

❖The load current is constant and contributed by each diode of 120^O duration.

❖The current in three phases starts and stops instantaneously.

Ideal 3-Pulse Converter



Overlap

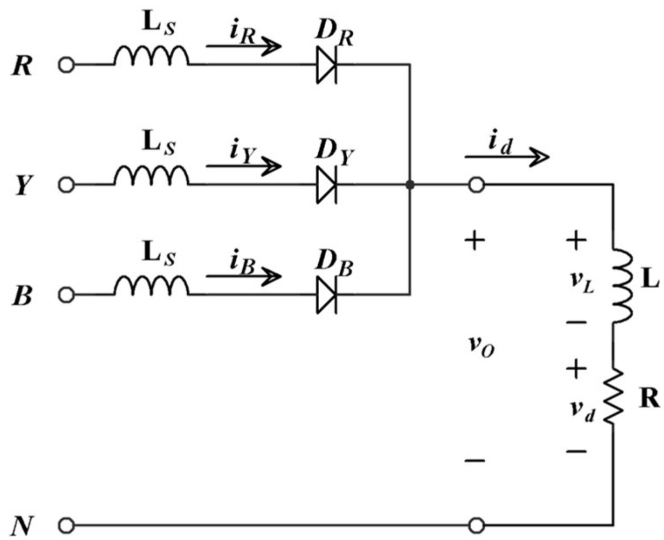
Introduction

❖In practice, the source have some impedance

❖So time is required for the currents to change.

❖The major contributor of this impedance is leakage inductances of the transformer.

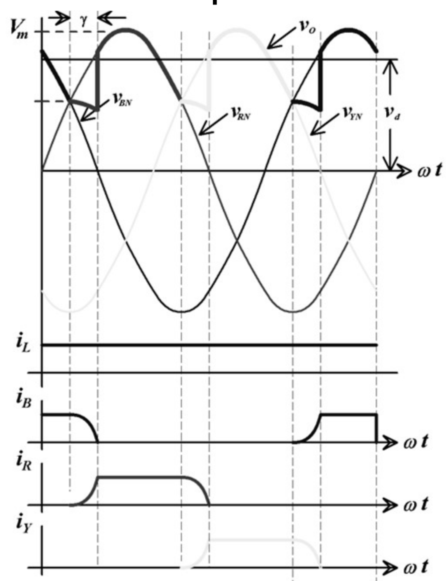
Effect of Source Impedance



Effect of Source Impedance

- Consider the circuit with supply inductance.
- The phase currents $\boldsymbol{i_R}$, $\boldsymbol{i_Y}$ and $\boldsymbol{i_B}$ can no longer start and stop instantaneously.
- But volt-second will be absorbed in establishing and extinguishing the phase currents in $\boldsymbol{L_s}$.

Effect of Source Impedance



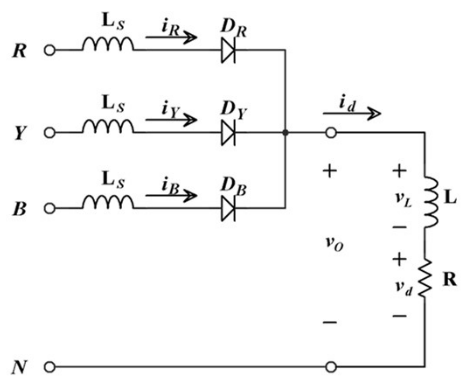
Effect of Source Impedance

This effect modifies the rectifier behavior in two significant ways:

- ❖ *The mean output voltage,* ***V_d*** *is reduced and the harmonic components of* ***V_o*** *are modified.*
- ❖ *The harmonic components in supply current waveform are modified, mainly by the attenuation of the higher frequency components.*

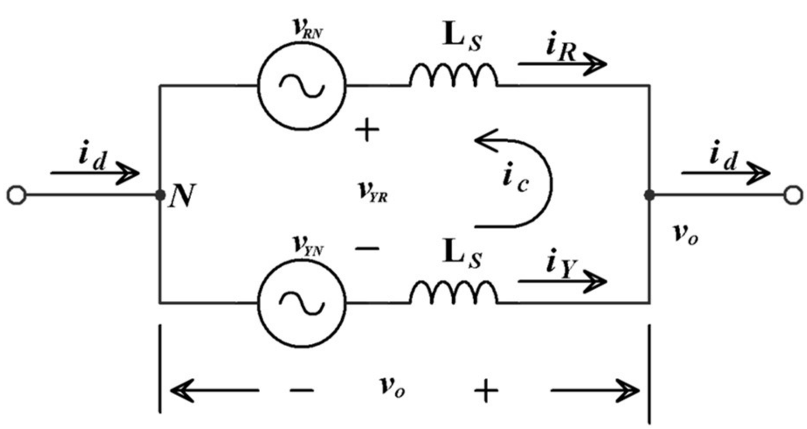
Overlap Analysis

- Consider commutation from D_R to D_Y which will be initiated as V_{YN} exceeds V_{RN}. at time t_0.
- This is the time when line voltage, V_{YR} is passing through zero to become positive.

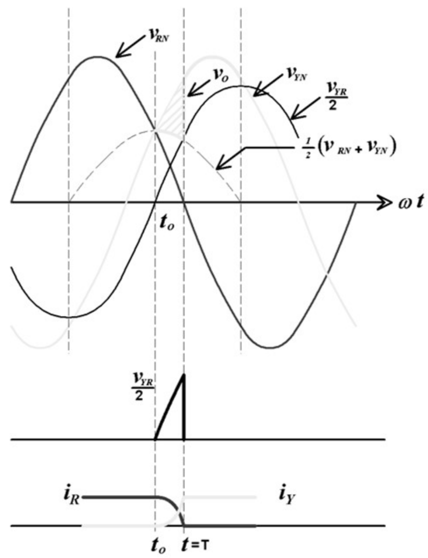


Overlap Analysis

- To analyze the commutation events, the equivalent circuit is shown below.

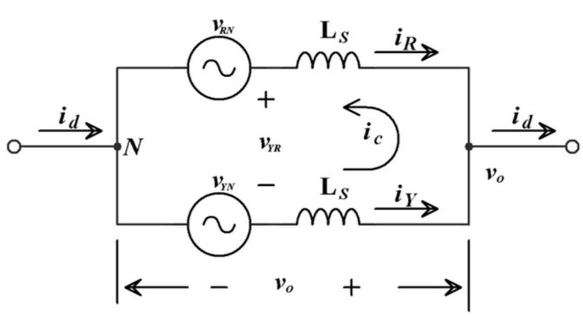


Overlap Analysis



Overlap Analysis

- The voltage V_{YR} drives the circulating current, i_C in the direction shown.
- When i_C reaches the value I_d, i_R will become zero and D_R is extinguished and i_Y has become equal to I_d and has taken over the conduction.



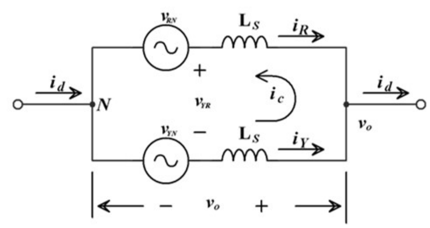
Overlap Analysis

- The period when both diodes are conducting is the *'overlap'*.
- It should be noted that

$$i_R + i_Y = I_d \quad (1)$$

$\therefore$

$$\frac{di_R}{dt} = -\frac{di_Y}{dt} \quad (2)$$



Overlap Analysis

The equation governing the equivalent Circuit with assumed sign convention is

$$v_{YR} = 2L_S \frac{di_C}{dt} \quad (3)$$

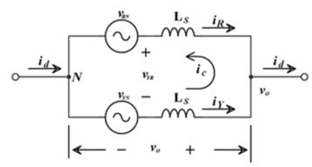
Overlap Analysis

$$L_S \frac{di_C}{dt} = \frac{v_{YR}}{2} \qquad \textbf{(4)}$$

Consequently $\boldsymbol{v_{YR}}$ is responsible for supplying the volt-seconds which change the current in $\boldsymbol{L_S}$.

Furthermore during the overlap time the output voltage, $\boldsymbol{v_o}$ of the rectifier is:

$$v_o = v_{YN} - \frac{v_{YR}}{2}$$

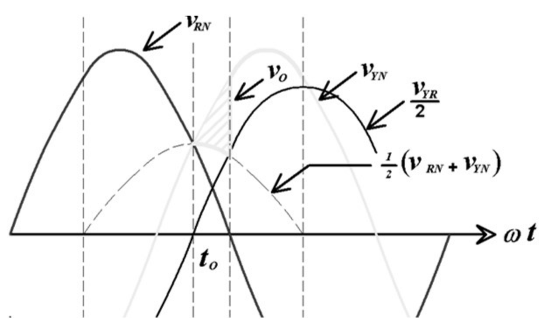


Where $\boldsymbol{v_{YR}/2}$ is the inductance $\boldsymbol{L_S}$ drop as can be seen from the equivalent circuit during overlap.

Overlap Analysis

$$v_o = v_{YN} - \left(\frac{v_{YN}}{2} - \frac{v_{RN}}{2} \right)$$

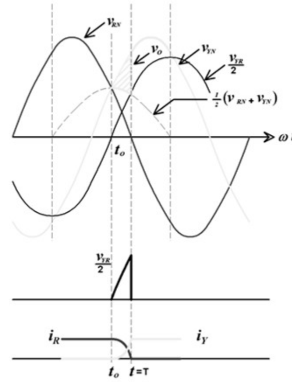
$$v_o = v_{YN} - \frac{v_{YN}}{2} + \frac{v_{RN}}{2}$$



$$v_o = \frac{1}{2}\left(v_{RN} + v_{YN}\right) \qquad \textbf{(5)}$$

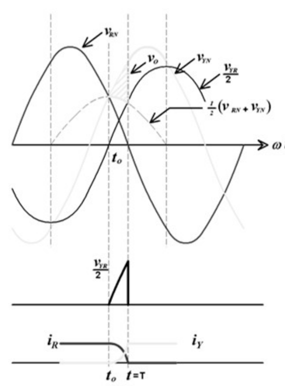
Overlap Analysis

- Hence v_o is the instantaneous average of the red and yellow phase voltages as shown above and not the yellow phase voltage for the ideal case when $L_S=0$.
- Thus for the period up until t_0, the output voltage 'v_o' has been equal to v_{RN}.
- From t_0 onwards, v_o becomes $1/2(v_{RN}+v_{YN})$ until conduction has been transferred from red to yellow phase.



Overlap Analysis

- After conduction transfer, v_o will become v_{YN} as before.
- Analytical expressions for the instantaneous phase currents during overlap can be derived from equation (4) because $i_Y = i_C$ during this time.
- i_Y is initially zero, and rises according to i_C when overlap starts.



Overlap Analysis

$$\therefore i_Y = \frac{1}{2L_S}\int_0^t v_{YR}\,dt$$ **(6)**

From equation (4) it can be seen that as t=0 at ***t_0***

$$i_{YR} = \sqrt{3}v_{RN}\sin\omega t$$ **(7)**

$$i_Y = \frac{\sqrt{3}v_{RN}}{2\omega L_S}\left(1-\cos\omega t\right)$$ **(8)**

Overlap Analysis

As from equation (1)

$$i_R + i_Y = I_d$$

$$i_R = I_d - i_Y$$

$$i_R = I_d - \frac{\sqrt{3}v_{RN}}{2\omega L_S}\left(1-\cos\omega t\right)$$ **(9)**

Equation (8) and (9) define the instantaneous currents during the overlap time

Overlap Analysis

- These sinusoidal transitions replace the instantaneous switching from one diode to another that take place with zero source impedance.
- The shape of $\boldsymbol{V_O}$ is shown in the diagram. It follow $\boldsymbol{V_{RN}}$ up to $\boldsymbol{t_0}$, then follow $\boldsymbol{\frac{1}{2}(v_{RN} + v_{YN})}$ during overlap and then recovered to $\boldsymbol{v_{YN}}$ when $\boldsymbol{t = T}$.
- The duration of the overlap can be derived from equation (8), because overlap finishes when $\boldsymbol{i_Y = I_d}$

Overlap Analysis

Hence

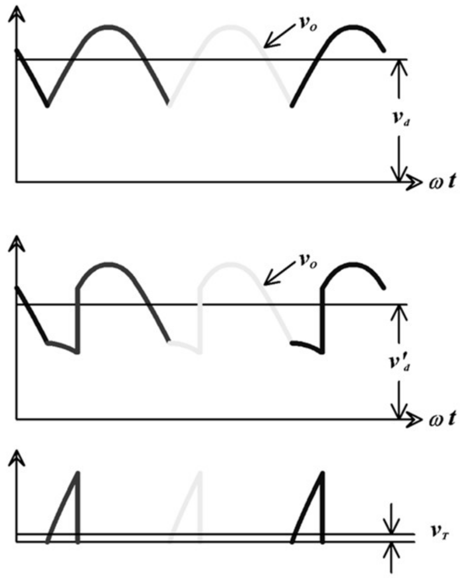
$$I_d = \frac{\sqrt{3}v_{RN}}{2\omega L_S}(1 - \cos\omega T)$$

Therefore

$$T = \frac{1}{\omega}\cos^{-1}\left\{\left(1 - \frac{2\omega L_S I_d}{\sqrt{3}v_{RN}}\right)\right\} \qquad \textbf{(10)}$$

Equation (10) is not a simple expression, but nevertheless allows '***T***' to be calculated. The average output voltage, $\boldsymbol{V_d}$ is reduced because of the volt-second shown shaded in the Figure.

Overlap Analysis



Overlap Analysis

- That volt-second is absorbed across the source impedance each time current commutates from one phase to another.
- The output voltage reduction due to overlap can be estimated form the waveform shown.

$$V'_d = V_d - V_T \qquad (11)$$

Where V'_d is actual voltage, V_d is ideal voltage and V_T is the loss of voltage due to overlap.

Overlap Analysis

The volt-seconds needed to change the current in the yellow phase inductance L_S , from 0 to I_d is clearly $L_S I_d$.

Hence

$$V_T = \frac{3L_S I_d}{T} \qquad \textbf{(12)}$$

Where the factor 3 is included because there are three overlap events in each period of Mains cycle, T.

$$T = \frac{1}{f} = \frac{2\pi}{\omega} \qquad \textbf{(13)}$$

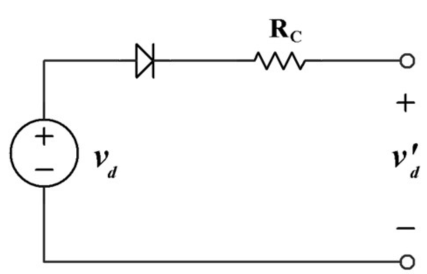
$$V_T = \frac{3\omega L_S}{2\pi} I_d \qquad \textbf{(14)}$$

Overlap Analysis

Finally, putting values in equation (4) gives

$$V_d' = \frac{3\sqrt{3}}{2\pi} v_{RN} - \frac{3\omega L_S}{2\pi} I_d \qquad \textbf{(15)}$$

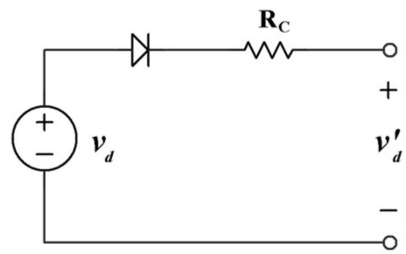
Equation (15) suggest an equivalent circuit as shown



Overlap Analysis

The half bridge rectifier is viewed as a DC source of value

$$V_d = \frac{3\sqrt{3}}{2\pi} v_{RN} \quad \textbf{(16)}$$



With in internal source resistance of

$$R_C = \frac{3\omega L_S}{2\pi} \quad \textbf{(17)}$$

It should be noted that there is not loss associated with ***R_C***.
This model only applies when the overlap condition prevails.

Summary

- ❖In this lecture, the effect of source impedance on the performance of the rectifier circuit is investigated.
- ❖The inductive reactance of the ac supply is normally much greater than its resistance.
- ❖Due to the source inductance, time is required to change the current resulting a delay in current commutation.

Summary

- Three pulse half bridge circuit with source inductance is used to explain the phenomenon of overlap.
- Once the overlap phenomenon is understood, it can be applied to other practical converter circuits.

Thank you

For your attention

DC to DC Converters

Dr. Tahir Izhar

Basic DC-DC converters

- Basic DC-DC converter topologies
  - Buck converter
  - Boost Converter
  - Buck/Boost converter

Basic DC-DC converters

Each converter is realized by using:

- Transistor Switch,
- Diode,
- Inductor,
- Capacitor
- Load resistor.

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Buck Converter Topology

- The most common topology.
- Basic of many switch mode power supplies.
- Ranging from 10's of watts to MW level.
- The operating frequencies 25KHz to 500kHz.

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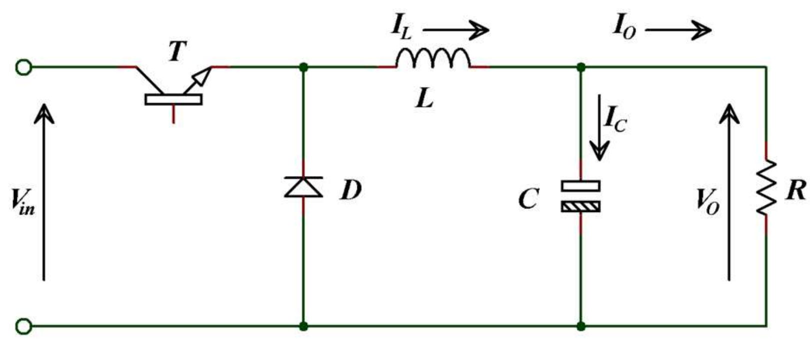
Basic Circuit of Buck Converter



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Modes of Operations

Two Mode of operation;

- Continuous mode
- Discontinuous mode.

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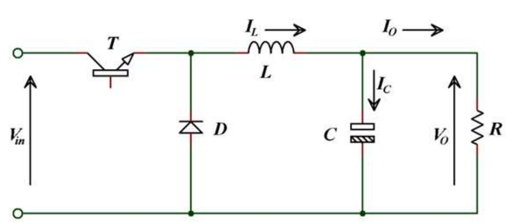
Modes of Operations

- ***Continuous mode;***
  - the inductor current flows all the time continuously.
- *Discontinuous mode;*
  - the inductor current does not flow continuously.
  - time intervals with zero indictor current.

Preferably operated in Continuous mode.

Continuous mode Operation

- When the transistor is turned on, the diode is reverse biased and a voltage (Vin-Vo) is applied across the inductor.
- The inductor current lineally rise.



Continuous mode Operation

$$L\frac{di}{dt}=V_L$$ (1)

$$\frac{di}{dt}=\frac{V_L}{L}$$ (2)

$$Rate=\frac{V_L}{L}=\left(\frac{V_{in}-V_O}{L}\right)$$ (3)

Operation

- When the transistor is switched off the inductor current is diverted to diode.
- A reverse voltage 'V_O' appears across the inductor causing a linear decrease in current with a rate $-V_O/L$.
- The output ripple is assumed to be zero, the load ripple current is zero.
- The inductor ripple current flows through the capacitor.

Operation

- The average DC current of the inductor flows into the load.
- The peak to peak ripple current, which is equal to peak to peak capacitor ripple current is given by

$$\Delta I = \left(\frac{V_O (1 - D) T}{L} \right) \qquad (4)$$

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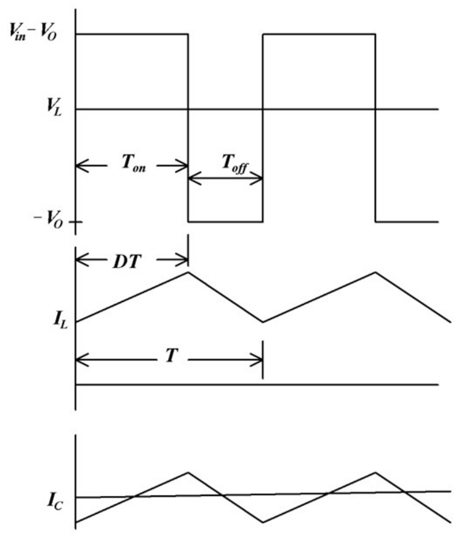
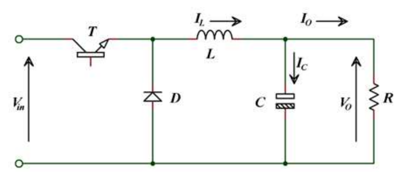
Waveforms





$$\left(\frac{T_{on}}{T} \right) = D \qquad (5)$$

$$T_{on} = DT \qquad (6)$$

Range of *'D'* is

$$D = 0 \rightarrow 1 \qquad (7)$$

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Conversion Ratio

- The input to output voltage conversion ratio of the converter can be obtained by equation the positive and negative volt-seconds impressed across the inductor over one switching cycle.
- Under steady state condition, there is no net volt-second across the inductor over a switching period since the inductor current at the beginning and end of the period must be equal.

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Conversion Ratio

Therefore

$$(V_{in} - V_O)DT = V_O(1 - D)T \qquad (8)$$

$$\left(\frac{V_{in}}{V_O}\right) - 1 = \frac{1 - D}{D} \qquad (9)$$

$$V_O = V_{in}D \qquad (10)$$

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Conclusions

- The output voltage may be controlled by the duty-ratio D but can not be larger than the input voltage.
- The voltage conversion ratio depends solely on duty-ratio and is independent of load conditions.
- The capacitor ripple current is independent of load current.
- The off-state voltage stress across the device is V_{in}.
- The value of rms current in the components can be obtained from the idealized waveform.

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Boost Converter

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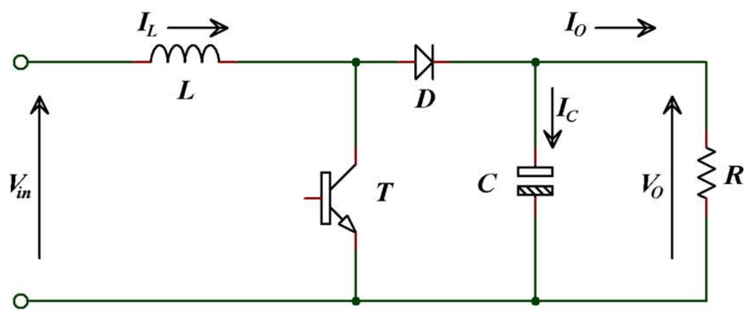
Boost Converter



- The power circuit diagram of a boost converter is shown above.
- It can be compared with buck converter.
- It uses the same components but the arrangement is changed.

Operation

- The boost converter is preferably operated in discontinuous mode due to control issues.
- In discontinuous mode, the inductor current falls to zero and remain at zero until the transistor is switched 'on' again.
- When the transistor is turned on, the input DC supply is connected across the inductor, the current rises linearly from zero.
- During T_{on} the input DC source can not supply the power to the output.
- The output power is drawn from the stored energy in the capacitor.

Operation

- During Ton the diode is reverse biased and the inductor stores energy from the supply.
- When the transistor is turned off, the inductor behaves as a source in series with the input voltage, the diode is forward biased, and the capacitor is charged to a voltage higher than the input DC voltage. Hence the output voltage is always larger than the input voltage.
- All the stored energy in the inductor is transferred to the capacitor.
- The current linearly ramps down to zero during T_{off}.
- During T_{off}, Input source and inductor provide the power to the load and the charge to the capacitor.

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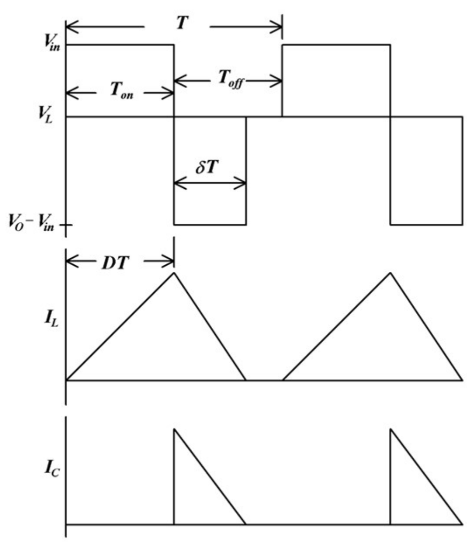
Waveforms



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Conversion Ratio

The voltage conversion ratio can be obtained by equating the input and output power

$$\frac{V_{in}^{2} D(D+\delta)T}{2L} = \frac{V_O}{R} \qquad \text{(11)}$$

By inductor volt-second balance

$$V_{in} D = (V_O - V_{in})\delta \qquad \text{(12)}$$

$$\frac{V_O}{V_{in}} = \frac{1+\sqrt{1+4D^2/k}}{2} \qquad \text{(13)}$$

Where $$k = \frac{2L}{RT} \qquad \text{(14)}$$

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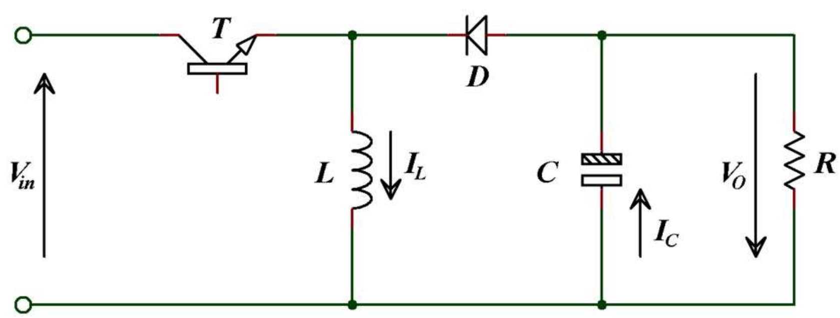
Buck-Boost Converter



- The above circuit show the connections of Buck boost converter which is also know as polarity inverting converter.

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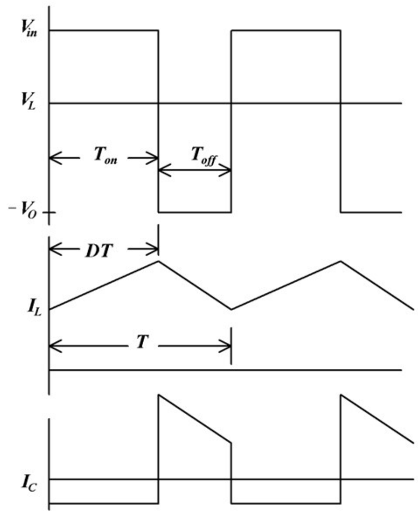
Waveforms



- In contrast to the buck and boost converter, the output polarity in this converter is inverted.
- This converter is also known as polarity inverting converter.

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Operation

- When the transistor is on the input DC voltage is applied across the inductor.
- This causes a linear rise in current with a rate of Vin/L.
- The diode is reverse biased.
- The load current is entirely supplied by the output capacitor.
- When the transistor is switched off, the reverse voltage is induced across the inductor.
- The inductor current keeps flowing in the same direction and charges the capacitor while the diode is forward biased.
- The inductor current linearly falls with a rate (Vo/L).

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Conversion Ratio

- The voltage conversion ratio may be obtained by equating volt-second products during on and off times.

$$V_{in} DT = V_O (1 - D) T \quad \textbf{(15)}$$

$$\frac{V_O}{V_{in}} = \frac{D}{1 - D} \quad \textbf{(16)}$$

Where D varies from 1 to 0.
For D=0 to 0.5 the output is less than input resulting buck operation
For D=0.5, the input is equal to output
For D=0.5 to 1 the output is larger than input resulting boost operation
The maximum conversion ratio is limited in practice due to circuit losses.

Thank you

For your attention