UNIT-II

ANALYSIS OF RECTIFIER CIRCUITS

õ= **ASSUMPTIONS AND JUSTIFICATIONS:**

- AC Source has no impedance and delivers **constant Voltage** of **Sinusoidal** waveform at **constant Frequency**.
- If polyphase it delivers **Balance Voltages.**
- Transformers have no leakage Impedances or Exciting Admittances
- DC load has infinite inductance (DC current is constant and ripple free).
- Valve is ideal (**zero resistance** during Conduction and **infinite resistance** in Non Conduction state)

DEFINITIONS:

õ= **VALVE RATING**: It is Volt ampere rating of a valve which is the product of Average Current to Peak Inverse Voltage

- **PEAK INVERSE VOLTAGE(PIV):** It is the peak voltage that occurs across the valve during Non Conduction state
- **TRANSFORMER VA RATING:** It is the product of RMS voltage and RMS currents of either primary or secondary windings.
- **PULSE NUMBER (p):** It is number of pulsations of output DC voltage per one cycle of AC voltage input

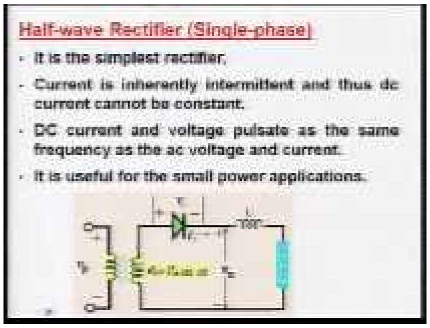
$$p = q*s*r$$

- **COMMUTATION GROUP(q)**: A group of Valves in which one valve conducts at a time (Neglecting Overlap)

Where s = No of series Valves

r = No of Parallel valves

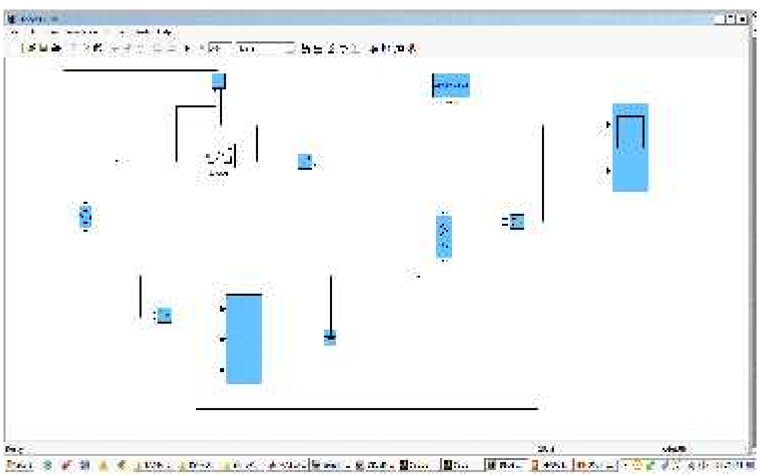
CONVERTER CIRCUITS

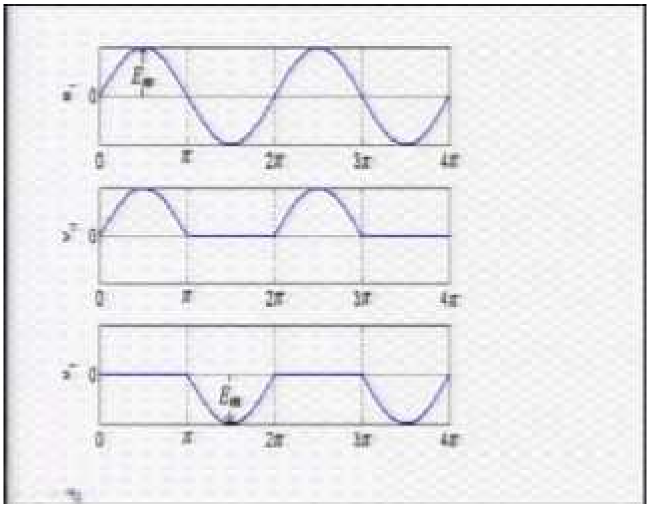


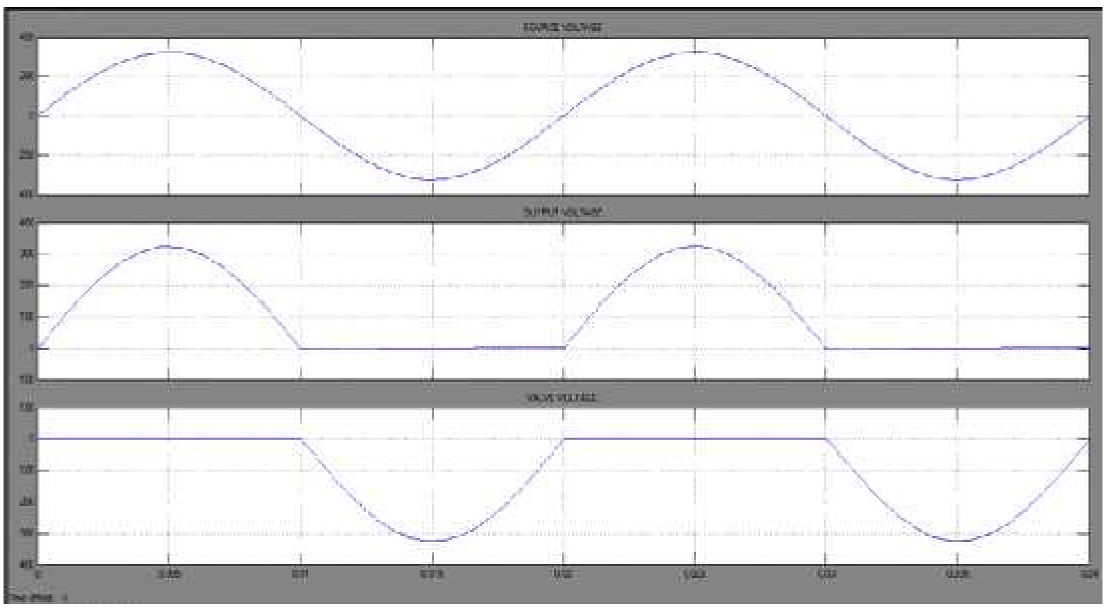
õ= **HALF WAVE RECTIFIER:**

- It is the simplest rectifier
- Current is inherently intermittent hence DC current cannot be constant.
- DC Voltage and current fluctuate at same frequency as that of AC voltage and currents.

õ= It is used for **Small Power Applications**







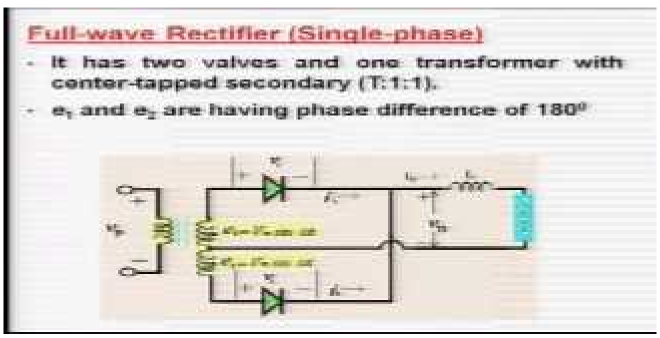
Average DC Voltage:

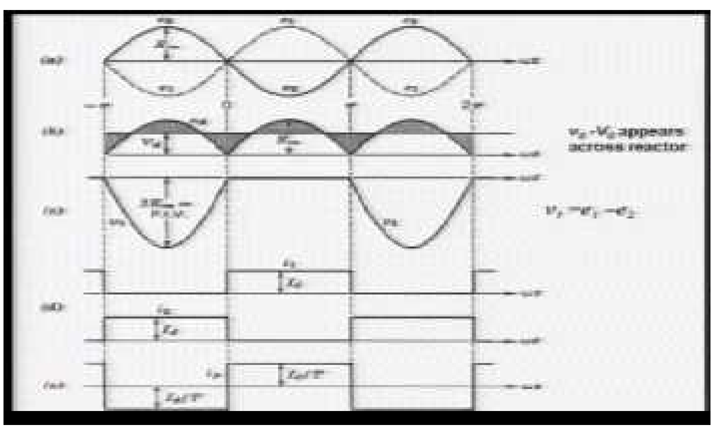
}

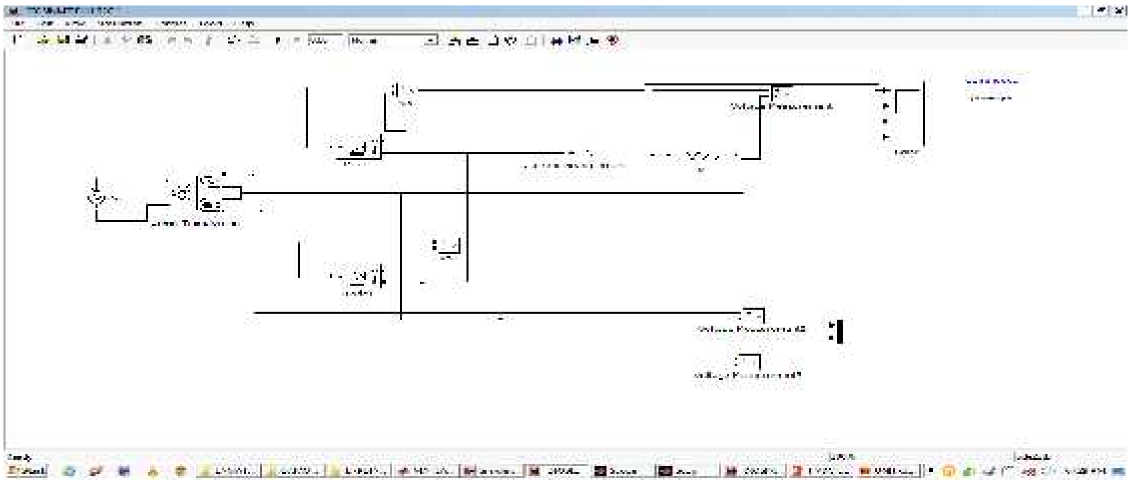
= =

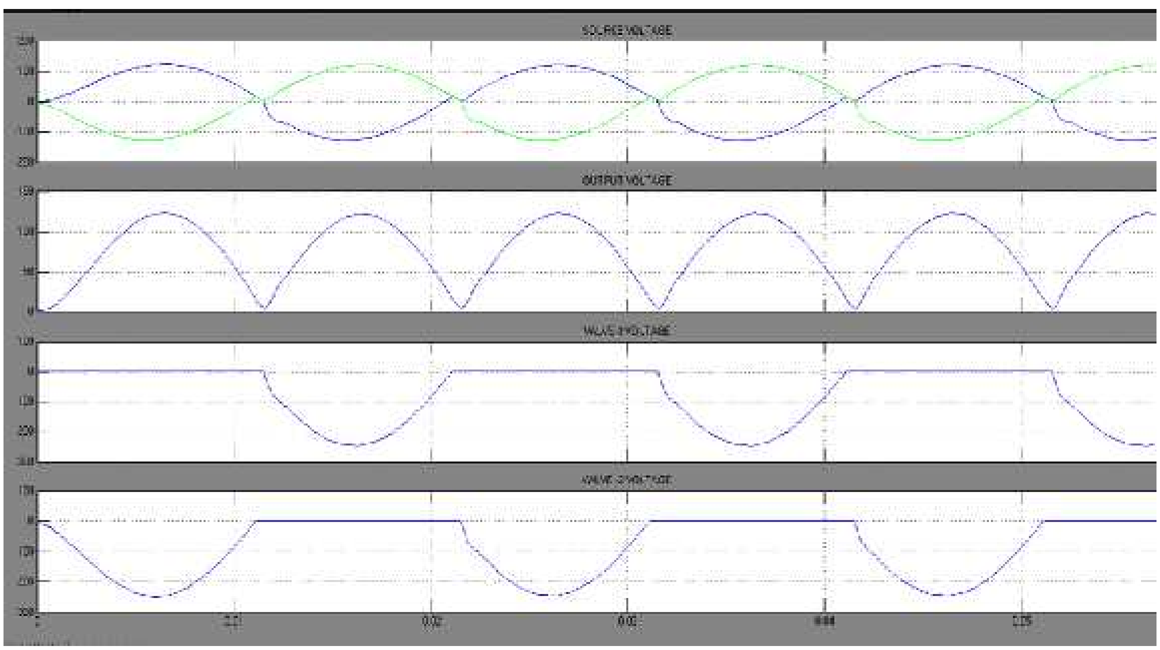
- **PIV = V_m**
- **Pulse number= 1**
- **Average Current = I_d**
- **Valve Rating = V_m I_d**
- **One Valve**

- **FULL WAVE MIDPOINT RECTIFIER:**

  - It has two valves and one transformer with centered tapped secondary (T:1:1).
  - The secondary has a phase difference of 180^0
  - 


TUF is low (50%)





Average DC Voltage:

=

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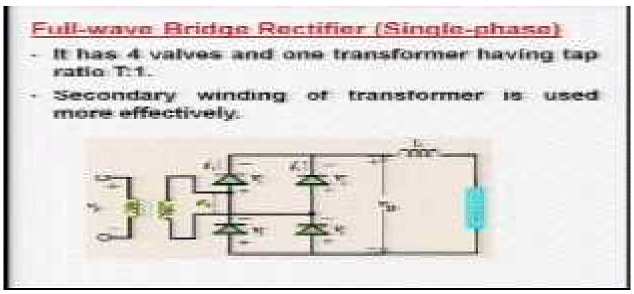
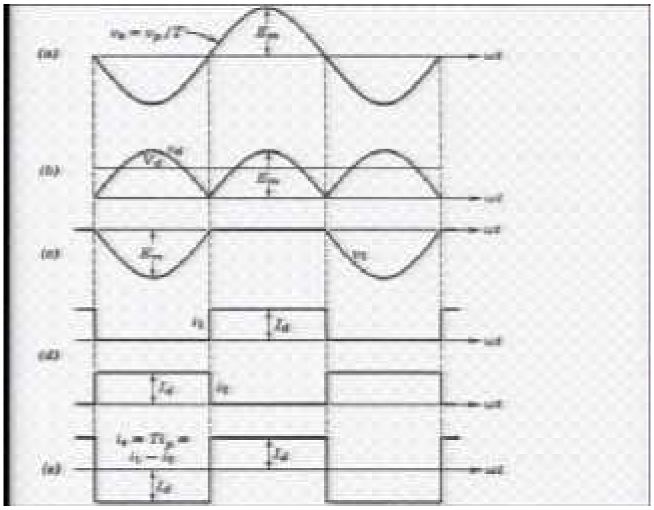
õ- **PIV = $2V_m$**

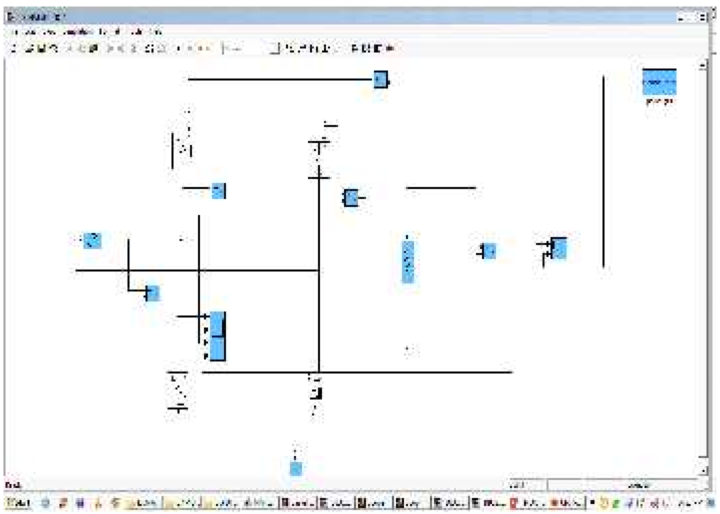
- **Pulse Number=2**
- **Average Current = $I_d/2$**
- **Valve Rating = $V_m I_d$**
- **Two valves**

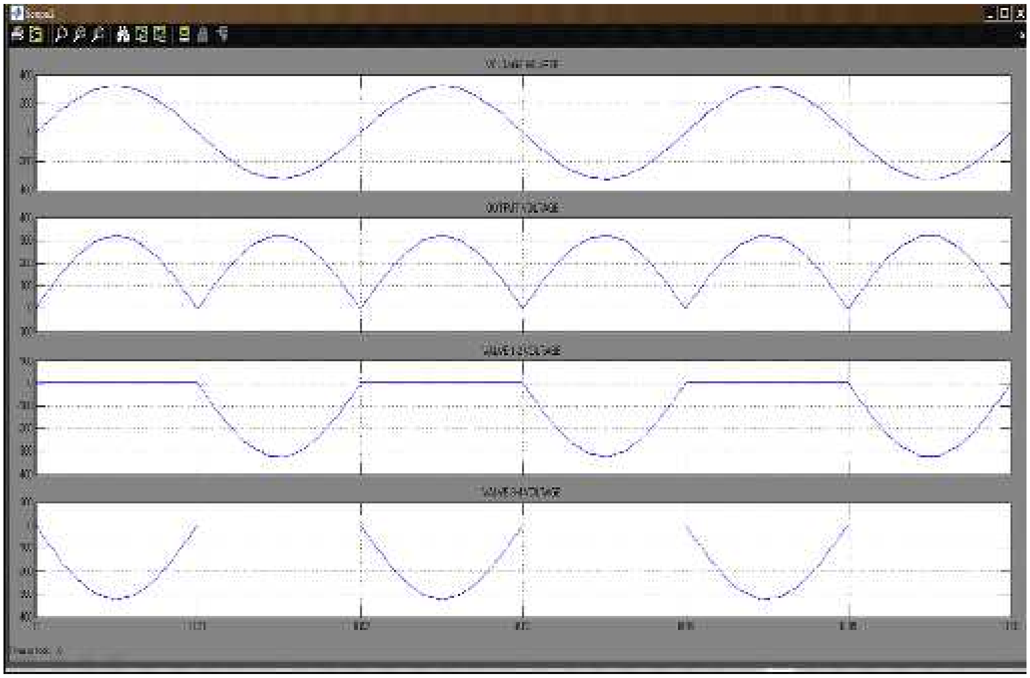
- **FULL WAVE BRIDGE RECTIFIER:**

- It has four valves and one transformer with tap ratio T:1.
- 

TUF = 100%





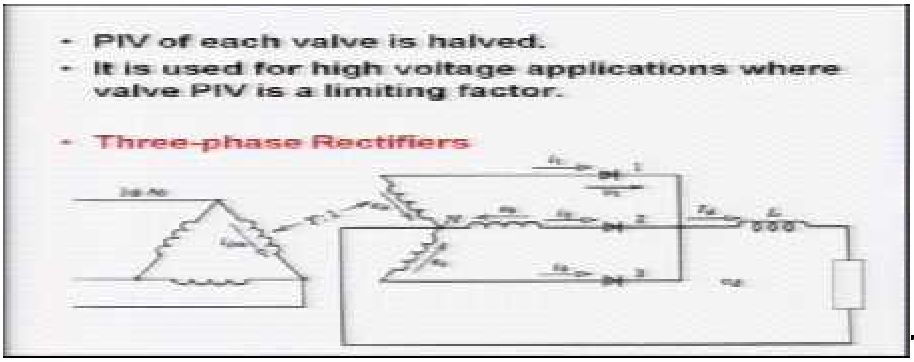


Average DC Voltage:

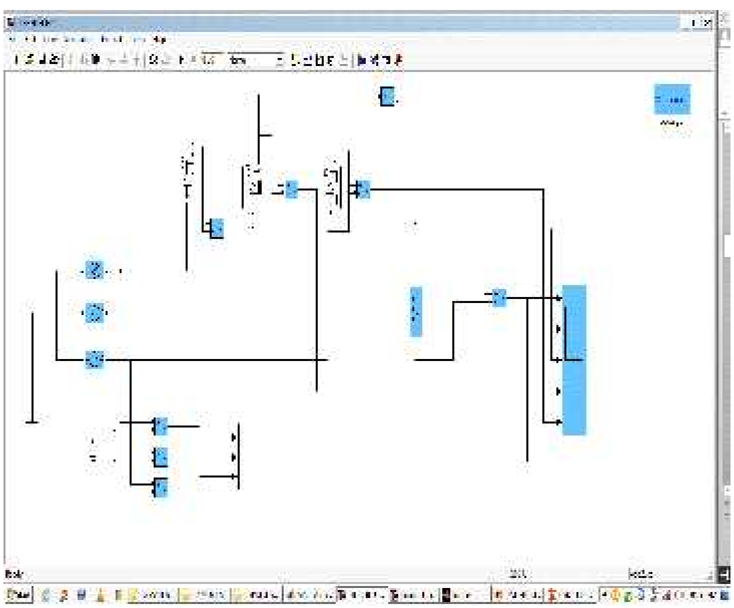
=

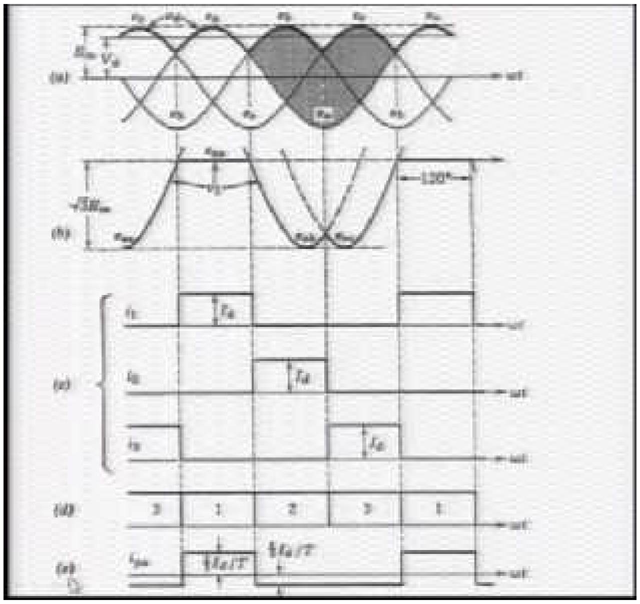
=

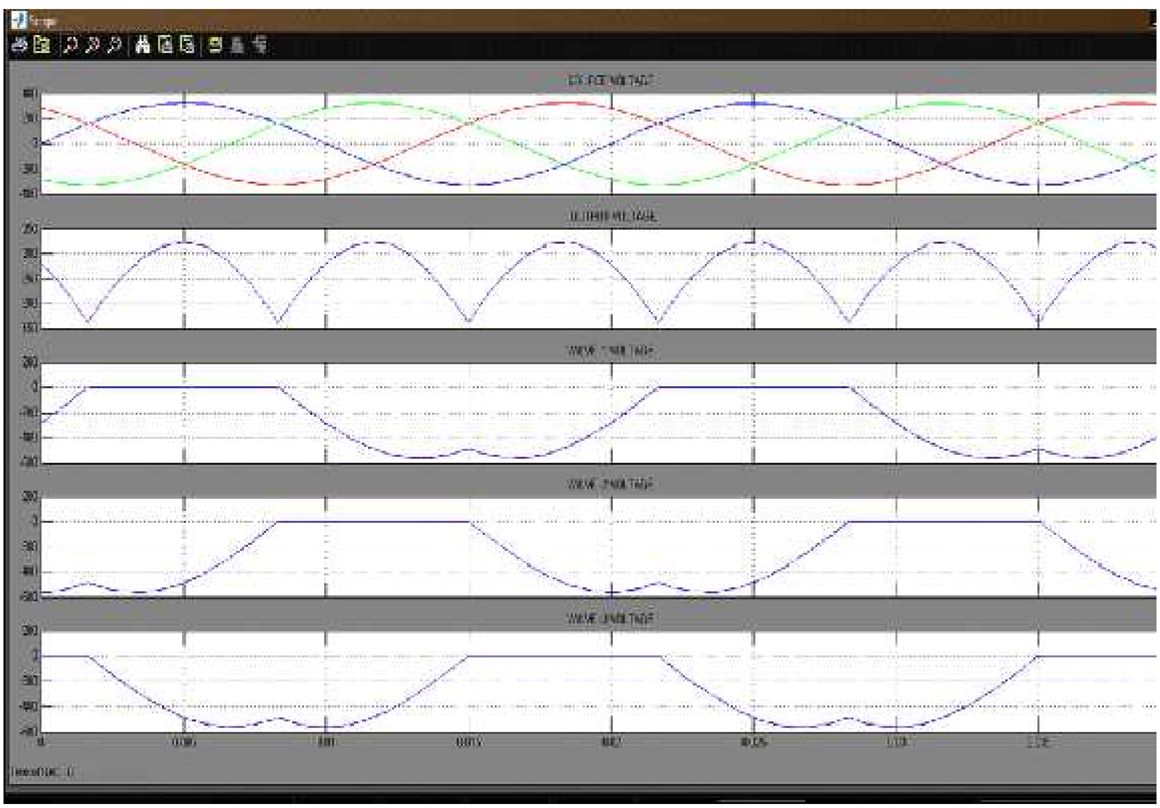
- **PIV = V_m**
- **Pulse Number=2**
- **Average Current = $I_d/2$**
- **Valve Rating = 0.5 V_m I_d**
- **Four Valves**
- **PIV is halved**
- **It is used for High Power Applications**



THREE PHASE ONE WAY RECTIFIER:







Average DC Voltage:

=

- **PIV = V_m**
- **Pulse Number=3**
- **Six Valves**
- **It is used for High Power Applications**

GENERALIZATION: p= q x s x r = 3 x 1 x 1= 3

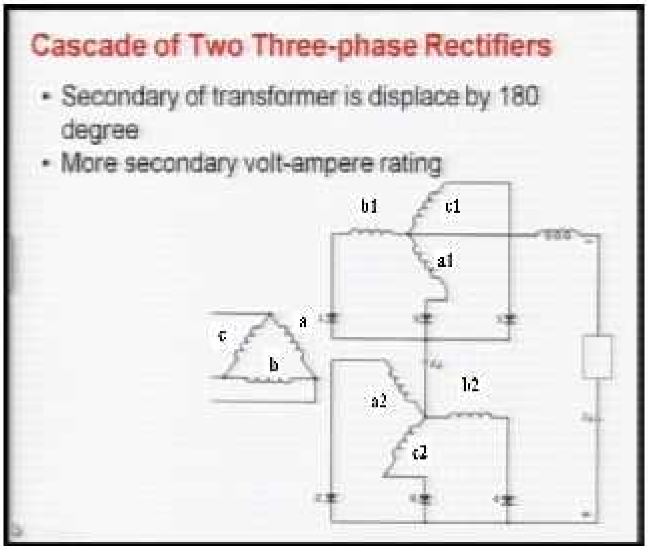
Dc output voltage:

sin(π/q)

If s series valves then

sin(π/q)

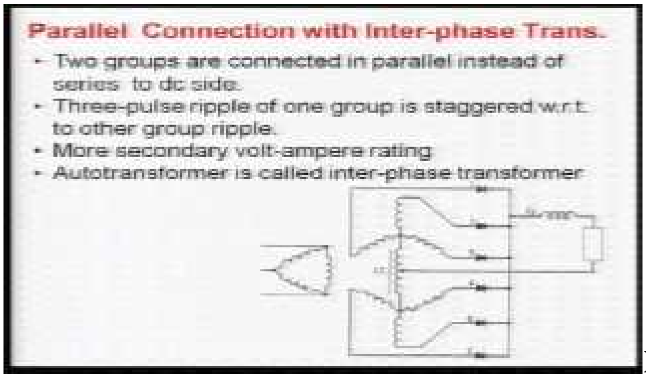
- **TOPOLOGIES OF SIX PULSE CONVERTERS:**
  - CASCADE OF TWO THREE PHASE RECTIFIERS
  - PARALLEL CONNECTION WITH INTERPHASE TRANSFORMER
  - SIX PHASE DIAMETRICAL CONNECTION
  - CASCADE OF THREE SINGLE PHASE FULL WAVE RECTIFIERS
  - THREE PHASE TWO WAY RECTIFIER

õ= 

CASCADE OF TWO THREE PHASE RECTIFIERS:

- Two three phase groups of valves are in series on the DC side.
- Both groups have common cathode.
- Both transformers are connected in star star in $180^{0.}$
- TUF is poor
- Secondary has more VA rating

õ= **PARALLEL CONNECTION WITH INTERPHASE TRANSFORMER:**

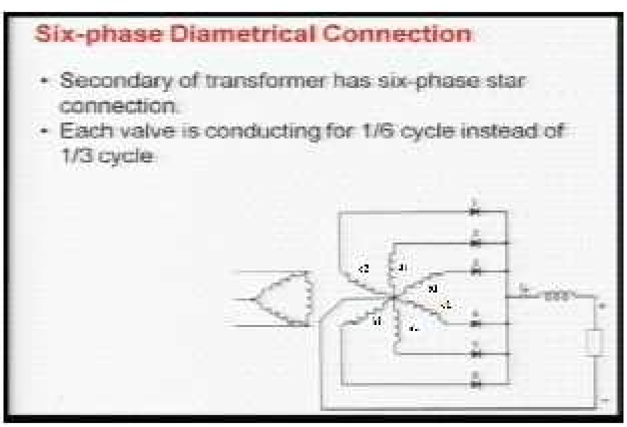
- 

Instead of two valve groups in

  series now they are connected in parallel.

- They cannot be connected directly in parallel as the pulse ripple is staggered wrt ripple of the other
- One DC pole is connected directly to like pole and other to other pole through a Autotransformer. This Autotransformer is also called Interface transformer.
- Here instantaneous voltages of the centre tap is equal to instantaneous voltages of the two ends of the winding.
- More secondary ampere turns
- This topology is not used for HVDC applications

SIX PHASE DIAMETRICAL CONNECTION:

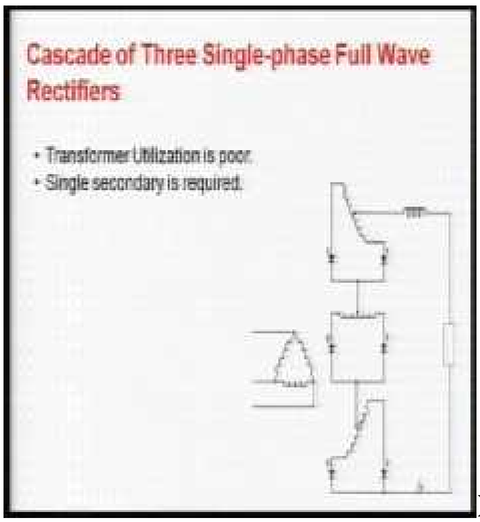
- 

Instead of interphase

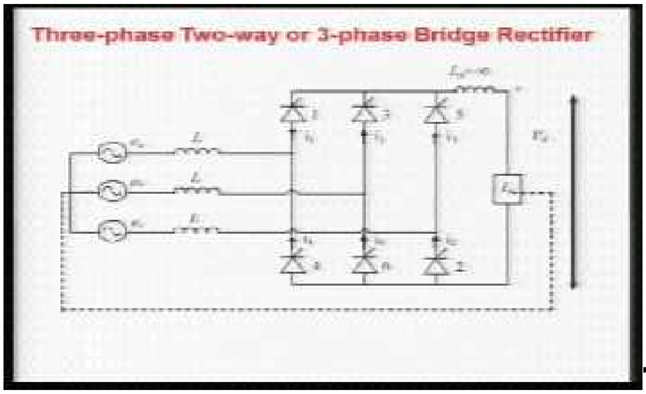
  transformer all the secondary Y points are solidly connected form a six phase.

- It is made of one centre tapped winding per core instead of two separate winding cores.
- Each valve conducts for 1/6th of the cycle instead of 1/3rd as in the three phase connection.
- TUF is poorer

õ= **CASCADE OF THREE SINGLE PHASE FULL WAVE RECTIFIERS:**

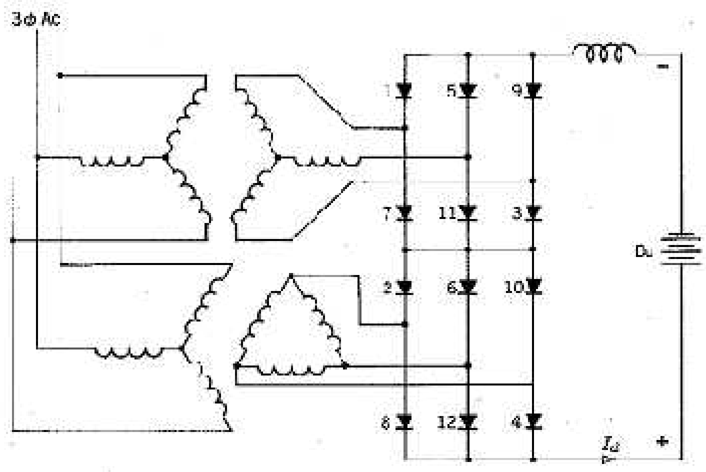
- 

It appears like it gives more DC output voltage wrt PIV but not.
- TUF is poor

õ= 

THREE PHASE TWO WAY RECTIFIER:

- In the circuit (3 phase one way), if the three phases are reversed the circuit operates as before but the directions of the DC voltages and currents are reversed.
- In the bridge converter the same transformer is feeding the two one way rectifiers of opposite connections.
- The output voltage is doubled and thus power for the same current but the PIV is same. Thus this circuit is used for high voltage and high power applications.
- No DC current in the transformer windings.
- Pulse number is 6

õ= 

TWELVE PULSE CONVERTER:

- Here two six pulse converters are connected in series.
- One converter is connected to phase star – star connection and other in star –delta.
- Y-Y- 6 Pulse + Y-Δ- 6 Pulse= 12 Pulse.
- One converter gives 6 Pulse output and due to phase displacement of 30^0 gives another 6 pulse and total in series which is 12 Pulses

DESIRED FEATURES OF THE CONVERTER CIRCUIT:

õ= High Pulse Number (p).

õ= PIV/V_{d0} should be as low as possible.

- V_{d0}/V should be as high as possible.
- TUF should be near to unity.

õ= **High Pulse Number (p):**

- The converter should have high pulse number if pulse number increases the low order harmonics are eliminated.

õ= **PIV/V_{d0}:**

- This ratio should be as low as possible.
- Cost of the Valve becomes low is the PIV is less.
- The cost of the Valve depends on the valve rating which depends on PIV if PIV is less cost decreases.
- The output voltage of the converter should be as high as possible.

õ= **V_{d0}/E:**

- This ratio should be as high as possible.
- The output voltage of the converter should be as high as possible.
- The input of the converter should be low.
- We expect with less input output should be high.

õ= **TRANSFORMER UTILIZATION FACTOR(TUF):**

- This factor gives us the information how best the transformer material is utilized.
- TUF should be near to unity.

TUF = Transformer Rating/ DC power output

- If q is Even, then the PIV occurs when the valve with a phase displacement of 180^0 is

  conducting and will be equal to **PIV = E_m.**

- If q is odd PIV occurs when the valve with phase displacement of π +(π/q) is

  conducting and will be equal to

$$\textbf{PIV} = 2E_m \cos(\pi/2q)$$

- The ratio of PIV/V_{d0} is given by

- The ratio of V_{d0}/E is given by

- The current rating of the transformer is given by

From DC current waveform

- The transformer rating will be

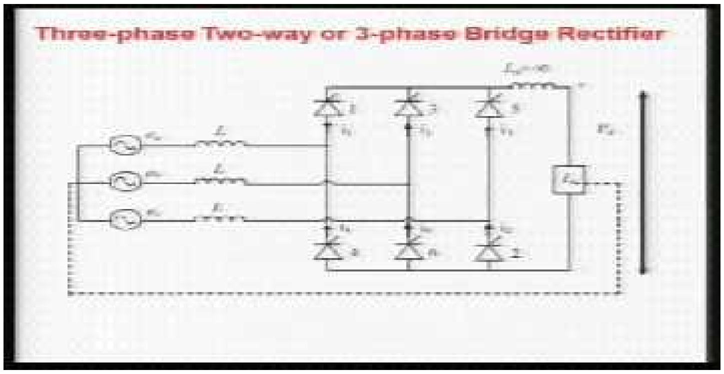
- Transformer Utilization Factor is given by

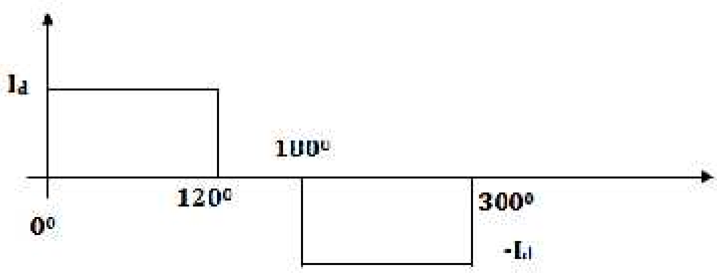
we can say that TUF is a function of q

6 Pulse Converter						
S:No	**q**	**r**	**S**	**PIV/V_{d0}**	**V_{d0}/E**	**TUF**
1	2	1	3	1.047	2.700	1.571
2	2	3	1	3.142	0.900	1.571
3	3	1	2	1.047	2.340	1.481
4	3	2	1	2.094	1.169	1.481
5	6	1	1	2.094	1.350	1.814

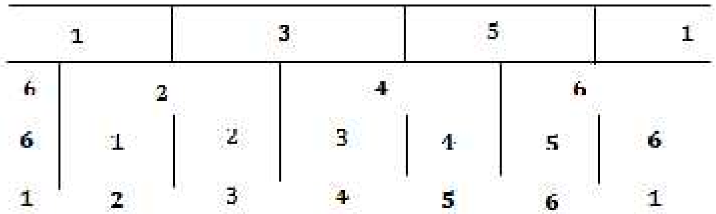
*From the above table we can pick up S:No: 1 and 3 but TUF is good for S:No: 3
*The configuration which is best suited for **q=3, r=1 and s=2** is nothing but **Bridge Circuit** and it also called "**EUROPEAN GRAETZ CIRCUIT"**
The current rating of the transformer can be further increased by a factor of while decreasing the no of the winding by a factor of 2

EUROPEAN GRAETZ CIRCUIT:

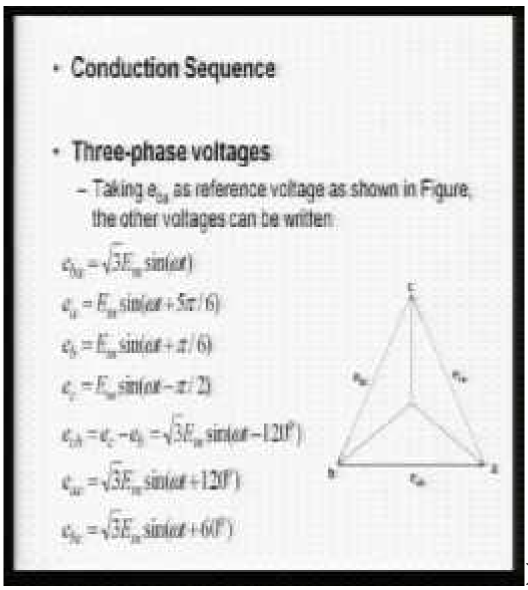




CONDUCTION SEQUENCE:



- If no overlap at any given instant two devices will be conducting one from upper and one from lower



Here for three phase voltages $\mathbf{e_{ba}}$ is taken as reference

ASSUMPTION:

- Power sources consisting of balance sinusoidal EMF of constant voltage and frequency with equal lossless inductances.
- The DC current is constant.
- Valves have zero resistances when on an infinite resistance when off.
- Valves are fired with equal intervals of 60^0.
- A valve is fired when there is sufficient forward voltage across it and gate pulse is available

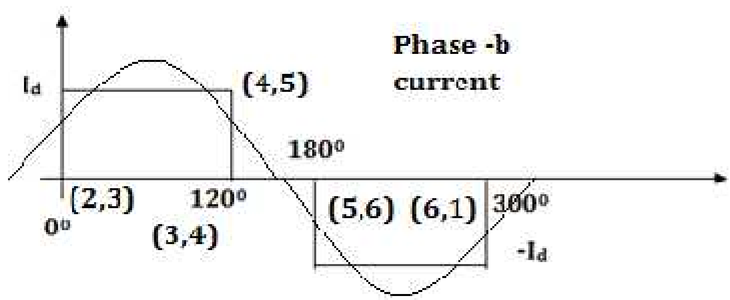
MODE-1:

Average output Voltage with-out overlap : when 1 and 2 are fired at some interval 3 is about to get fired when 3 is fired then one will be off and valve 2 and 3 starts conducting the output voltage is E_{bc}

- For $\alpha < 90^0$ the converter acts as Rectifier = +ve
- For $\alpha > 90^0$ the converter acts as Inverter = - ve
- For $\alpha = 90^0$ = 0

- Although delay angle α can vary from 0 to 180^0 delay angle cannot be less than certain minimum limit (α min = 5^0) in order to ensure the firing of all series connected Thyristors.
- Similarly the upper limit of the delay angle is also restricted due to turnoff of the valve.
- The α value is not allowed to go beyond $(180^0 - \gamma)$ where γ is the Extinction angle it is also called minimum margin angle which is typically 15^0.
- However in normal operation of the inverter it is not allowed to go below 15^0 the value of the γ will be in between (15^0 - 20^0).

FUNDAMENTAL CURRENT:



Fundamental Peak current:

Where I_1 is the fundamental component of current

I_h is harmonic current

Total Current = Harmonic current + fundamental current

POWER FACTOR:

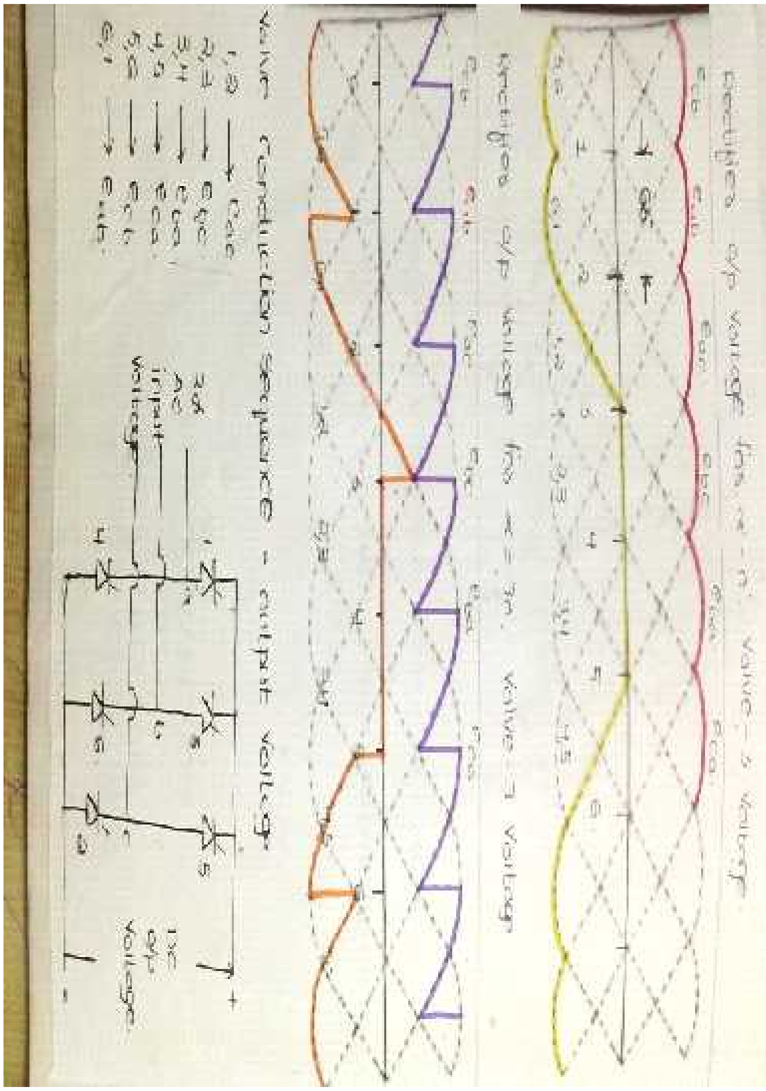
Where

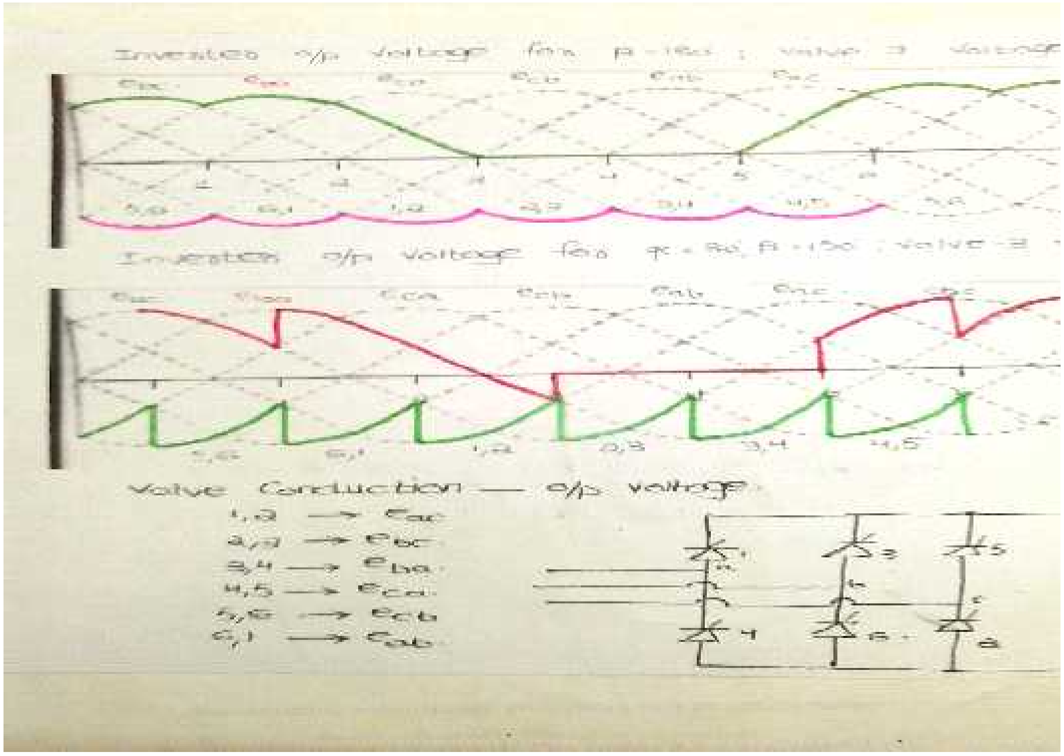
Neglecting the losses

$$\cos\phi = \cos\alpha$$

This shows that when delay angle an increase, the power factor reduces and thus more reactive power requirement.

Power factor





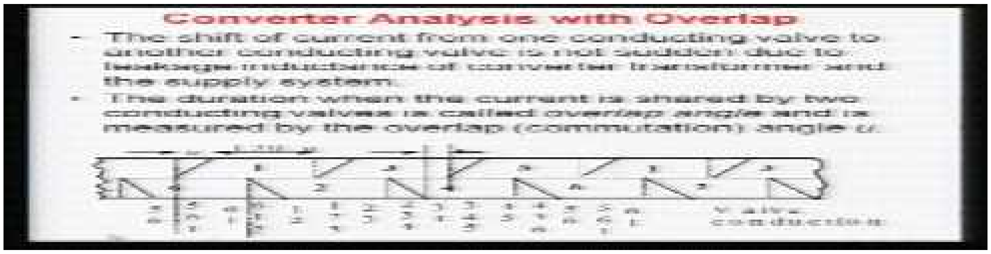
OVERLAP ANGLE (μ):

- The duration when the current is shared by conducting valves in a commutation group is called overlap angle and measured by overlap angle.
- The overlap angle depends on the source inductance the current from one phase to other phase will not be instantaneous there fore depending on the overlap angle the conduction of no of valves will be dependent.

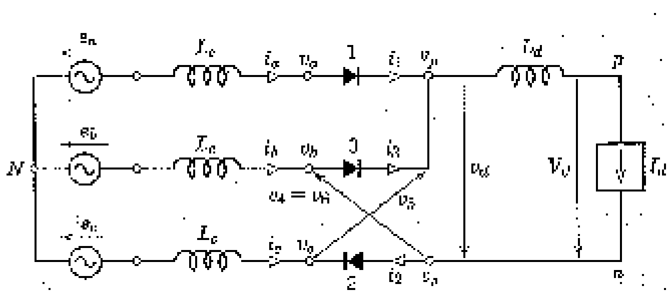
Based on the overlap angle there are three modes of operation

S:No	Mode of operation	Overlap value	No of devices Conducting	Case
1	Mode-1	$\mu = 0$	2	Ideal
2	Mode-2	$\mu < 60^0$	2 to 3	Practical
3	Mode-3	$\mu = 60^0$	3	Practical
4	Mode-4	$\mu > 60^0$	3 to 4	Worst

MODE-2: Two To Three Valves Conduction



Here in mode-2 valve 1 and 2 starts conduction when valve 3 starts due to inductance the current shifts from valve 1 to 3 will not take place instantaneously during the current sharing period valve 1 2 and 3 will be conducting



Applying nodal analysis at node-A

Adding above two equations we get

But we know during commutation $I_1 + I_3 = I_d$

Derivating the above equation we get

Substituting the above relation in the equation we get

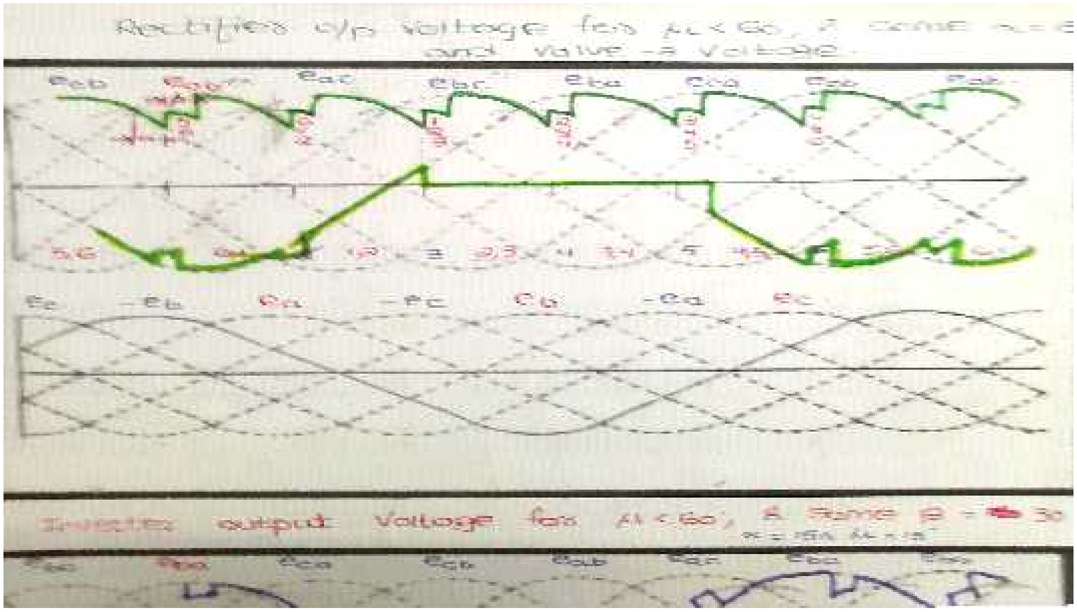
In our Assumption we have

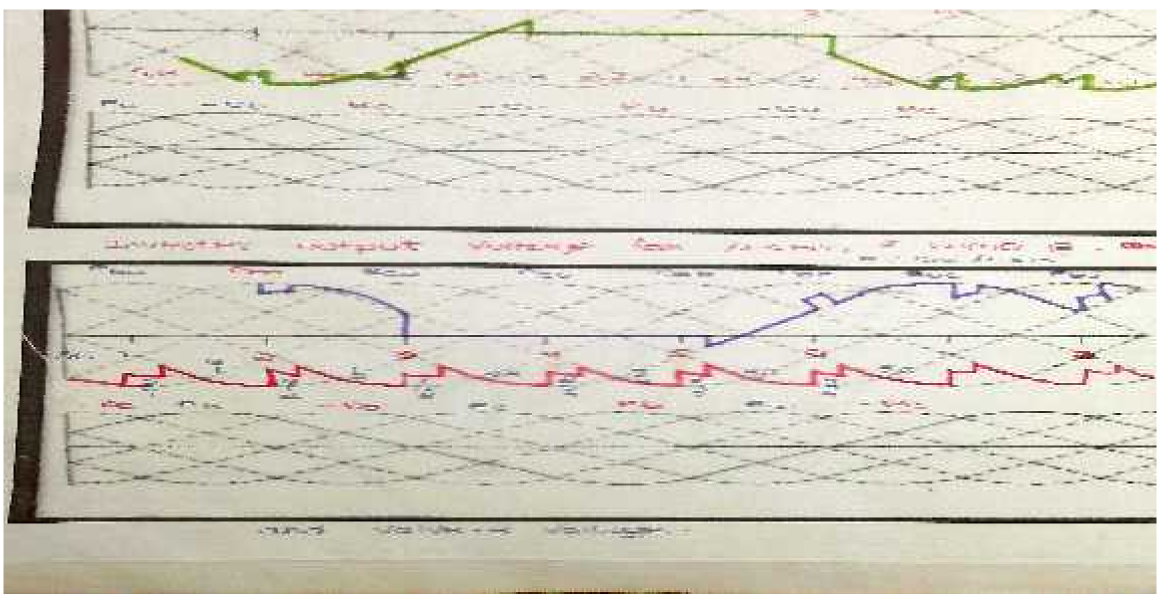
But

Therefore the instantaneous DC output voltage of the bridge is

The Average DC Voltage

OR





PATTERN OF CURRENT SHIFT:

Subtracting above two equations we get

But we know during commutation $I_1 + I_3 = I_d$

Integrating the above equation we get

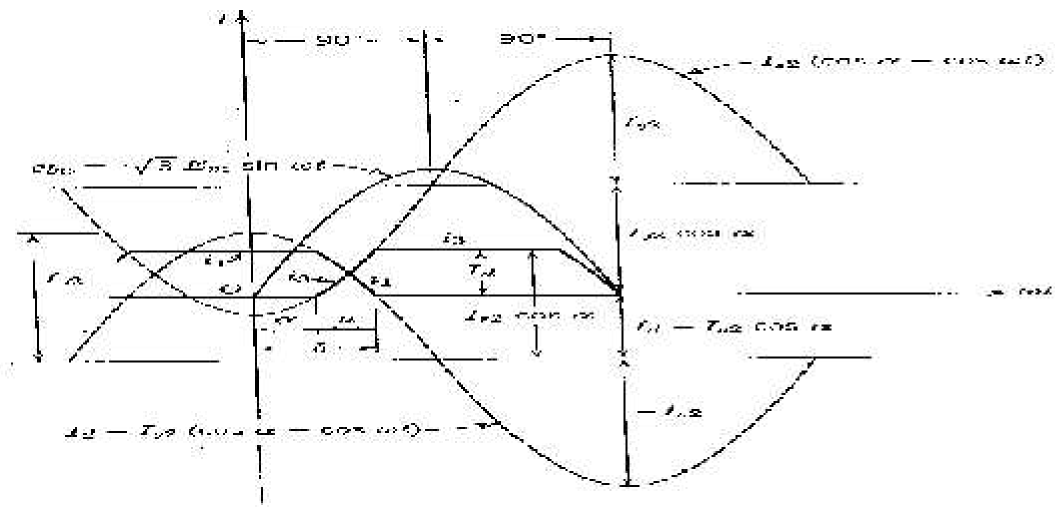
Where A is the Integral Constant in order to find the constant A we have to use initial conditions

At **ωt = α** the instant valve 3 is fired the value of **= 0**

Substituting the value of A in the above

for α ≤ ≤ α+μ

But we know that $I_1 + I_3 = I_d$



EQUIVALENT CIRCUIT OF HVDC:

We know that from the above derivation

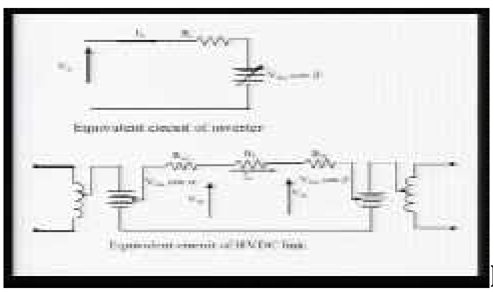
At **$\omega t = \alpha + \mu$** the instant valve 3 is taking care of complete current and Valve-1 is off is fired the value of **$= I_d$**

Substituting in above equation:

Here in the above Equation **α is Controllable** and **μ is not controllable**

Put this cos(α+μ) value in the above output voltage equation then we get

Where R_C is the commutating Reactance



EQUIVALENT CIRCUIT OF RECTIFIER

For Inverter the process is same but the parameters are different in rectifiers we use delay angle α, δ=α+μ for the inverter we use Advance Angle β= π-α and Extinction Angle γ= β-μ

The DC voltage in the Inverter Operation is

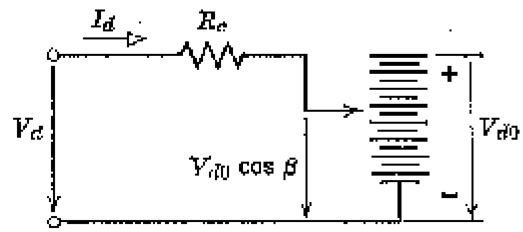
The DC voltage is taken as Negative because inverter uses Opposite Polarity

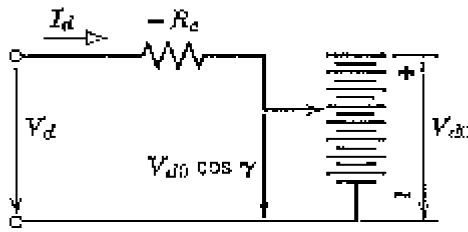
Instead of β if we want to use γ for inverter equation then the equation becomes

From

Substituting the above value in

EQUIVALENT CIRCUIT OF INVERTER





OVERALL EQUIVALENT CIRCUIT OF HVDC SYSTEM