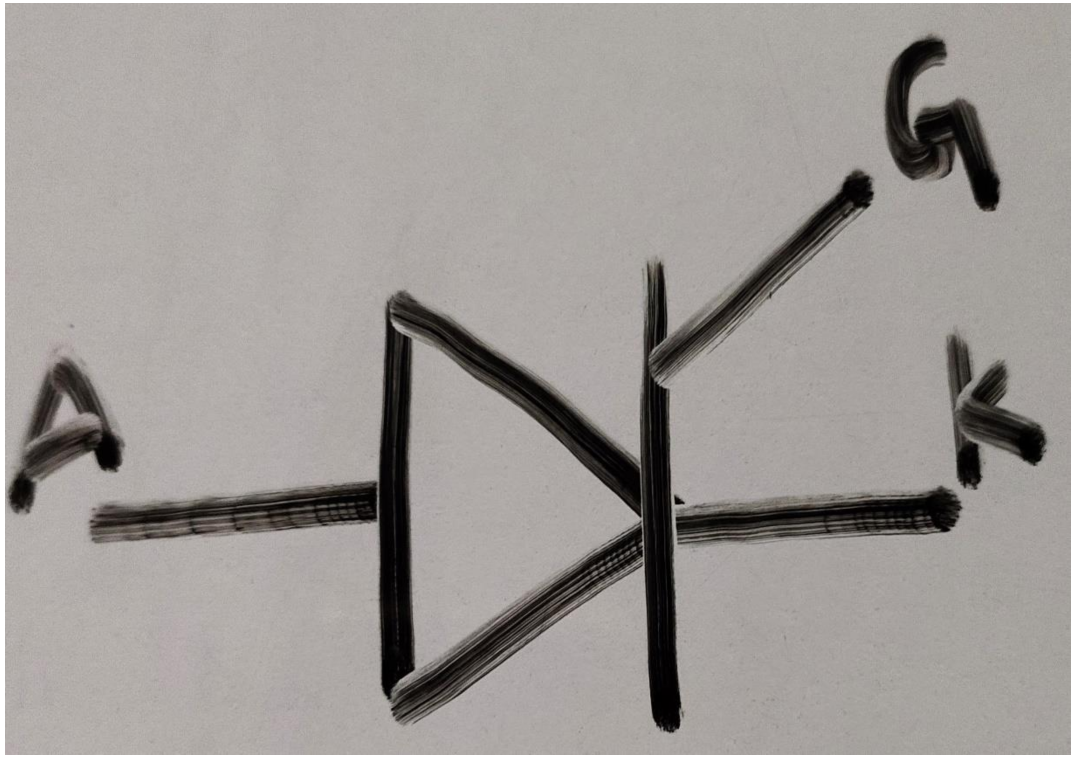
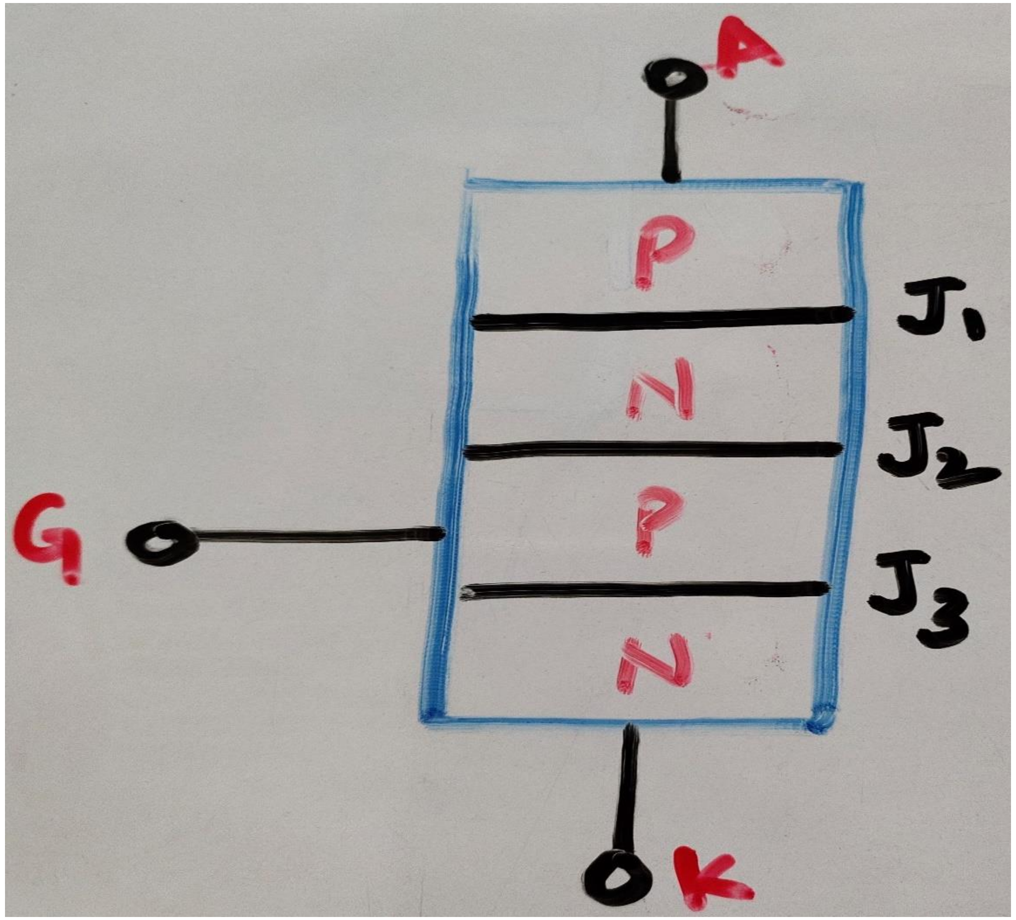
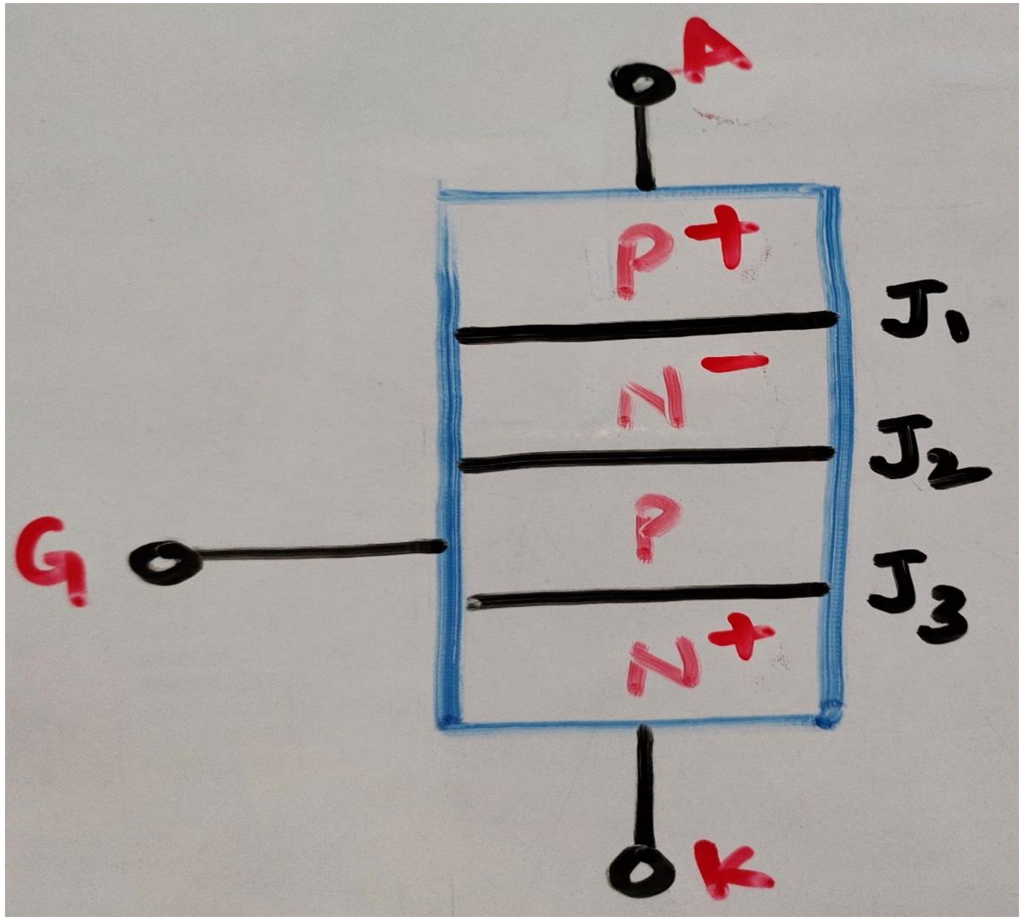
Silicon Controlled Rectifier

- SCR is a Four layered device
- SCR is a Three junction device
- SCR is a Three terminal device
- SCR is a half controlled device
- SCR is a DC switch i.e in an SCR current only flow in one direction
- Anode(A) and Cathode(K) are Power terminals and Gate(G) is a Controlled terminal.



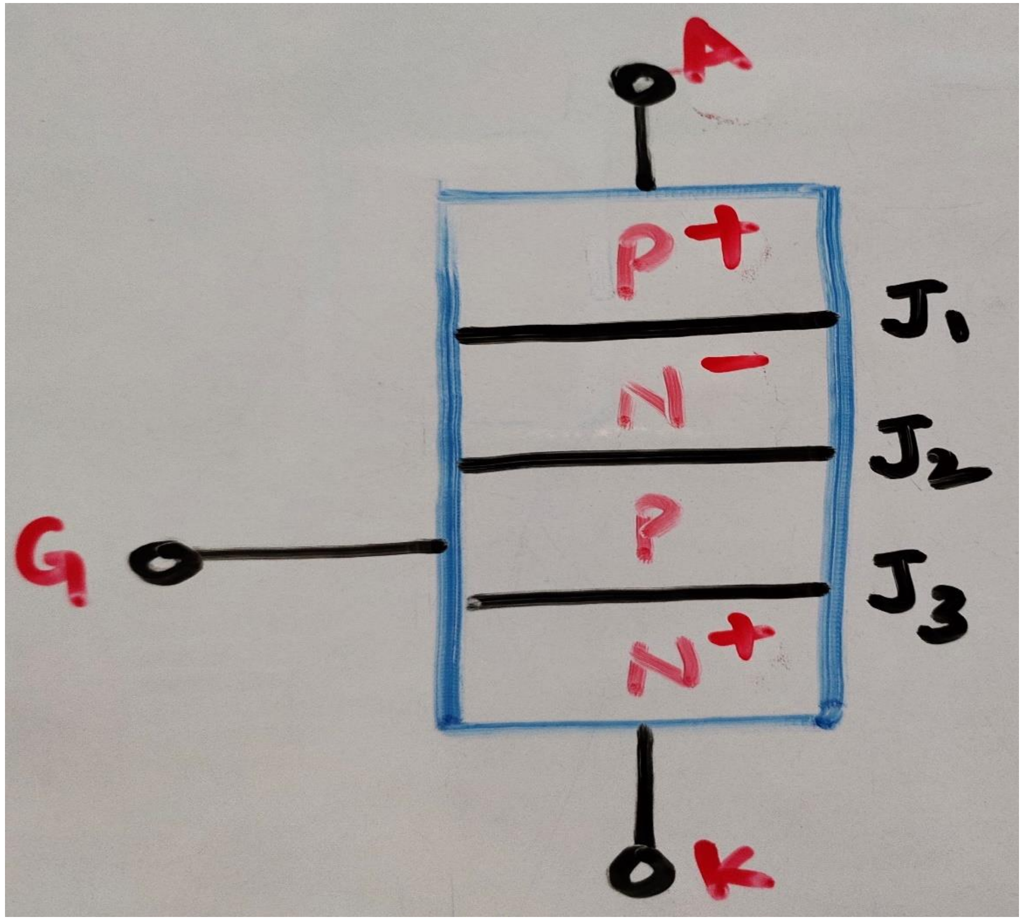
Silicon Controlled Rectifier





Silicon Controlled Rectifier

- P+ and N+ represents highly doped
- N- represents lightly doped
- P represents Moderately doped
- Highly doped elements contribute less in forming the depletion region and lightly doped elements contribute more in forming the depletion region.



Modes of Operation of SCR

- The three modes of operation of SCR are

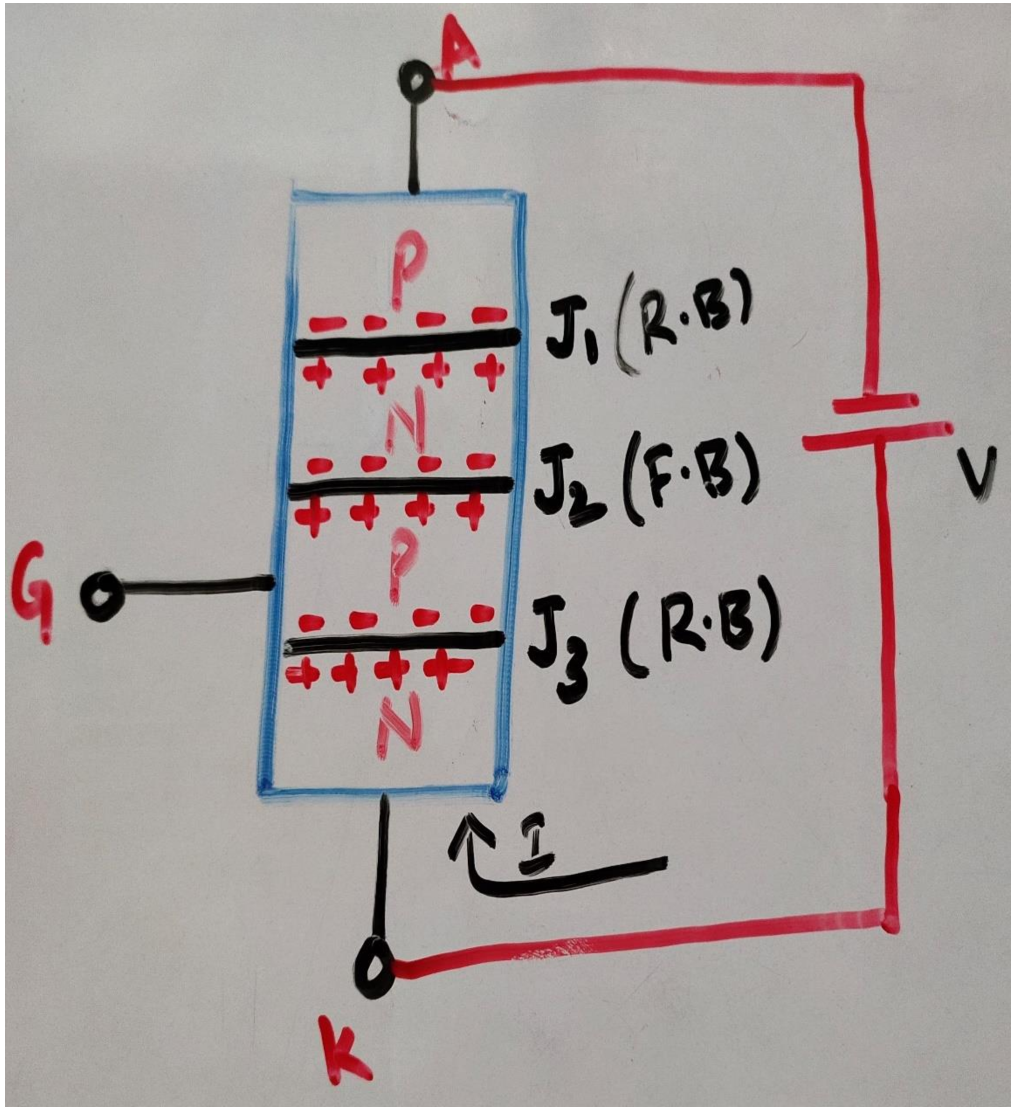
  1. Reverse Blocking Mode

  2. Forward Blocking Mode

  3. Forward Conducting Mode

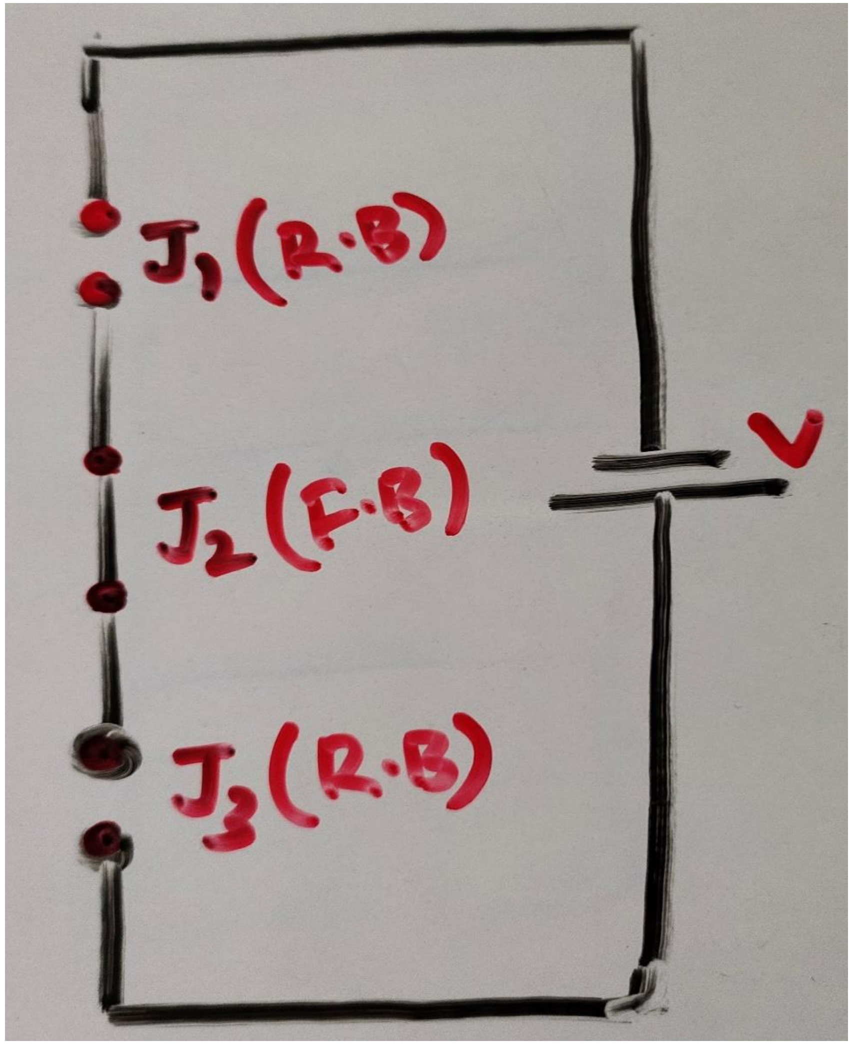
Reverse Blocking Mode

- The Anode is connected to the negative terminal of the battery and the cathode is connected to the positive terminal of the battery, then it is said to be **Reverse Biased.**
- In this Condition, Junctions **J1** and **J3** are **Reverse biased** and Junction **J2** is **Forward biased.**



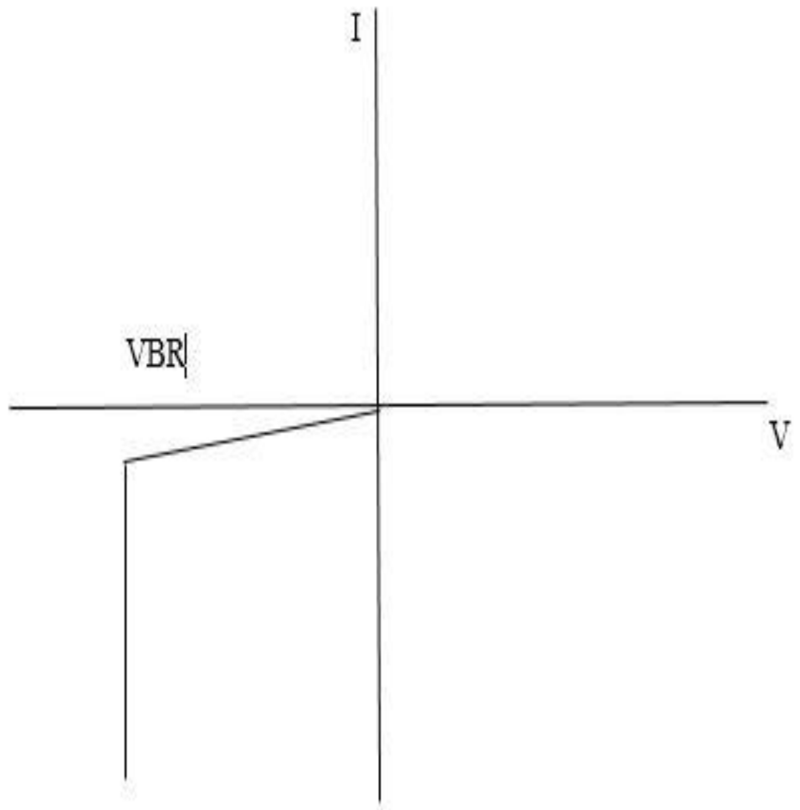
Reverse Blocking Mode

- The voltage across J2 = 0 v (Short circuited)
- As the Junctions J1 and J3 are reverse biased, there will be an Open circuit at the junctions and hence **ideally** the current flowing in the circuit will be equal to zero i.e. I= 0 Amps.
- But in **Practical**, there exists a little reverse leakage current(very less).
- As the Junction J2 cannot block the voltage in the circuit, the entire voltage will be blocked by two remaining junctions J1 and J3.



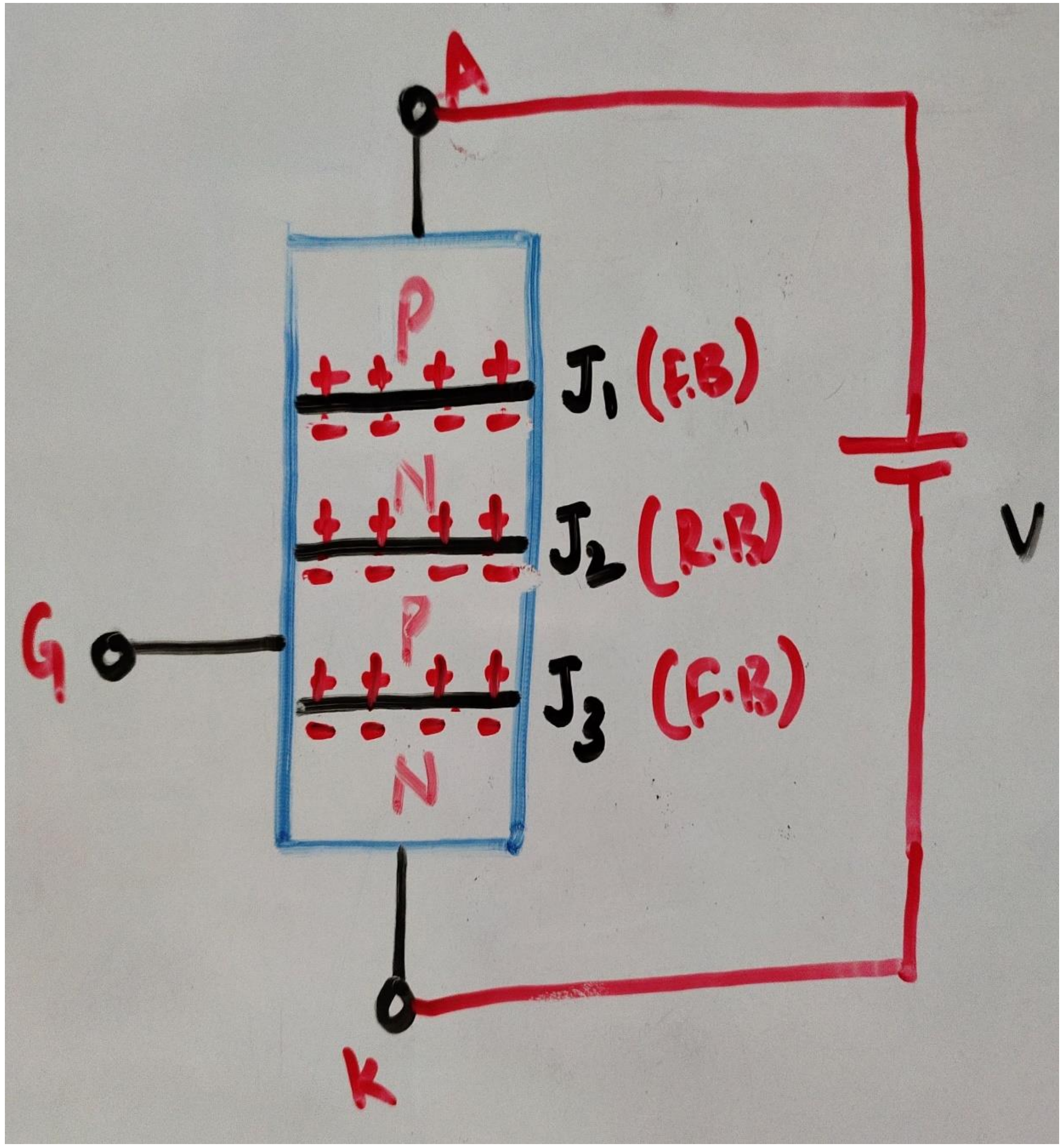
Reverse Blocking Mode

- In Reverse blocking mode, J1 has more depletion width when compared to J3 and hence large amount of voltage will be blocked at Junction J1.
- When we increase the reverse voltage, at a critical breakdown level called Reverse Breakdown voltage(VBR), an avalanche breakdown will occur at the junctions J1 and J3 increasing the current sharply as shown in the figure..
- Under reverse Blocking mode, SCR behaves as an OFF switch.



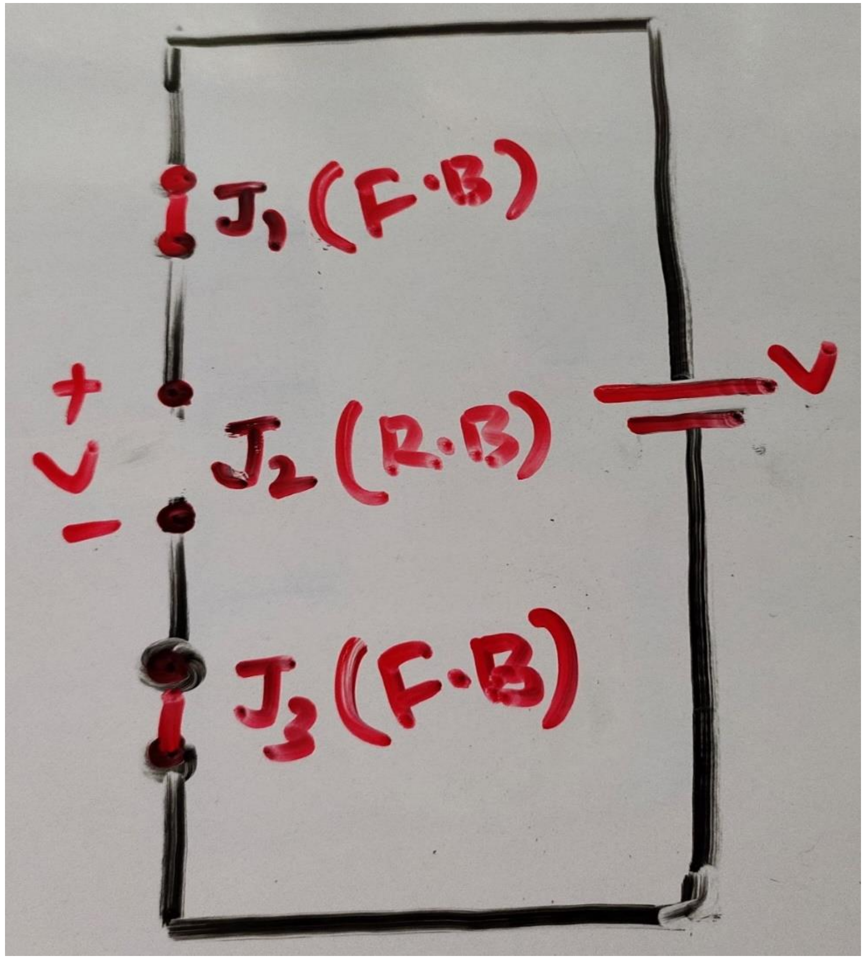
Forward Blocking Mode

- In this region, the Anode is made positive with respect to the cathode.
- J1 and J3 are forward biased and J2 is reverse biased.
- The anode current is a small leakage forward current.

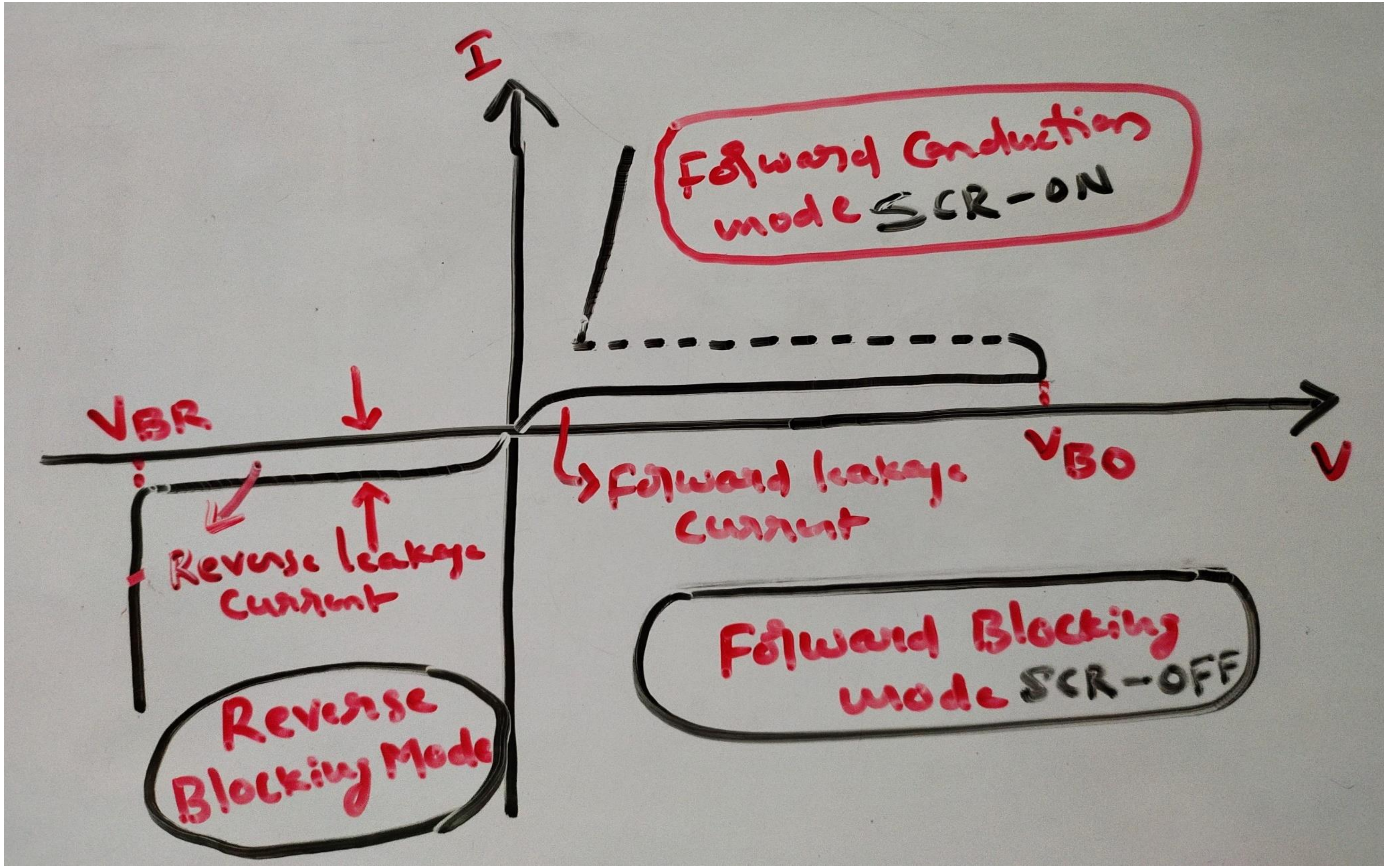


Forward Conduction Mode

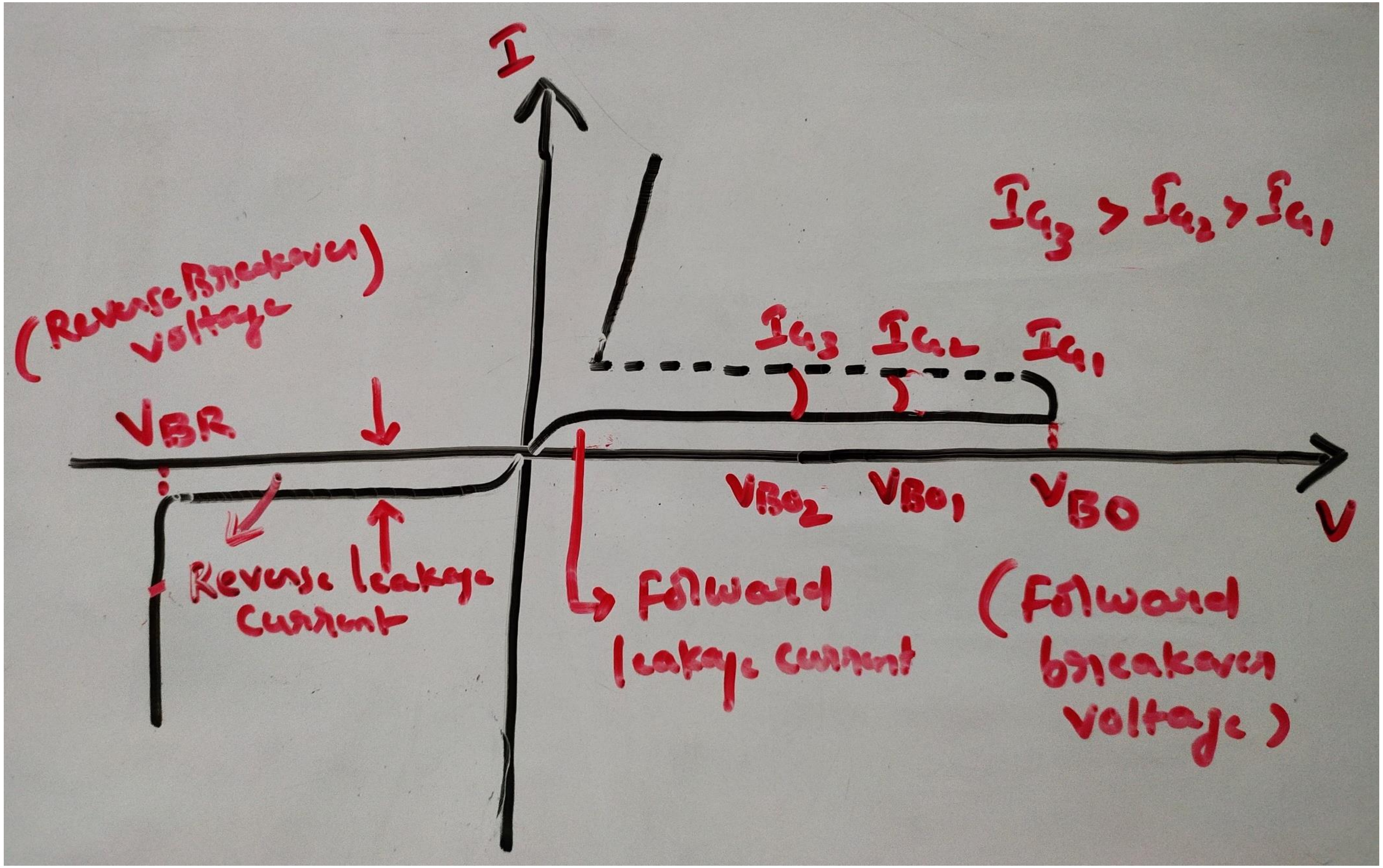
- When the Anode to Cathode voltage is increased with the gate circuit kept open, avalanche breakdown occurs at Junction J2 at critical forward break-over voltage(VBO).
- The SCR now switches into a low impedance condition (high conduction mode).
- When a gate signal is applied, the SCR turns –ON before VBO is reached.
- The forward voltage at which the device switches to ON state depends upon the magnitude of gate current.
- Higher the gate current, lower is the forward breakover voltage(VBO).



SCR V-I Characteristics



SCR V-I Characteristics

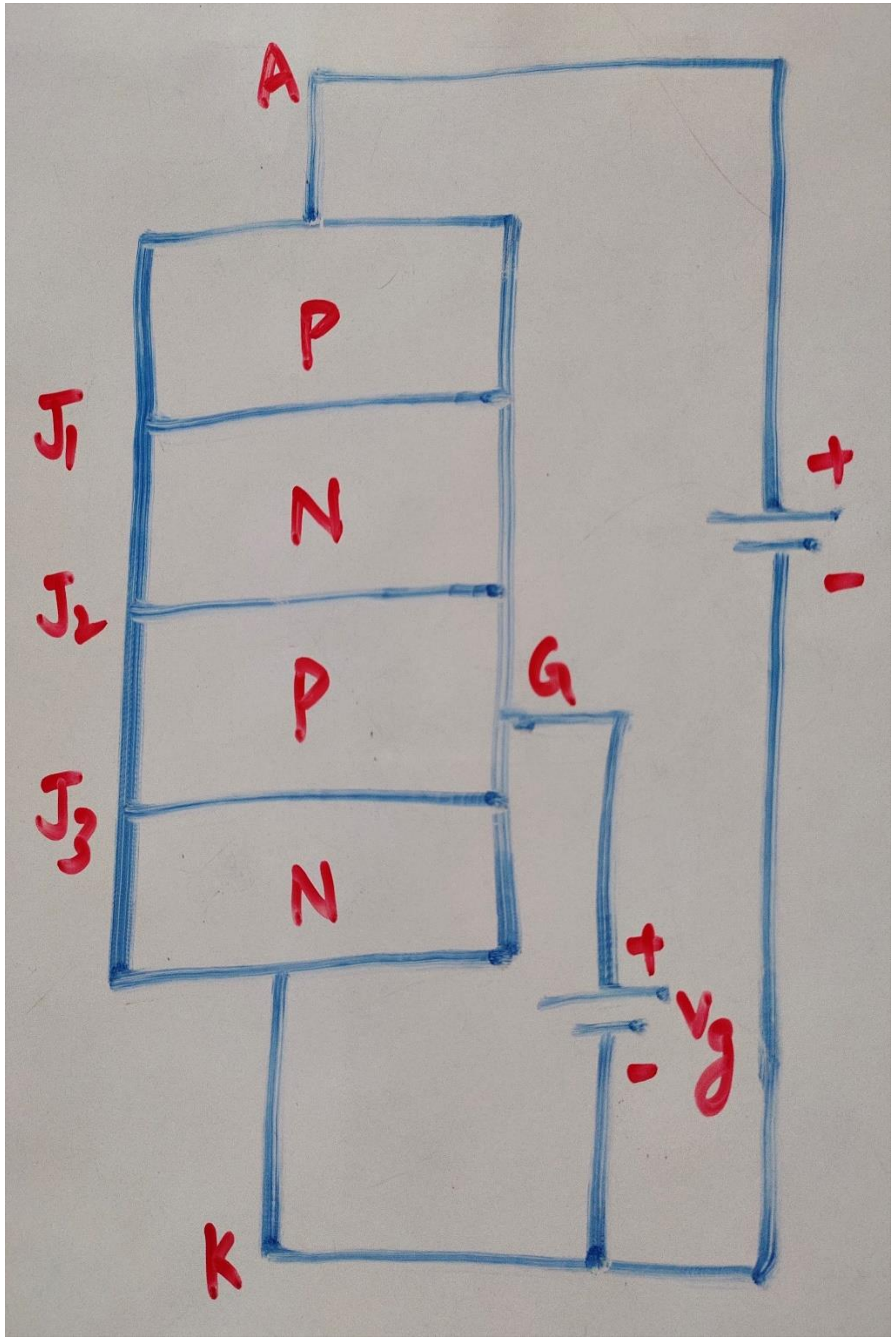


Switching Characteristics

- The Static characteristics gives no indication as to the speed at which the SCR is capable of being switched from the forward blocking voltage to the conducting state and vice-versa.
- However, the transition from one state to other does not take place instantaneously, it takes a finite period of time.
- The total turn-on time, t_{on} of the SCR is subdivided into three distinct periods, called the Delay time, Rise time and Spread time.
- These time periods are defined in terms of the waveforms of the anode voltage and current obtained in a circuit in which the anode-load consists of pure-resistance.

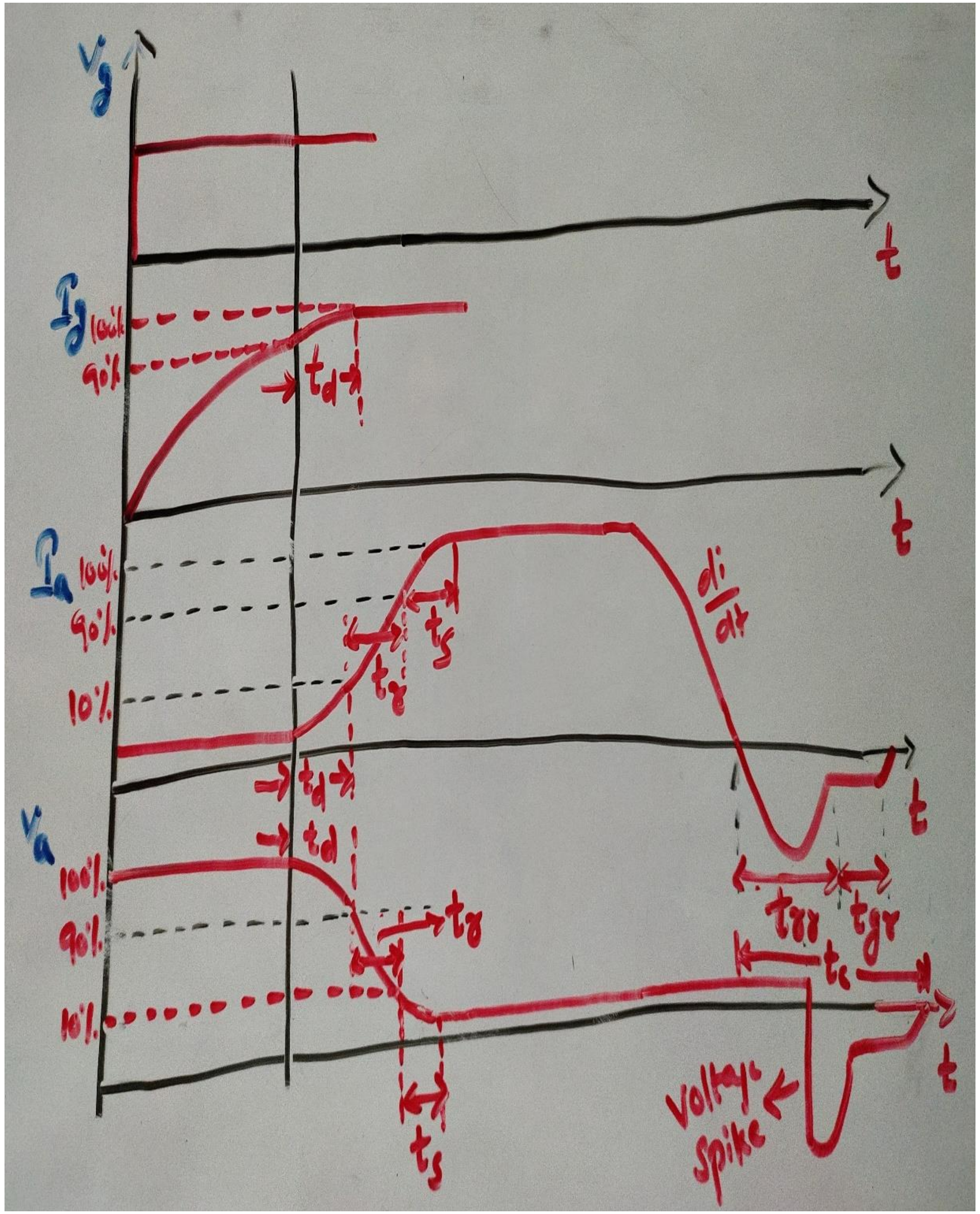
Turn-ON Characteristics of SCR

- These characteristics are also called Dynamic Characteristics.
- These characteristics deals with Turn-ON and Turn-OFF times.
- To Turn-ON the SCR, a forward biased voltage has been applied between Anode and cathode as shown in the figure.
- If we increase the gate current I_g, then SCR can reach the conduction state before reaching forward breakover voltage, V_{BO}.
- To increase the gate current, an voltage of V_g is applied between cathode and cathode terminals.



Turn-ON Characteristics of SCR

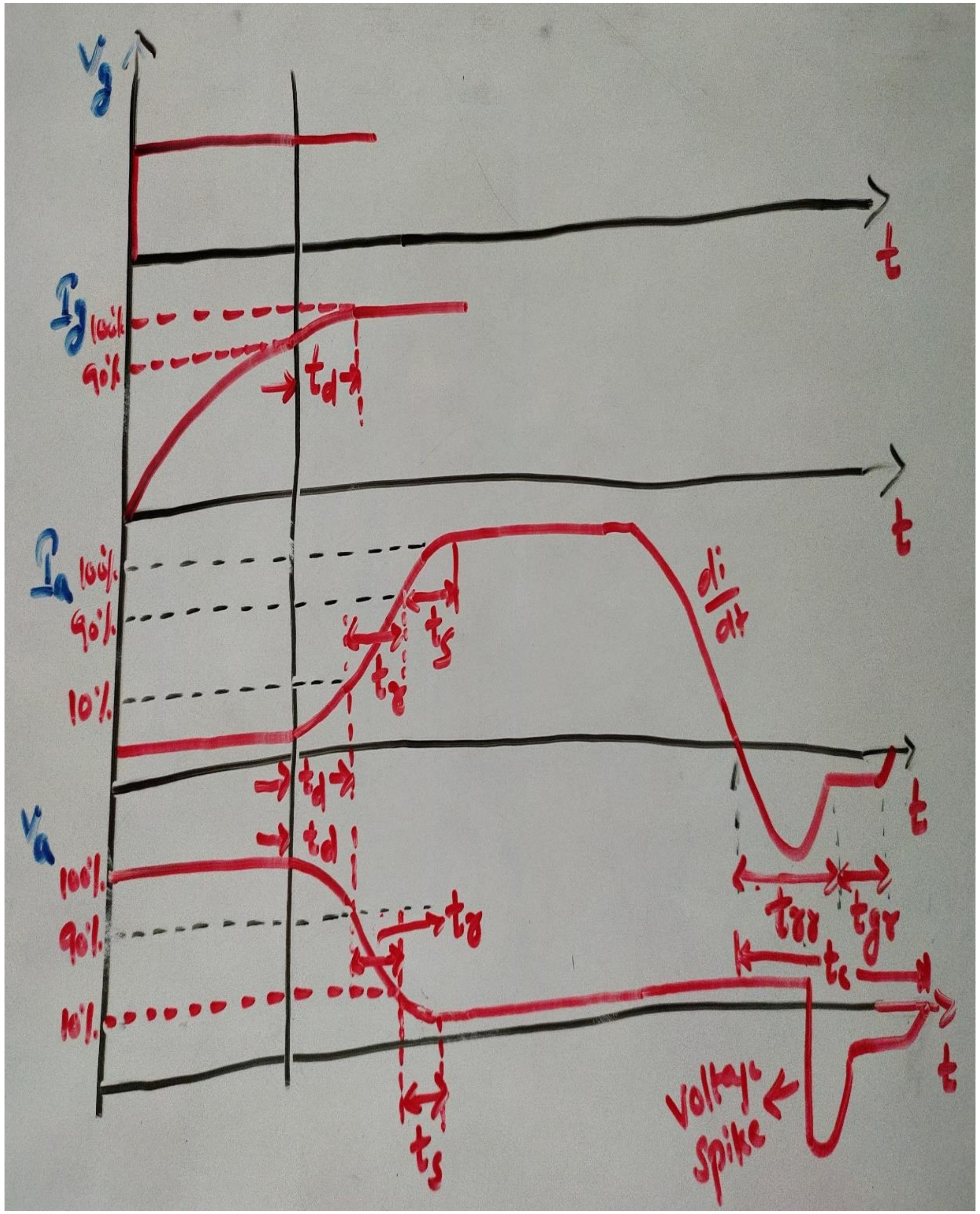
- When we apply a gate voltage V_g, gate current I_g will start flowing.
- At this condition, initially the anode current I_a is very low and anode voltage V_a is very high.
- As gate current increase from 90% to 100%, I_a increase from leakage current to 10% of its final value whereas the anode voltage falls from V_a to 90% of V_a.



Delay Time, t_d

From the characteristics, Delay time can be defined as follows.

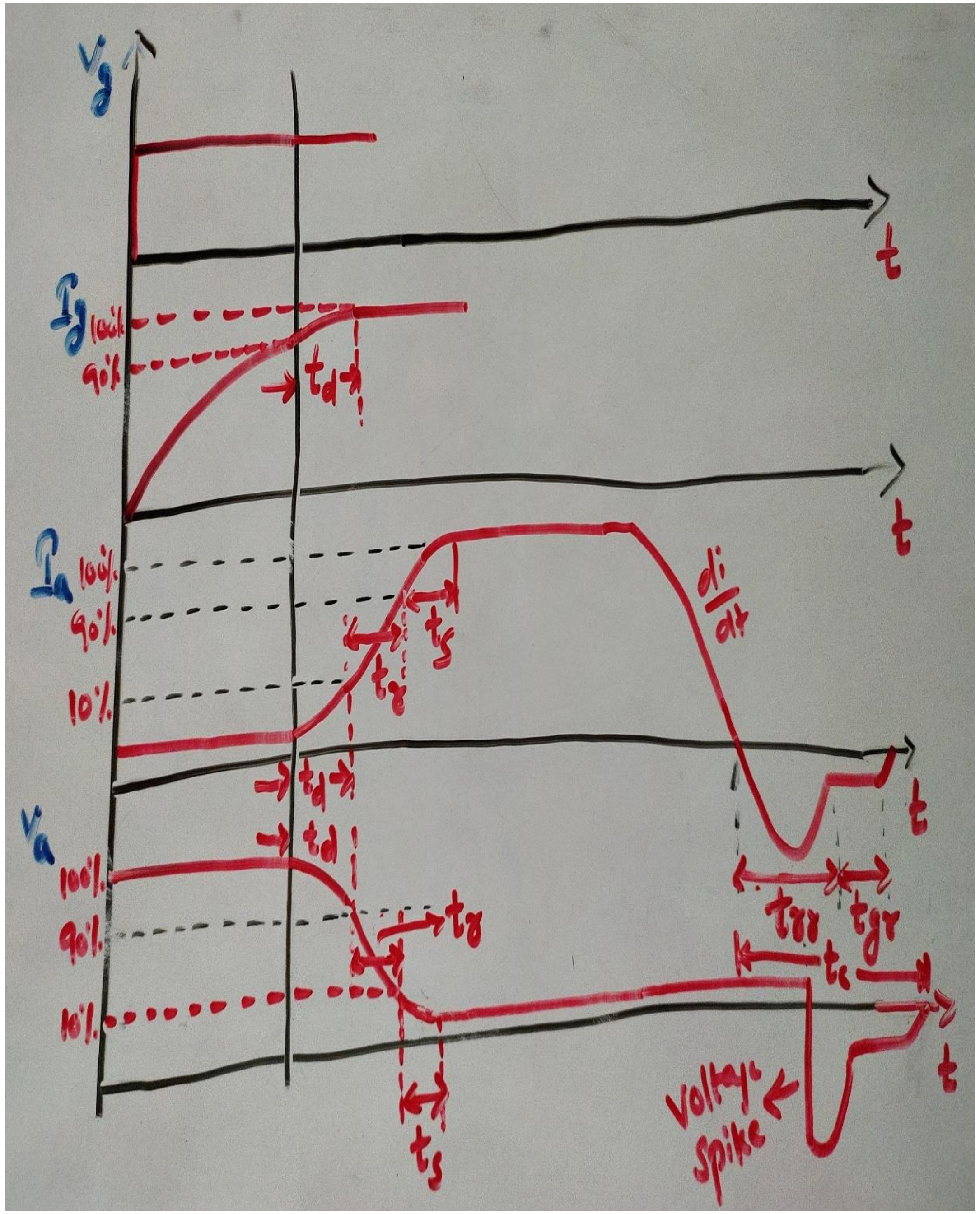
- It is the time during which the gate current reaches from 90% to its final value of I_g.
- It is the time during which the anode current reaches10% of its final value.
- It is the time during which anode voltage falls from V_a to 90% of V_a, where V_a is the initial value of the anode voltage.



Rise Time, t_r

From the characteristics, Rise time can be defined as follows.

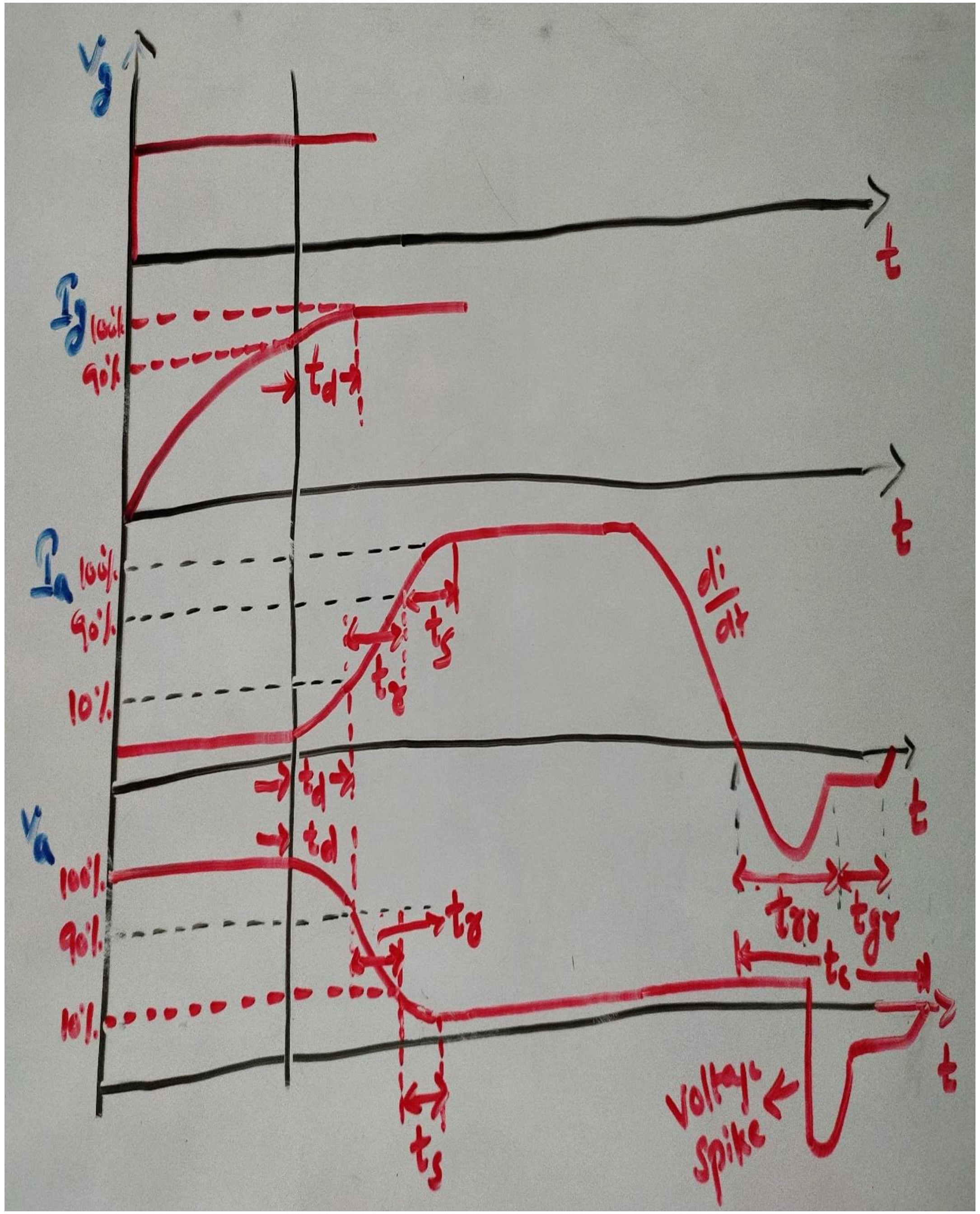
- It is the time required for the anode current to rise from 10% to 90% of its final value.
- It is the time required for the anode voltage to fall from 90% to 10% of its initial value.
- This time is inversely proportional to the magnitude of the gate current and its build up rate.
- The rise time t_r can be minimized if high and steep current pulses are applied to the gate.



Spread Time, ts

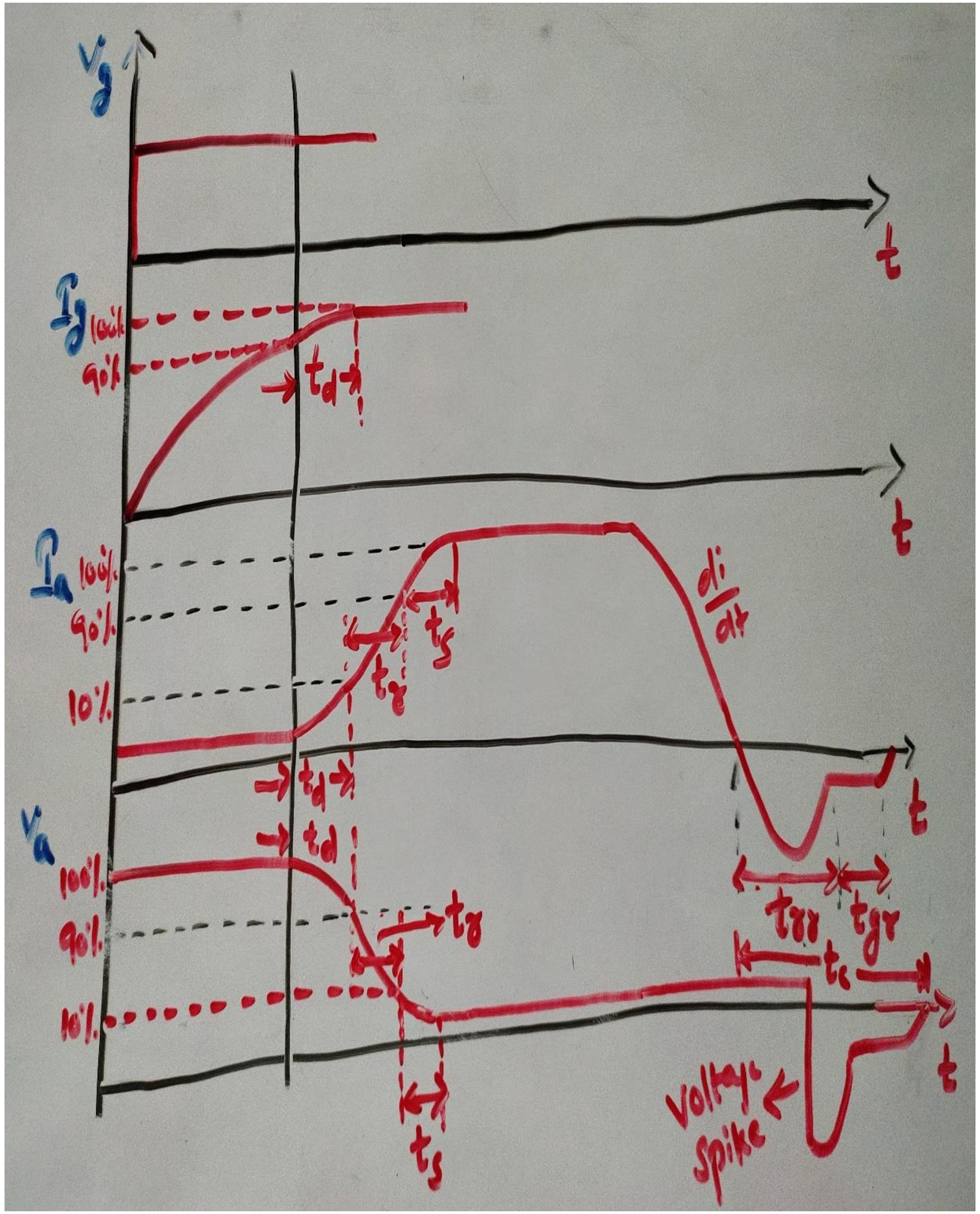
From the characteristics, Spread time can be defined as follows.

- It is the time required for the anode current to rise from 90% to 100% of its final value.
- It is the time required for the anode voltage to fall from 10% to forward conducting voltage(1 to 1.5v).
- Turn-ON time is the sum of the delay time, rise time and spread time.
- This is typically of the order of 1 to 4 micro seconds and depends upon the anode current circuit parameters and the gate signal wave shapes.



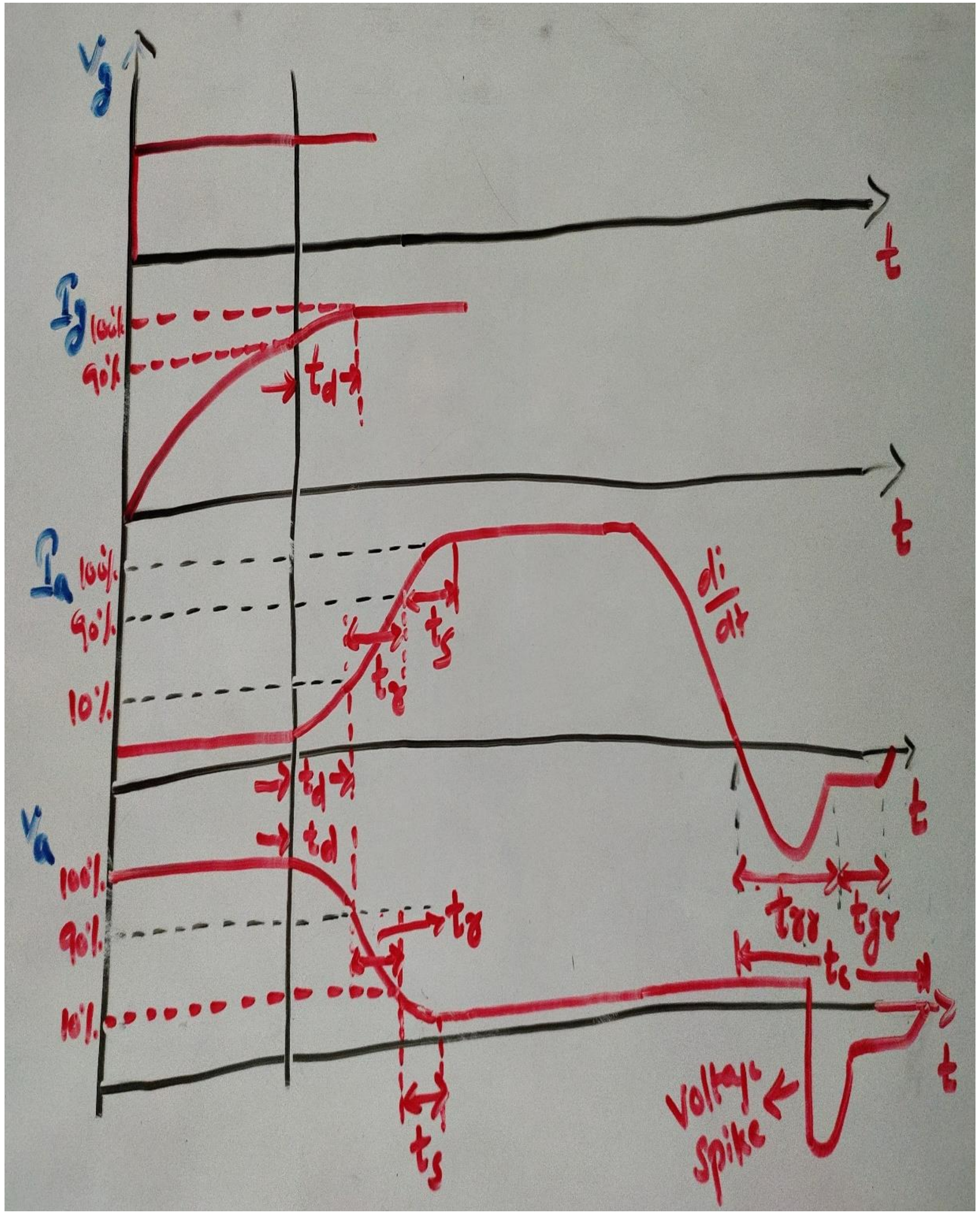
Turn-OFF Characteristics of SCR

- Once SCR Turn-ON, there will be charge carriers present at all the three junctions.
- To Turn-OFF the SCR, we need to remove the complete charge carriers across the three junctions.
- The time required to remove the charge carriers from the junctions J1 andJ3 is called Reverse Recovery time(t_{rr}).
- The time required to remove the charge carriers from the junction J2 is called Gate Recovery time(tgr).



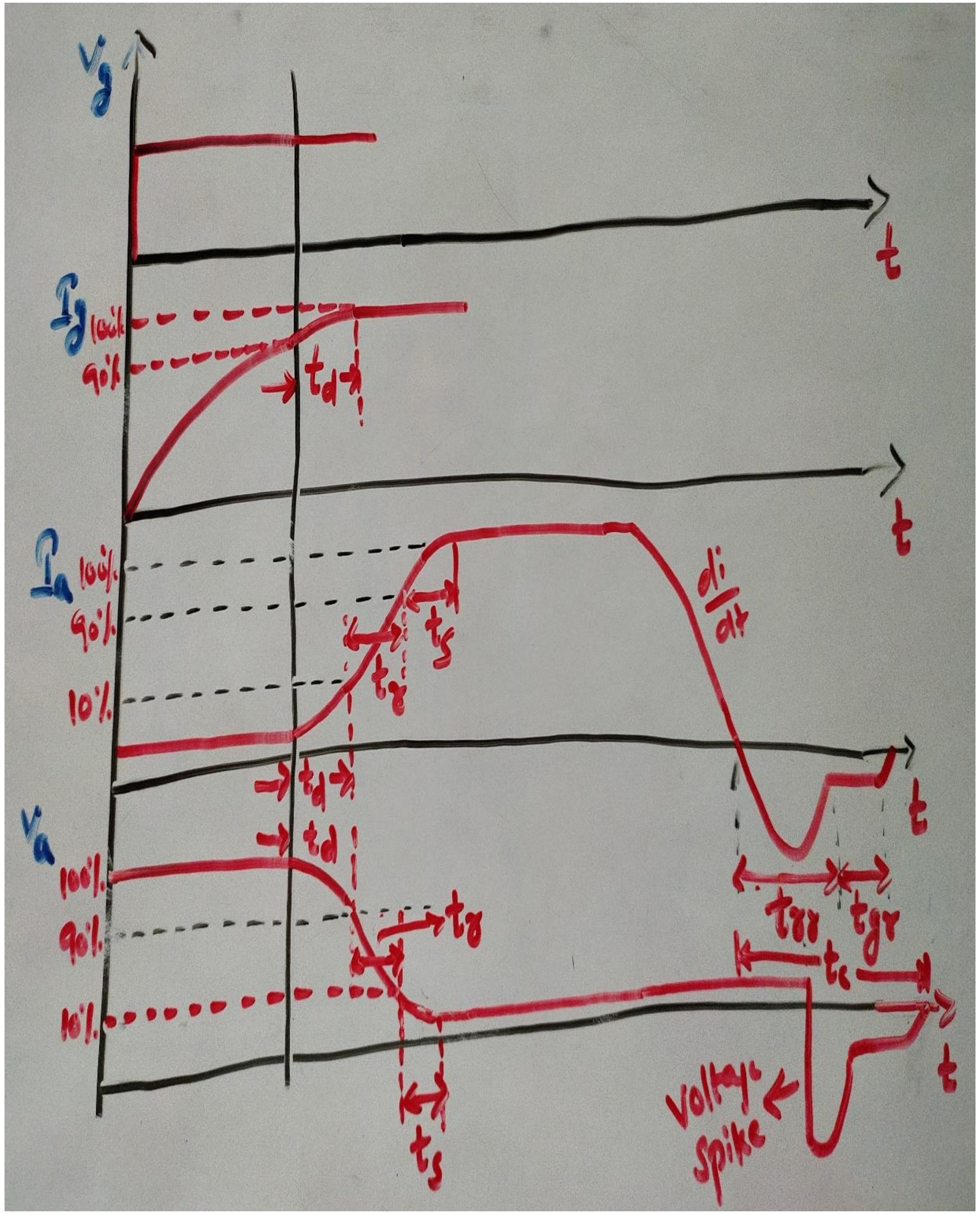
Turn-OFF Characteristics of SCR

- Turn OFF time is the sum of the reverse recovery time and the gate recovery time.
- To turn-OFF the SCR, the anode current should be decreased below the holding current.
- The anode current decrease with a rate of dI/dt and reaches to a negative maximum value and then increase to reach steady state value and finally attain zero value.
- It reaches negative maximum because of the presence of charge carriers at the junctions J1, J2 and J3.

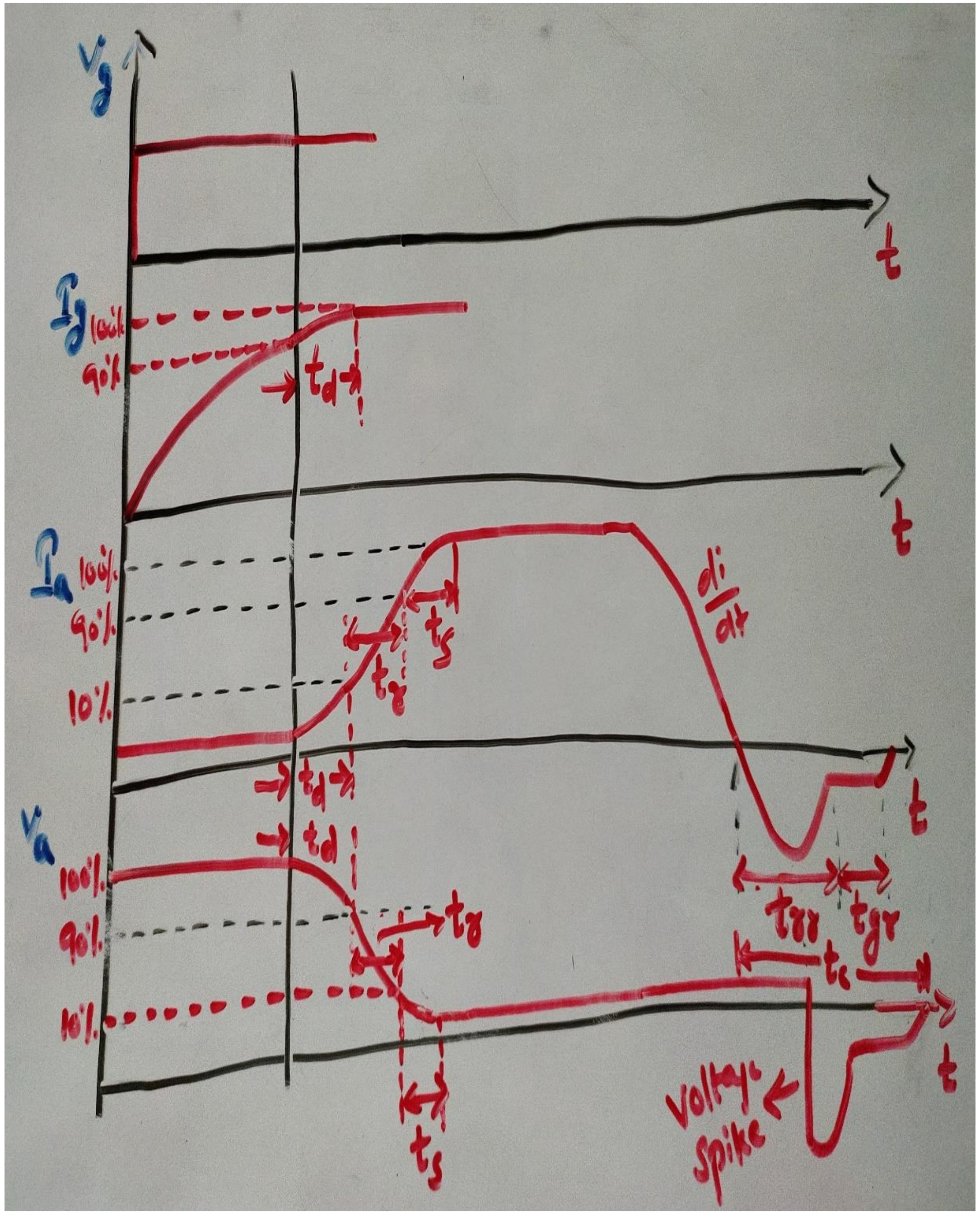


Turn-OFF Characteristics of SCR

- As the anode current reaches negative maximum, the anode voltage has a spike and after the removal of charge carriers at the junctions J1 and J3, it reaches to zero as shown in the figure.
- The SCR is OFF but there are some charge carriers present at the junction J2.
- To make it completely OFF, we have to remove the charge carriers present at the junction J2 and the time required for removing the charge carriers at the junction J2 is called Gate recovery time(t_{gr}).



Turn-OFF Characteristics of SCR



- The time required from anode current reaches to zero to anode voltage reaches to zero is called the Circuit Turn-OFF time(t_c).

Gate Characteristics of SCR

- In an SCR, the gate is connected to the cathode through a PN junction and resembles a diode. Therefore, the V-I characteristics of a gate is similar to a diode but varies considerably in units.
- The circuit which supplies firing signals to the gate must be designed :

    1. To accommodate these variations

    2. Not to exceed the maximum voltage, and power capabilities of the gate

    3. To prevent triggering from false signals or noise, and

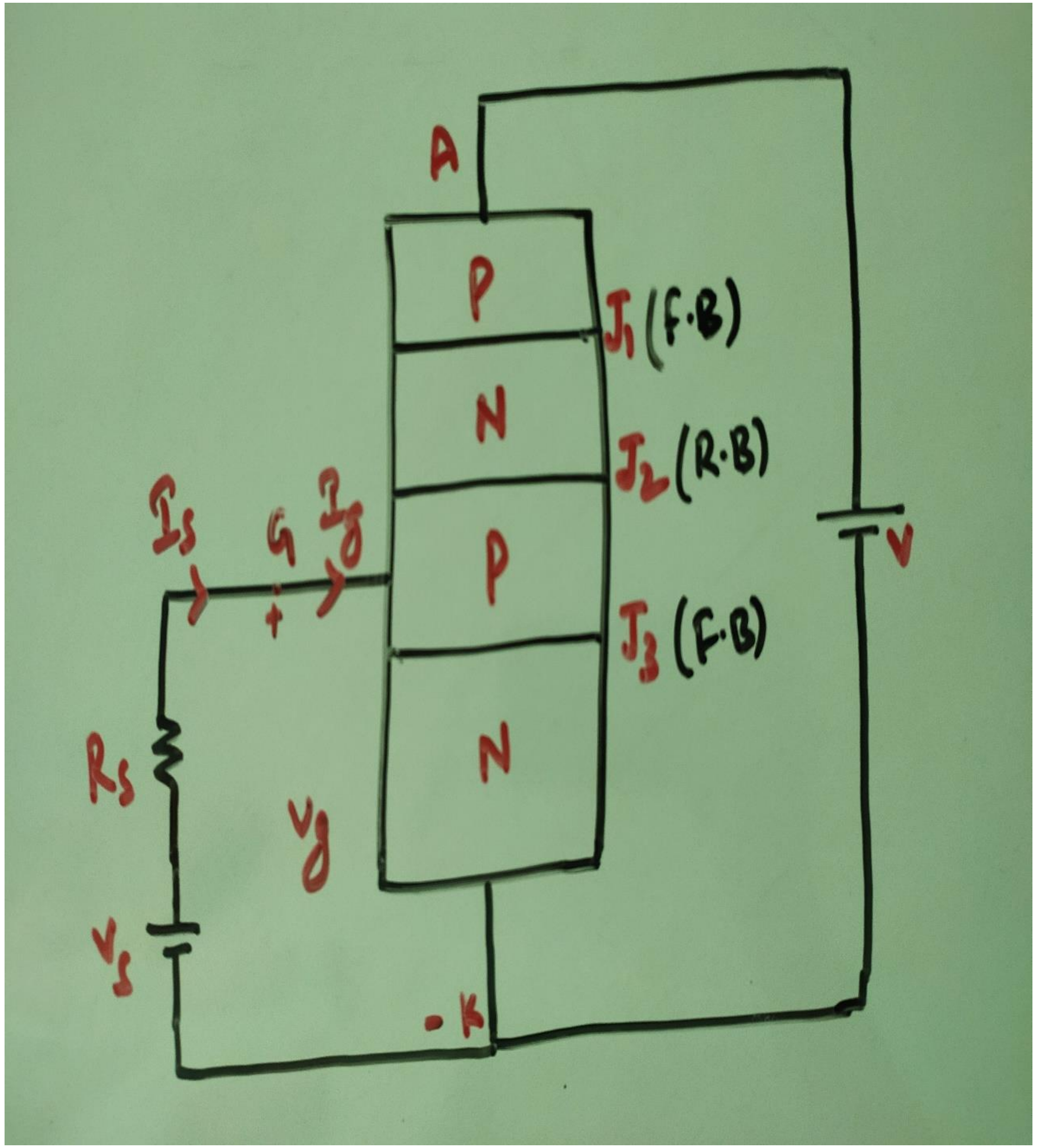
    4. To assure desired triggering.

- The design specification pertaining to gate characteristics are usually provided by the manufacturers.

Gate Characteristics of SCR

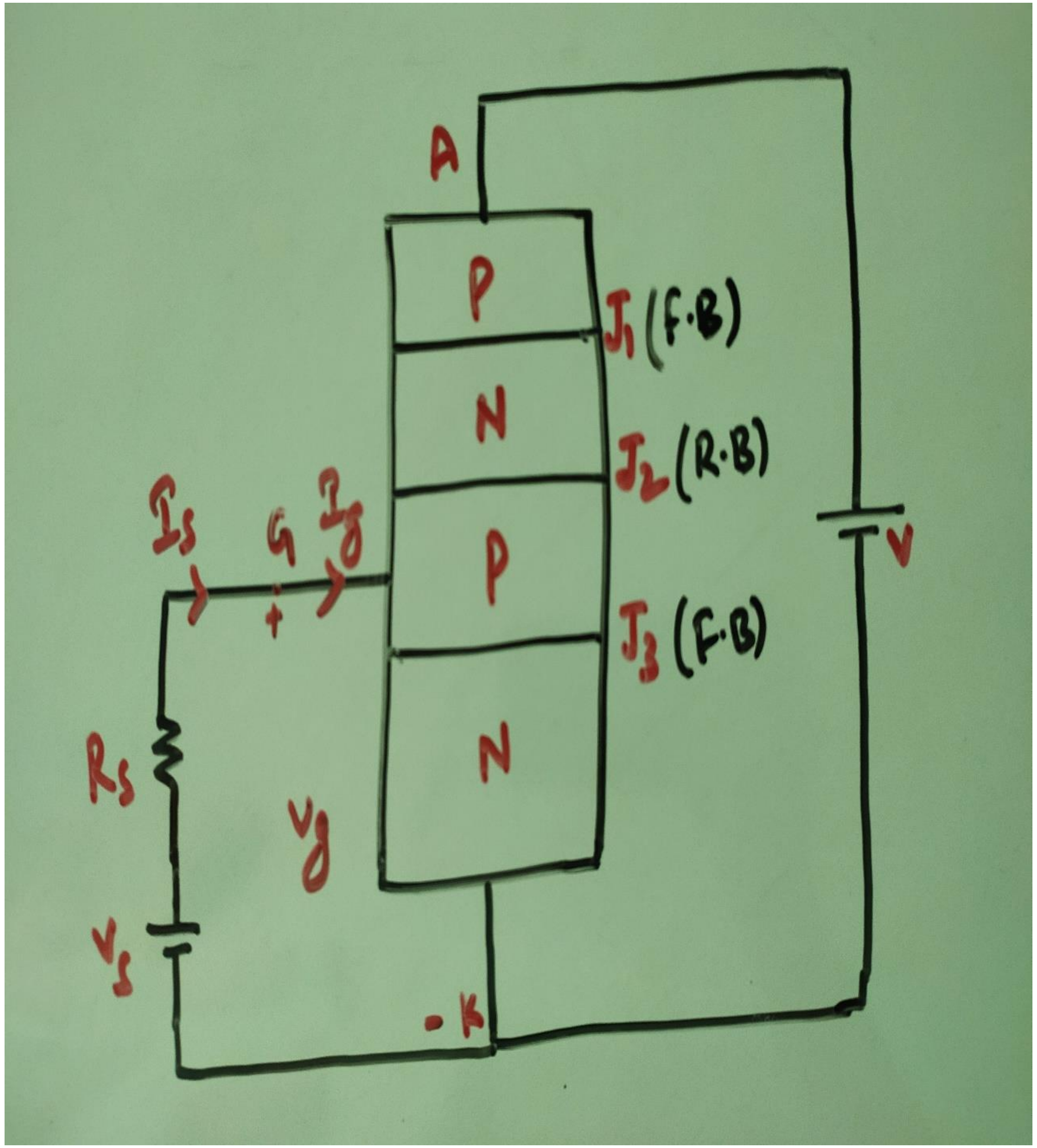
Let

- Vs= Gate sourse voltage
- Is= Gate source current
- Rs= Gate source resistance
- Vg= gate voltage or Trigger voltage
- Ig= Gate current
- Pg(avg)= Vg*Ig



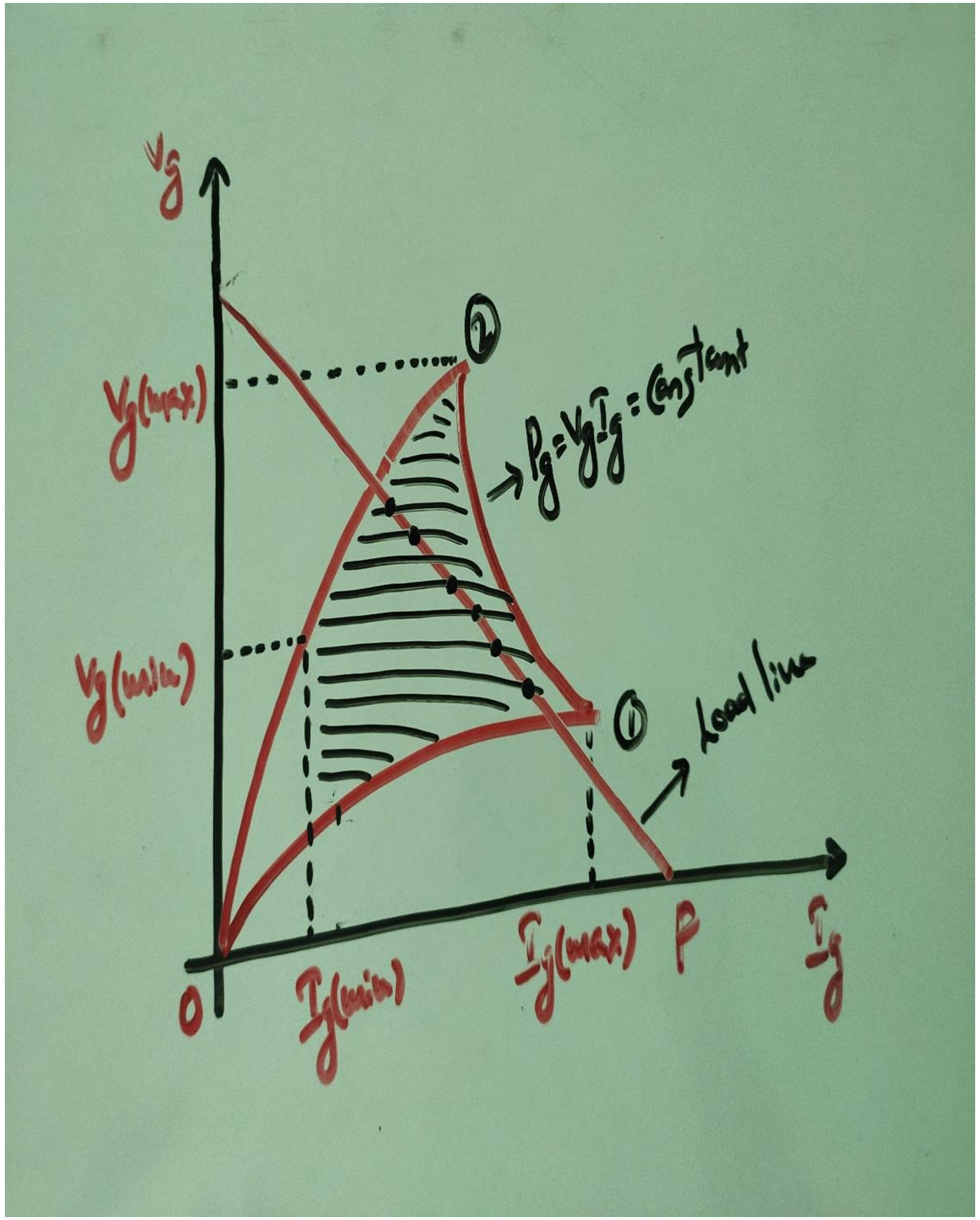
Gate Characteristics of SCR

- Figure shows an SCR in forward blocking mode and to trigger the SCR, an voltage “Vg” is applied between the gate and cathode terminals and hence a current, “Ig” flow in the circuit.
- As the Junction “ J3” is present in between the gate and cathode, the gate characteristics are related to this junction only.
- Hence we need to draw the forward bias characteristics of a PN junction at J3.

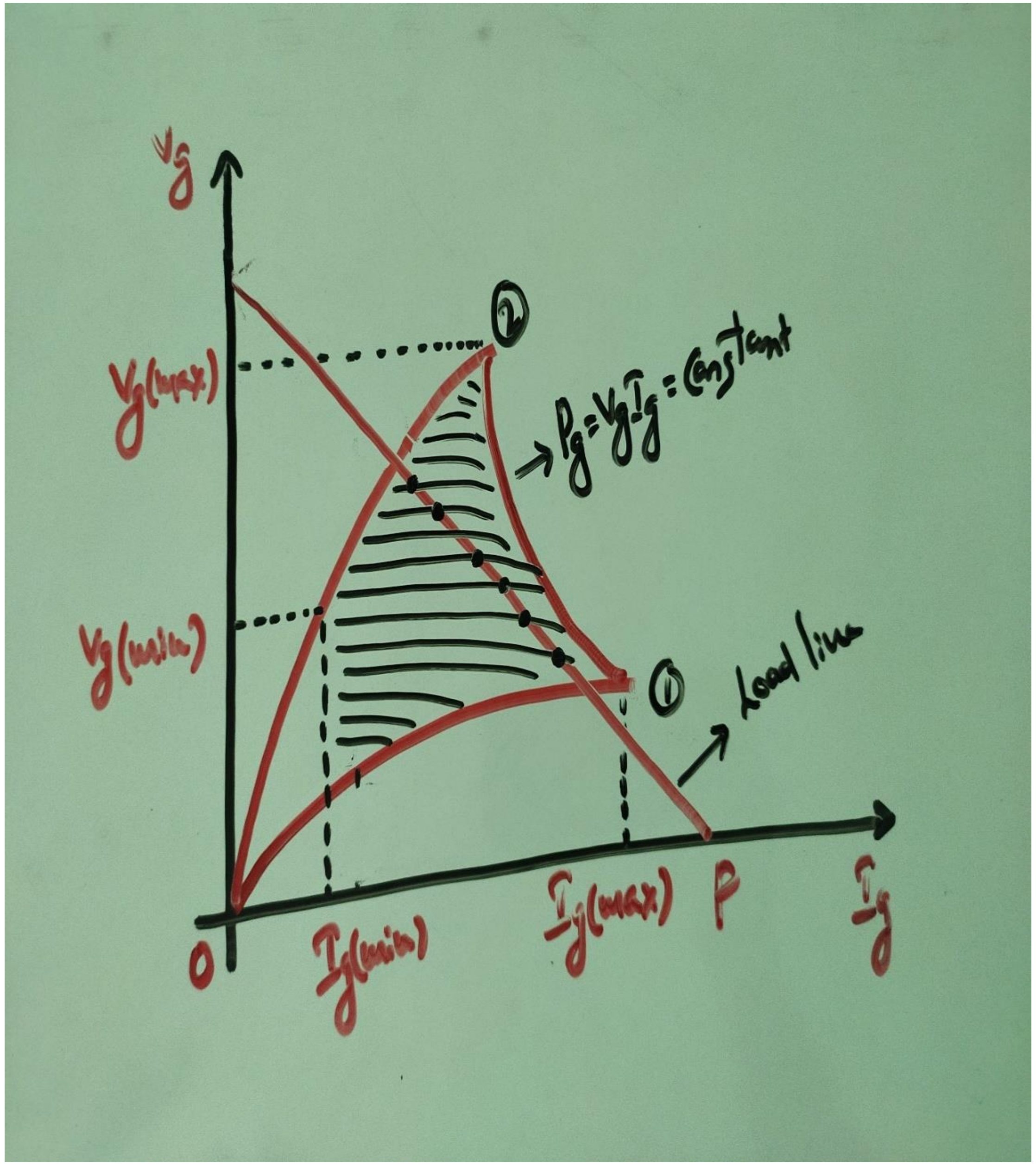


Gate Characteristics of SCR

- In a highly doped junction, the breakdown strength is low and thereby fast breakdown occurs and hence Maximum amount of current will flow.
- Hence the change in the current is fast and the change in the voltage is slow (curve-1).
- For a lightly doped junction, the change in the current is slow and the change in the voltage is fast (curve-2).



Gate Characteristics of SCR



- Represent Ig(max) and Vg(max) values in the characteristics.
- Gate power, $P_g = V_g * I_g =$ constant. This represent a characteristic of Rectangular Hyperbola.
- In order to provide the power to the gate circuit, a practical voltage source is needed.

Gate Characteristics of SCR

Draw the Load line:

From the circuit,

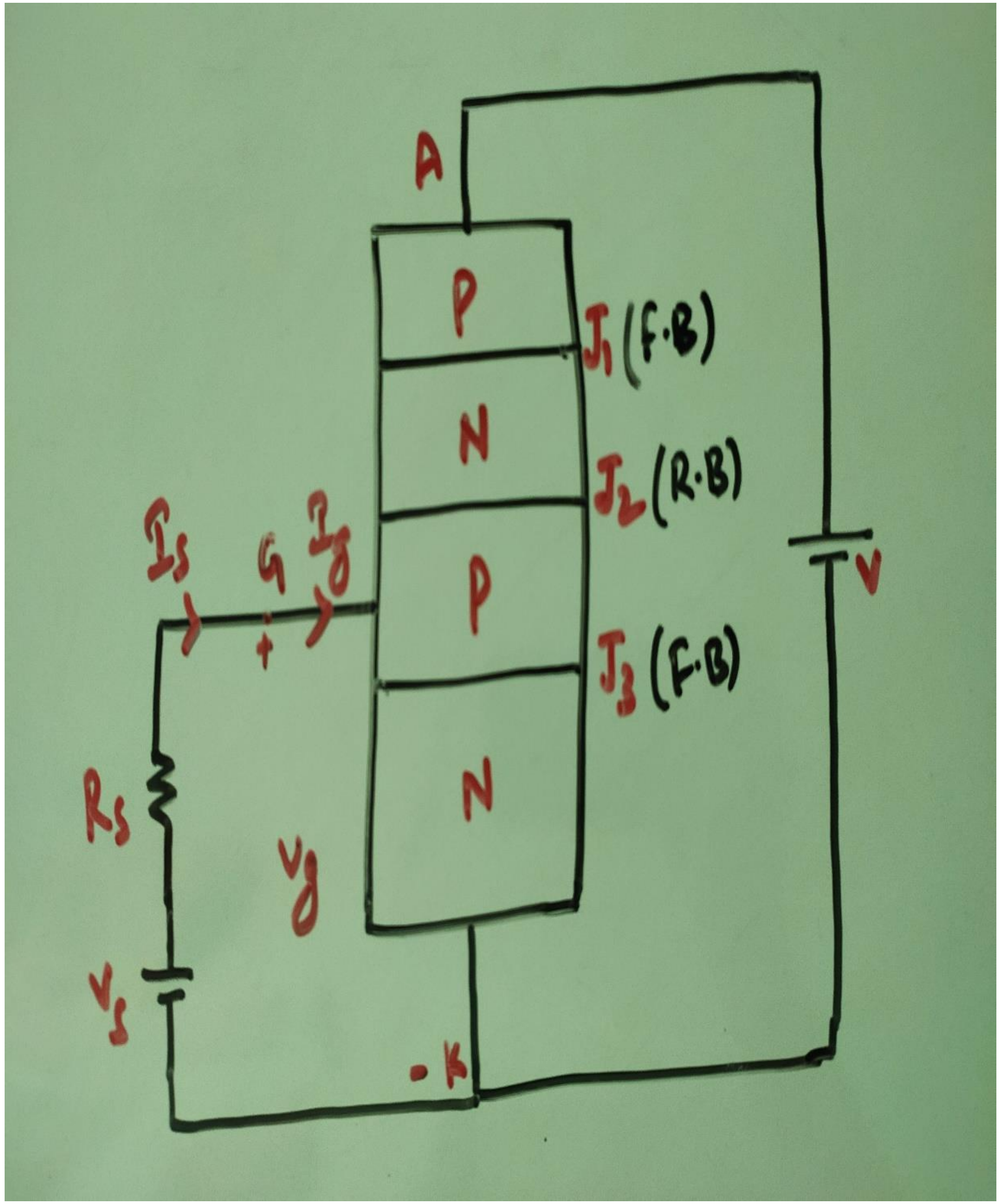
$$I_g = I_s \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$$V_S = I_S * R_s + V_g \ldots\ldots\ldots(2)$$

Substitute equation(2) in equation(1),

$$V_S = I_g * R_s + V_g \ldots\ldots\ldots(3)$$

We can draw the load line by using the equation (3).



Gate Characteristics of SCR

Draw the Load line:

Case 1:

Put $V_g=0$ → $V_s= I_g*R_s$

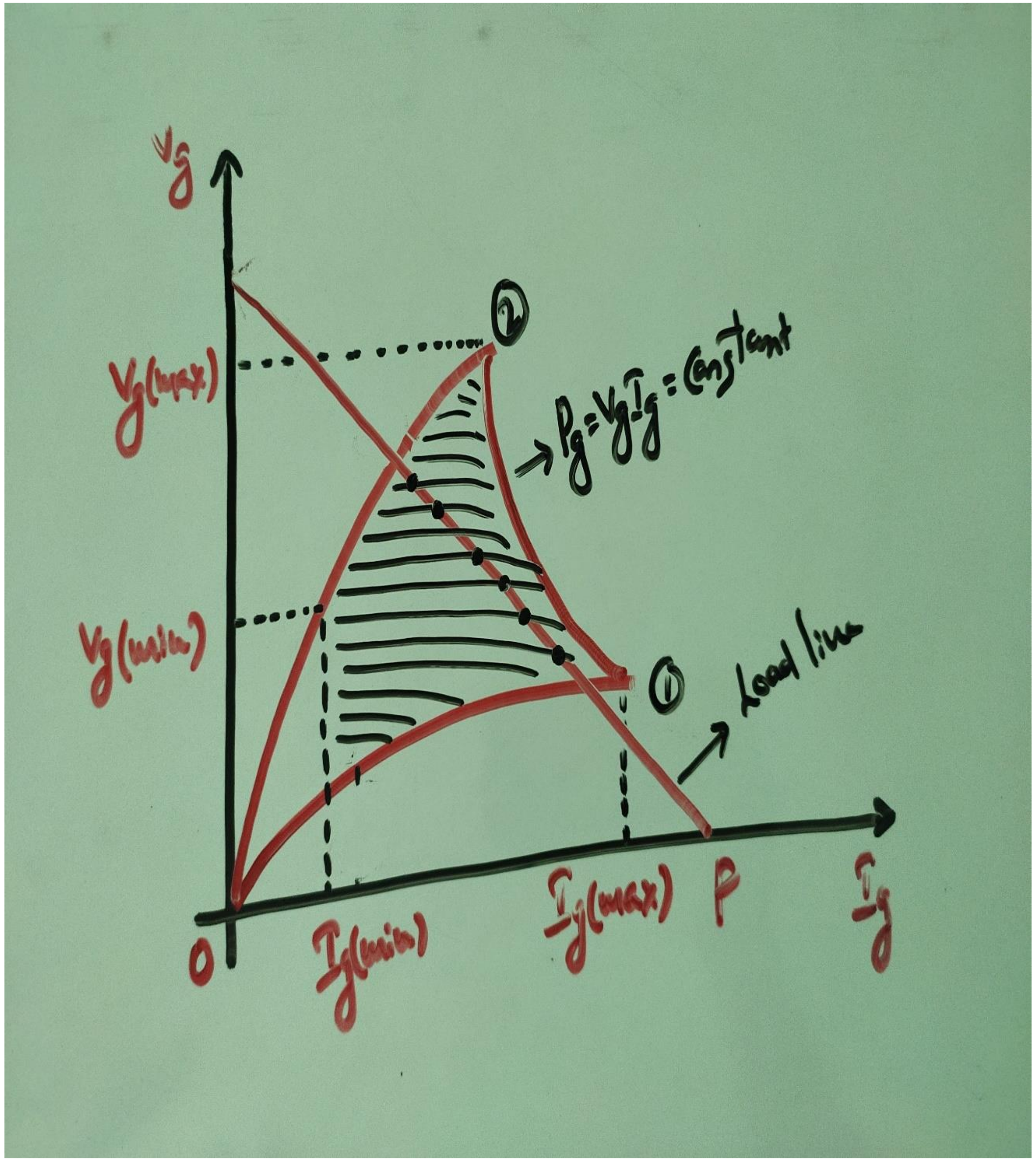
→ $I_g= V_s/R_s$….(4)

P represent the **“V_s/R_s”** in equation (4).

Case 2:

Put $I_g=0$ → $V_s= V_g$……(5)

Q represent the value of **“V_s”** in equation (5).



Gate Characteristics of SCR

Draw the Load line:

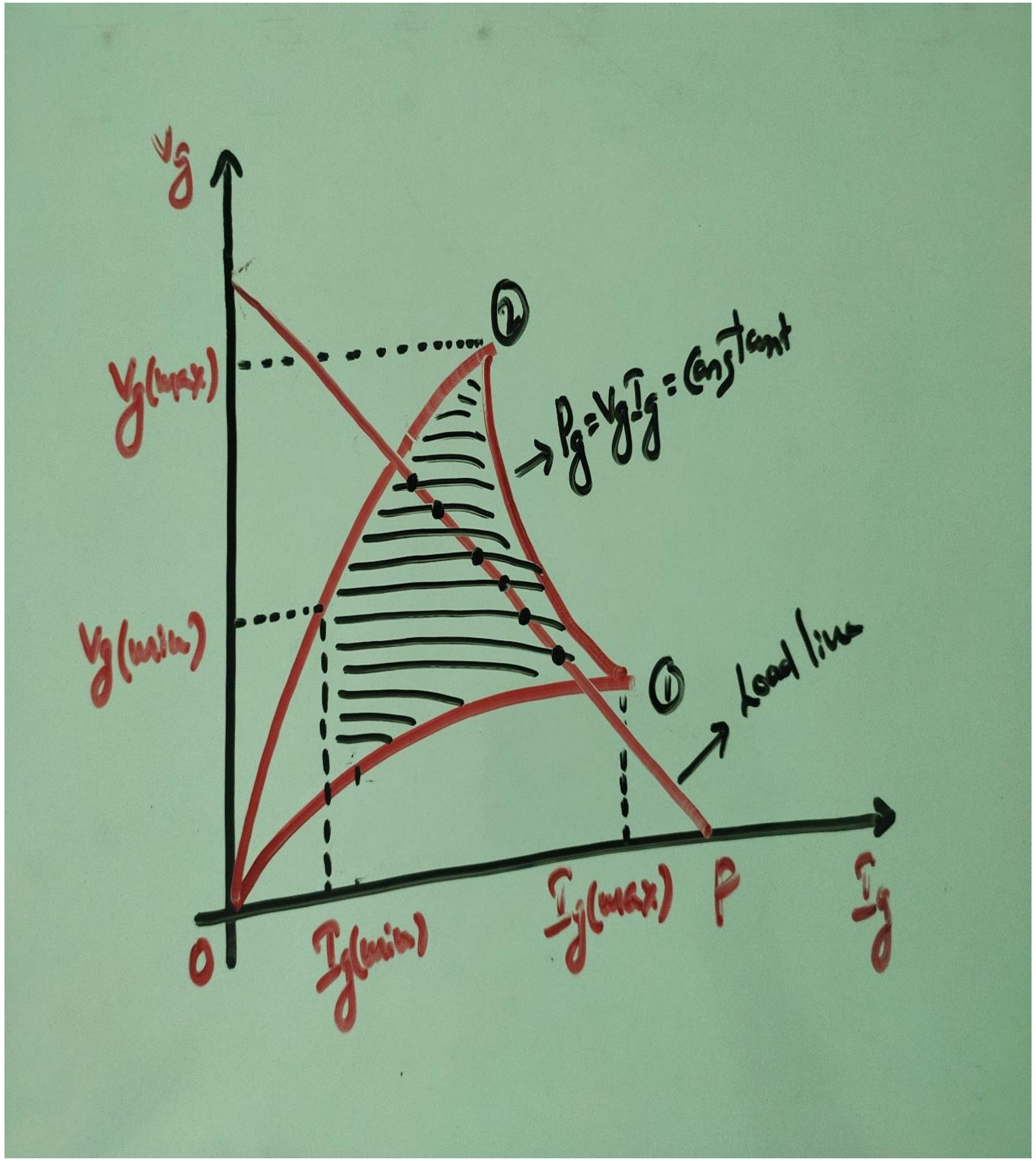
- Now join the points **P** and **Q**.
- The line obtained is called **“Load Line”.**
- The slope of the line is negative and is equal to R_s.

$$V_g = V_s - I_g * R_s \ldots\ldots(6)$$

The above equation is compared with the line equation

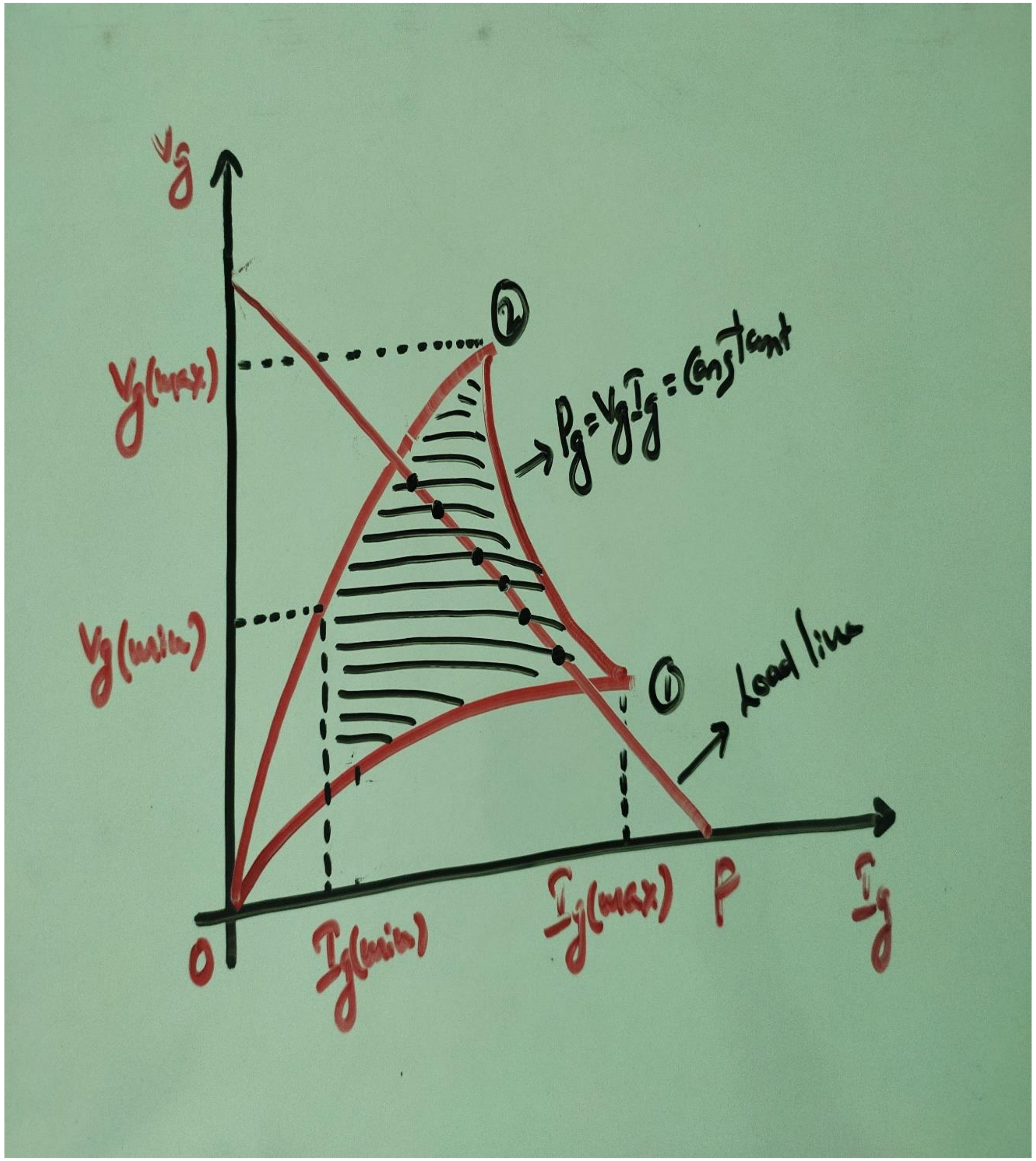
$$y = mx + C$$

$$\text{Slope} = -R_s$$



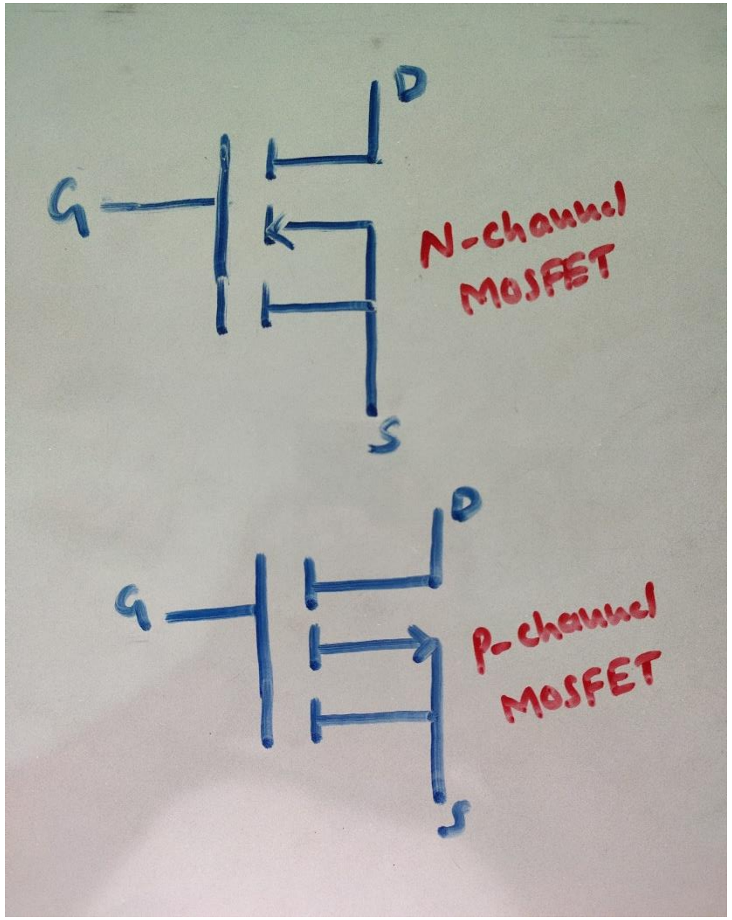
Gate Characteristics of SCR

- The SCR will operate in between the minimum and maximum limits.
- Hence Vg(min) and Ig(min) shown in the figure represent the minimum values of voltage and current below which the device cannot operate.
- If the device operates above the maximum limits, then the device will be damaged.
- The operating region is shown in the diagram with shaded lines.



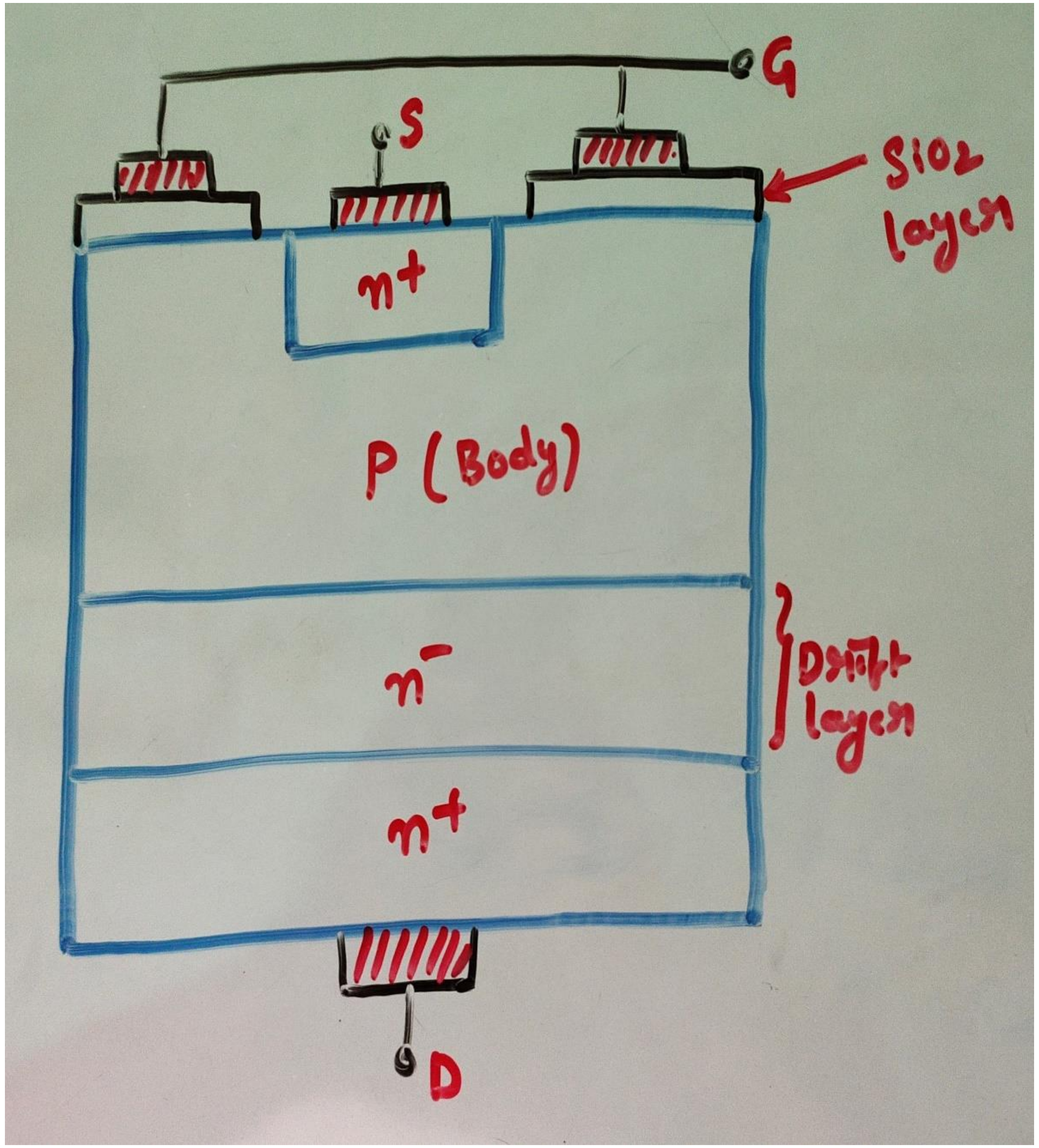
Power MOSFET

- Power MOSFET : Power Metal oxide semiconductor Field effect transistor
- It has high switching frequencies of about 100 KHz
- Low input current
- Voltage controlled device
- High switching speed
- They do not have the problem of second breakdown
- High input impedance



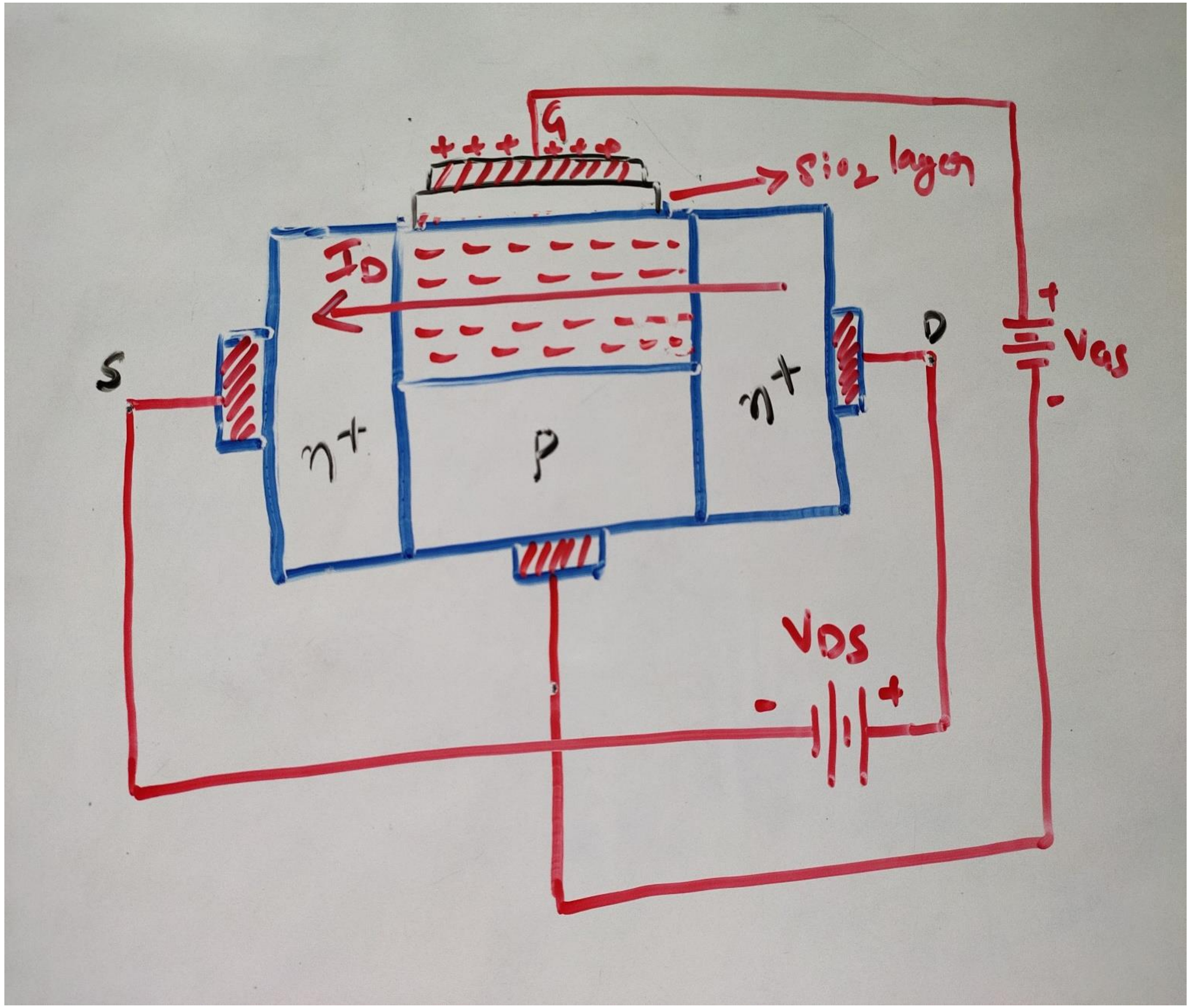
Power MOSFET

- Three terminals i.e., Gate , Drain and Source.
- SiO2 layer creates the Capacitance.
- Source and Drain are connected to the “n+” layers which are highly doped.
- The drift layer (n- region) improves switching speed and voltage handling capacity.



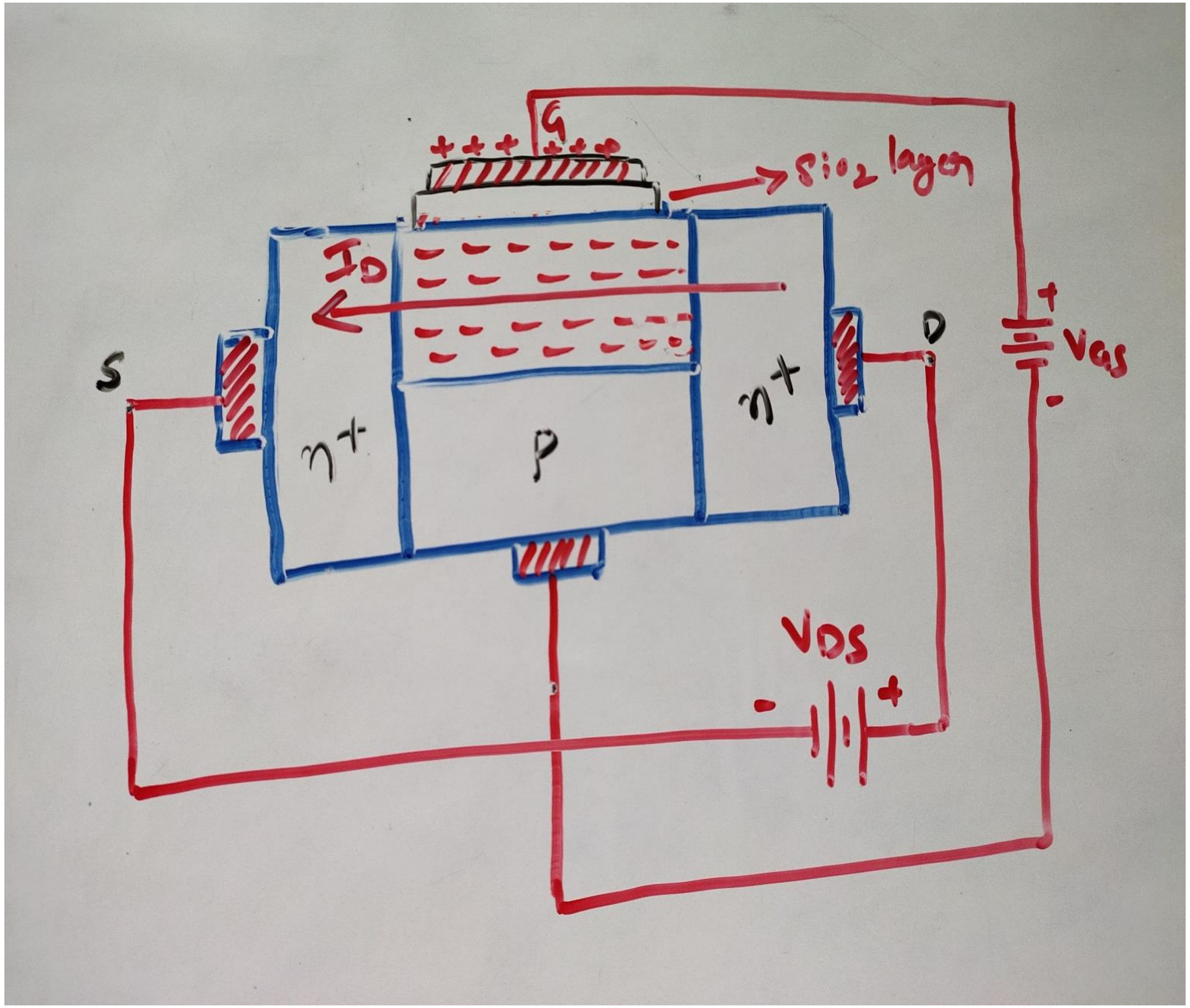
Working of Power MOSFET:

- When we apply the voltage **Vgs**, SiO2 layer acts as a Capacitor and hence induces **+ve charge** and **–ve charge** on the plates as shown in the figure.
- If we increase **Vgs, -ve charge** generation increases and finally it forms a channel.
- This channel is called **Induced channel** or **Inversion layer**.



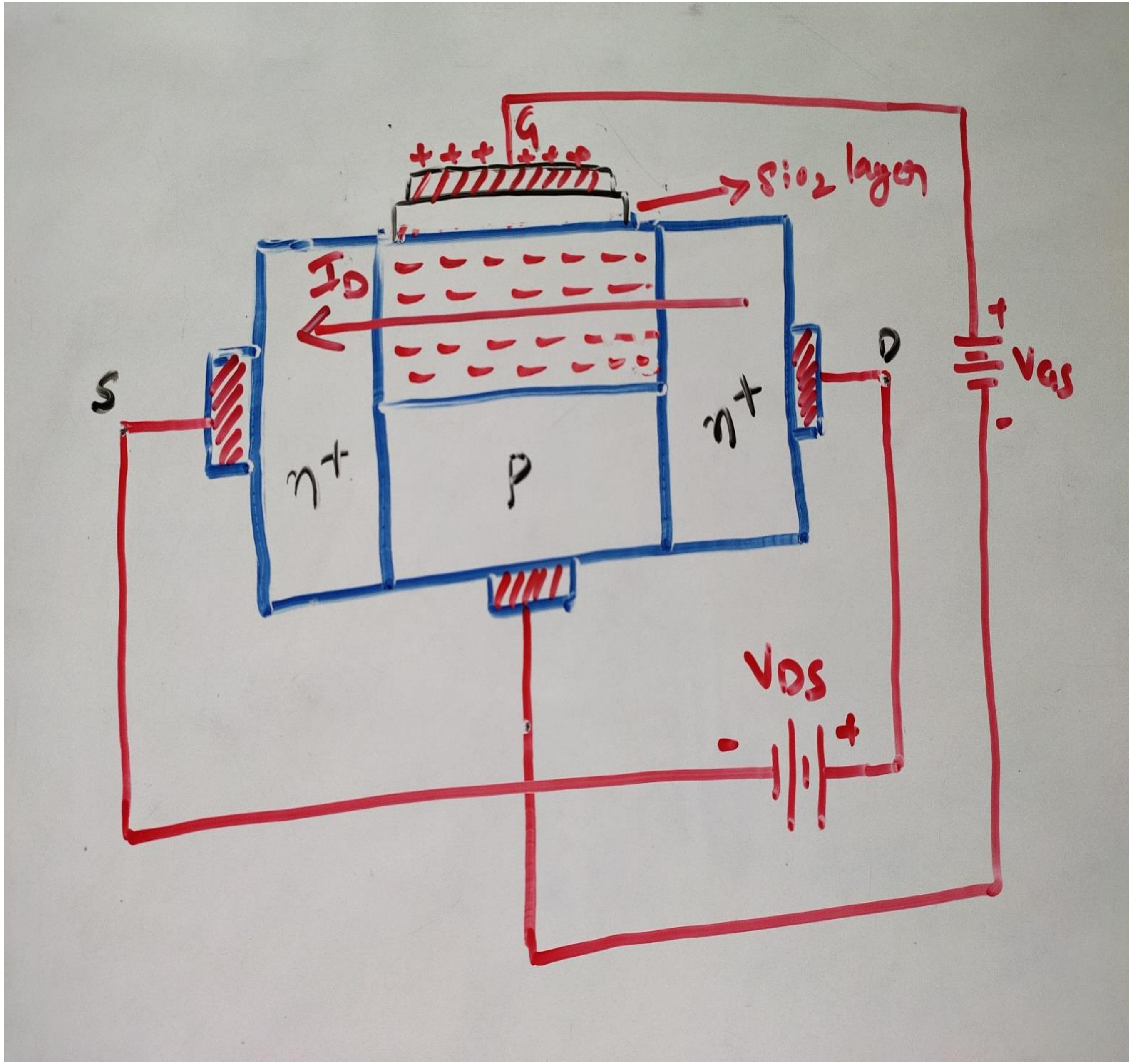
Working of Power MOSFET Contd..,,:

- Now connect the drain and source to a battery with the polarities as shown in the figure.
- In that case, drain current flow from the drain to the source.
- If there is no channel i.e., Induced channel which is formed due to increase in **Vgs voltage**, then there will be a depletion region in between both n+ layers and hence it does not allow the drain current to flow.



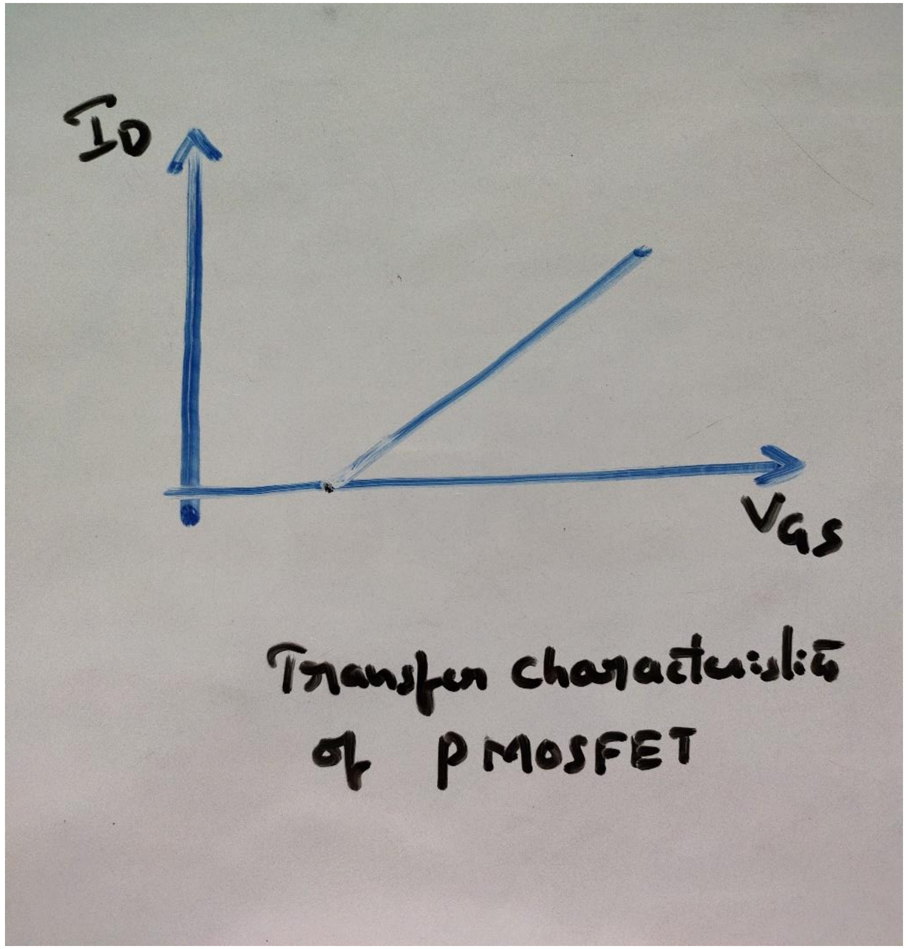
Working of Power MOSFET Contd..,,:

- Hence for the flow of drain current, there should be the induced channel and for this, we should increase **Vgs voltage**.
- Hence Power MOSFET is a **Voltage Controlled device.**

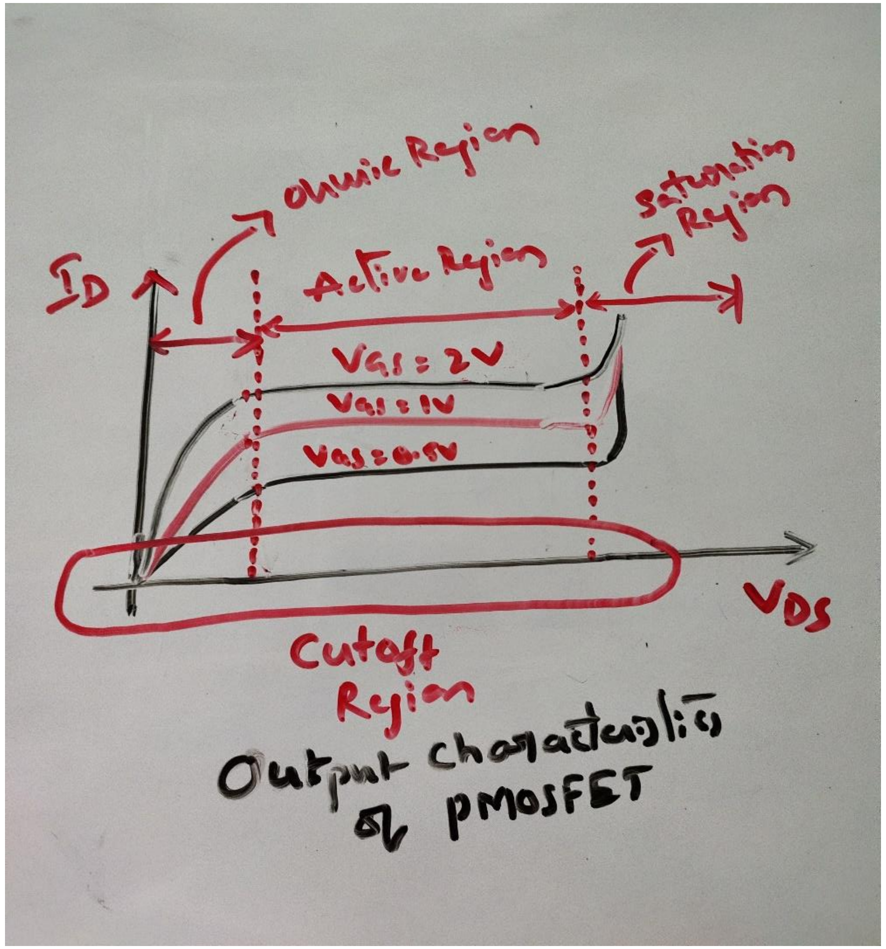


Characteristics of Power MOSFET

Transfer Characteristics

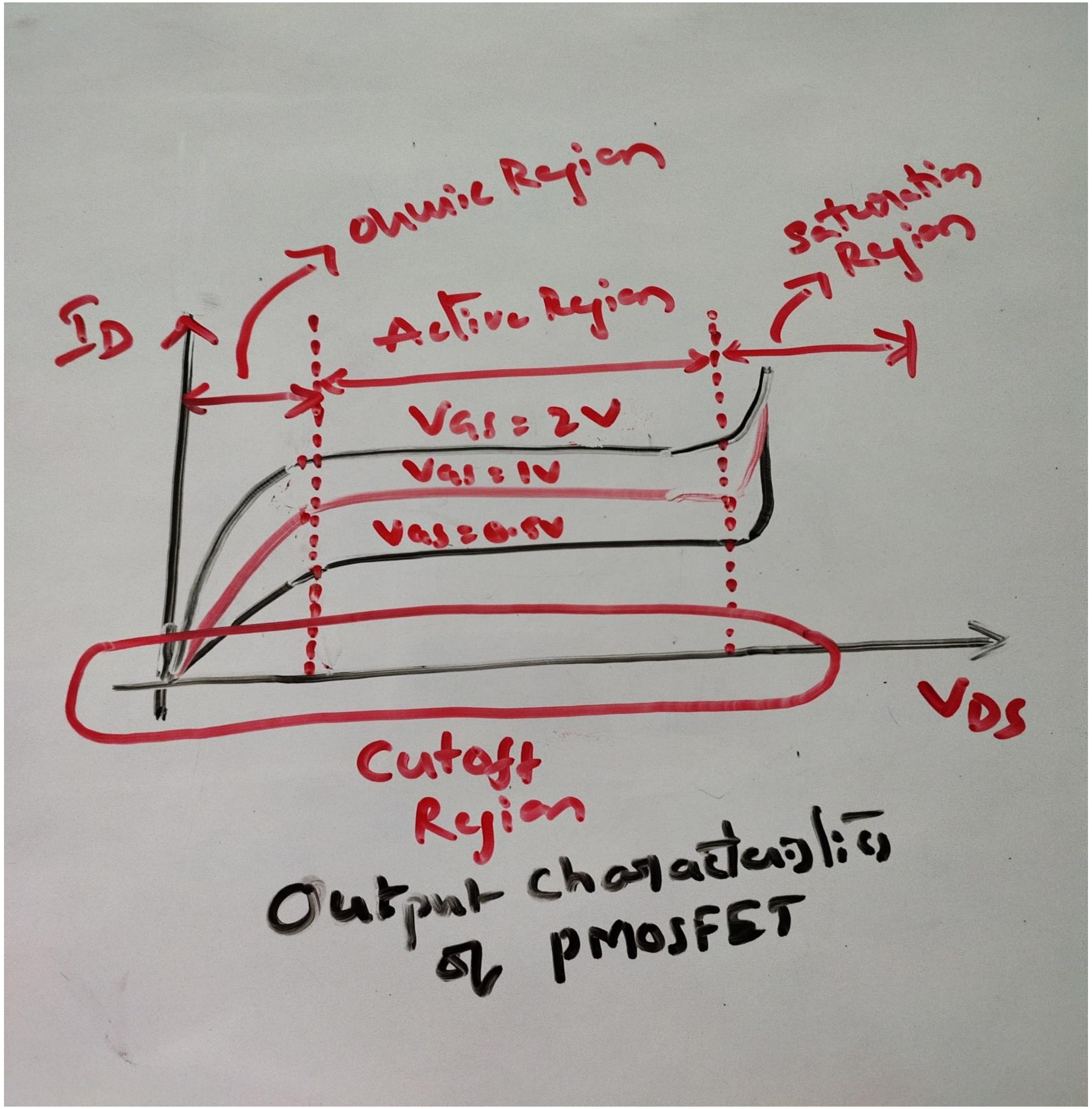


Output Characteristics



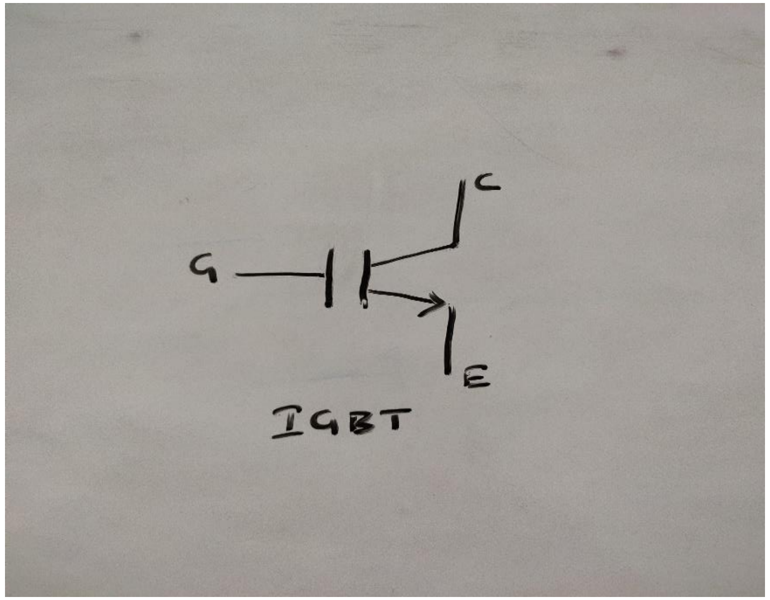
Characteristics of Power MOSFET contd..,,

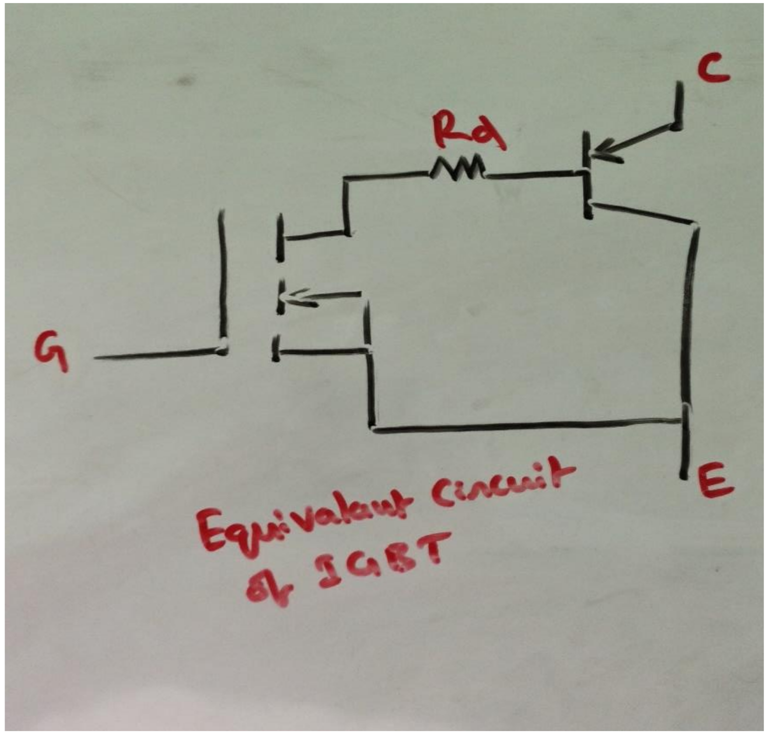
- In output characteristics, as we increase **Vds voltage**, initially drain current increases and this attains a constant value and after breakdown, there will be a high amount of flow of drain current.
- It was repeated for different values of **Vgs voltage** as shown in the figure.



Power IGBT

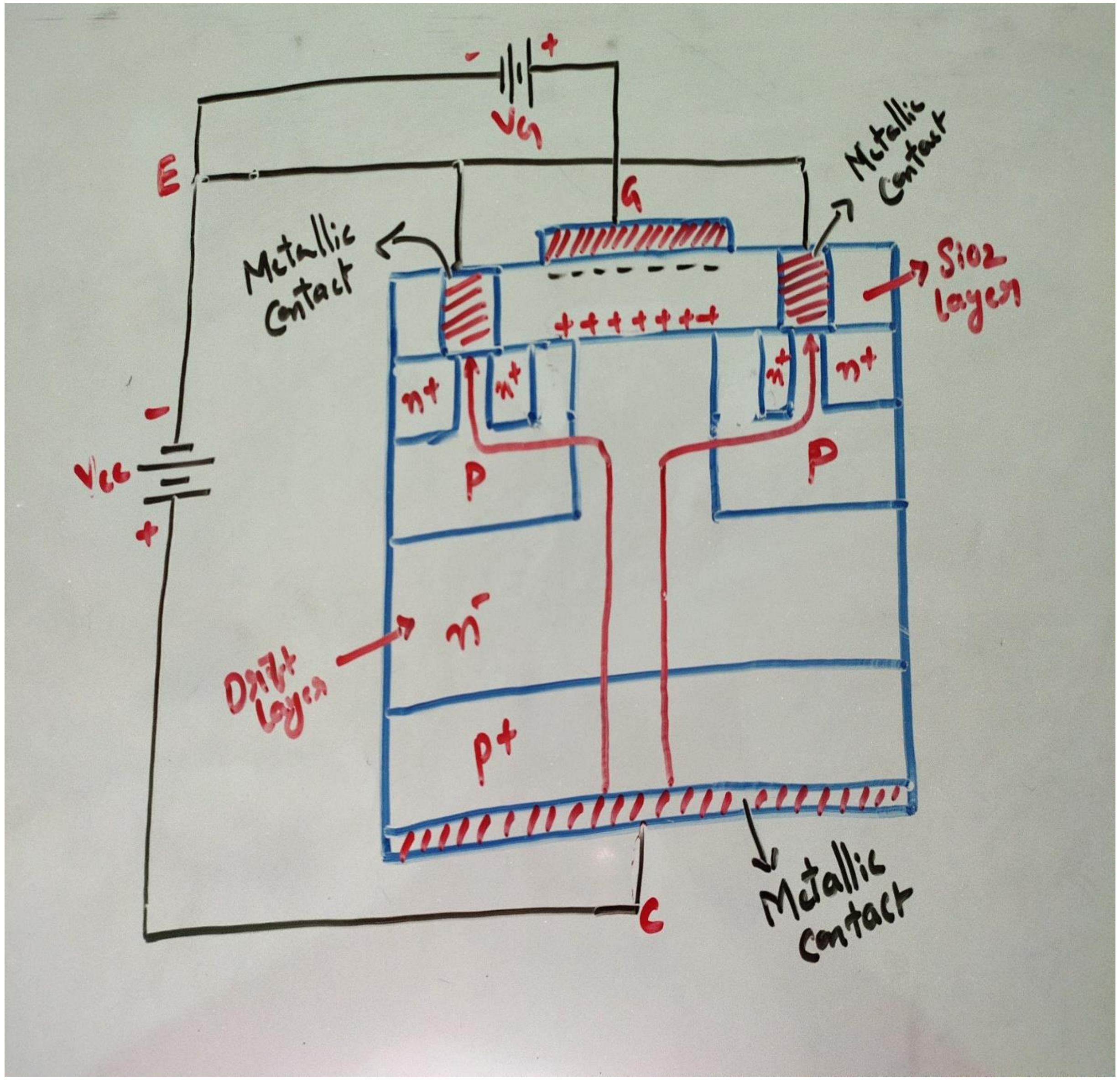
- It has the best combination quality of BJT and MOSFET
- It has high input impedance like MOSFET
- It has low ON state power loss as in BJT
- Three terminals i.e. Gate , Emitter and Collector





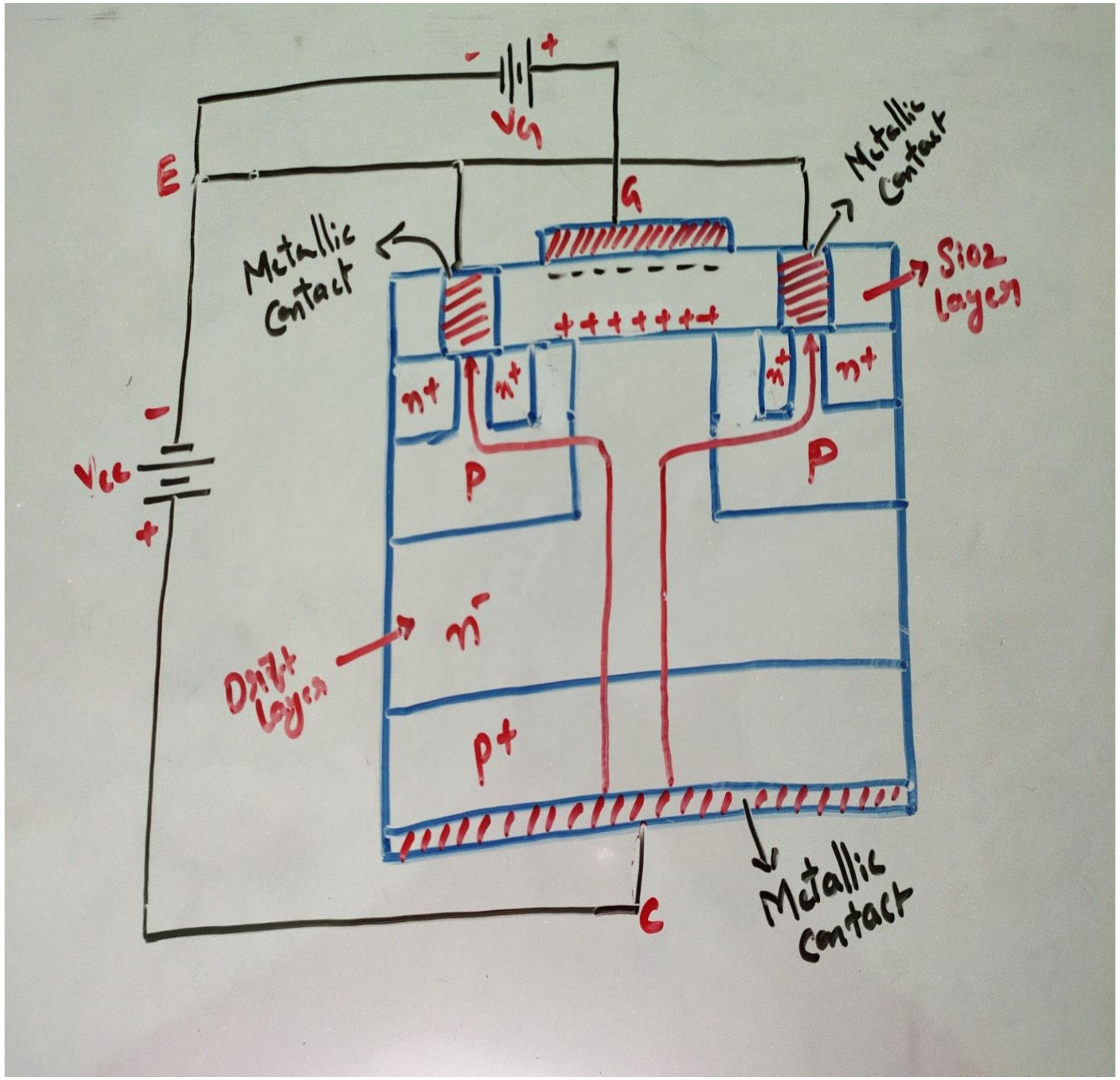
Power IGBT Contd..,,

- The space in the figure represents “SiO2” layer which creates a Capacitor.
- It is because, it is insulated and hence it is a capacitor between gate and the semiconductor material.
- Voltage between Gate and Emitter is **Vg** volts.
- Voltage between Emittor and the collector is **Vce** volts.



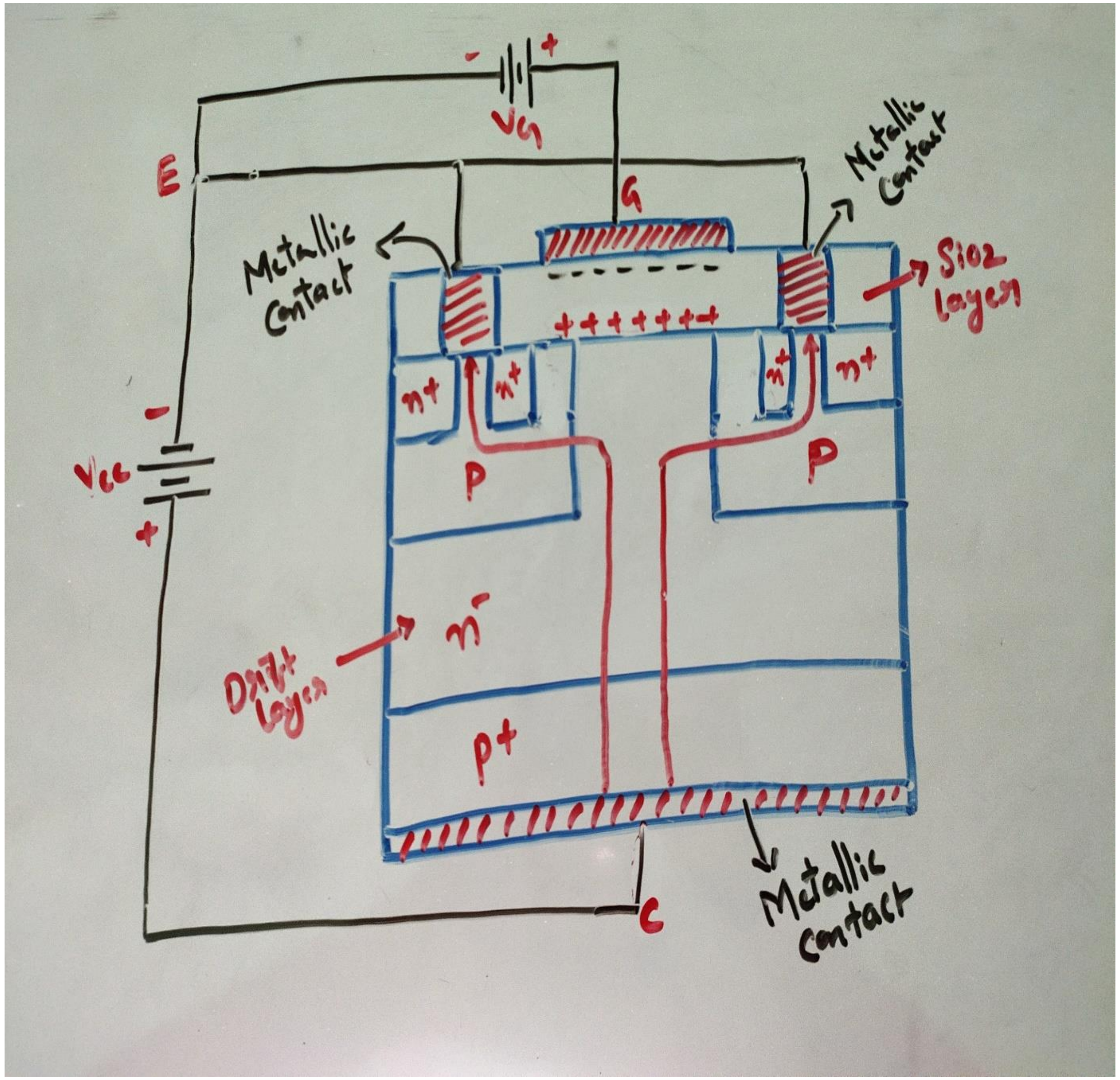
Power IGBT Contd..,,

- Initially connect the gate and the emitter terminal with a battery (Vg) and connect collector and emitter with a battery(Vce).
- Because of Vce voltage, i.e., as the collector is +ve with respect to the emitter, Junction **J1** is **forward biased** and **J2** is **reverse biased.**
- As J2 is reverse biased, the current will not flow from collector to the emitter.



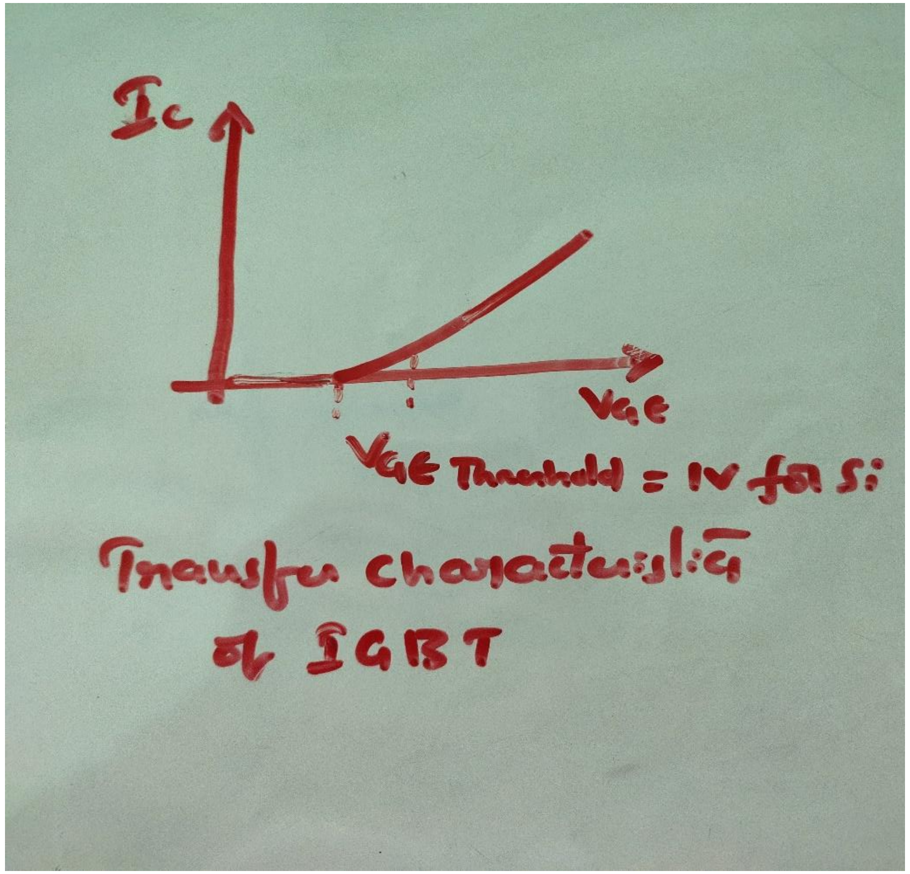
Power IGBT Contd..,,

- As we increase **Vg b voltage** , then the capacitor is formed inside the “SiO2” layer and it injects a negative charge over the regions as shown in the figure and hence the channel will be formed which gives a path to flow of current from collector to emitter.

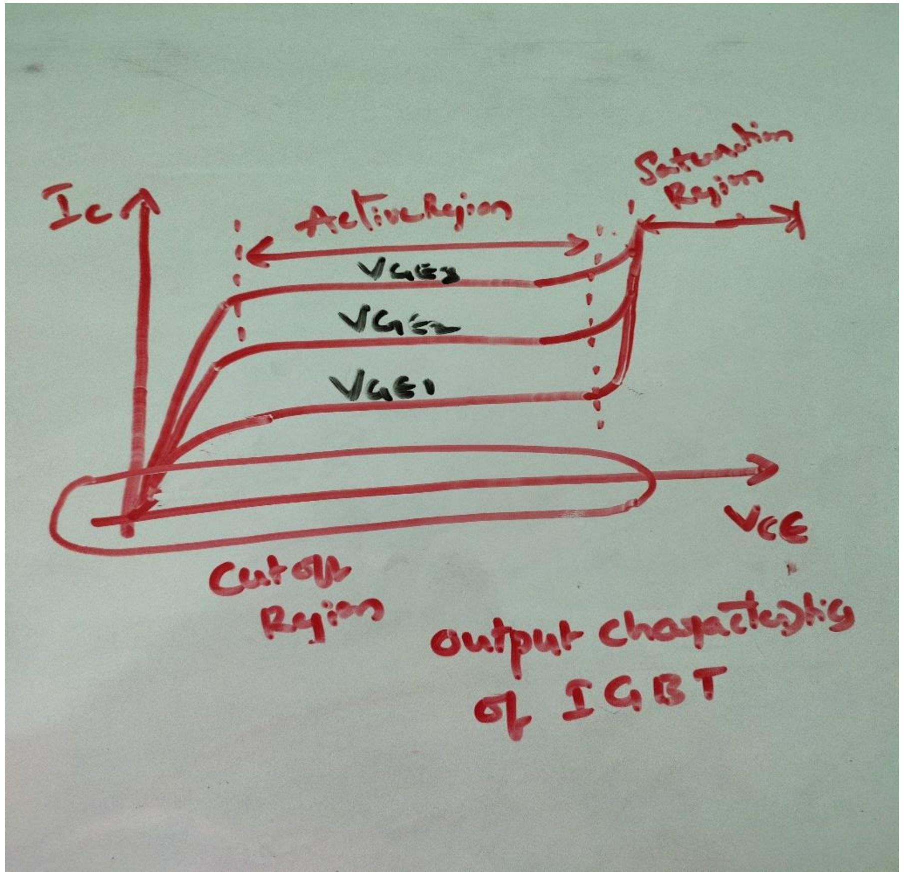


Characteristics of Power IGBT

Transfer Characteristics



Output Characteristics

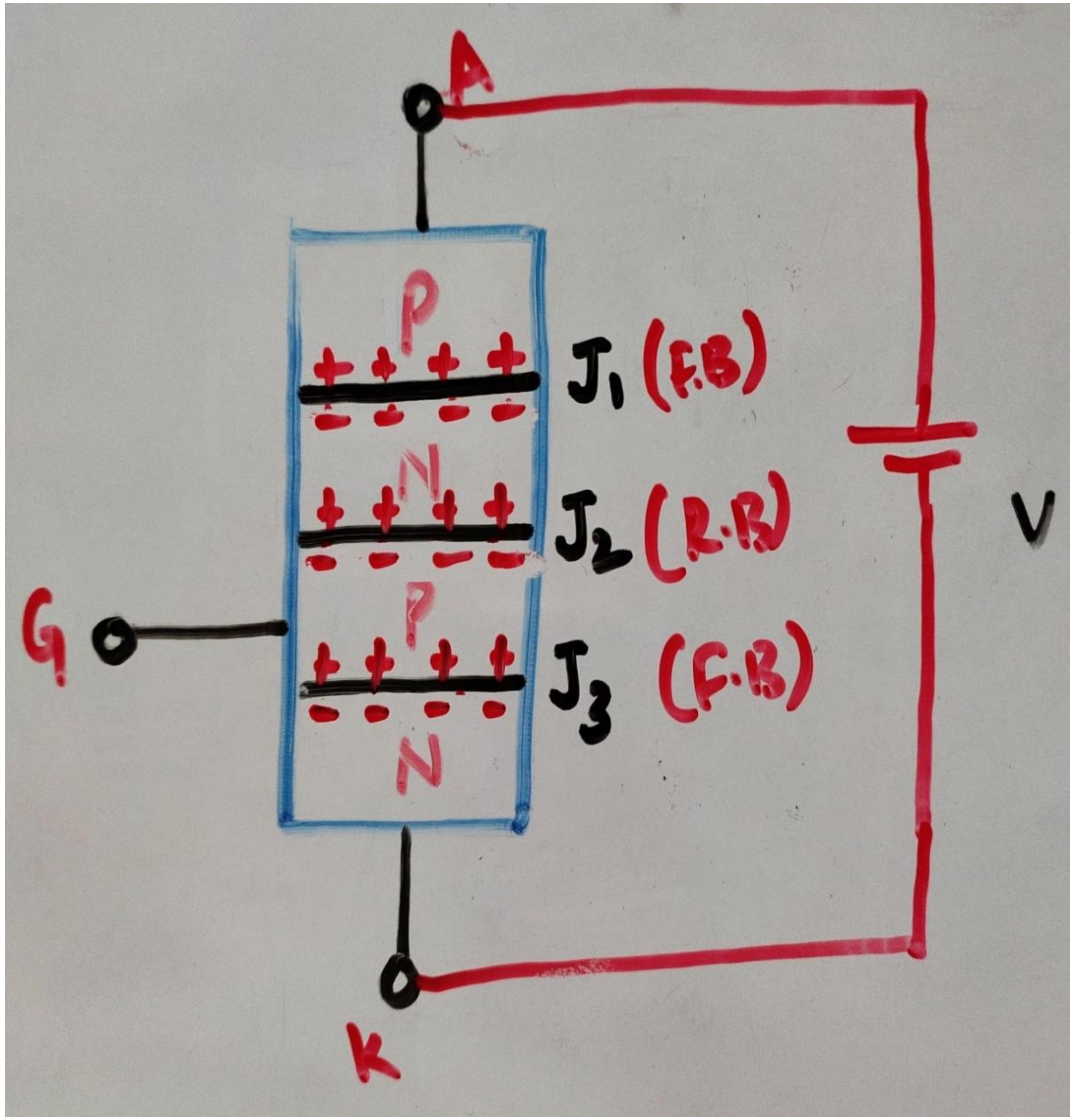


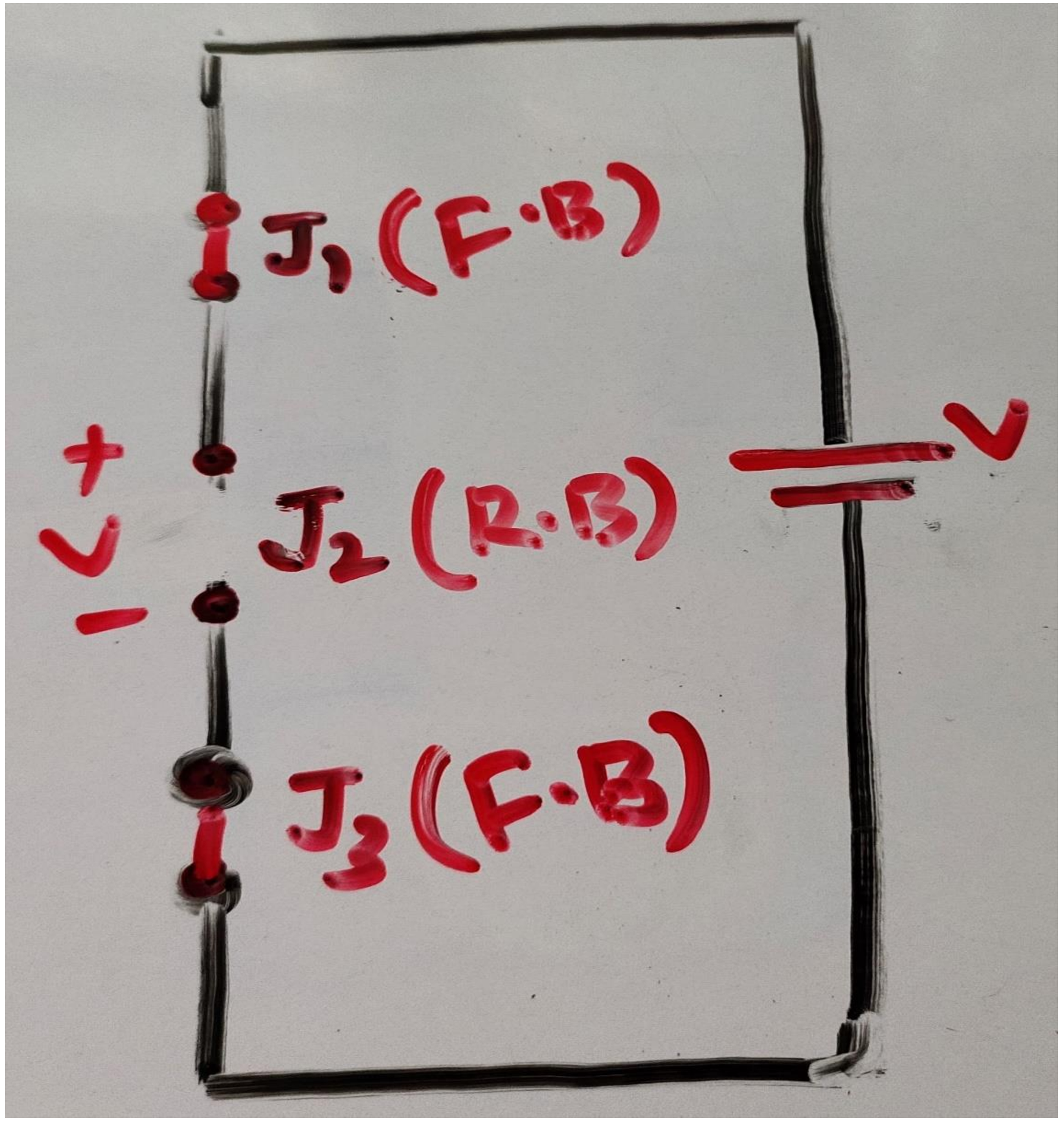
Turn-On Methods of an SCR

An SCR can be switched from a non conducting state to a conducting state in several ways and are described as follows.

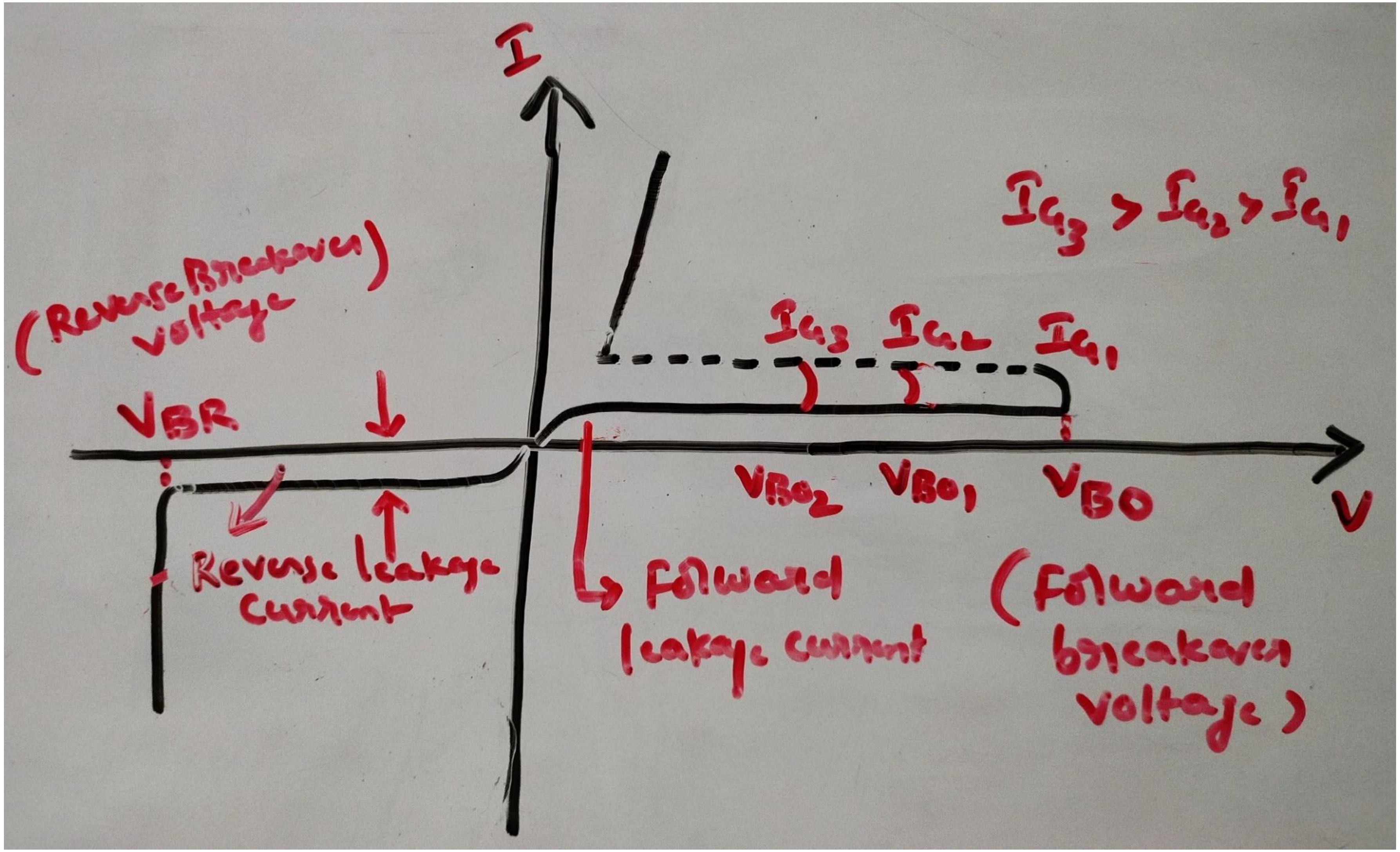
1. Forward voltage triggering
2. Thermal triggering(Temperature triggering)
3. Radiation triggering(Light triggering)
4. dv/dt triggering
5. Gate triggering

Forward Conduction Mode of SCR





Static V-I Characteristics of SCR



Forward Voltage Triggering

- When anode-to-cathode forward voltage is increased with gate circuit open, the reverse biased junction J_2 will have an avalanche breakdown at a voltage called Forward break over voltage V_{BO}.
- At this voltage, the SCR changes from OFF state(high voltage with low leakage current) to ON state characterized by a low voltage across it with large forward current.
- The forward voltage drop across the SCR during the ON state is of the order of 1 to 1.5V and increases slightly with the load current.

Thermal Triggering(Temperature Triggering)

- Like any other semiconductor, the width of the depletion layer of an SCR decreases on increasing the junction temperature.
- Thus, in an SCR, when the voltage applied between the anode and cathode is very near to its breakdown voltage, the device can be triggered by increasing its junction temperature.
- By increasing the temperature to a certain value(within the specified limits), a situation comes when the reverse biased junction collapses making the device conduct.
- This method of triggering the device by heating is known as the Thermal triggering method.

Radiation Triggering(Light Triggering)

- In this method, as the name suggests, the energy is imparted by radiation.
- The SCR is bombarded by energy particles such as Neutrons or Photons.
- With the help of this external energy, electron-hole pairs are generated in the device, thus increasing the number of charge carriers.
- This leads to instantaneous flow of current within the device and the triggering of the device.
- For radiation triggering to occur, the device must have high value of rate of change of voltage(dv/dt).
- LASCR and LASCS are the examples of this type of triggering.

dv/dt Triggering

- We know that with forward voltage across the anode and cathode of a device, the junctions J_1 and J_3 are forward biased, whereas the junction J_2 becomes reverse biased.
- This J_2 has the characteristics of a capacitor due to charges existing across the junction.
- If a forward voltage is suddenly applied, a charging current will flow tending to turn the device ON.
- If the voltage impressed across the device is denoted by V, the charge by Q and the capacitance by C_j, then

$$i_c = dQ/dt = d(C_j * V)/dt = C_j * dV/dt + V * dC_j/dt$$

- The rate of change of junction capacitance may be negligible as the junction capacitance is almost constant.
- Therefore, if the rate of change of voltage across the device is large, the device may turn-on even though the voltage appearing across the device is small.

Gate Triggering

- By applying a positive signal at the gate terminal of the device, it can be triggered much before the specified break over voltage.
- The conduction period of the SCR can be controlled by varying the gate signal within the specified values of the maximum and minimum gate currents.
- For gate triggering, a signal is applied between the gate and the cathode of the device.

Turn-Off Methods of an SCR

The two methods by which an SCR can be turned off are as follows.

1. Natural Commutation

2. Forced Commutation

Commutation

- The term Commutation is basically means the transfer of current from one path to another.
- In SCR, this term is used to describe the process of transferring the current from one SCR to another.
- In general, it is not possible to for an SCR to turn itself OFF; the circuit in which it is connected must reduce the SCR current to zero to enable it to turn off.
- Commutation is the term to describe the methods of achieving this.

Natural Commutation

- The simplest and most widely use of method of commutation makes use of the alternating, reversing nature of ac voltages to effect the current transfer.
- We now that in ac circuits, the current always passes through zero every half cycle.
- As the current passes through natural zero, a reverse voltage will simultaneously appear across the device.
- This immediately turns-off the device.
- This process is called Natural commutation since no external circuit is required for this purpose.
- This method may use ac mains supply voltages or ac voltages generated by local rotating machines or resonant circuits.
- The line commutated converters and inverters comes under this category.

Forced Commutation

- Once SCRs are operating in the ON state, carrying forward current, they can only be turned OFF by reducing the current flowing through them to zero for sufficient time to allow the removal of charge carriers.
- In case of DC circuits, for switching off the SCRs, the forward current should be forced to zero by means of some external circuits.
- The process is called Forced Commutation and the external circuits required for it are called Commutation circuits.
- The components (inductance and capacitance) which constitutes the commutating circuits are called Commutating components.
- A reverse voltage is developed across the device by means of a commutating circuit that immediately brings the forward current in the device to zero, thus turning off the device.

Class A commutation

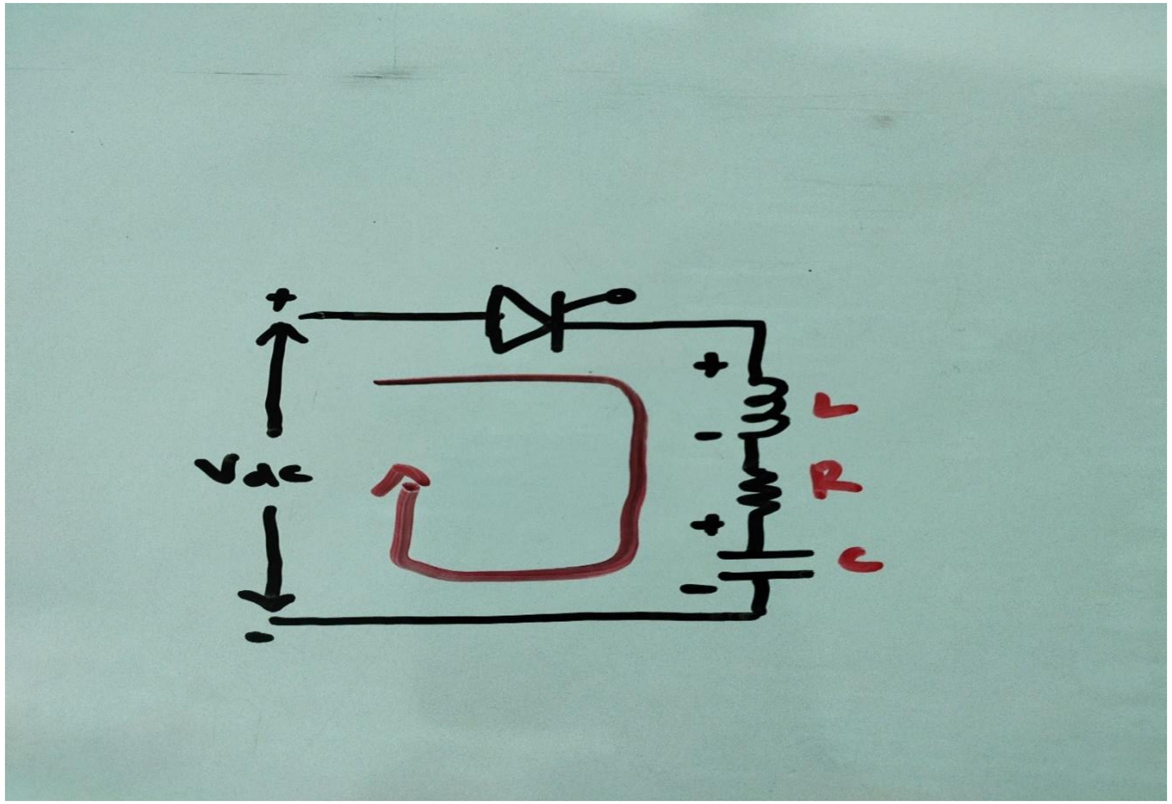
Class A commutation is also called Load

Commutation and the commutation is

Done by the load current.

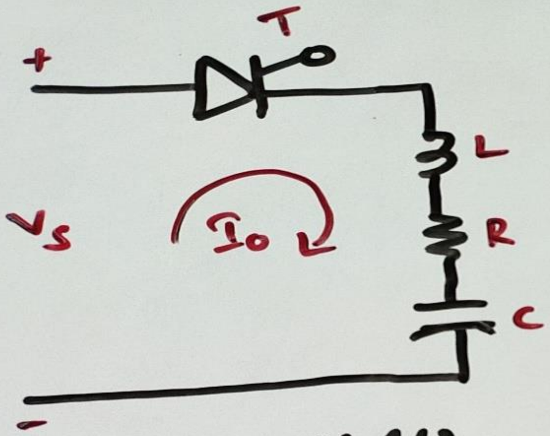
The circuit consist of ,

- Supply voltage ,Vs
- SCR
- Load Resistance, R
- Commutating elements L and C



Working of Class A commutation Circuit

Class A Commutation



$$I_0 = \frac{V_s(t)}{Z}$$

Apply L.T,

$$I_0 = \frac{V_s/s}{R + Ls + \frac{1}{Cs}}$$

$$\Rightarrow I_0 = \frac{V_s/L}{s^2 + \frac{R}{L}s + \frac{1}{LC}}$$

Characteristic equation,

$$s^2 + \frac{R}{L}s + \frac{1}{LC} = 0$$

Compare with

$$s^2 + 2\xi\omega_n s + \omega_n^2 = 0$$

$$\omega_n^2 = \frac{1}{LC} \Rightarrow \omega_n = \frac{1}{\sqrt{LC}}$$

$$2\xi\omega_n = \frac{R}{L}$$

$$\Rightarrow 2\xi\left(\frac{1}{\sqrt{LC}}\right) = \frac{R}{L}$$

$$\Rightarrow \xi = \frac{R}{2L}\cdot\sqrt{LC}$$

$$\Rightarrow \xi = \frac{R}{2}\sqrt{\frac{C}{L}}$$

To Turn off SCR, $I_A < I_H$

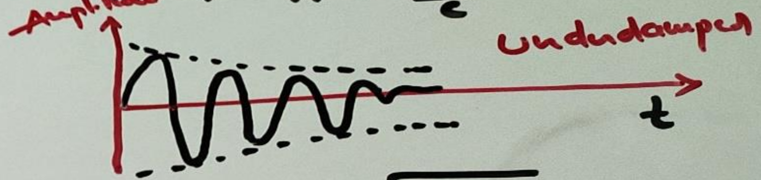
SCR can stay ON during 0 to π

For an underdamped system,

$$\xi < 1$$

$$\Rightarrow 1 > \frac{R}{2}\sqrt{\frac{C}{L}}.$$

$$\Rightarrow R^2 < \frac{4L}{C}$$



$$\omega_r = \omega_n\sqrt{1-\xi^2}$$

Max. Conduction time of SCR,

$$t\omega_r = \pi \Rightarrow t = \pi/\omega_r.$$

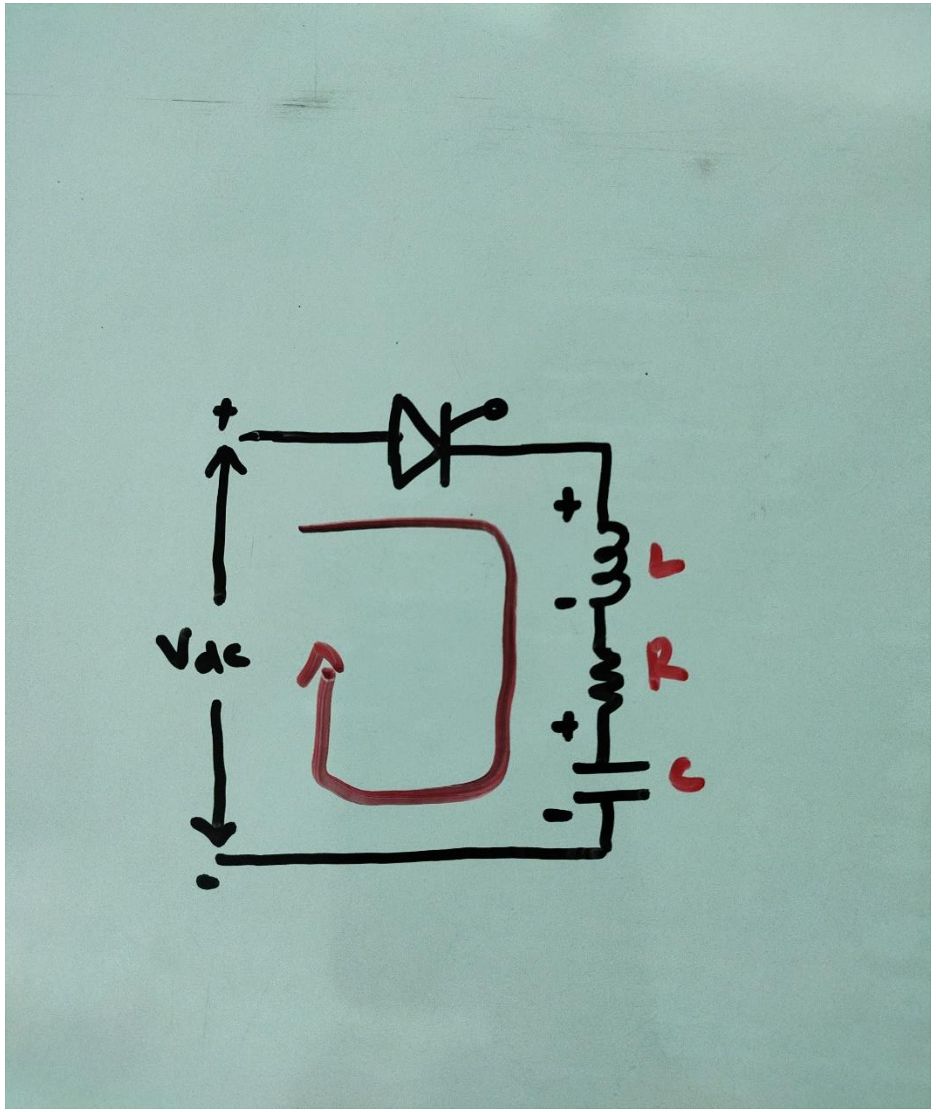
$$\Rightarrow t = \frac{\pi}{\omega_n\sqrt{1-\xi^2}}$$

Turn-on time of SCR for a "α" firing Angle is,

$$t = \frac{\pi-\alpha}{\omega_n\sqrt{1-\xi^2}}$$

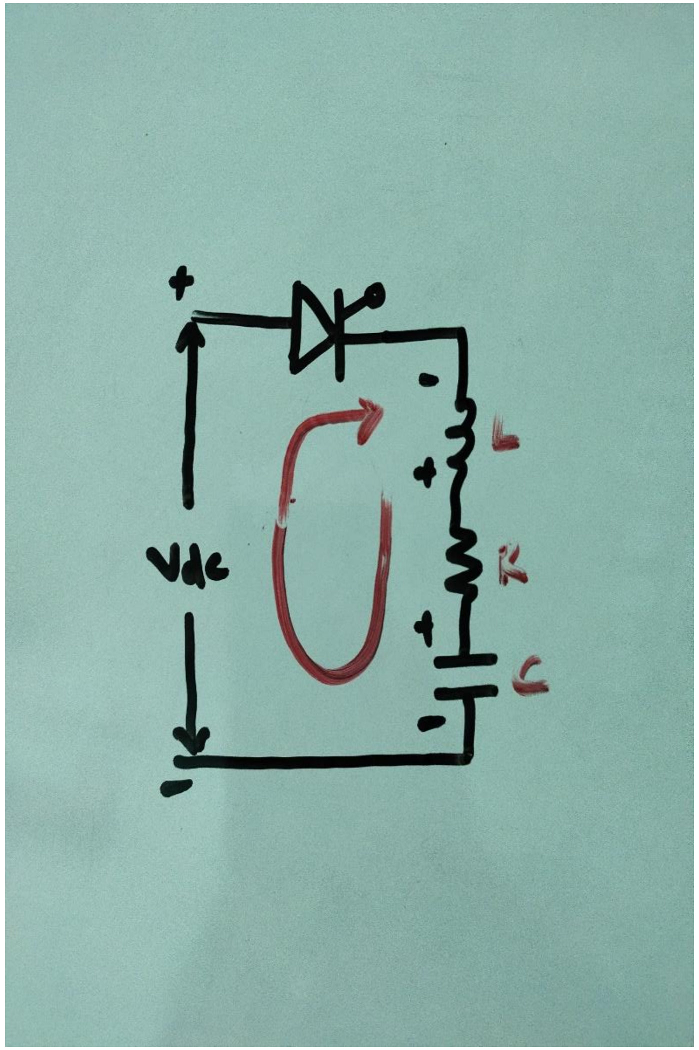
Working of Class A commutation Circuit

- Initially SCR is OFF.
- When we apply gate pulse, SCR will turn ON.
- The voltage across the capacitor will charge to supply voltage,Vs.
- Load current will flow in the circuit and increase till the capacitor will charge to supply voltage,Vs.
- As the SCR is ON, the voltage across the SCR will be Zero.



Working of Class A commutation Circuit

- Once the capacitor charge upto Vs, the polarities of the inductor will change and the energy stored in the inductor will discharge as like shown in the figure and hence it energize the capacitor and the capacitor will charge upto some extent further.
- The output current will start to decrease and reaches to zero and until it reaches zero,the SCR is in ON position and hence the voltage across the SCR will be zero.
- When the output current goes below the holding current, the SCR becomes OFF and the capacitor starts discharge and voltage across the SCR will start increase.



Output Waveforms of Class A commutation Circuit

- Initially SCR is OFF.
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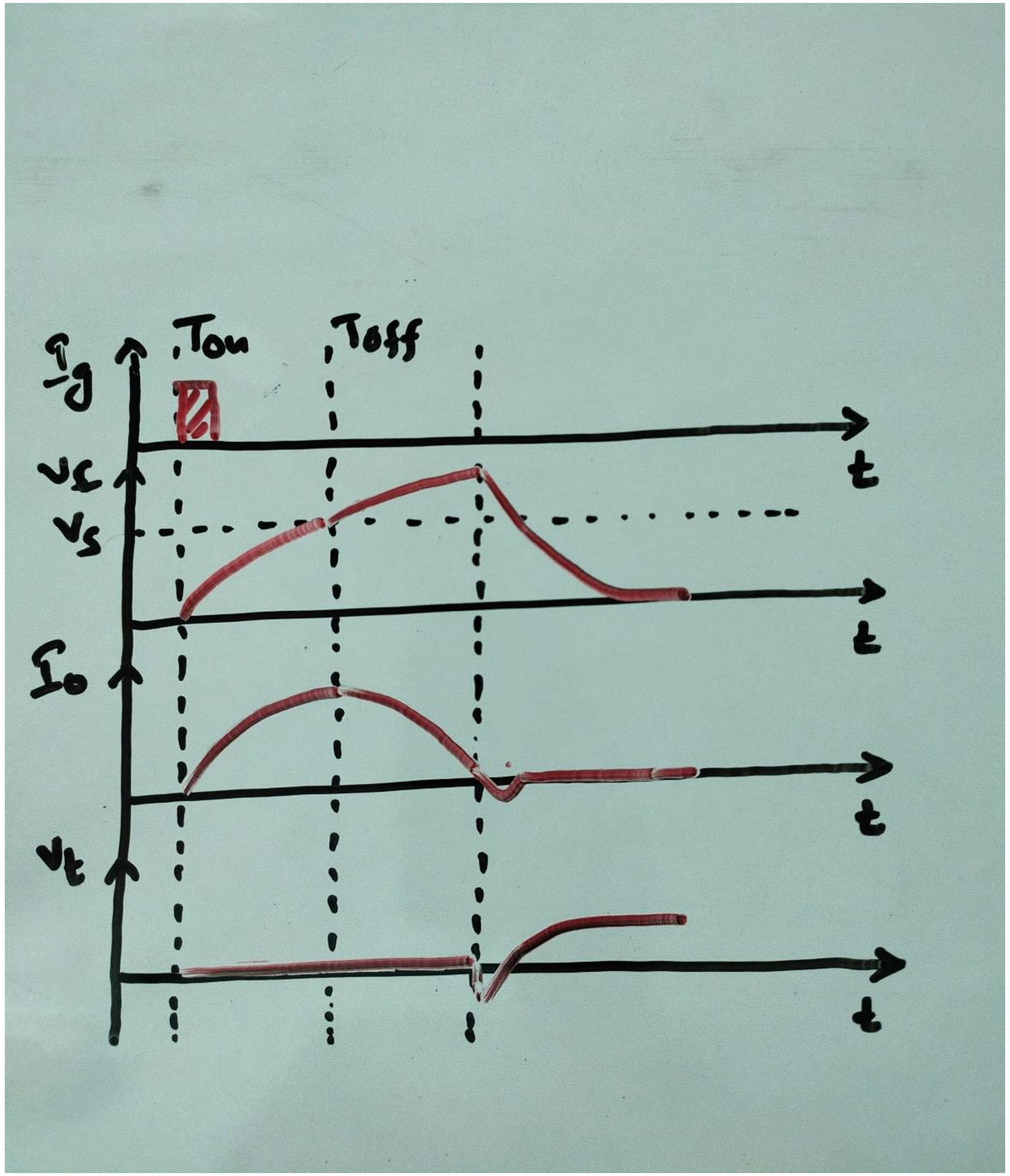

Output Waveforms of Class A commutation Circuit

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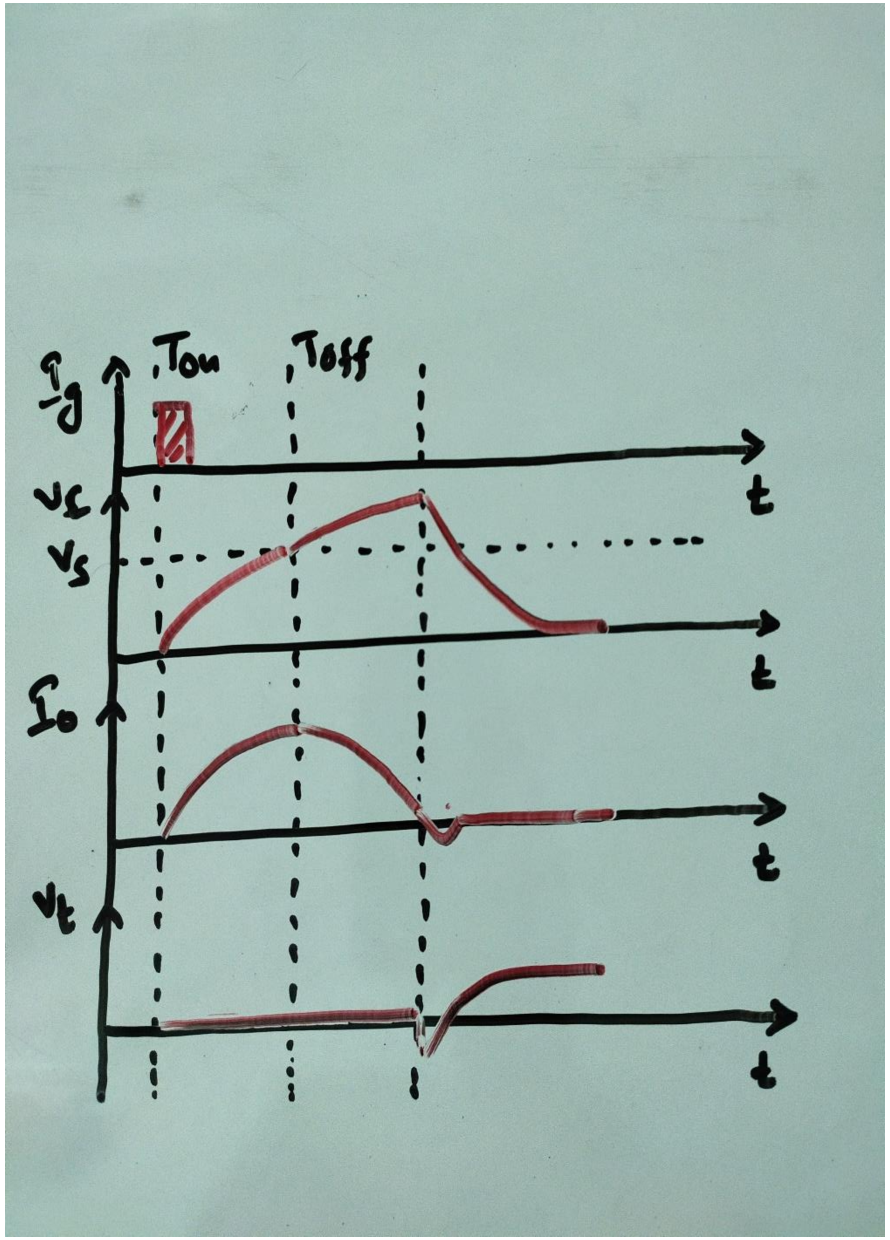


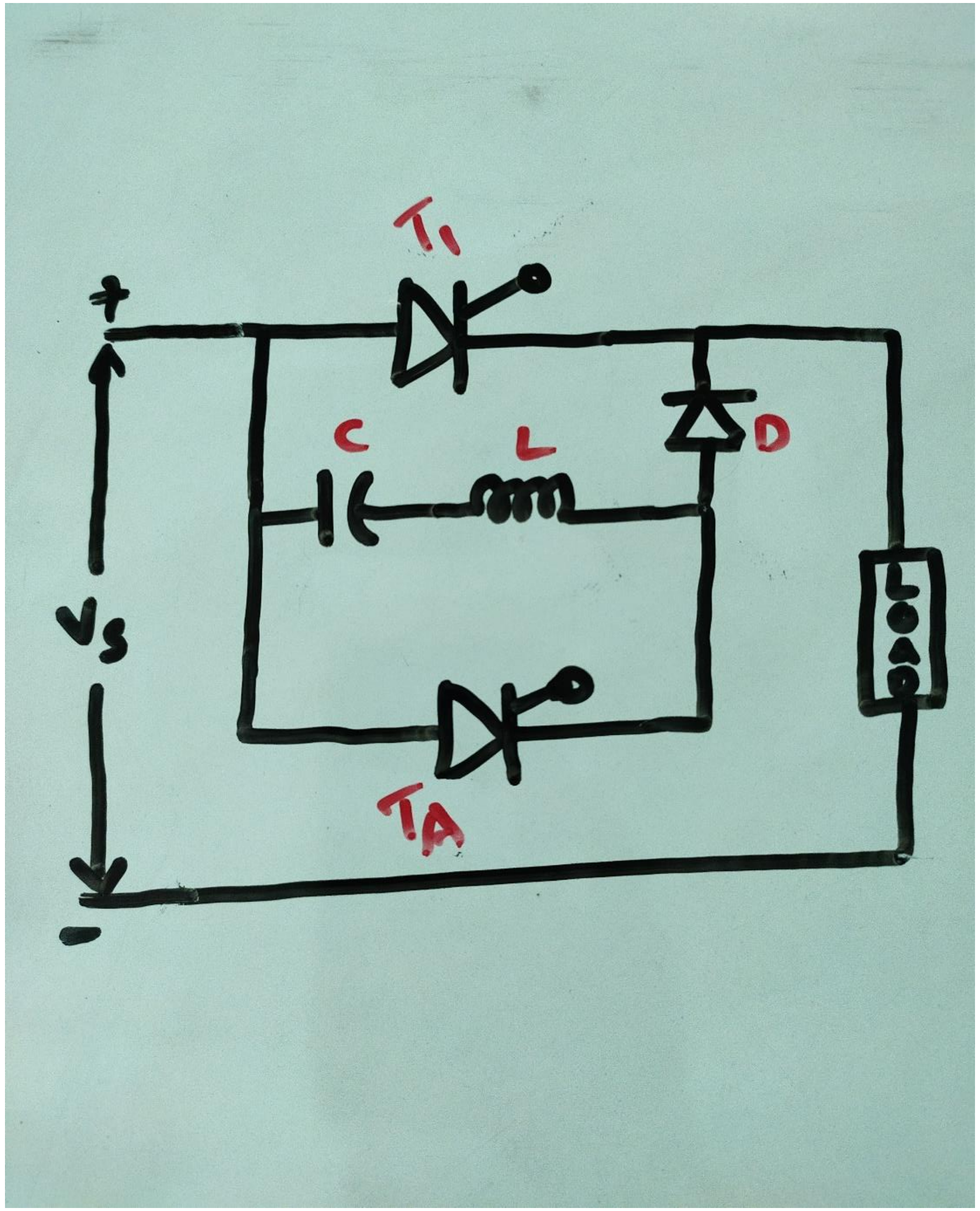
Class B Commutation

Also called Resonant Pulse Commutation or Current Commutation.

- T1= Main SCR
- T_A= Auxiliary SCR
- For resonant pulse generation, capacitor and inductor are connected.
- D=Diode

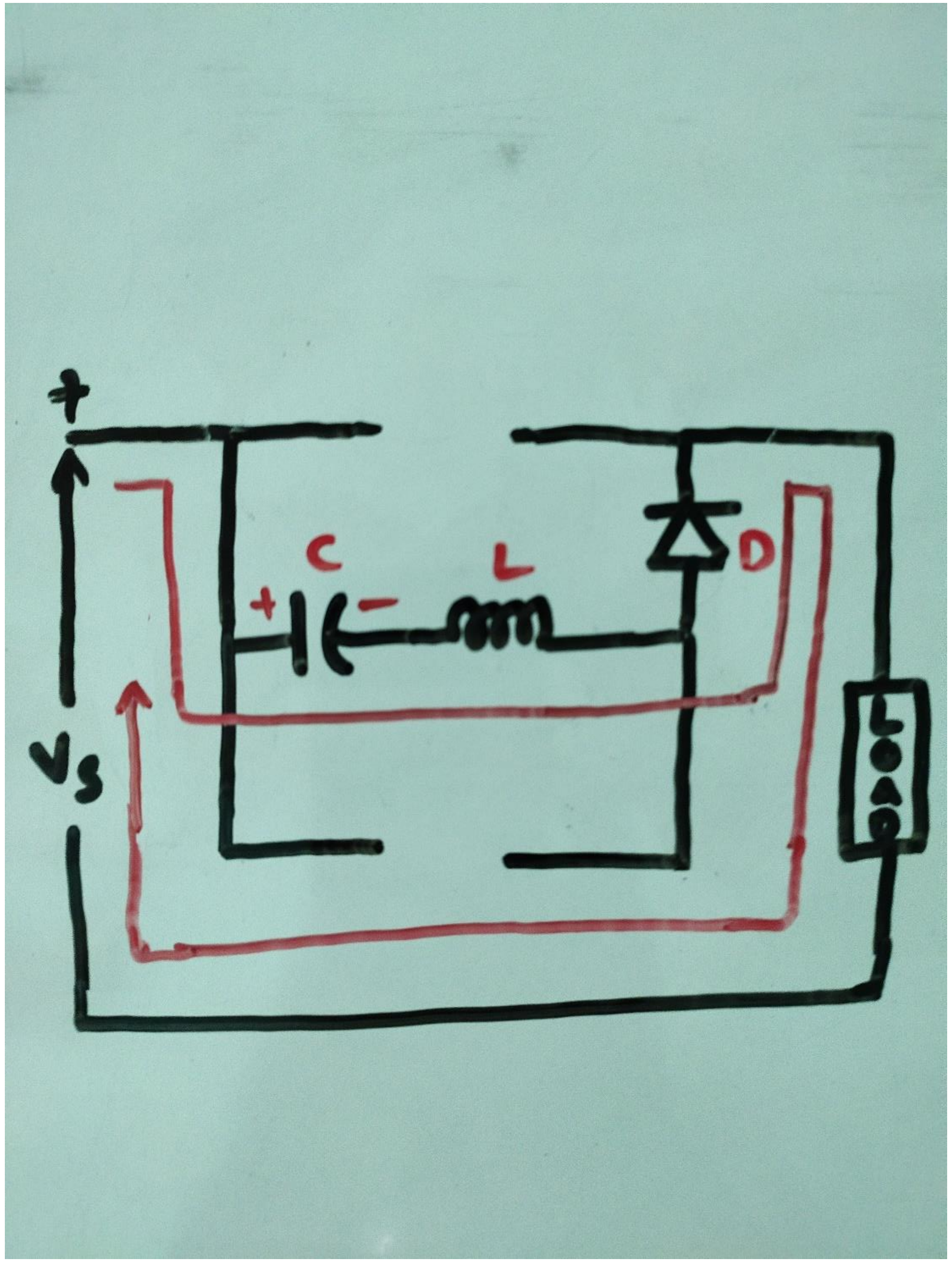
Assumptions:

- Load current is constant
- LC circuit is resonant in nature
- Capacitor is initially charged by supply voltage, V_s.



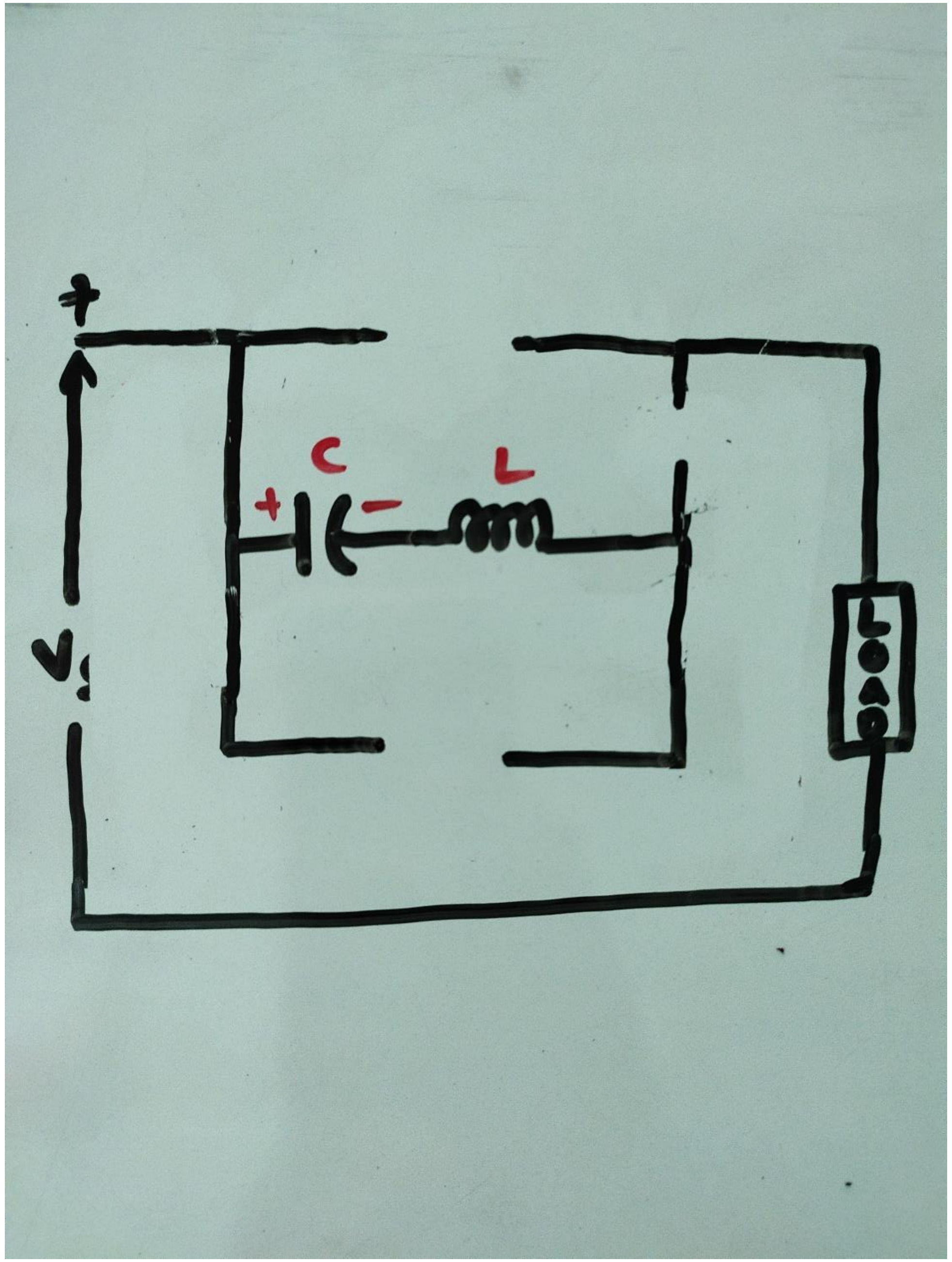
Working of Class B Commutation

- Initially both SCRs are OFF.
- The flow of current in the circuit will be like as shown in the figure.



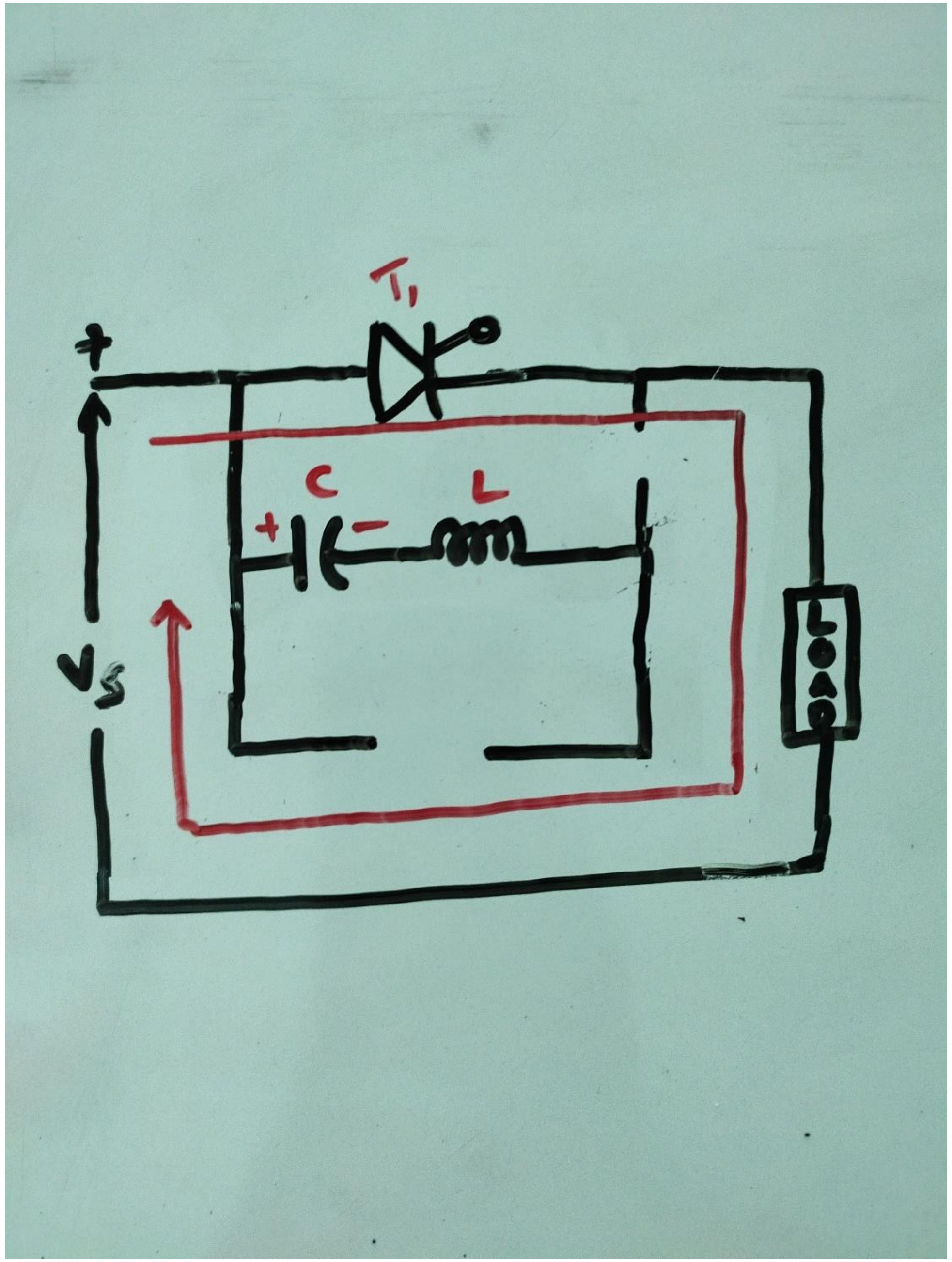
Working of Class B Commutation

- As the capacitor charges up to supply voltage, the diode will comes into reverse biased and diode will get turn off and at this condition the polarities of the capacitor will be like as shown in the figure.
- The capacitor does not have any path to get discharge.



Working of Class B Commutation

- SCR 1 is given a trigger signal to make it turn ON.
- The flow of current will be like as shown in the figure.
- But there is no path for the capacitor to get discharged.

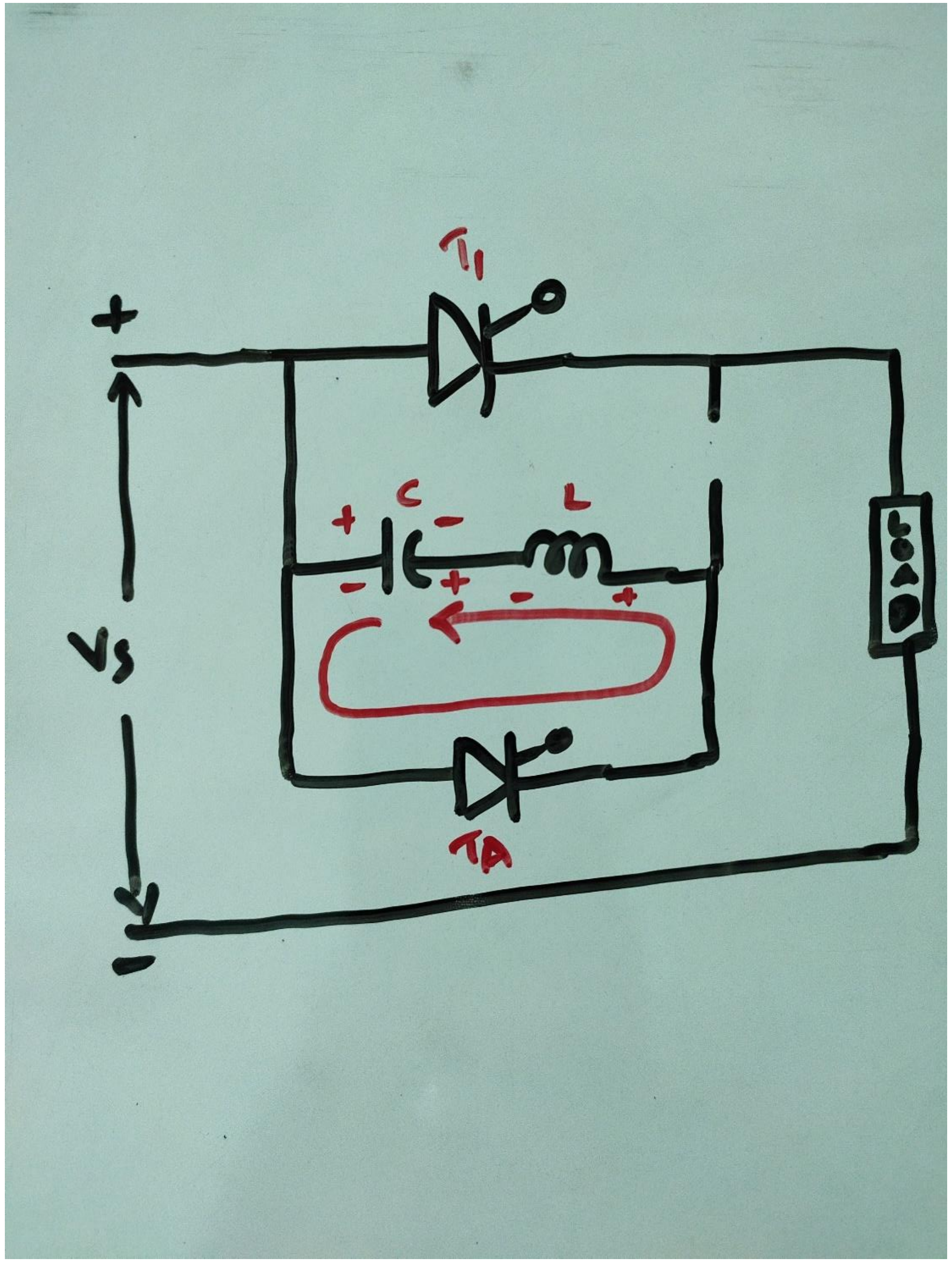


Working of Class B Commutation

- SCR A is given a trigger signal to make it turn ON.

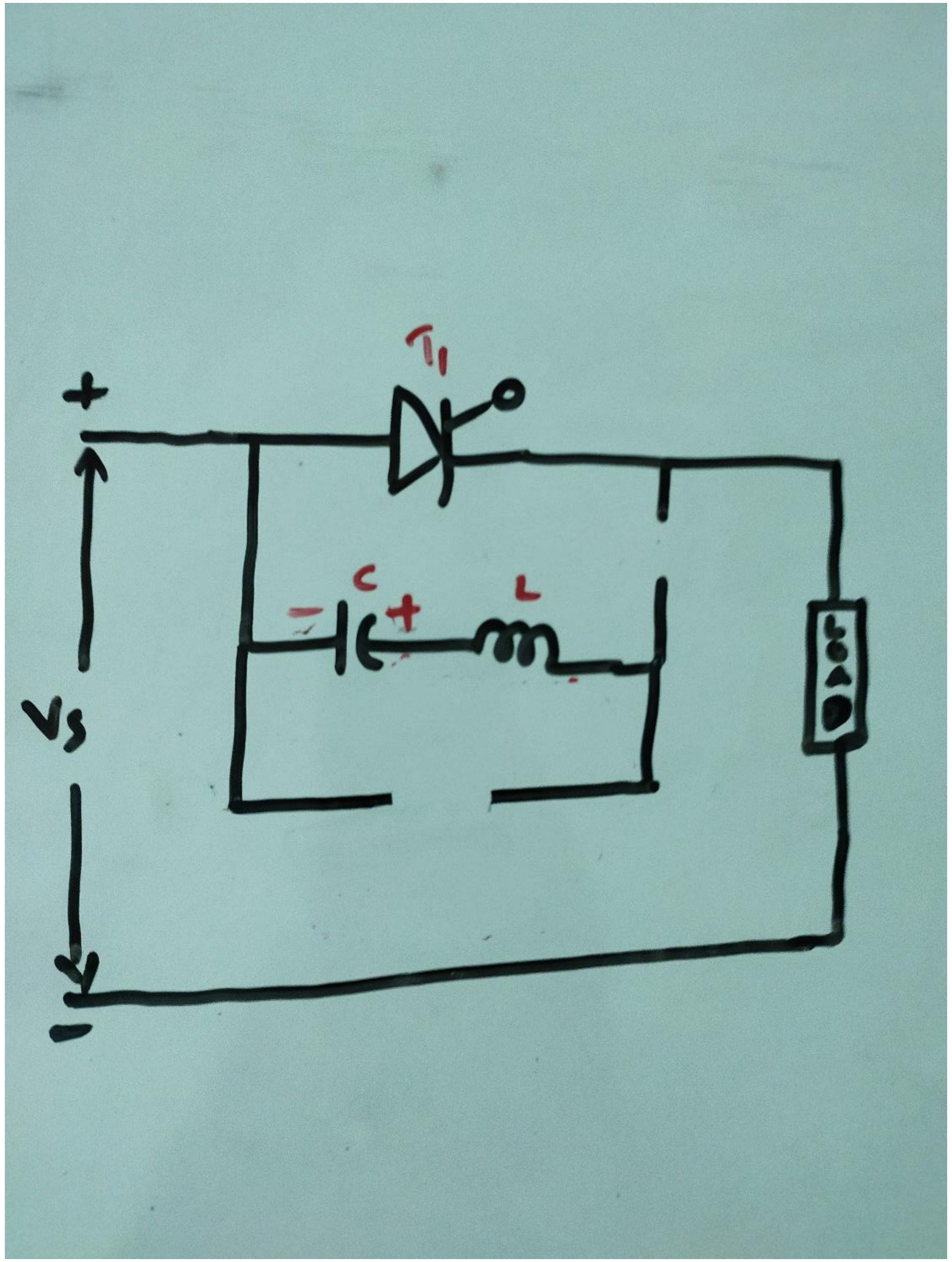
- The flow of current which is due to capacitor voltage Vs will be like as shown in the figure.

- The polarities of the capacitor will change as like shown and hence the auxiliary SCR will come into Reverse bias and hence SCR A will turn OFF.



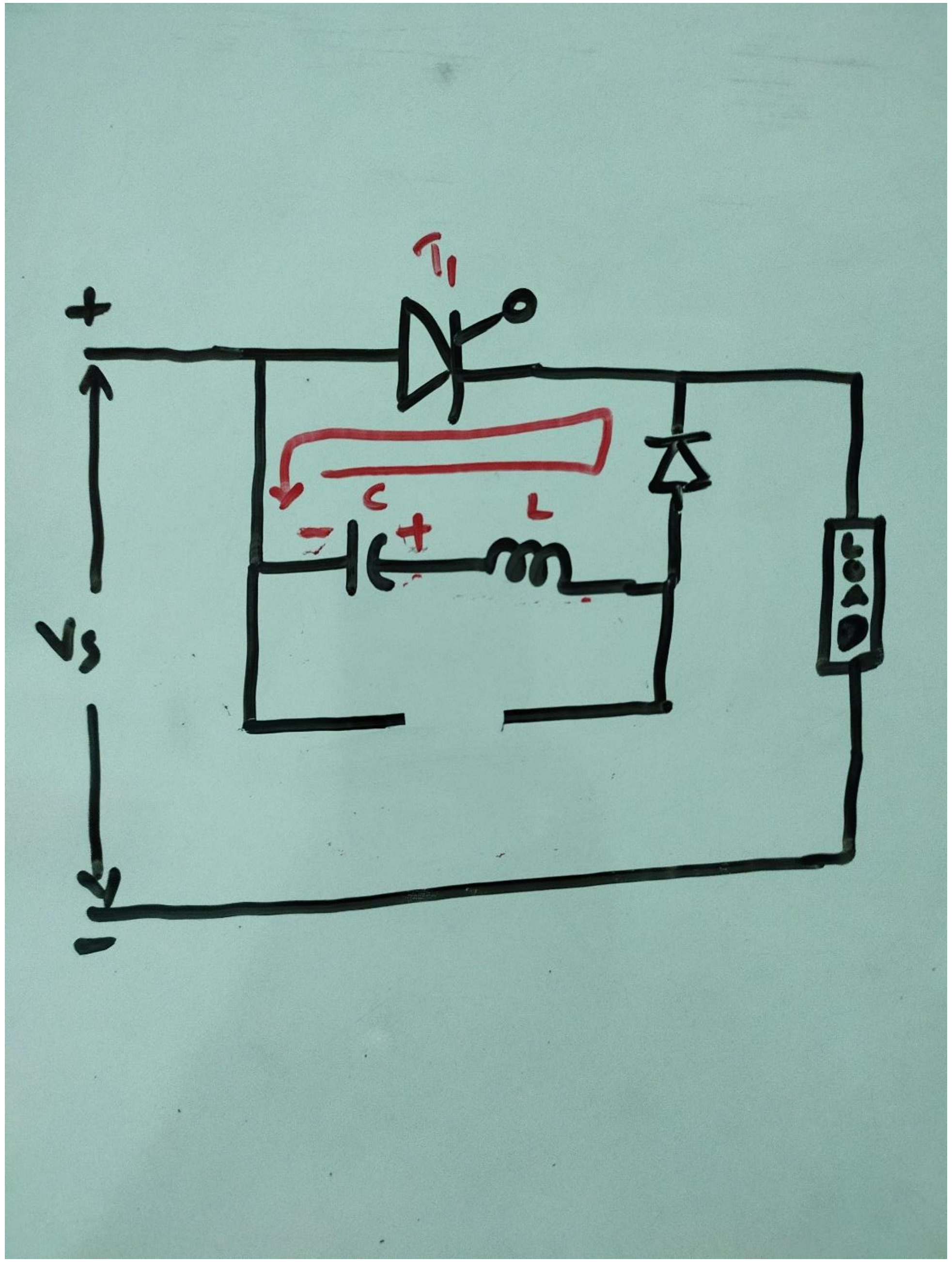
Working of Class B Commutation

- As the polarities of the capacitor voltage is reversed and hence the auxiliary SCR will come into Reverse bias and hence SCR A will turn OFF.

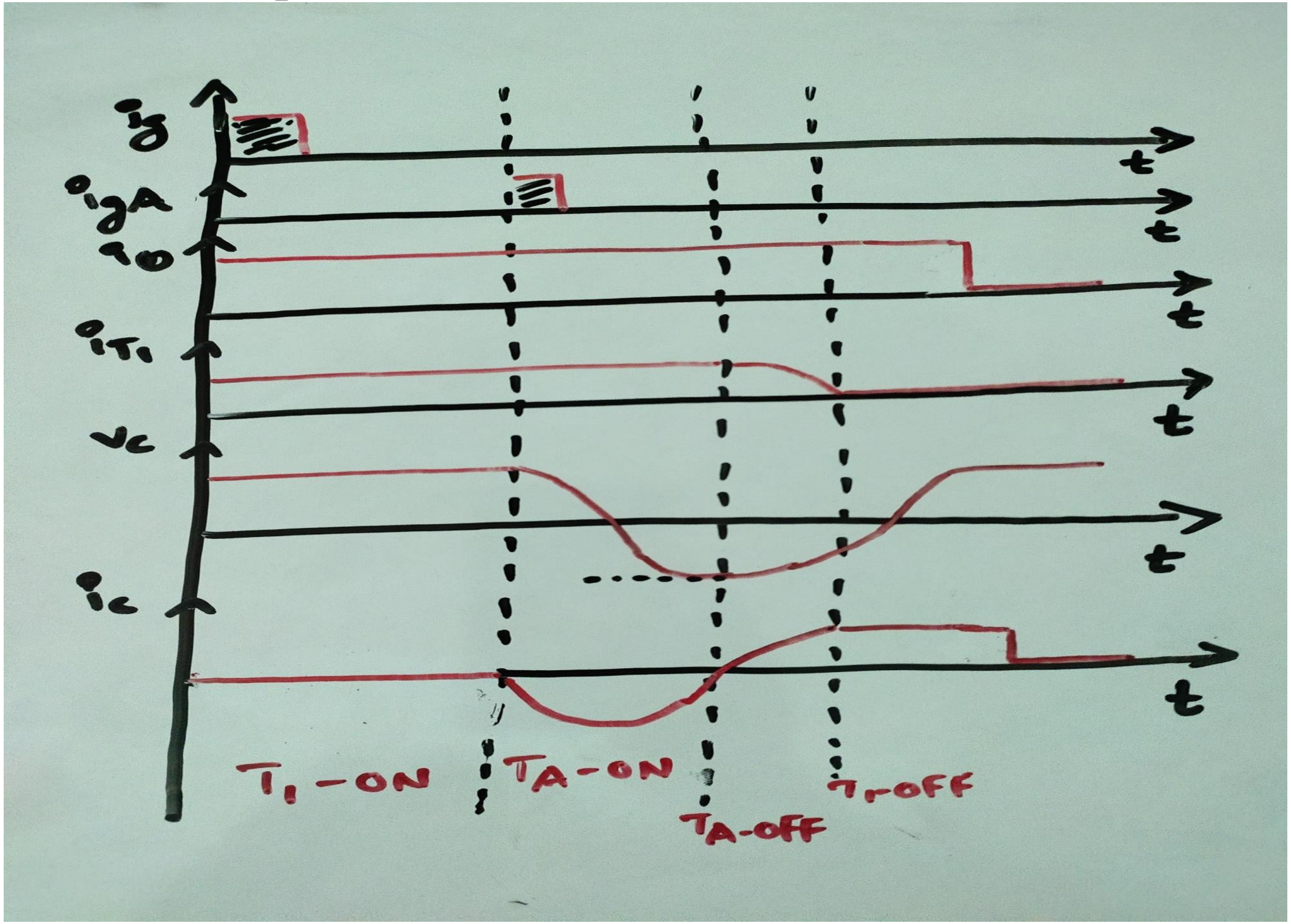


Working of Class B Commutation

- At this condition diode D will be forward biased and the flow of resonant current is like as shown in the figure.
- This current of capacitor will flow till the difference in the load current and the capacitor current will get zero.
- At this condition, the anode current in the SCR 1 will go below the holding current and hence SCR 1 will turn OFF.



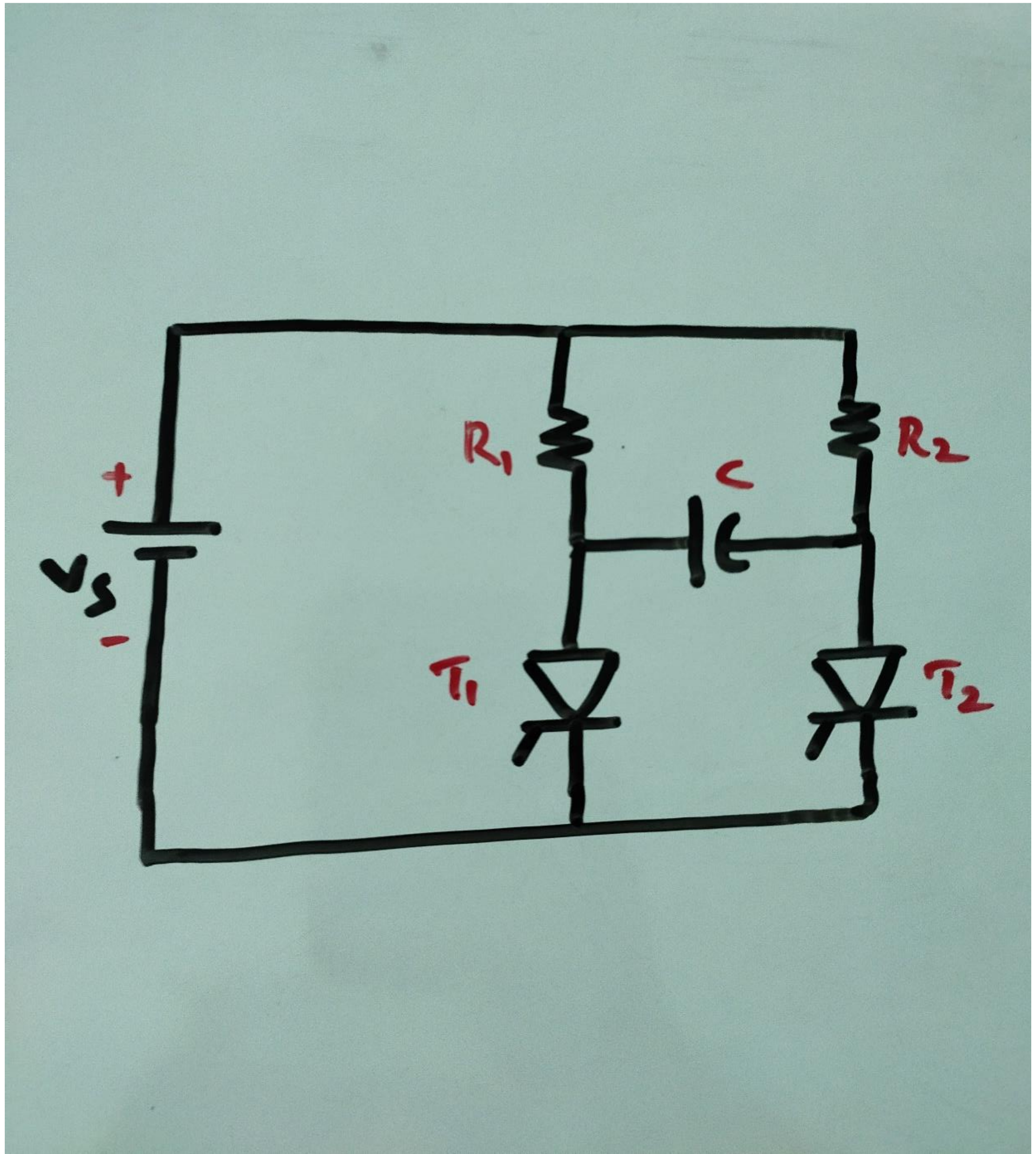
Output Waveforms of Class B Commutation



Class C Commutation

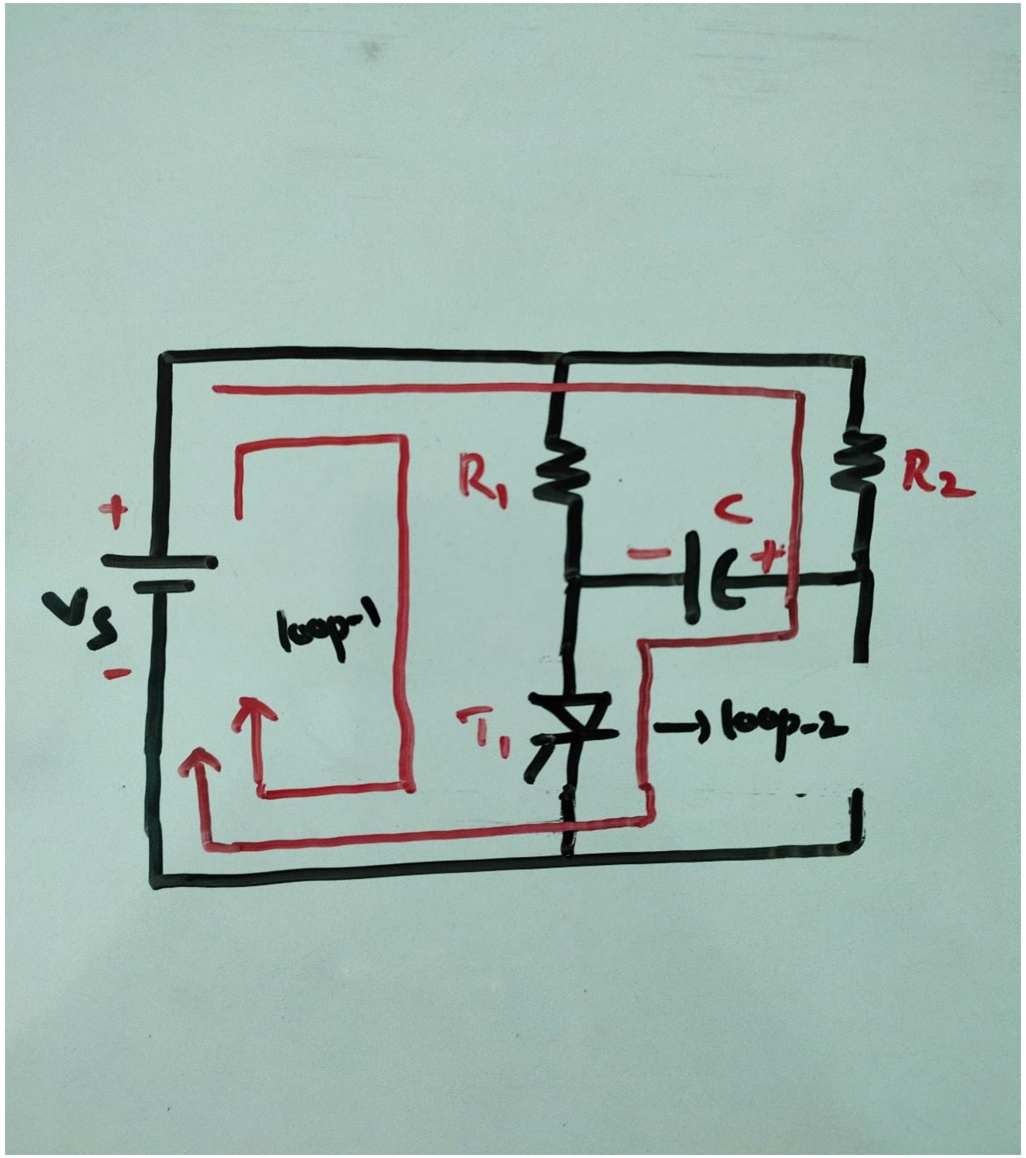
- It is also called Impulse Commutation.

- It is also called Complementary Commutation as to turn off one SCR, we should give gate signal to another SCR.



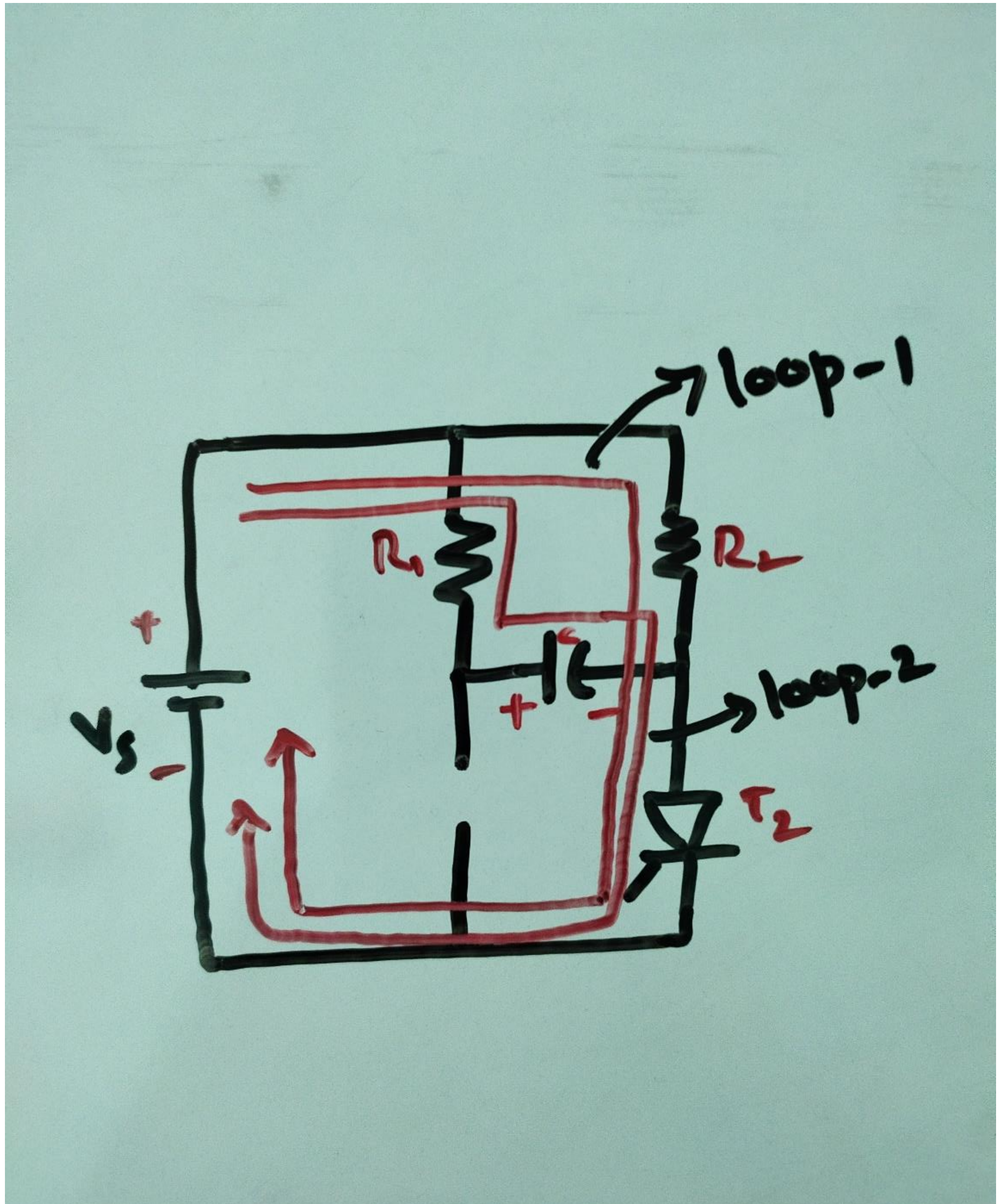
Working of Class C Commutation

- SCR 1 is ON
- Current will flow in two loops as shown in the figure.

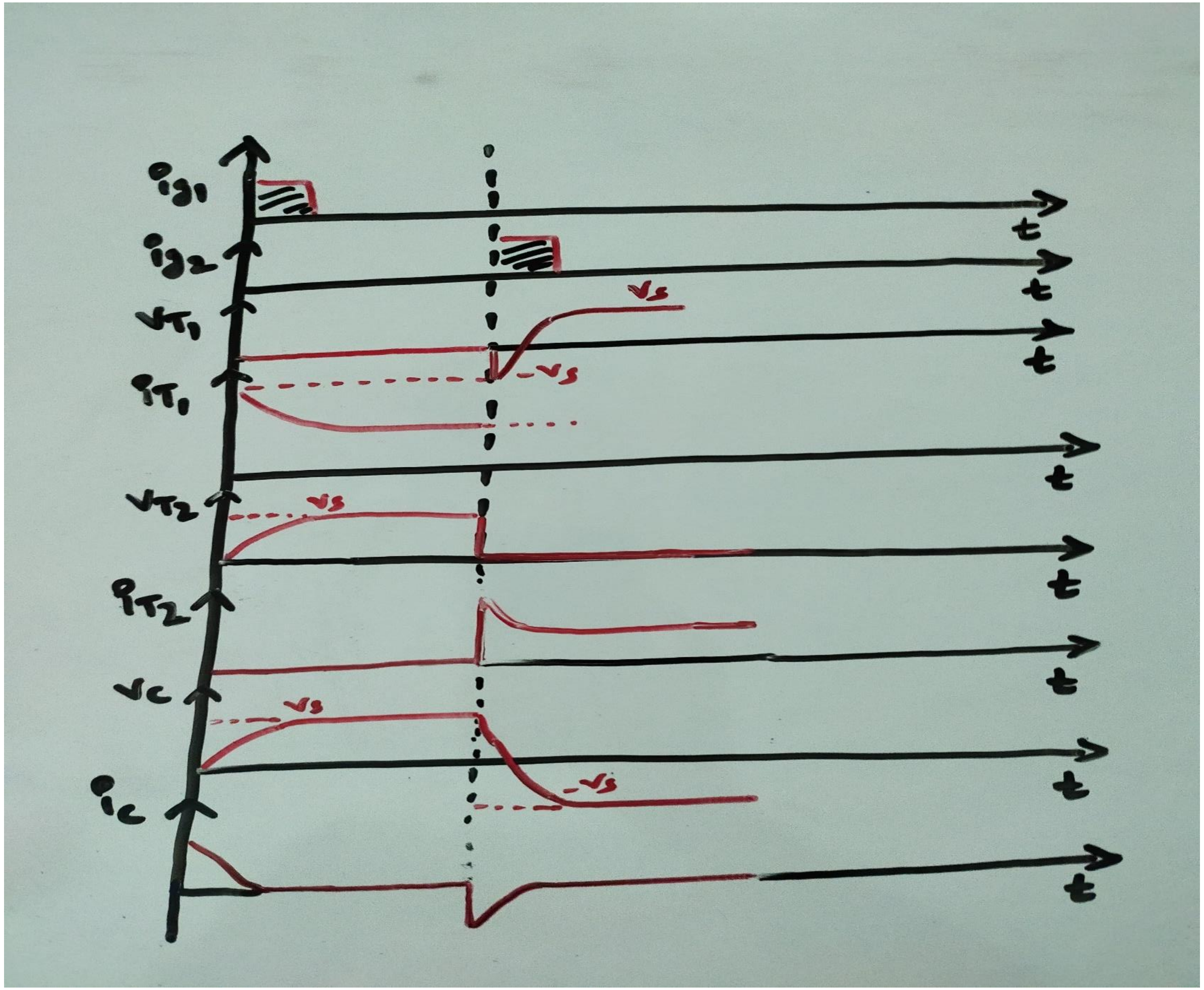


Working of Class C Commutation

- SCR 2 is ON
- Current will flow in two loops as shown in figure.
- To turn off SCR 2, gate signal is applied to SCR 1.



Output Waveforms of Class C Commutation



Class D Commutation

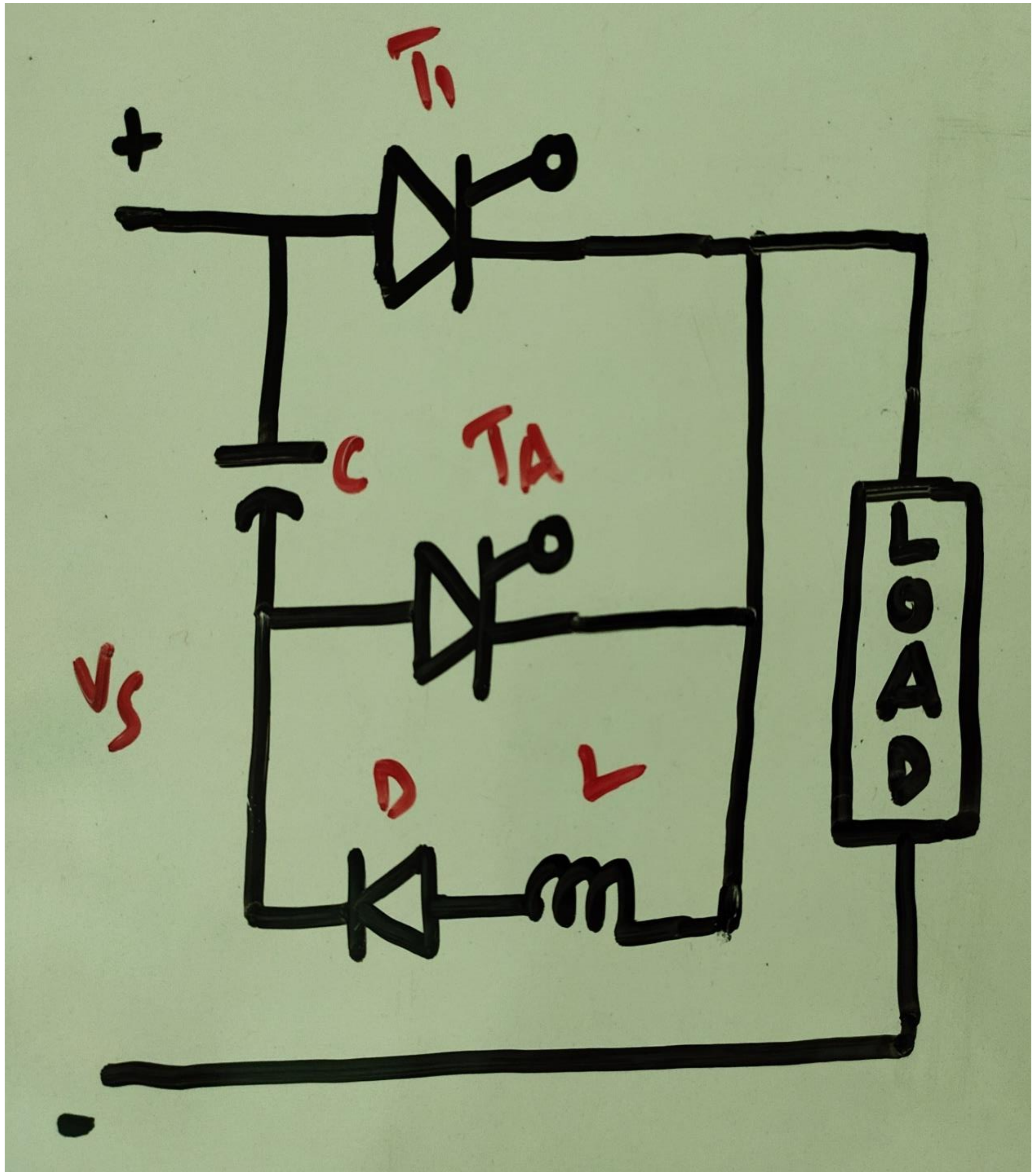
- It is also called Voltage Commutation as the SCR commutation is done by voltage.
- It is also called Auxiliary Commutation.
- It is also called Parallel capacitor commutation

Class D Commutation

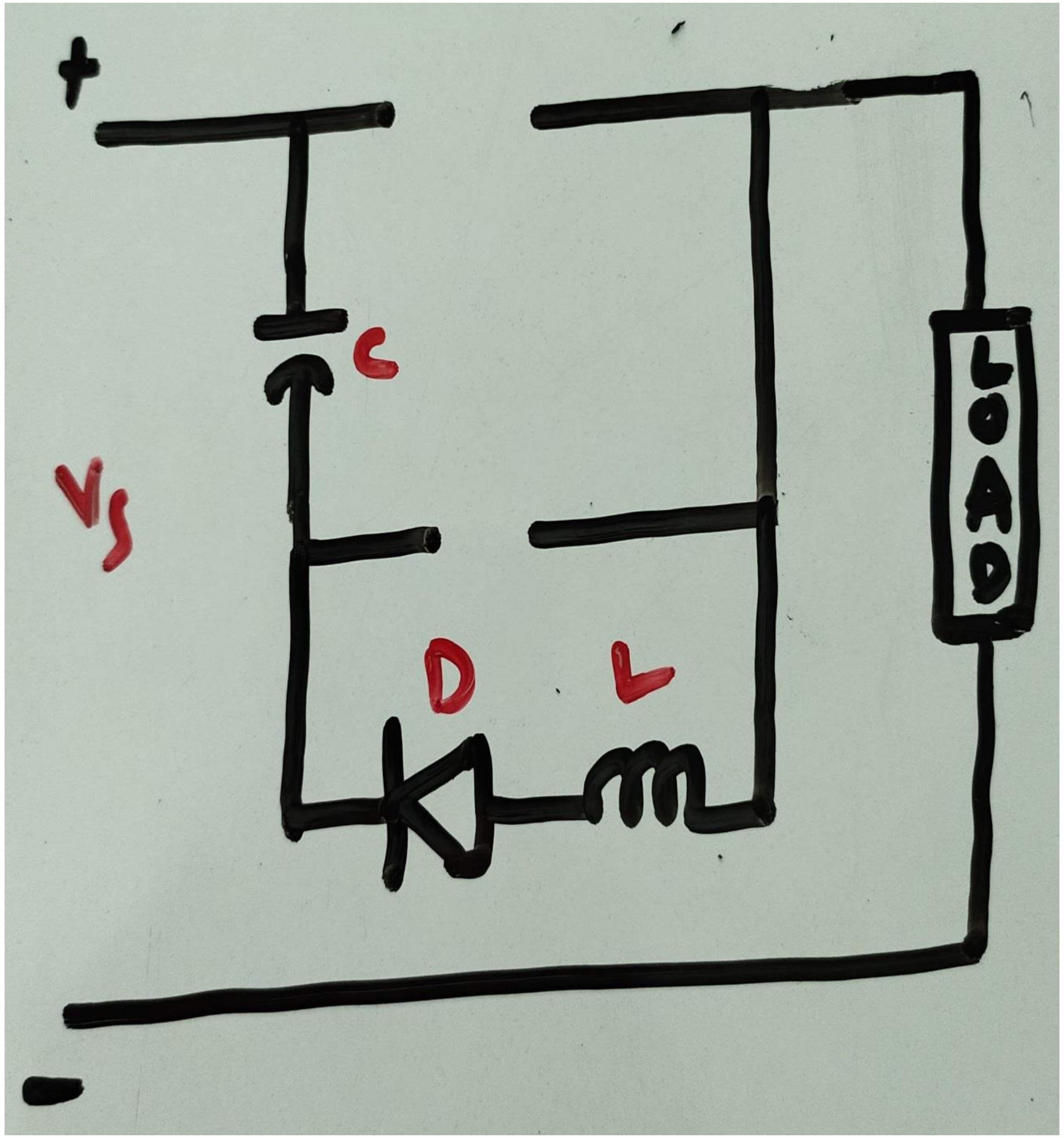
- T1=Main SCR
- TA=Auxiliary SCR
- D=Diode
- L=Inductor
- C=Capacitor
- Vs= Supply Voltage

Assumptions:

- Load current is constant
- Capacitor is initially charged by Vs.



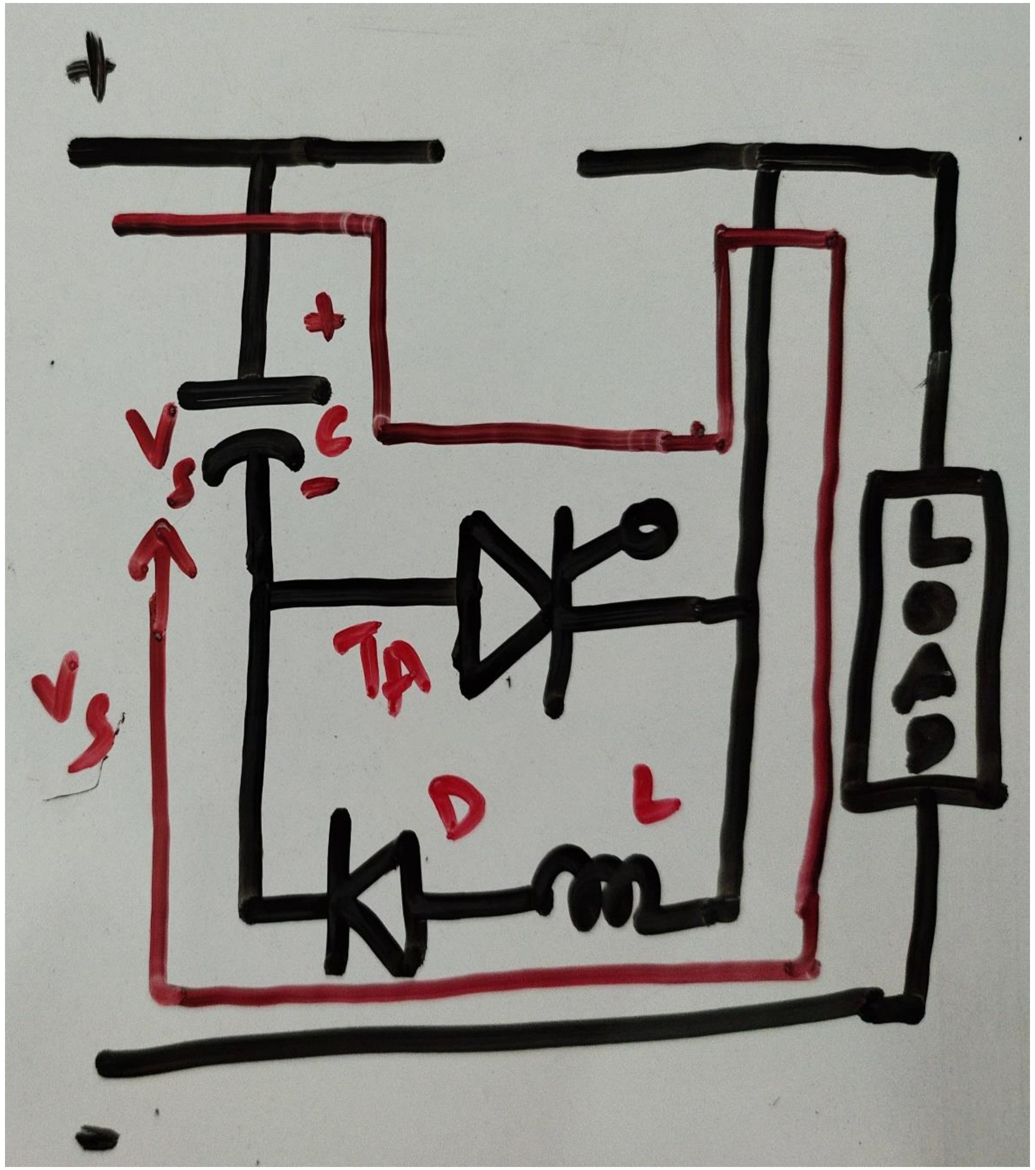
Class D Commutation



- Initially both SCRs are OFF.
- As the diode D is in Reverse biased condition, the capacitor cannot charge.

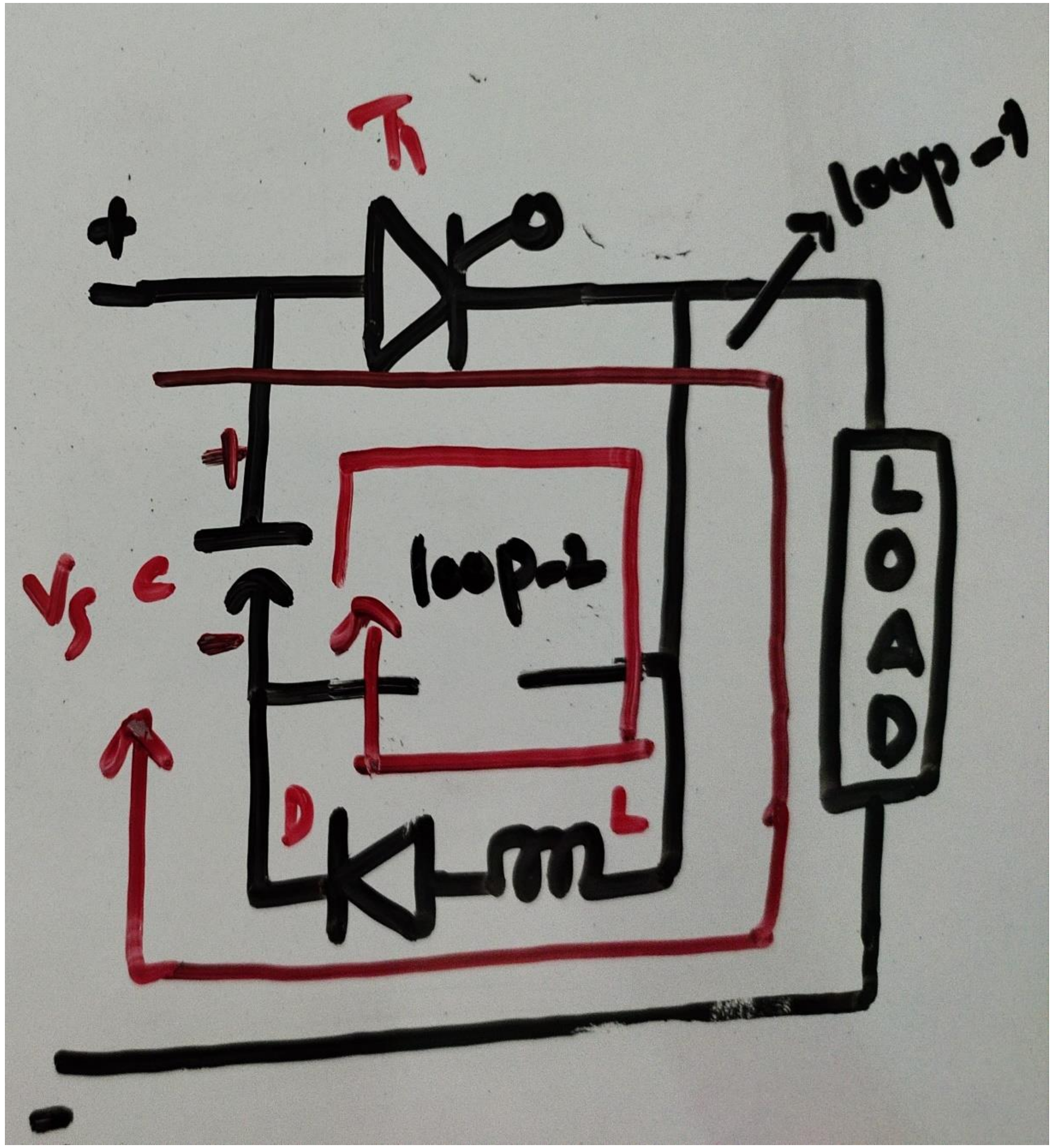
Class D Commutation

- TA is ON.
- The flow of current is like as shown in the figure.
- The capacitor will charge due to the loop current flowing in the circuit with the polarities (+,-) and with the voltage Vs as shown in the figure.
- As soon as the capacitor is fully charged, TA turns OFF. It is due to the fact that as the voltage across the capacitor increases, the current through the TA decreases since capacitor C and TA forms a series circuit.



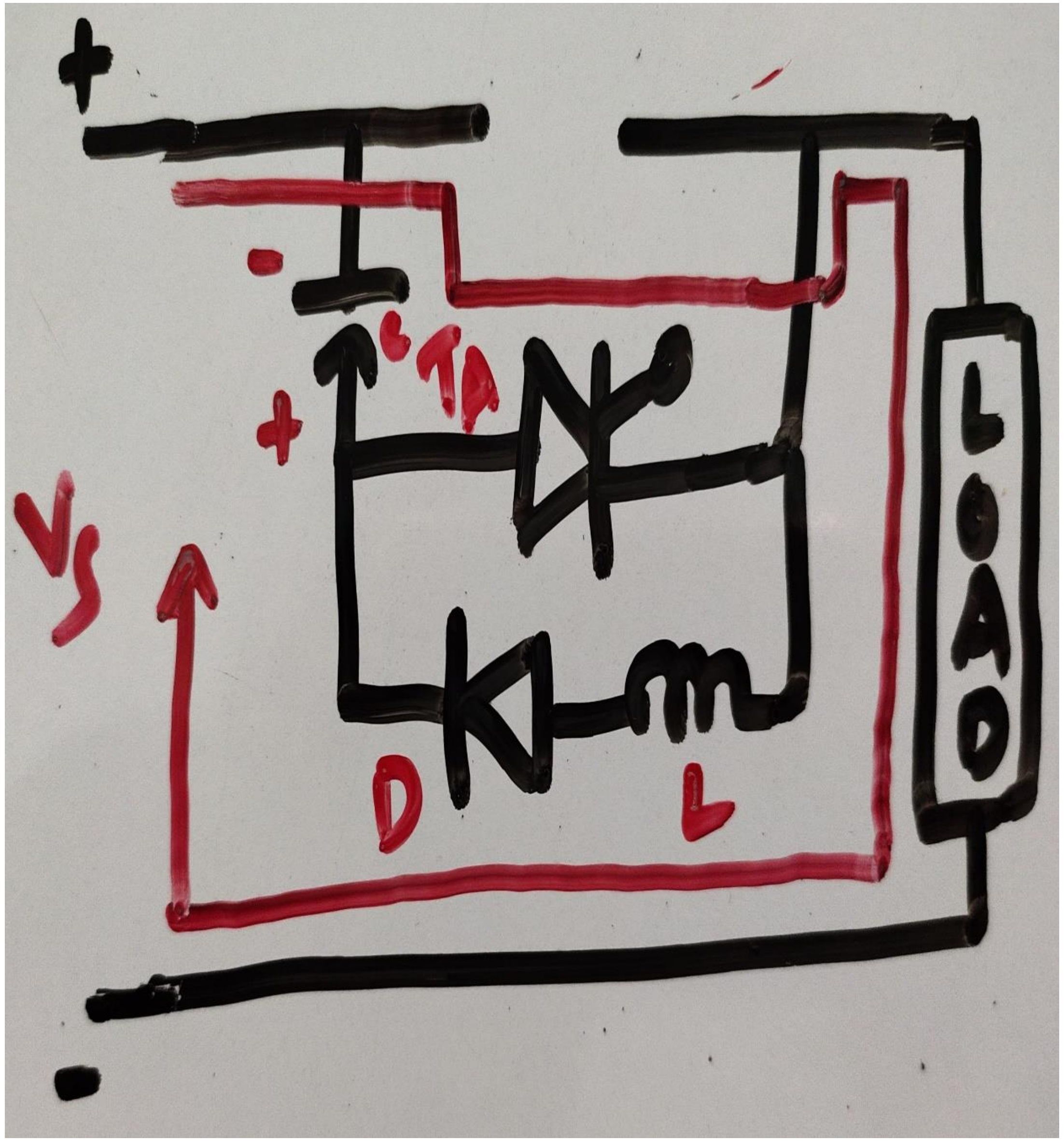
Class D Commutation

- T1 is ON.
- The flow of current will be in two loops as shown in the figure.
- Loop 2 is meant for discharging.
- In loop 2, Commutation current(capacitor discharges through) flows.
- After the capacitor has completely discharged, its polarity will be reversed(-,+) .
- As the reverse discharge of the capacitor C will not be possible due to the blocking diode D. Here in this mode, T1 –ON, TA –OFF and V_C=-Vs.



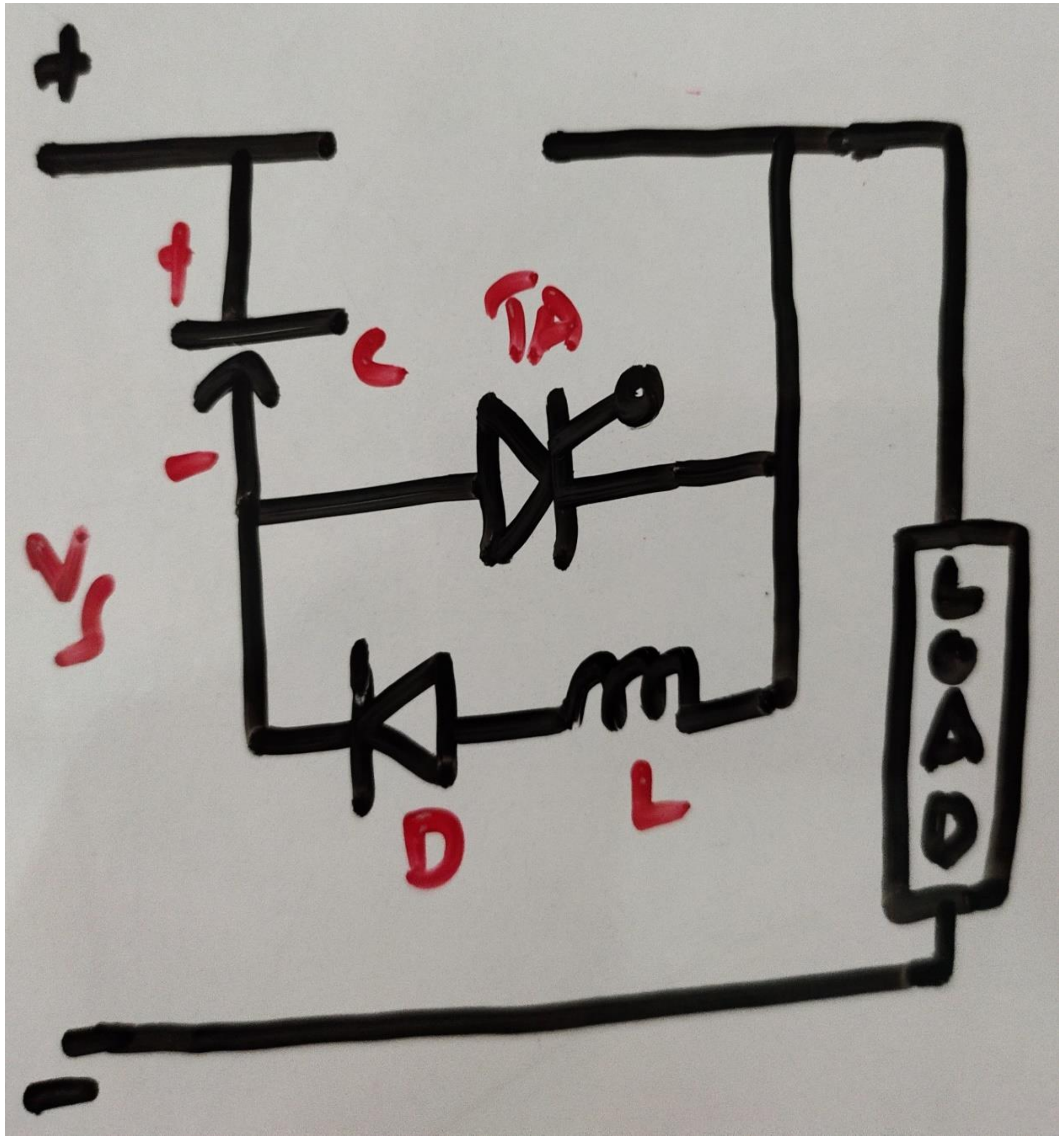
Class D Commutation

- To turn OFF T1, TA will be ON.
- The capacitor voltage with polarities(-,+) will appear across T1 and hence it get reverse biased and T1 turns OFF.
- The flow of current is like as shown in the figure.
- This current will flow until the capacitor voltage charges from –Vs to =Vs.

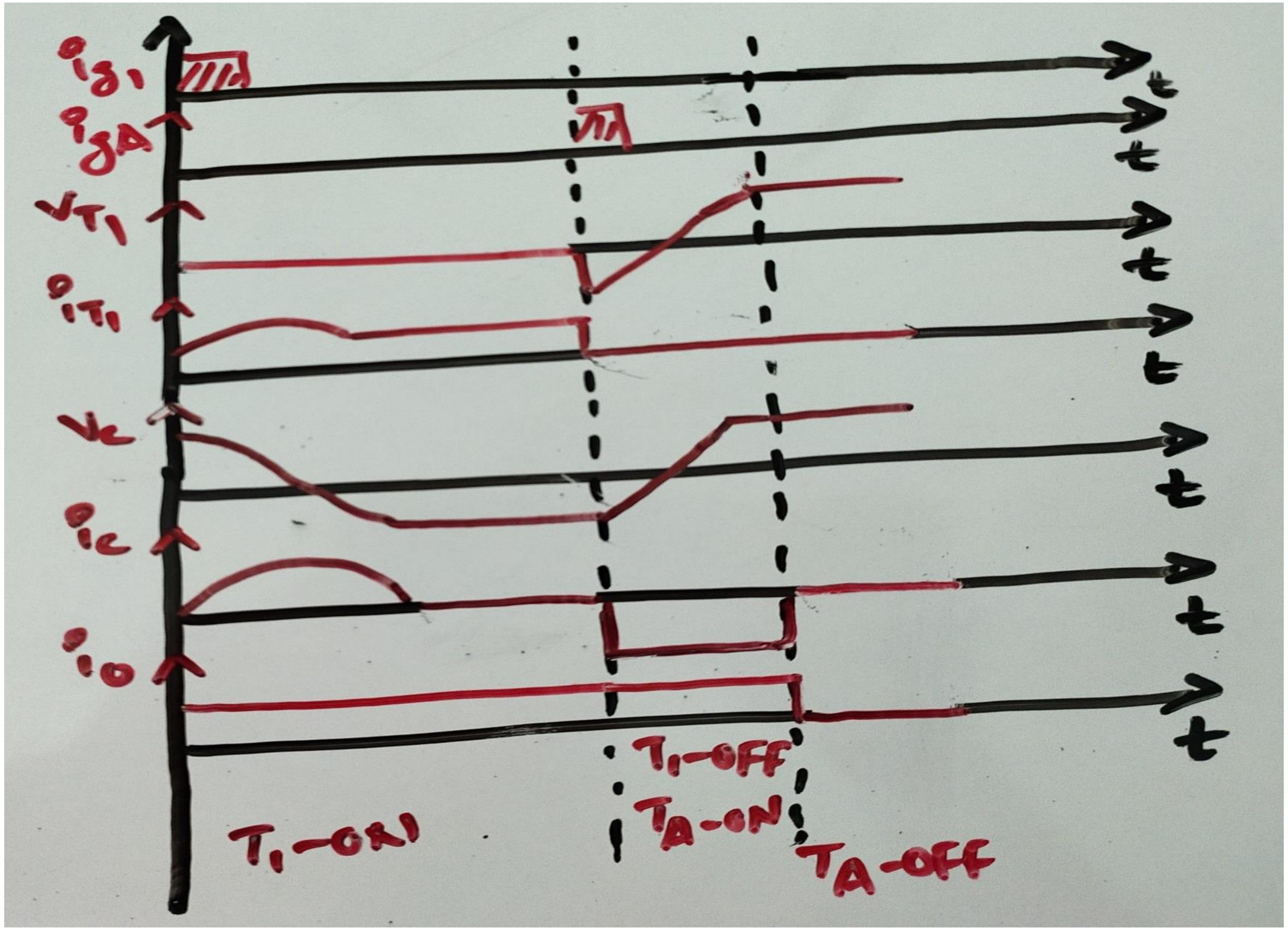


Class D Commutation

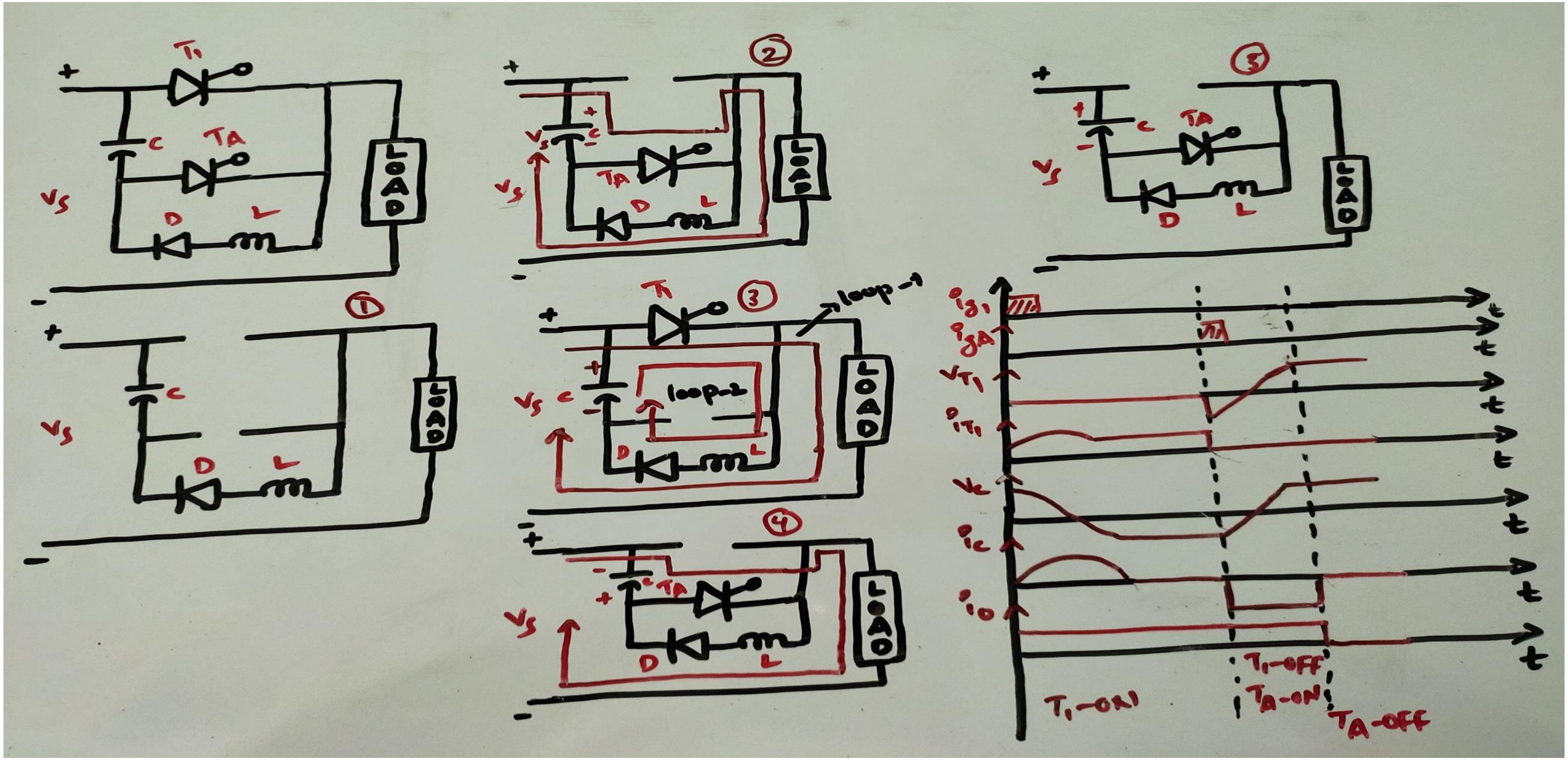
- As soon as the voltage polarities of the capacitor changes to (+,-) as shown in the figure, the T_A turns OFF.



Output Waveforms of Class D Commutation



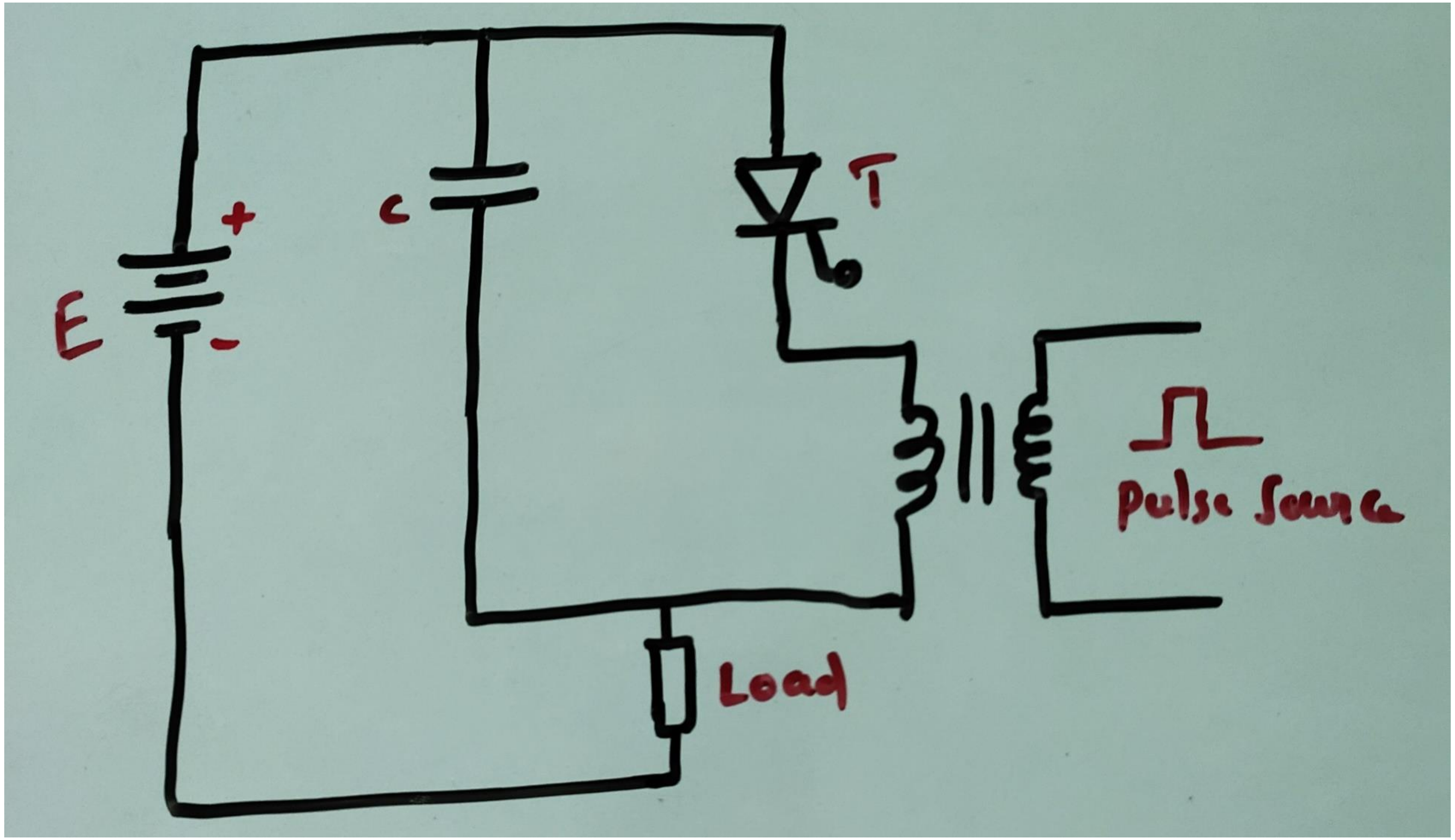
Class D Commutation in one diagram



Class E Commutation

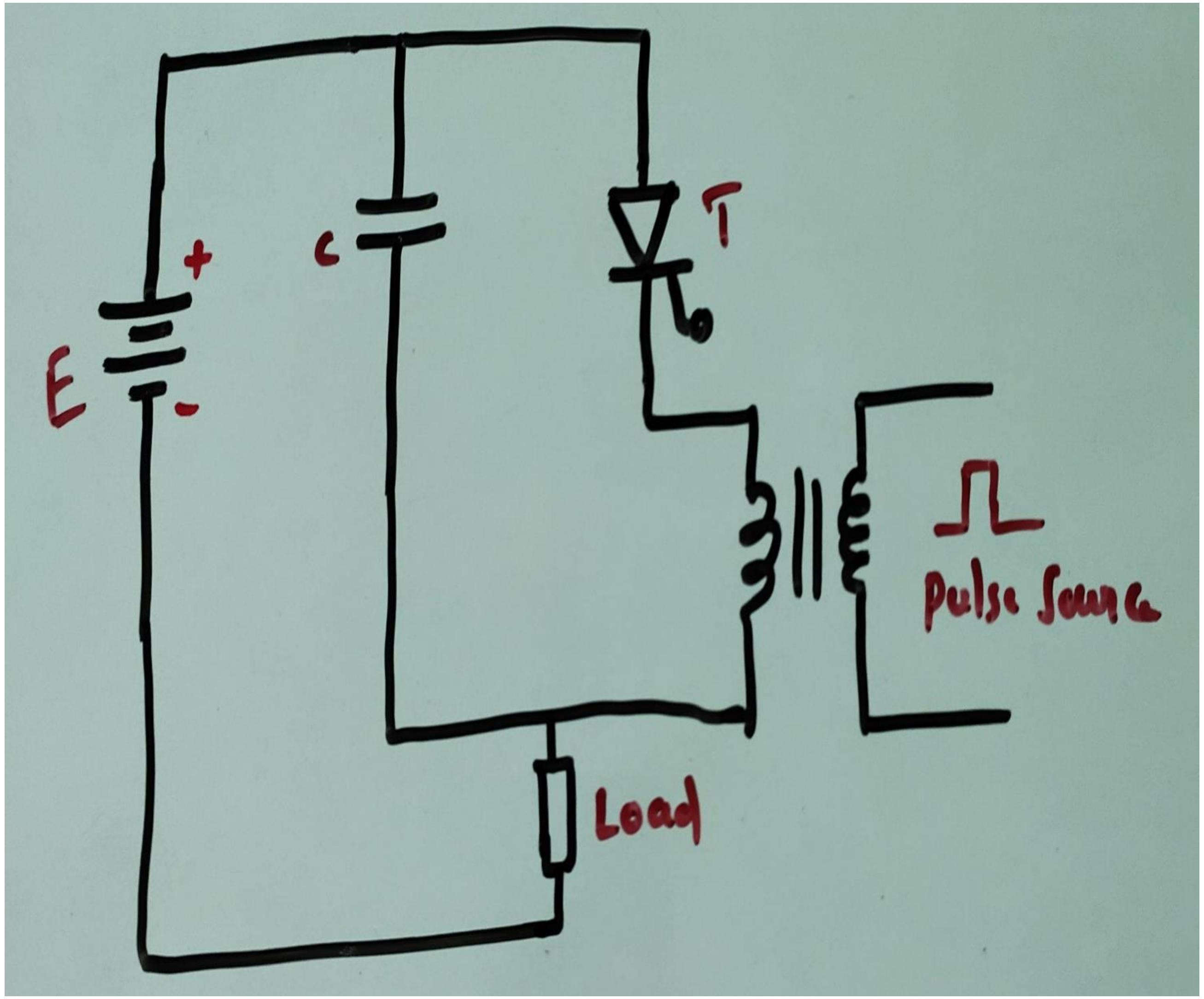
- In this commutation, a reverse voltage is applied to the current carrying SCR from ana external pulse source.
- Here the commutating pulse is applied through a pulse transformer which is suitably designed to have tight coupling between the primary and secondary.

Class E Commutation



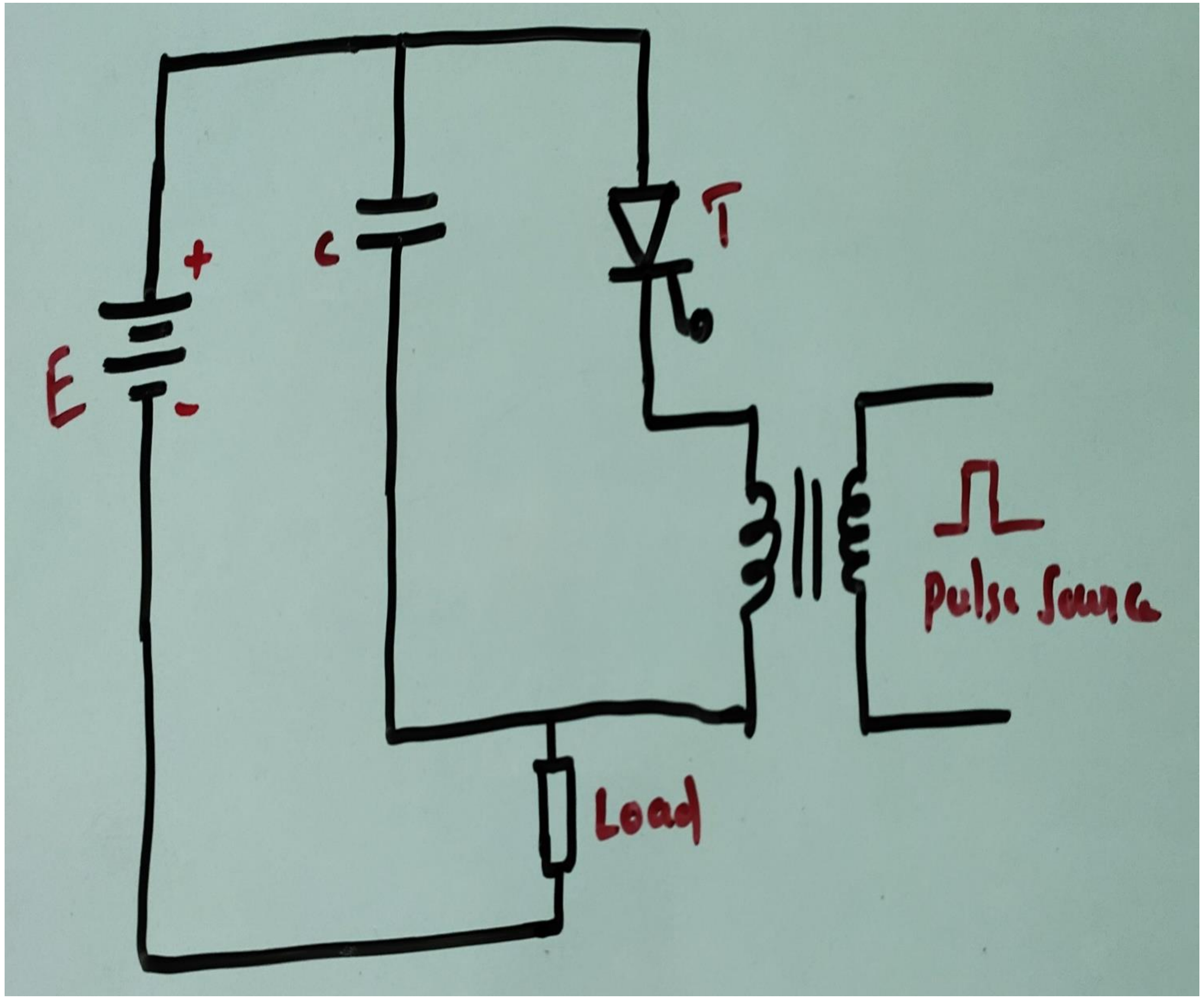
Class E Commutation

- When the SCR T is triggered, the current flows through the load and the pulse transformer.
- When a pulse voltage is applied to the primary of the pulse transformer, the voltage induced in the secondary appears across the SCR T as a reverse voltage and turn it OFF.



Class E Commutation

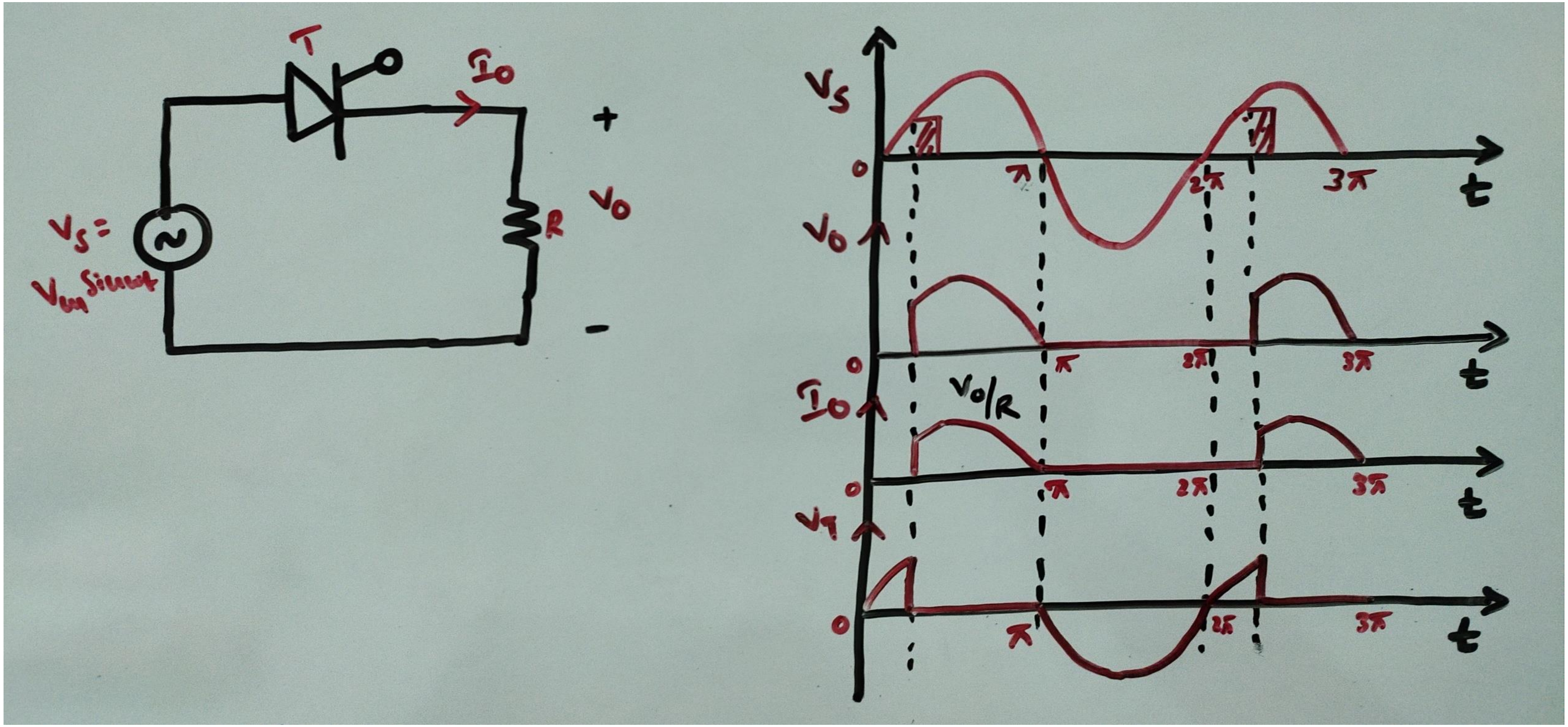
- Since the induced pulse is of high frequency, the capacitor offers almost zero impedance.
- After SCR T is turned OFF, the load current decays to zero.



Class F Commutation

- It is also called Line Commutation.
- If the supply is an alternating voltages, the load current will flow during the positive half cycle.
- During the negative half cycle, the SCR will turn off due to negative polarity across it.
- The duration of the half cycle must be longer than the turn off time of the SCR.
- The maximum frequency at which this circuit can operate depends on the turn off time of SCR.

Class F Commutation

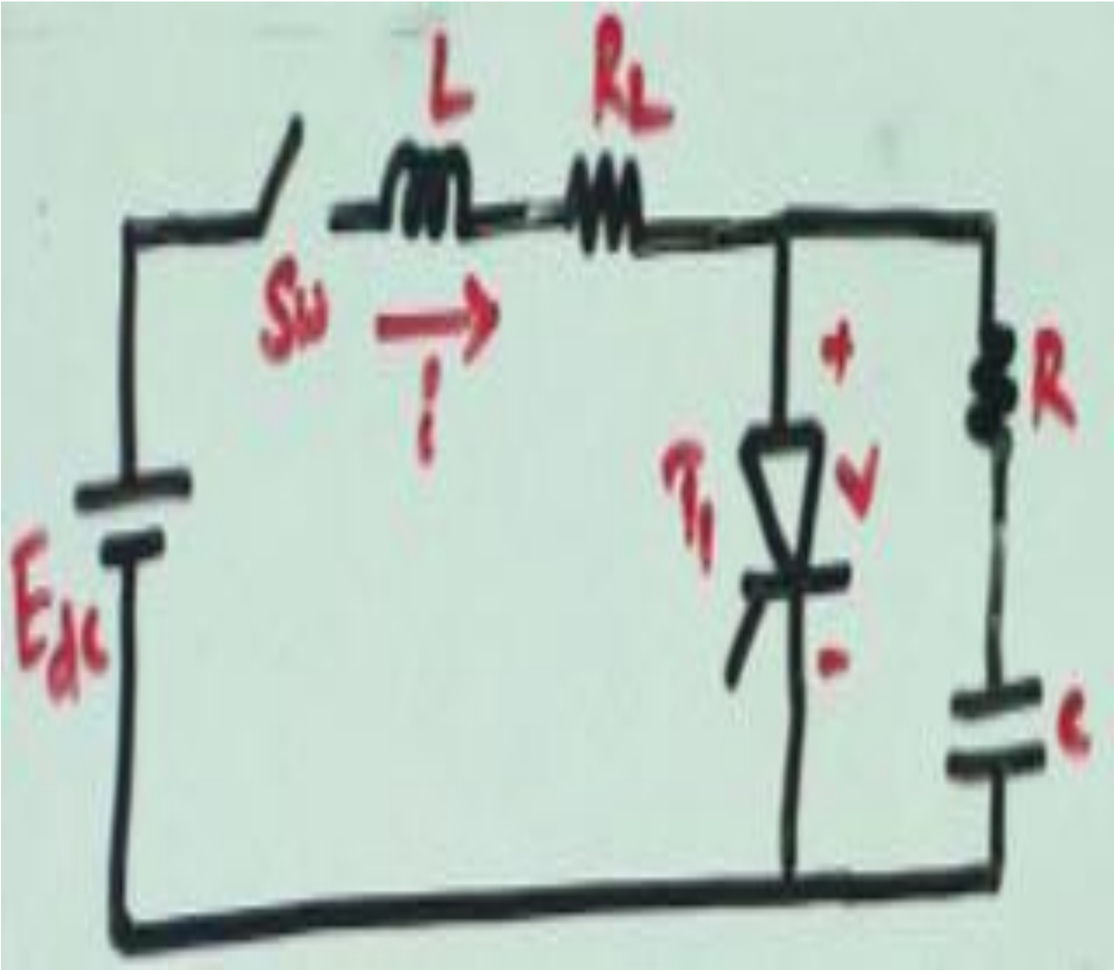


Snubber Circuits

- In most Power electronic circuits, protection is necessary against the effects of excessive rate of rise of forward voltage(dv/dt) across the devices, which can otherwise cause unintended breakover, leading to malfunction of the circuit and possible failure of the devices.
- The tendency to excessive dv/dt may arise from external cause such as the closing of main supply contactor, or from the operation of the circuit itself.
- dv/dt suppression is achieved by means of snubber circuits.
- The snubber circuit basically consists of a series connected resistor and capacitor placed on shunt with an SCR.
- A capacitor C across the SCR means that any high dv/dt appearing at the SCR terminals will set up an appropriate current(=Cdv/dt) in the capacitor.

Snubber Circuits

- The inductance in the circuit will severely limit the magnitude of the current to the capacitor and hence limit dv/dt.
- When the SCR turn-off, there is a brief pulse of reverse recovery current that rises to peak value, at which the device blocks.
- In the absence of RC snubber, the abrupt interruption of the reverse recovery current in the series inductance L, will cause transient Ldi/dt over voltages that may destroy the device itself or other semi conductors in the converter circuit.

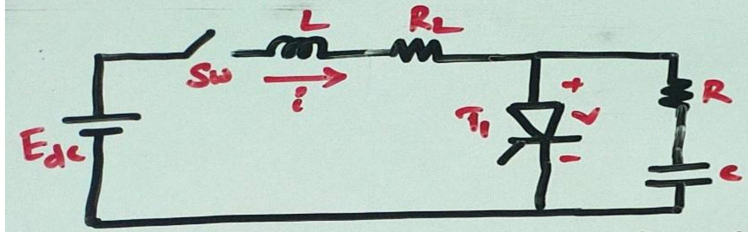


Snubber Circuits

- If an RC Snubber circuit is connected across the SCR, the reverse recovery current can transfer to the RC path when the device blocks.
- The voltage across the RC path appears as an oscillatory reverse voltage across the semiconductor.
- A correctly designed Snubber will limit the amplitude of this reverse recovery voltage and will also limit it rate of rise.
- By delaying the build-up of reverse voltage across the semiconductor, the recovery losses in the device are also reduced.
- If the Snubber resistance is too small, excessive ringing will occur in the LCR circuit, and the reverse blocking voltage capability of the semiconductor may be exceeded.
- When the SCR turns On, the Snubber capacitor, C discharges into the SCR but the resistor R limits the discharge current and prevents excessive di/dt at turn-on.

Design of Snubber Circuit

Design of Snubber Circuit



When switch is closed, "C" behaves like a short circuit and "T_1" in the forward blocking state offers a very high resistance.

R_L = Load Resistance
L = Source Inductance

For the circuit, the voltage equation is,

$$\boxed{E_{dc} = (R+R_L)\,i + L\cdot\frac{di}{dt}}$$

The solution of the above equation is,

$$\boxed{i = I\left(1-e^{-t/\tau}\right)} \rightarrow ①$$

Where,

$$I = \frac{E_{dc}}{R+R_L} \quad \text{and} \quad \tau = \frac{L}{R+R_L}$$

In equation ①, "t" is the time in seconds measured from the instant of closing the switch.

Differentiating ① w.r.t "t",

$$\frac{di}{dt} = I\cdot e^{-t/\tau}\cdot\frac{1}{\tau}$$

$$= \frac{E_{dc}}{\cancel{R+R_L}}\cdot\frac{\cancel{R+R_L}}{L}\cdot e^{-t/\tau}$$

$$= \frac{E_{dc}}{L}\cdot e^{-t/\tau}.$$

The value of $\frac{di}{dt}$ is maximum when $t=0$.

$$\left.\frac{di}{dt}\right|_{t=0} = \left.\frac{di}{dt}\right|_{max.} = \frac{E_{dc}}{L} \rightarrow ②$$

(or) $$\boxed{L = \frac{E_{dc}}{(di/dt)_{max.}}} \rightarrow ③$$

Now voltage across "T_1",

$$V = R\cdot i \Rightarrow \frac{dv}{dt} = R\cdot\frac{di}{dt}$$

(or) $$\left(\frac{dv}{dt}\right)_{max.} = R\cdot\left(\frac{di}{dt}\right)_{max.}$$

Substitute equation ②,

$$\left(\frac{dv}{dt}\right)_{max.} = R\left(\frac{E_{dc}}{L}\right)$$

$$\Rightarrow \boxed{R = \frac{L}{E_{dc}}\left(\frac{dv}{dt}\right)_{max.}} \rightarrow ④$$

L, R_L, R and C should be so selected that the circuit becomes critically damped.

$$\sqrt{(R_L+R)^2 - \frac{4L}{C}} = 0$$

$$\Rightarrow (R_L+R)^2 = \frac{4L}{C} \Rightarrow \boxed{R_L+R = 2\sqrt{\frac{L}{C}}} \rightarrow ⑤$$

We can determine the snubber components R and C by using equations ④ and ⑤.

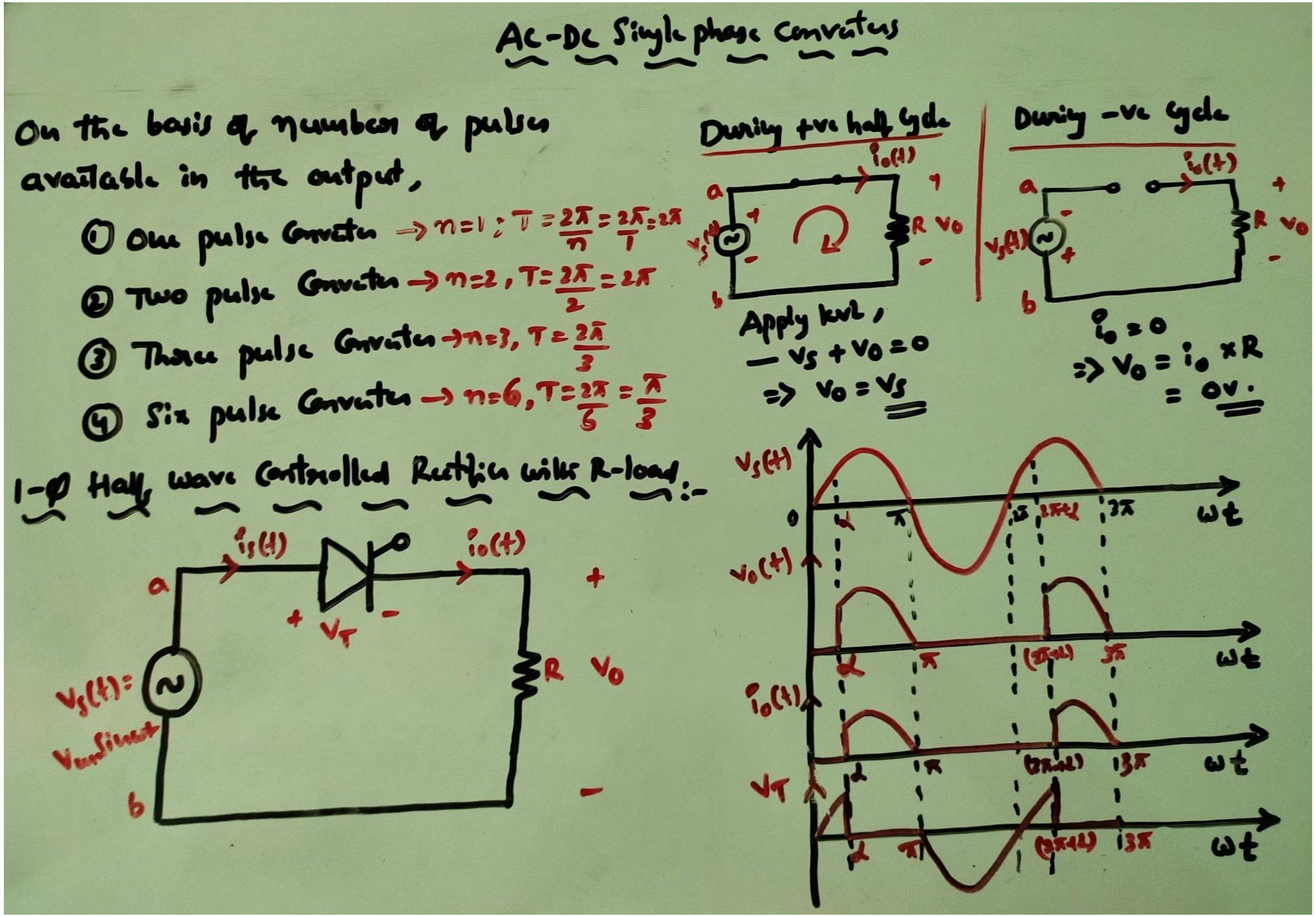
Rectifiers

- Rectification is a process of converting an alternating current or voltage into direct current or voltage.
- This conversion can be achieved by a variety of circuits based on and using switches.
- The widely used switching devices are diodes, thyristors, power transistors, power MOS etc.
- The rectifier circuits can be broadly classified into three classes : **Uncontrolled, Fully-controlled, and Half-controlled.**
- **An uncontrolled rectifier** uses only diodes and the dc output voltage is fixed in amplitude by the amplitude of the ac supply.

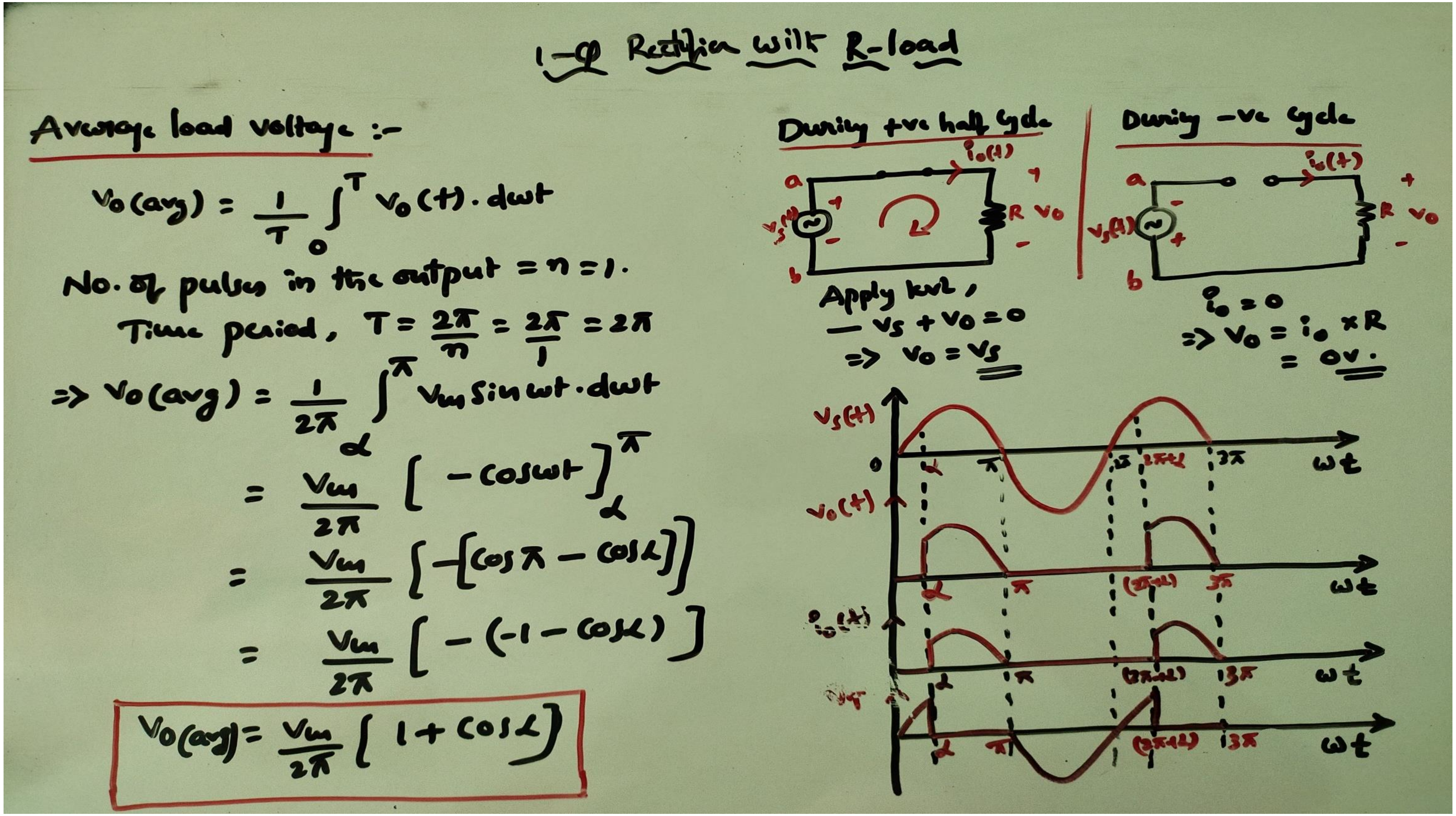
Rectifiers

- **The fully controlled rectifiers** uses Thyristors as the rectifying elements and the dc output voltage is a function of the amplitude of the ac supply voltage and the point on wave at which the thyristors are triggered(called Firing angle Alpha).
- **The half controlled rectifier** contains a mixture of diodes and thyristors, allowing a more limited control over the dc output voltage level than fully controlled rectifier.

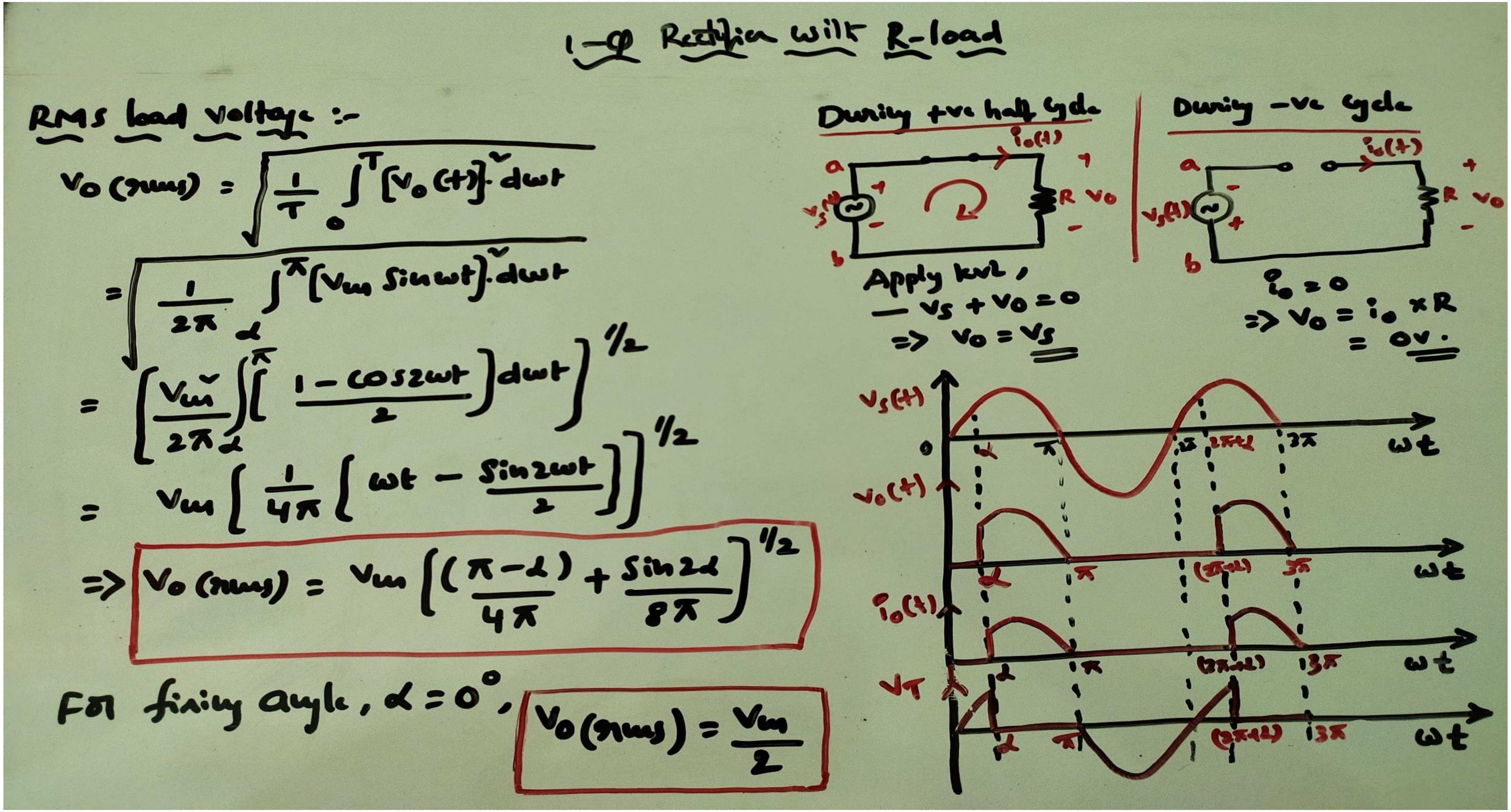
Single Phase half wave controlled rectifier with R-Load



Single Phase half wave controlled rectifier with R-Load



Single Phase half wave controlled rectifier with R-Load



Single Phase half wave controlled rectifier with R-Load

① If the half-wave controlled rectifier has a purely resistive load of "R" and the delay angle is $\alpha = \frac{\pi}{3}$. Determine:

(a) Rectification efficiency (b) Form factor

(c) Ripple factor (d) Transformer utilization factor

(e) peak inverse voltage for SCR

(a) Rectification efficiency, $\eta = \frac{P_{dc}}{P_{ac}}$

Where, P_{dc} = dc load power

$$= \frac{V_0^2(avg)}{R}$$

P_{ac} = rms load power

$$= \frac{V_0^2(rms)}{R}$$

For a Half-wave controlled rectifier,

$$V_0(avg) = \frac{V_m}{2\pi}\left[1+\cos\alpha\right]$$

$$V_0(rms) = V_m\left[\frac{\pi-\alpha}{4\pi} + \frac{\sin 2\alpha}{8\pi}\right]^{1/2}$$

At $\alpha = \pi/3$,

$$V_0(avg) = \frac{V_m}{2\pi}\left[1+\cos(\pi/3)\right]$$

$$= \frac{V_m}{2\times 3.14}\left[1+\frac{1}{2}\right]$$

$$= 0.239\,V_m \longrightarrow ①$$

$$V_0(rms) = 0.485\,V_m \longrightarrow ②$$

$$\eta = \frac{(0.239\,V_m)^2}{(0.485\,V_m)^2}$$

$$= 24.28\%$$

Single Phase half wave controlled rectifier with R-Load

① If the half-wave controlled rectifier has a purely resistive load of "R" and the delay angle is $\alpha = \frac{\pi}{3}$. Determine:

(a) Rectification efficiency (b) Form factor

(c) Ripple factor (d) Transformer utilization factor

(e) peak Inverse voltage for SCR

(b) Form factor $(FF) = \frac{V_{o(rms)}}{V_{o(avg)}}$

$$= \frac{0.485 V_m}{0.239 V_m} = 2.033 = 203.3\%$$

(c) Ripple factor $(Rf) = \left[(FF)^2 - 1\right]^{1/2}$

$$= \left[(2.033)^2 - 1\right]^{1/2}$$

$$= 1.77 = 177\%$$

(d) Transformer utilization factor,

$$TUF = \frac{P_{dc}}{V_{s(rms)} \cdot I_{o(rms)}}$$

$$V_{s(rms)} = \frac{V_m}{\sqrt{2}}, \quad I_{o(rms)} = \frac{V_{o(rms)}}{R}$$

$$\therefore TUF = \frac{V_{o(avg)}^2 / R}{\left(\frac{V_m}{\sqrt{2}}\right) \cdot \left(\frac{V_{o(rms)}}{R}\right)}$$

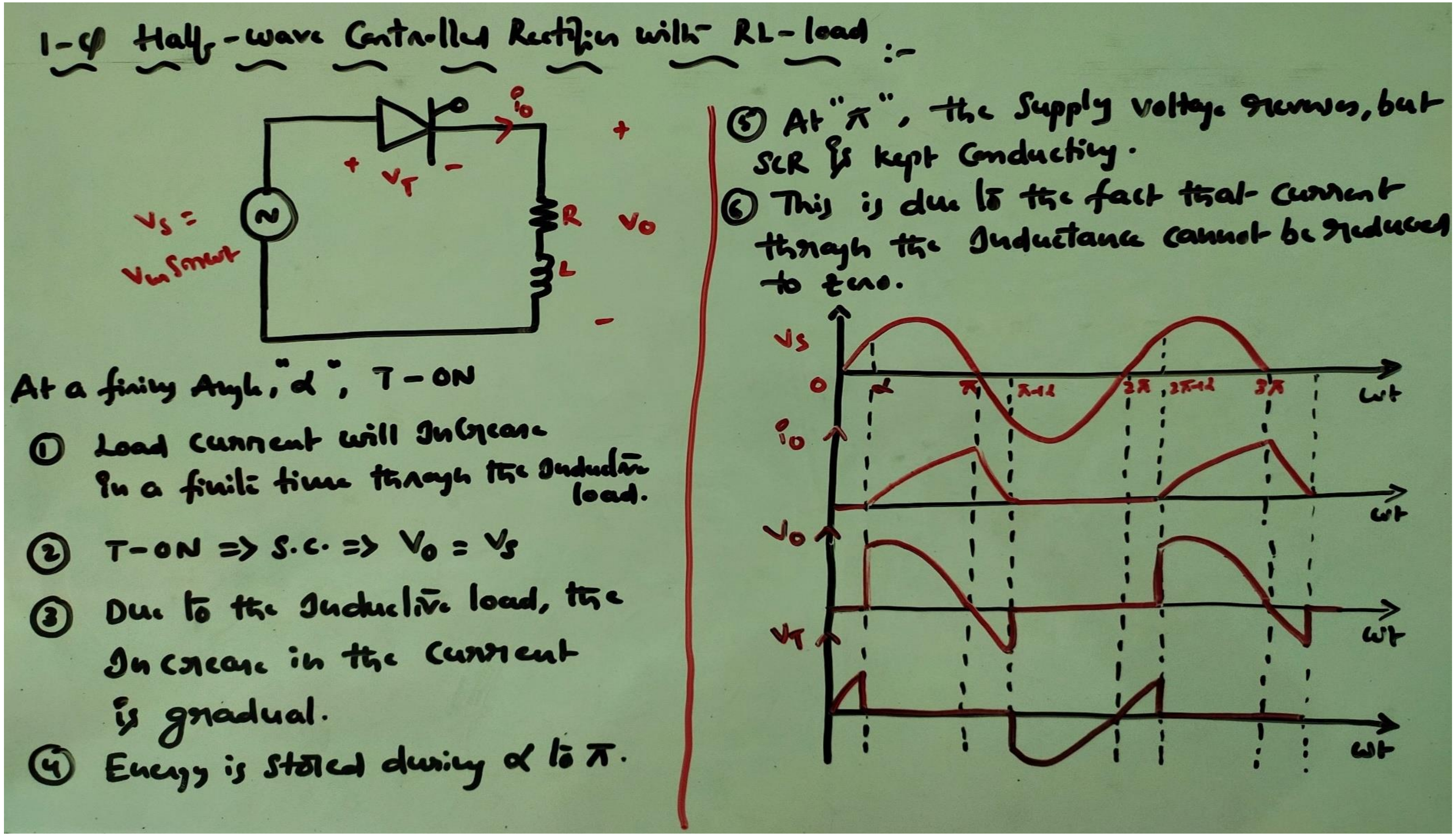
$$= \frac{(0.239 V_m)^2}{(0.707 V_m)(0.485 V_m)}$$

$$= 0.166 \text{ (or) } 16.6\%$$

(e) peak Inverse voltage,

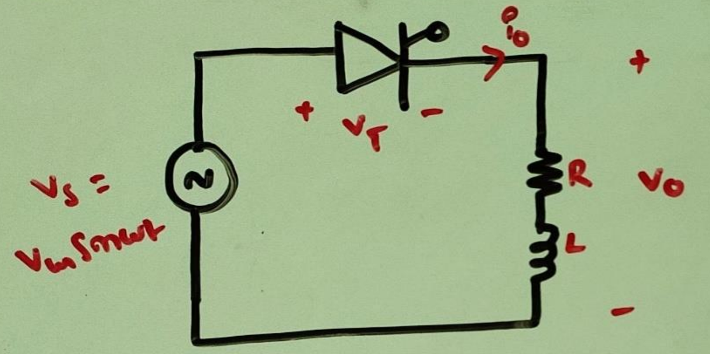
$$= V_m.$$

Single Phase half wave controlled rectifier with RL-Load without Free Wheeling Diode



Single Phase half wave controlled rectifier with RL-Load without Free Wheeling Diode

1-φ Half-wave Controlled Rectifier with RL-load :-

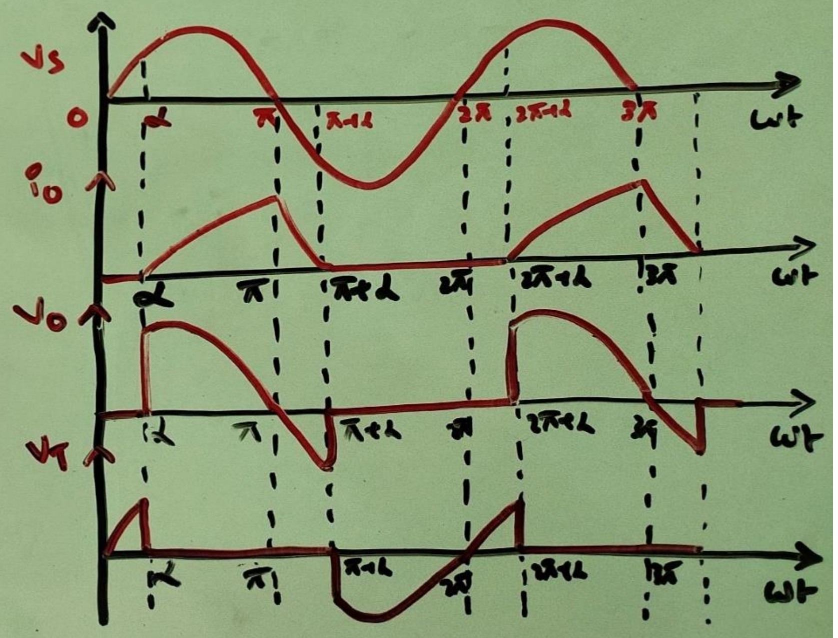


⑦ During -ve half-cycle, current continues to flow till the energy stored in the "L" in the load resistor and a part of the energy is fed back to the source.

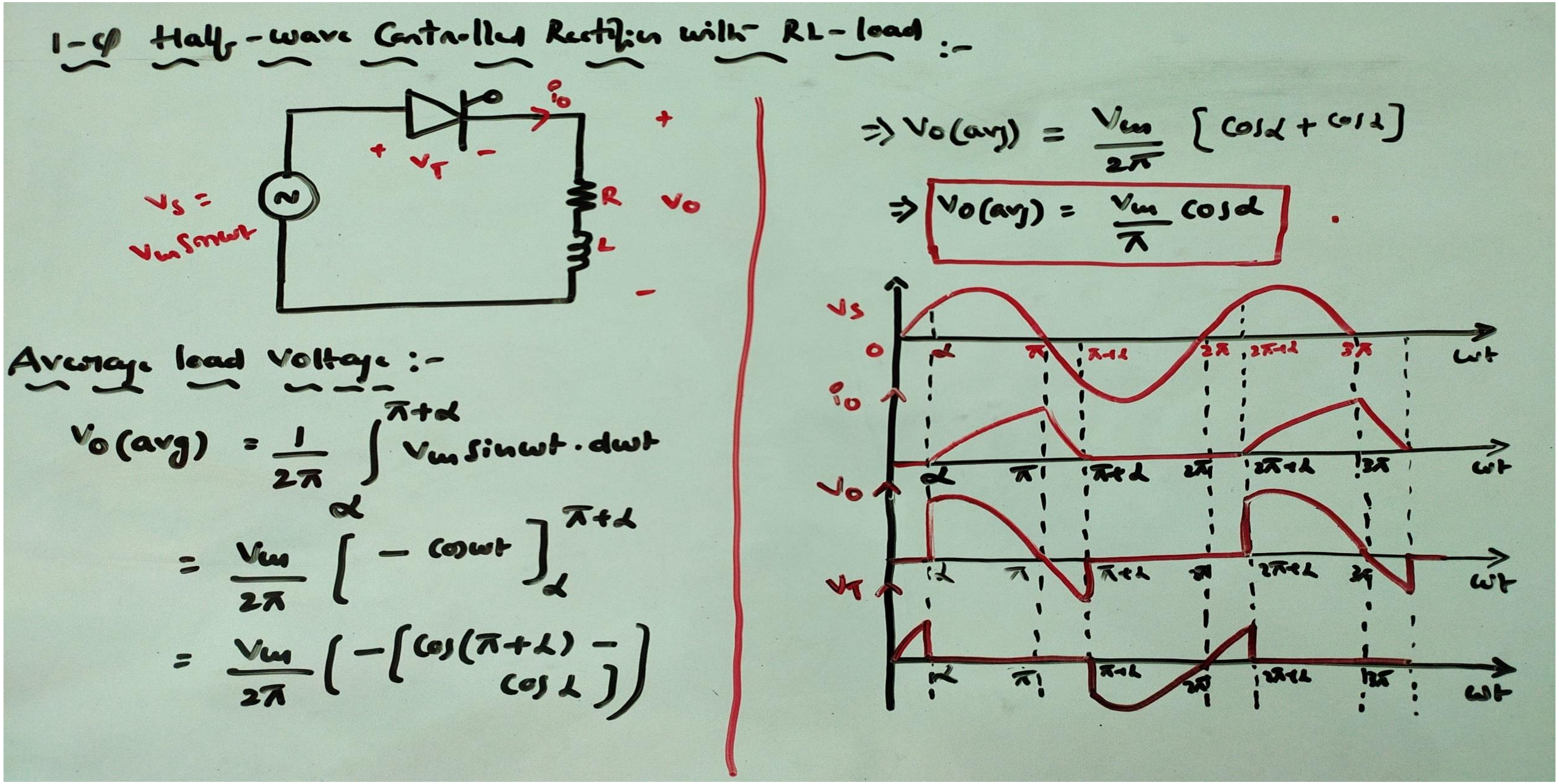
⑧ Hence due to energy stored in the Inductor, current continues to flow upto "π+α".

⑨ At π+α, load current is zero and due to negative supply voltage, T-OFF.

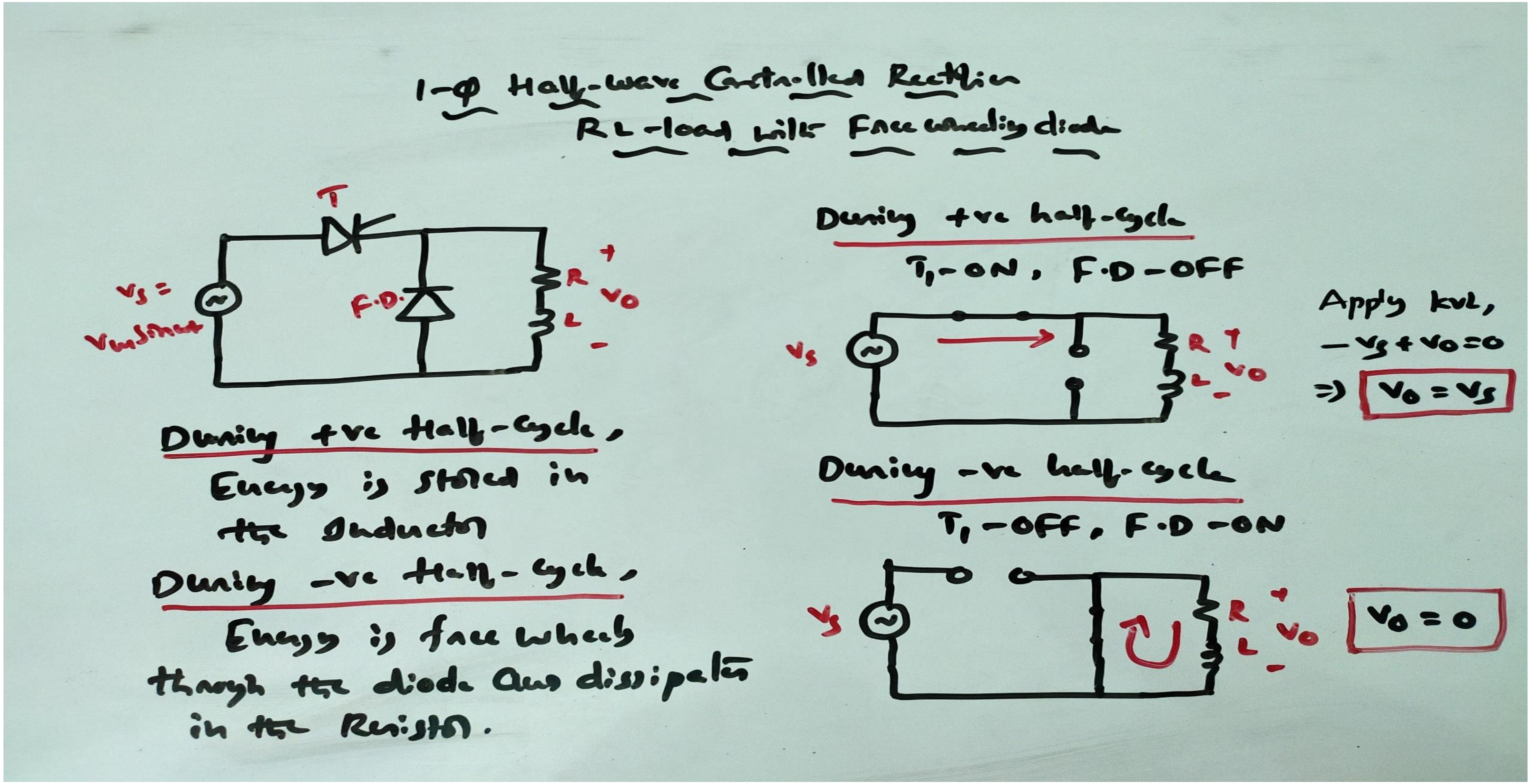
⑩ At "2π+α", again SCR is triggered.



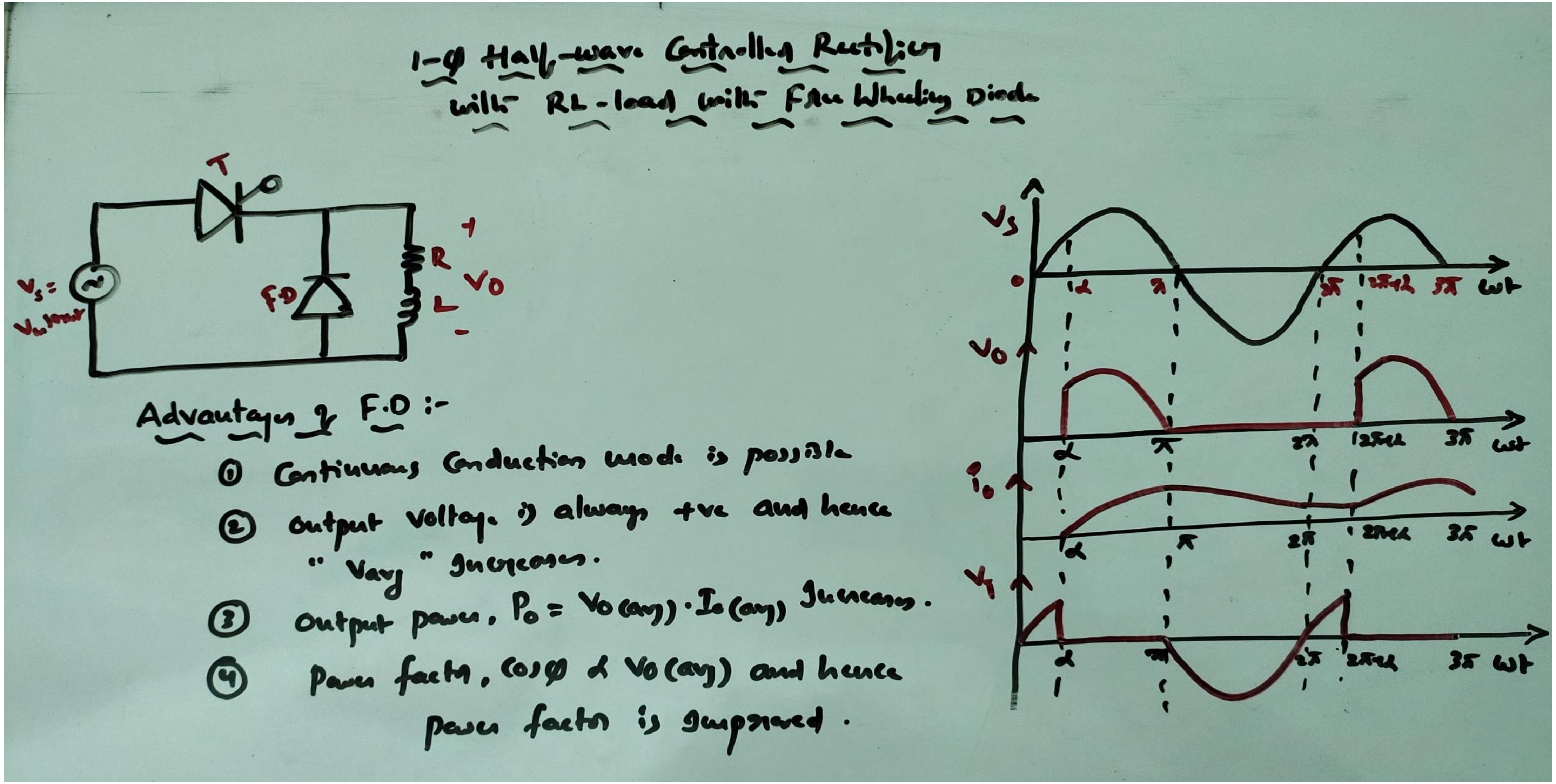
Single Phase half wave controlled rectifier with RL-Load without Free Wheeling Diode



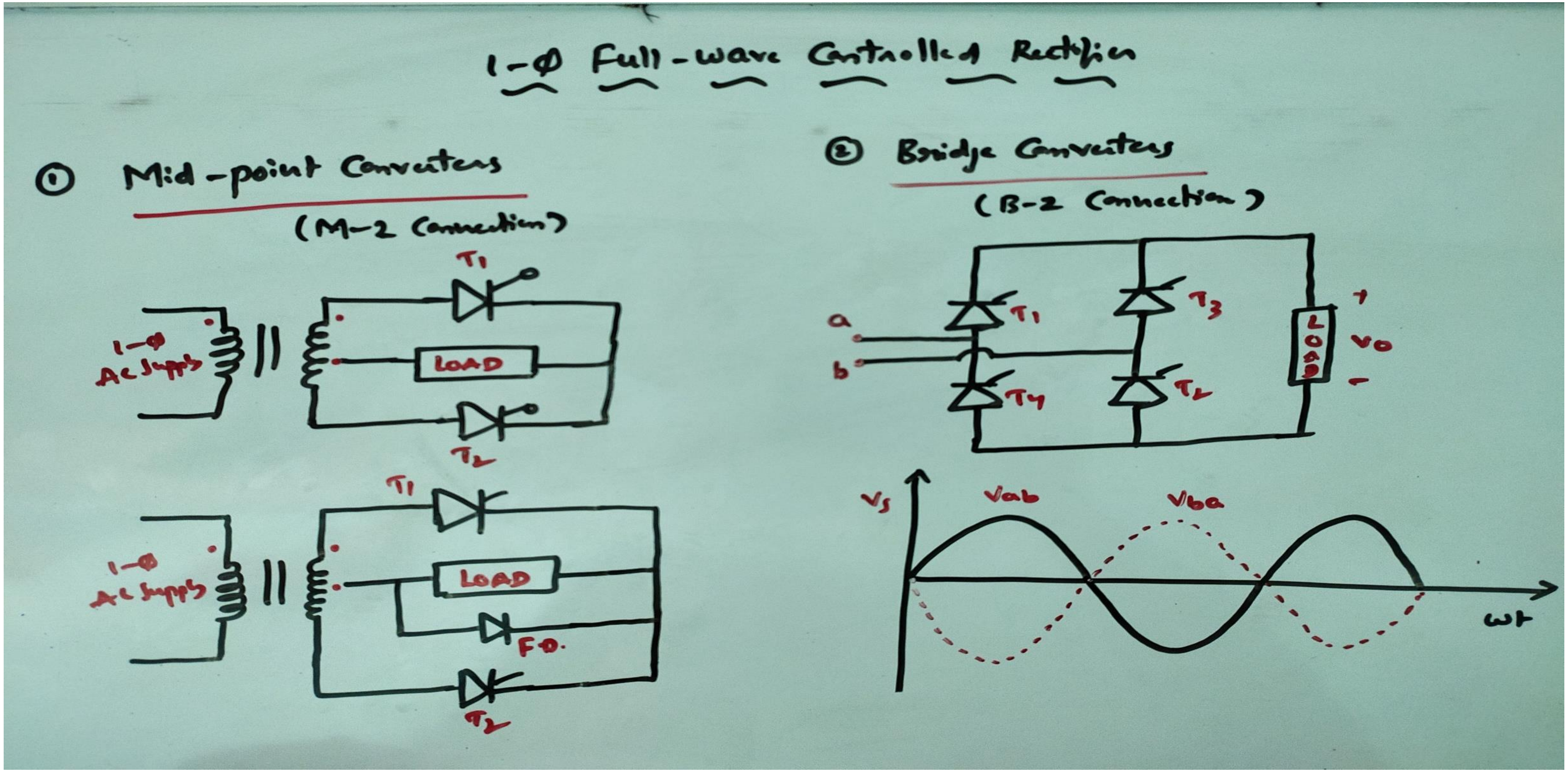
Single Phase half wave controlled rectifier with RL-Load with Free Wheeling Diode



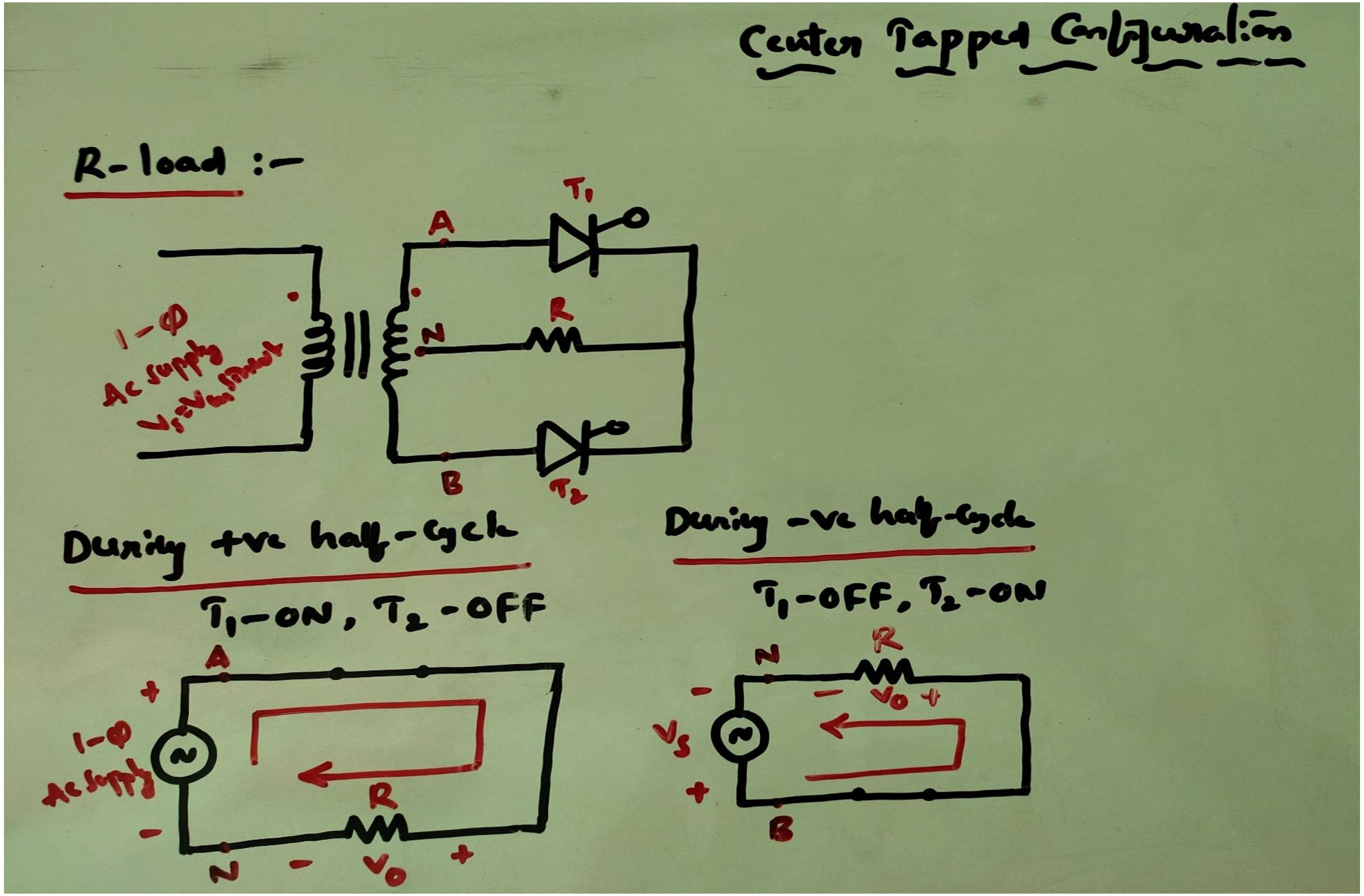
Single Phase half wave controlled rectifier with RL-Load with Free Wheeling Diode



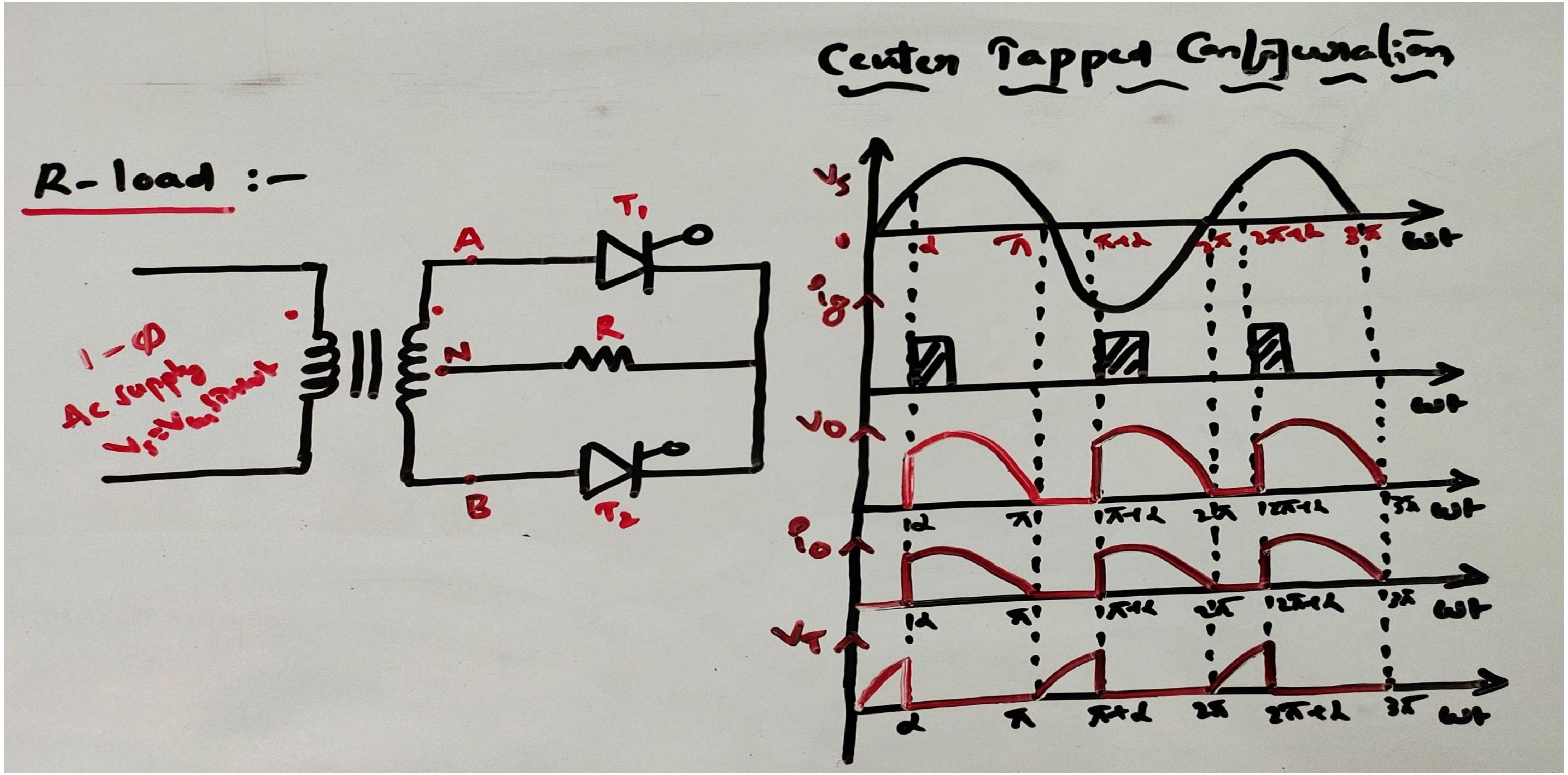
Single Phase full wave controlled rectifier



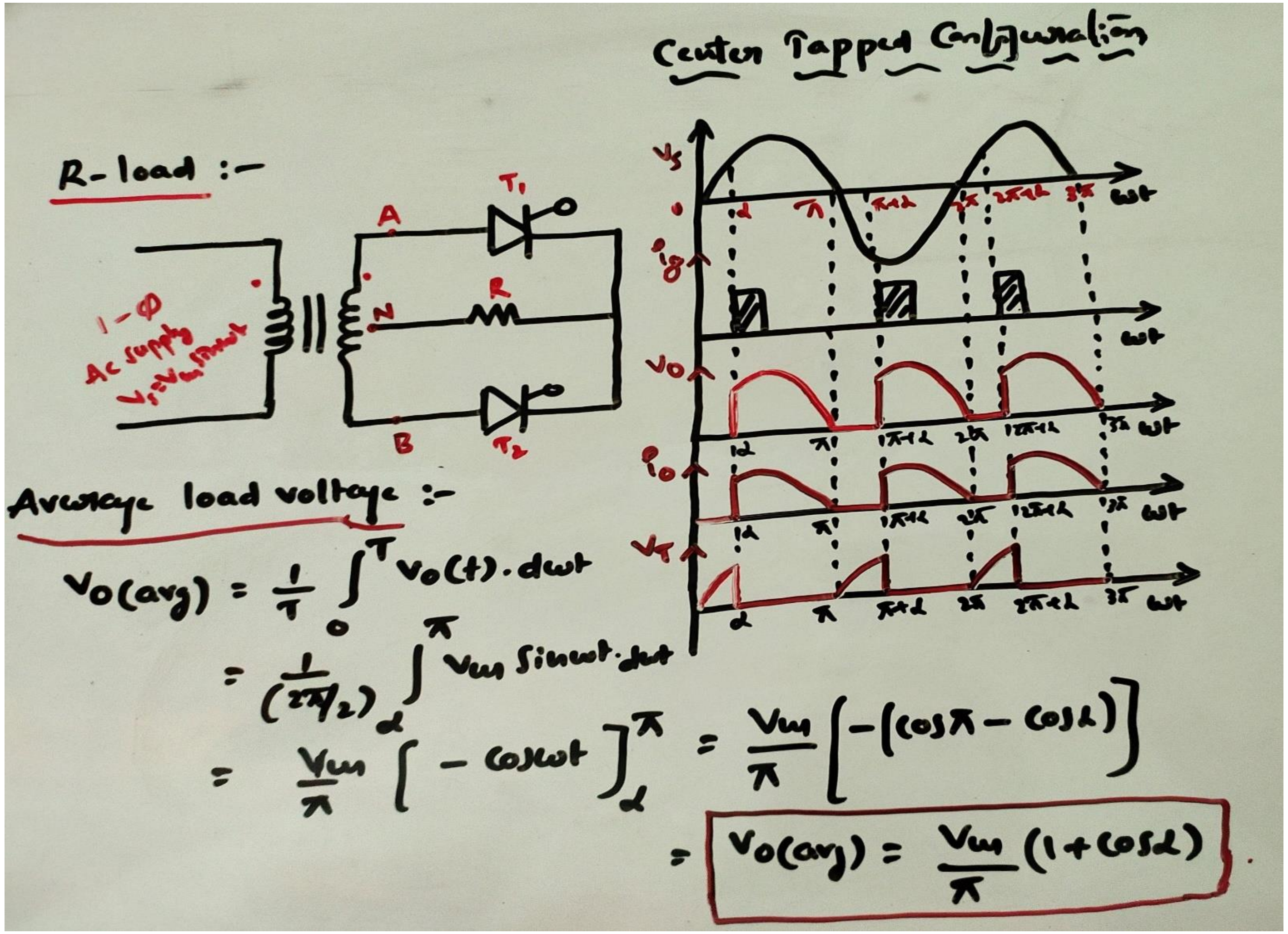
Single Phase full wave controlled rectifier-Center Tapped Configuration with R-Load



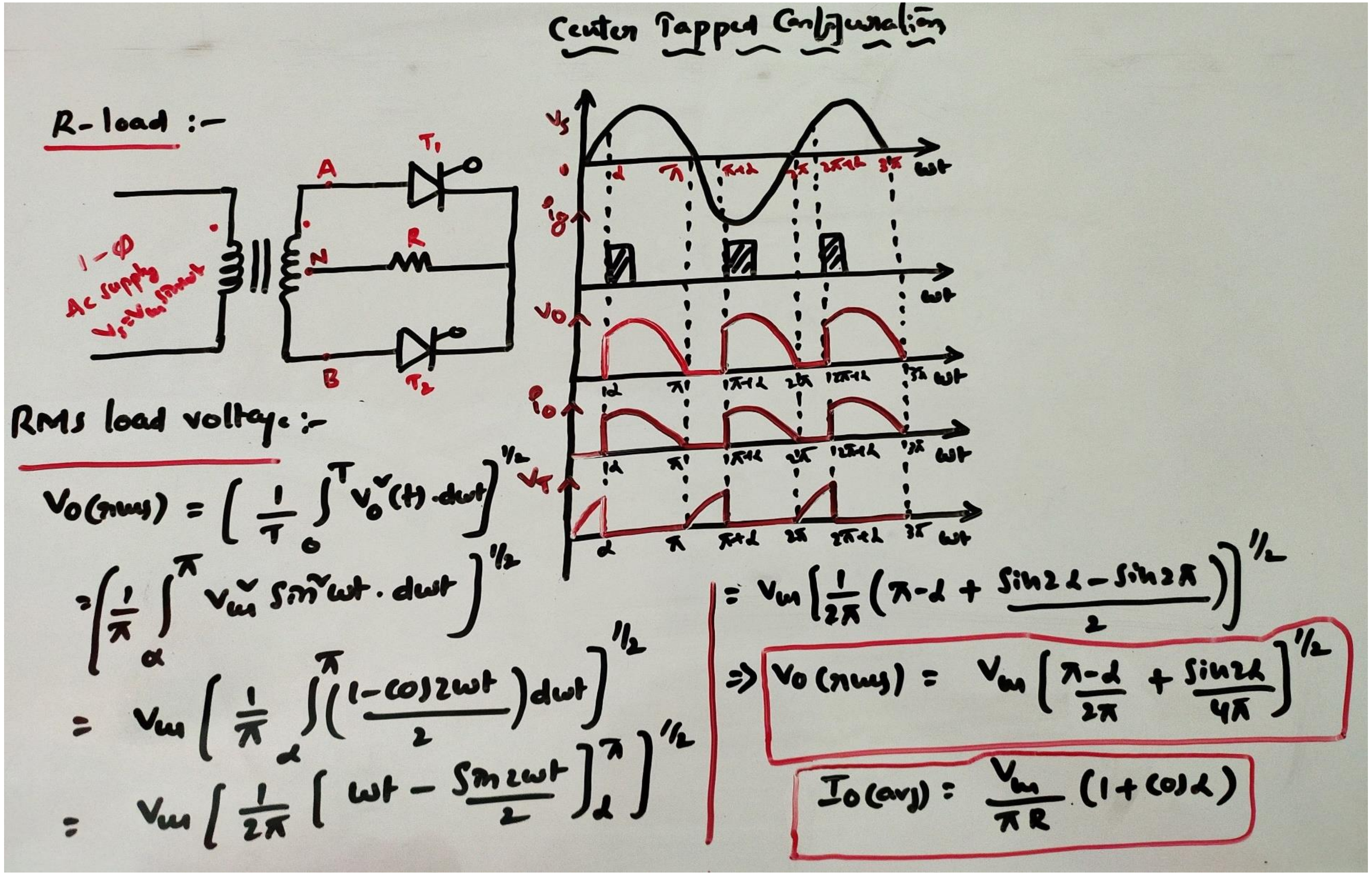
Single Phase full wave controlled rectifier-Center Tapped Configuration with R-Load



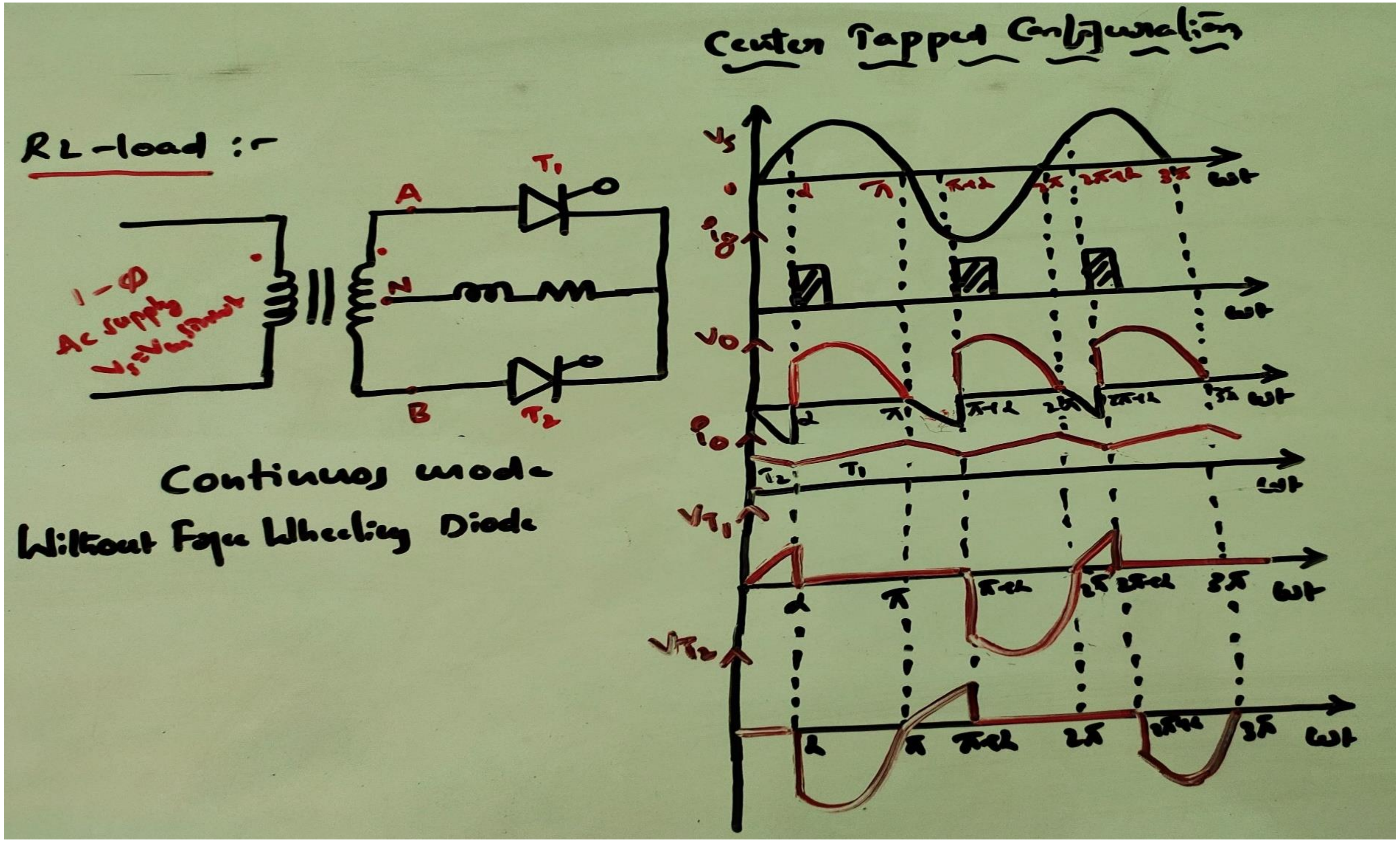
Single Phase full wave controlled rectifier-Center Tapped Configuration with R-Load



Single Phase full wave controlled rectifier-Center Tapped Configuration with R-Load



Single Phase full wave controlled rectifier-Center Tapped Configuration with RL-Load without Free wheeling Diode and Continuous Conduction Mode



Single Phase full wave controlled rectifier-Center Tapped Configuration with RL-Load without Free wheeling Diode and Continuous Conduction Mode

Center Tapped Configuration

For Continuous Conduction mode,

$$V_o(avg) = \frac{1}{T}\int_0^T v_o(t)\cdot d\omega t$$

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

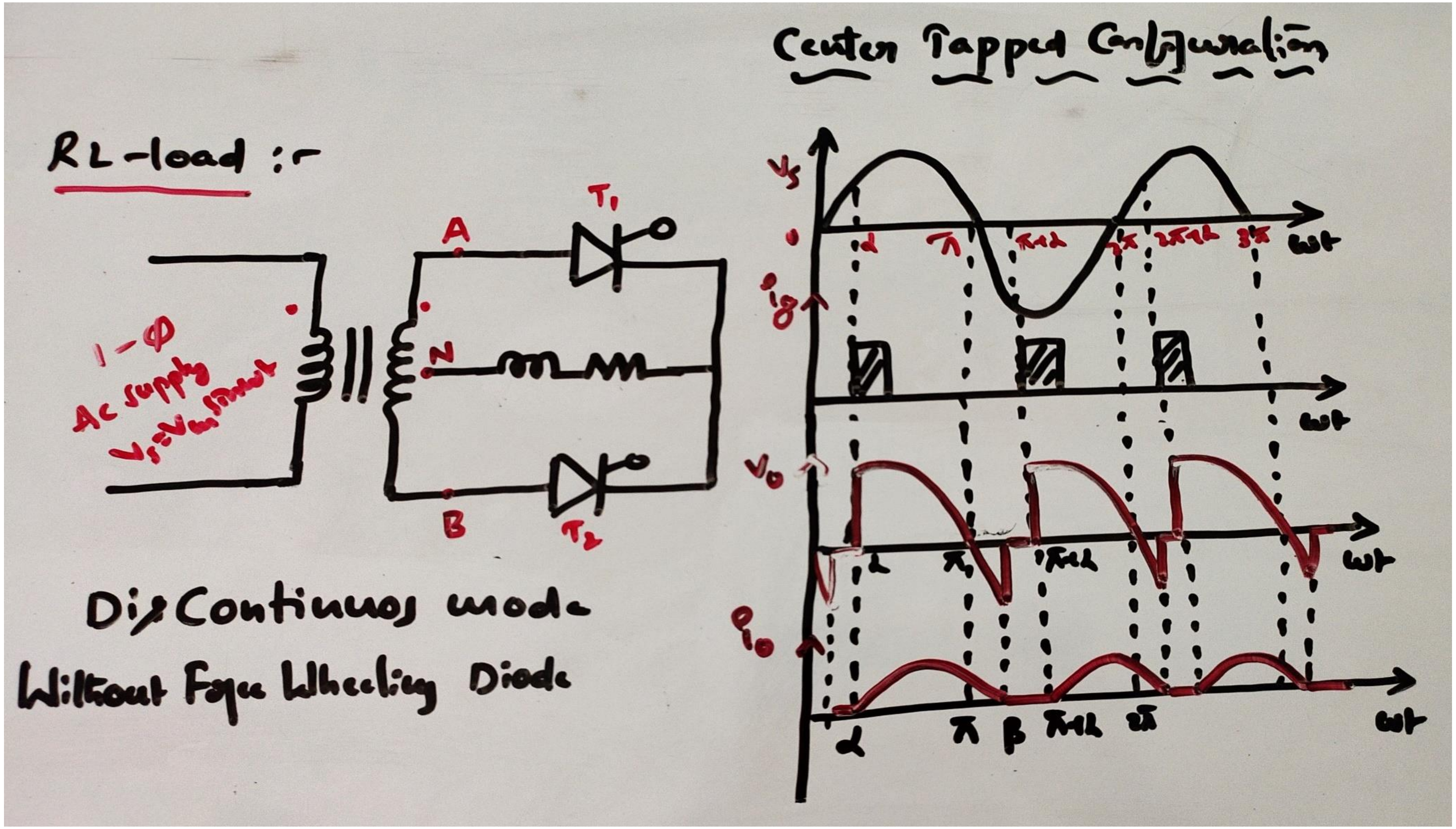
$$= \frac{V_m}{\pi}\left[-\cos\omega t\right]_\alpha^{\pi+\alpha}$$

$$= \frac{V_m}{\pi}\left[-\left[\cos(\pi+\alpha) - \cos\alpha\right]\right]$$

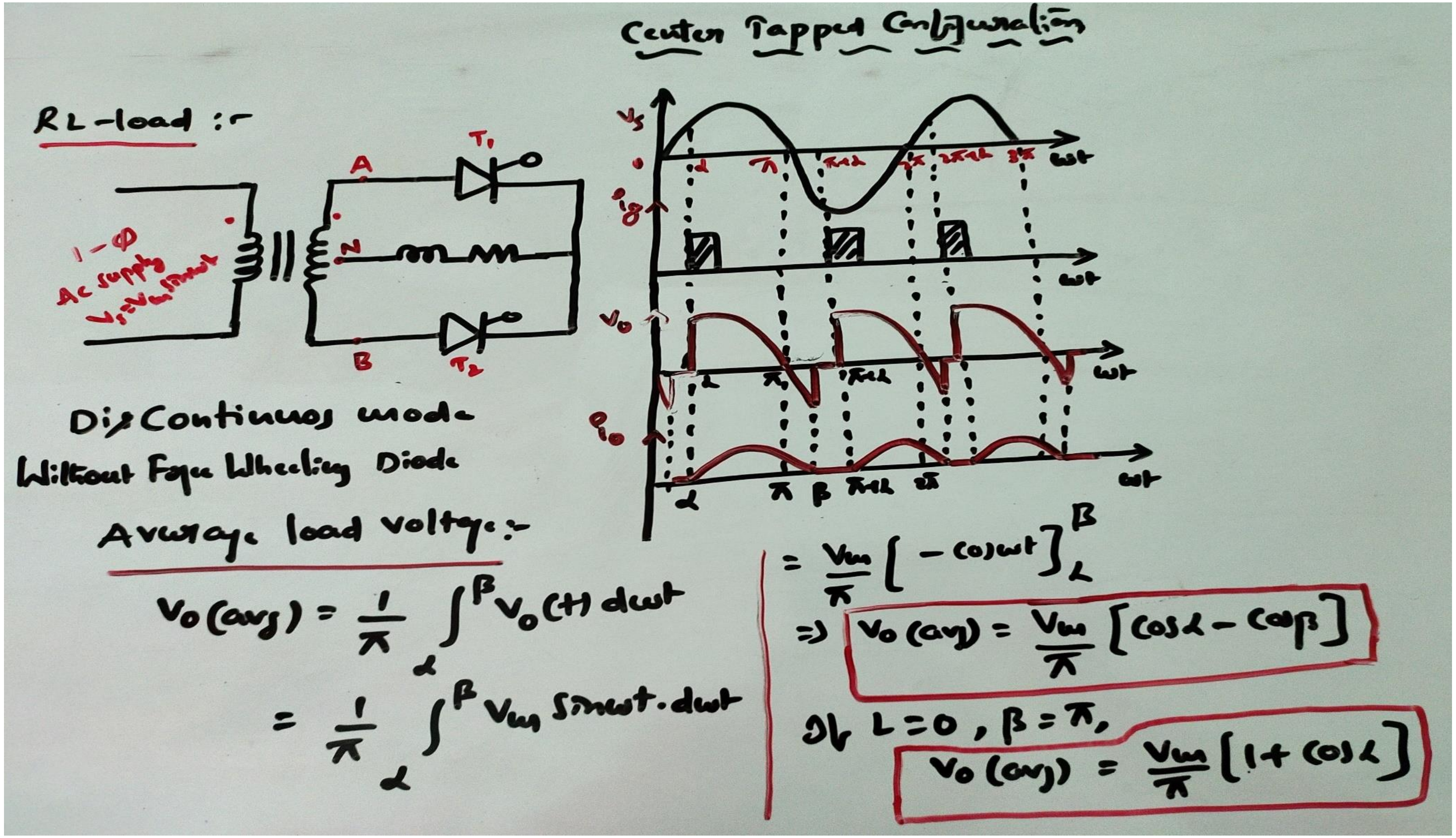
$$= \frac{V_m}{\pi}\left[-\left[-\cos\alpha - \cos\alpha\right]\right]$$

$$\Rightarrow \boxed{V_o(avg) = \frac{2V_m}{\pi}\cos\alpha}$$

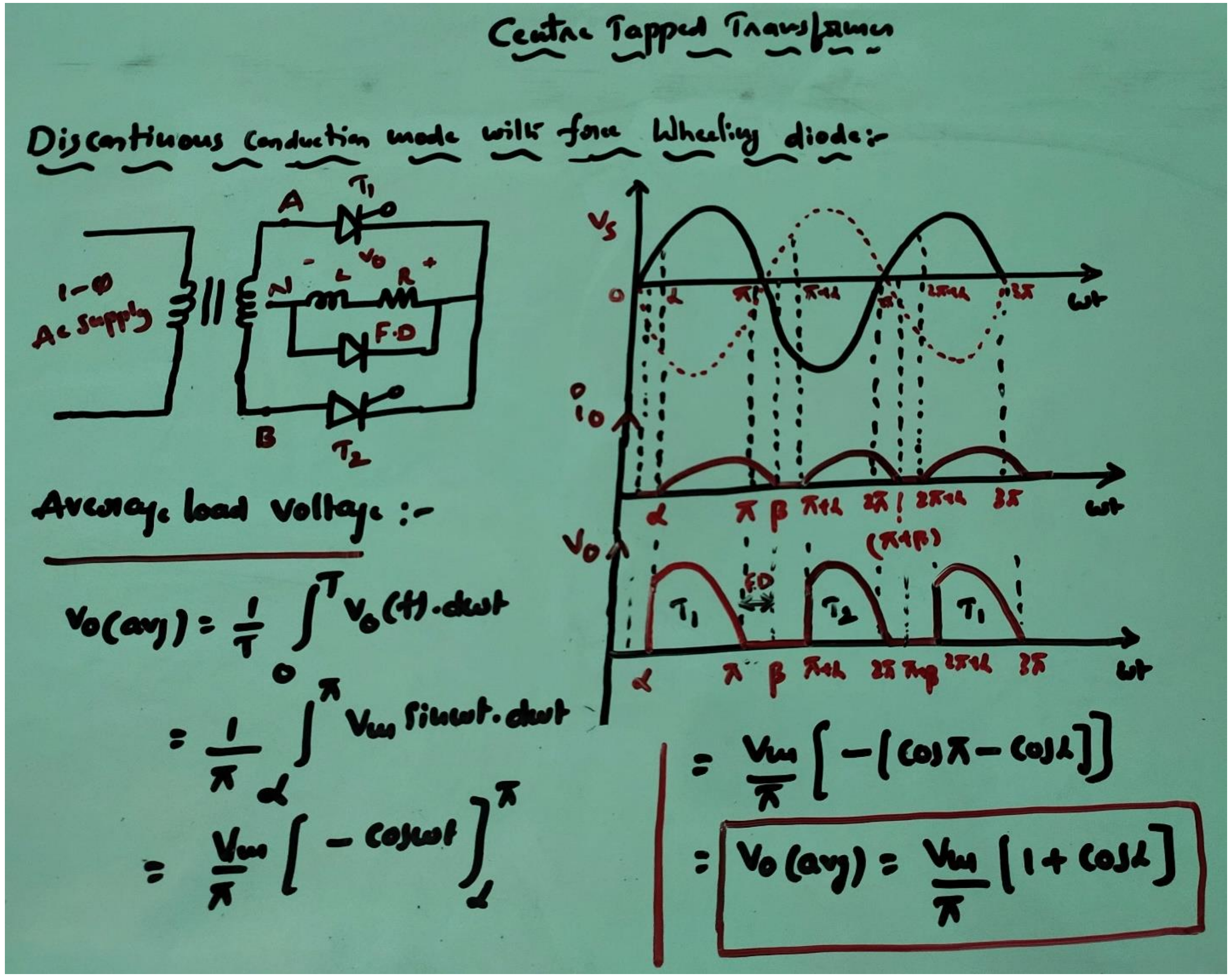
Single Phase full wave controlled rectifier-Center Tapped Configuration with RL-Load without Free wheeling Diode and Discontinuous Conduction Mode



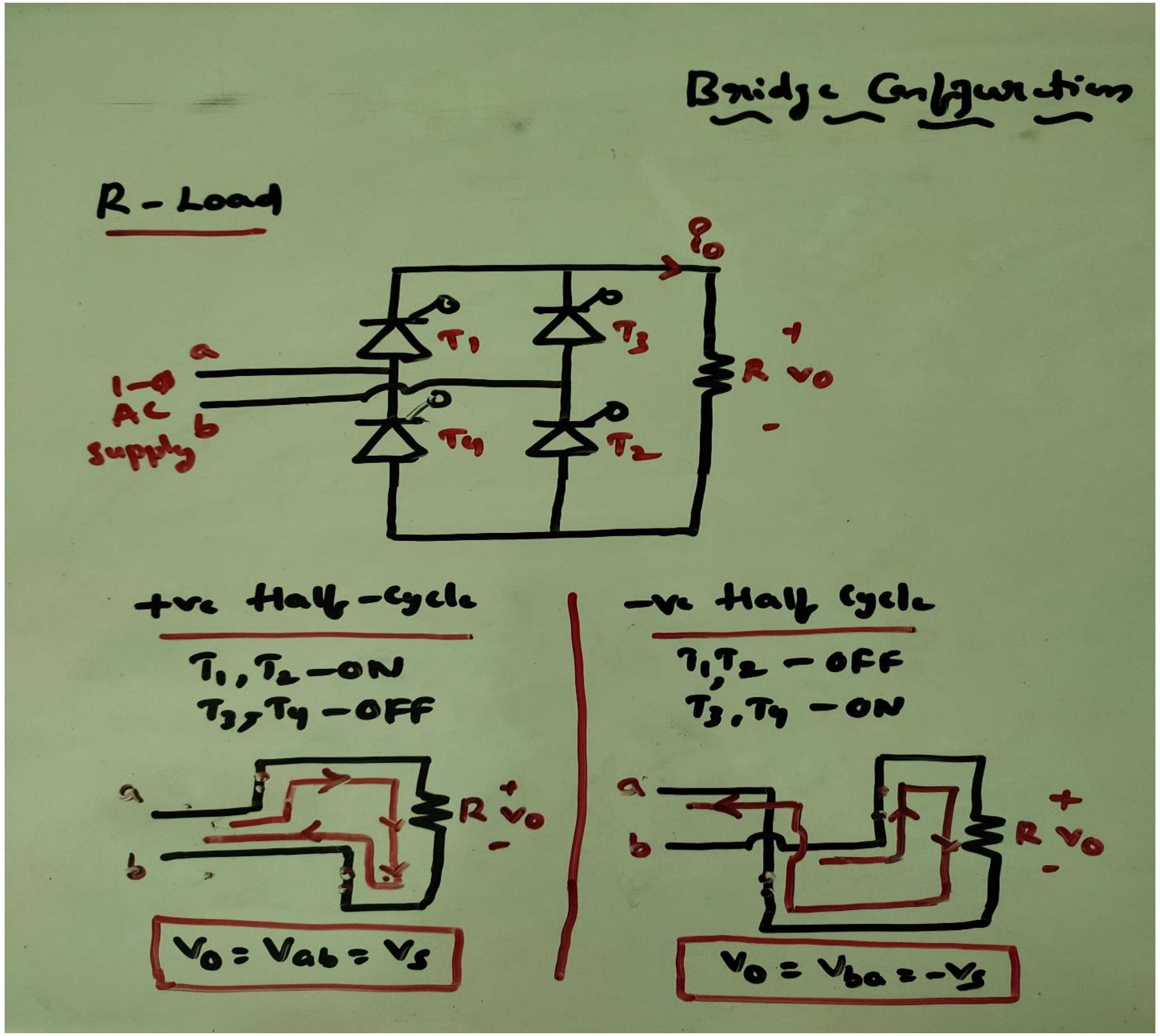
Single Phase full wave controlled rectifier-Center Tapped Configuration with RL-Load without Free wheeling Diode and Discontinuous Conduction Mode



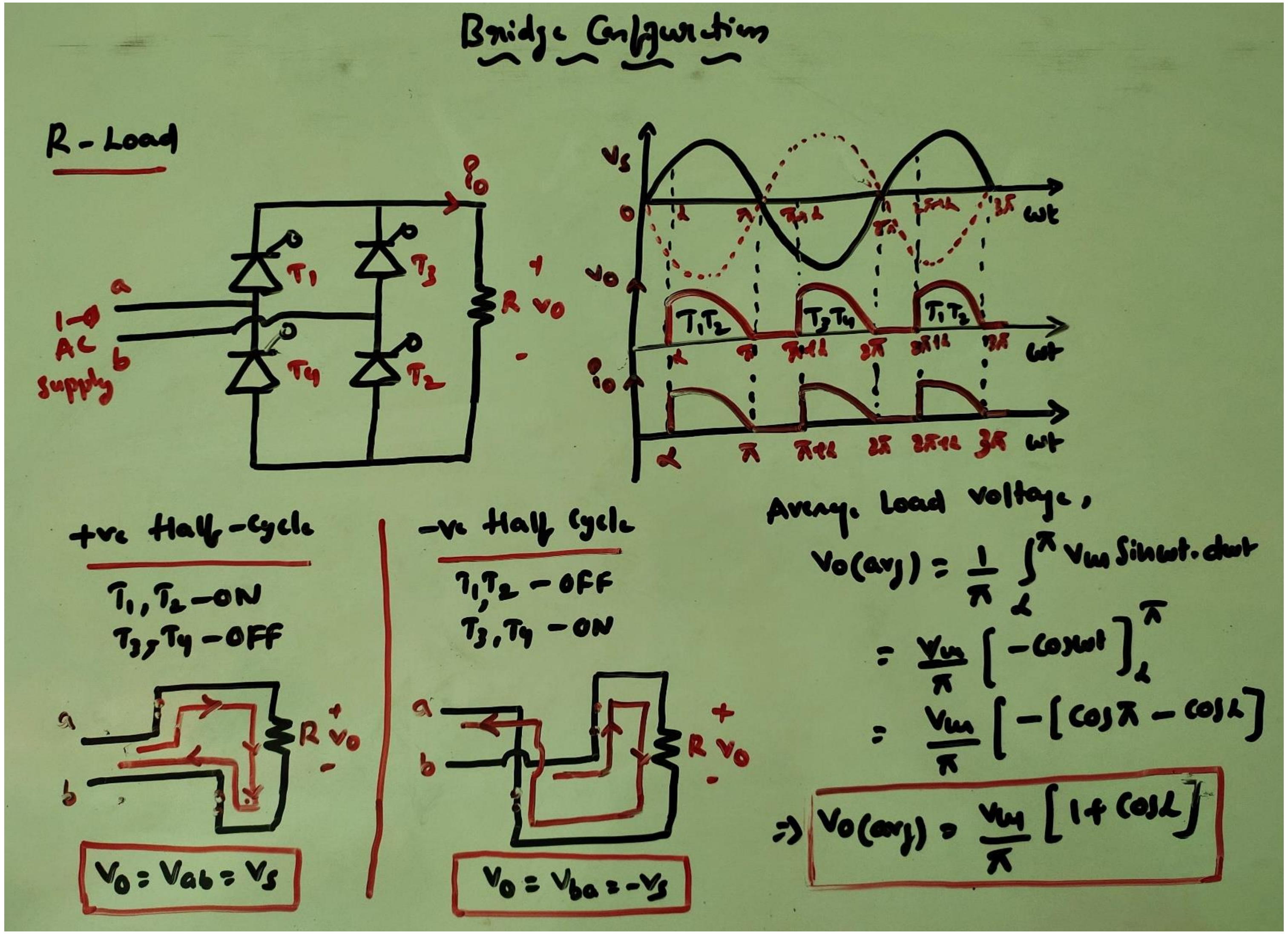
Single Phase full wave controlled rectifier-Center Tapped Configuration with RL-Load with Free wheeling Diode and Discontinuous Conduction Mode



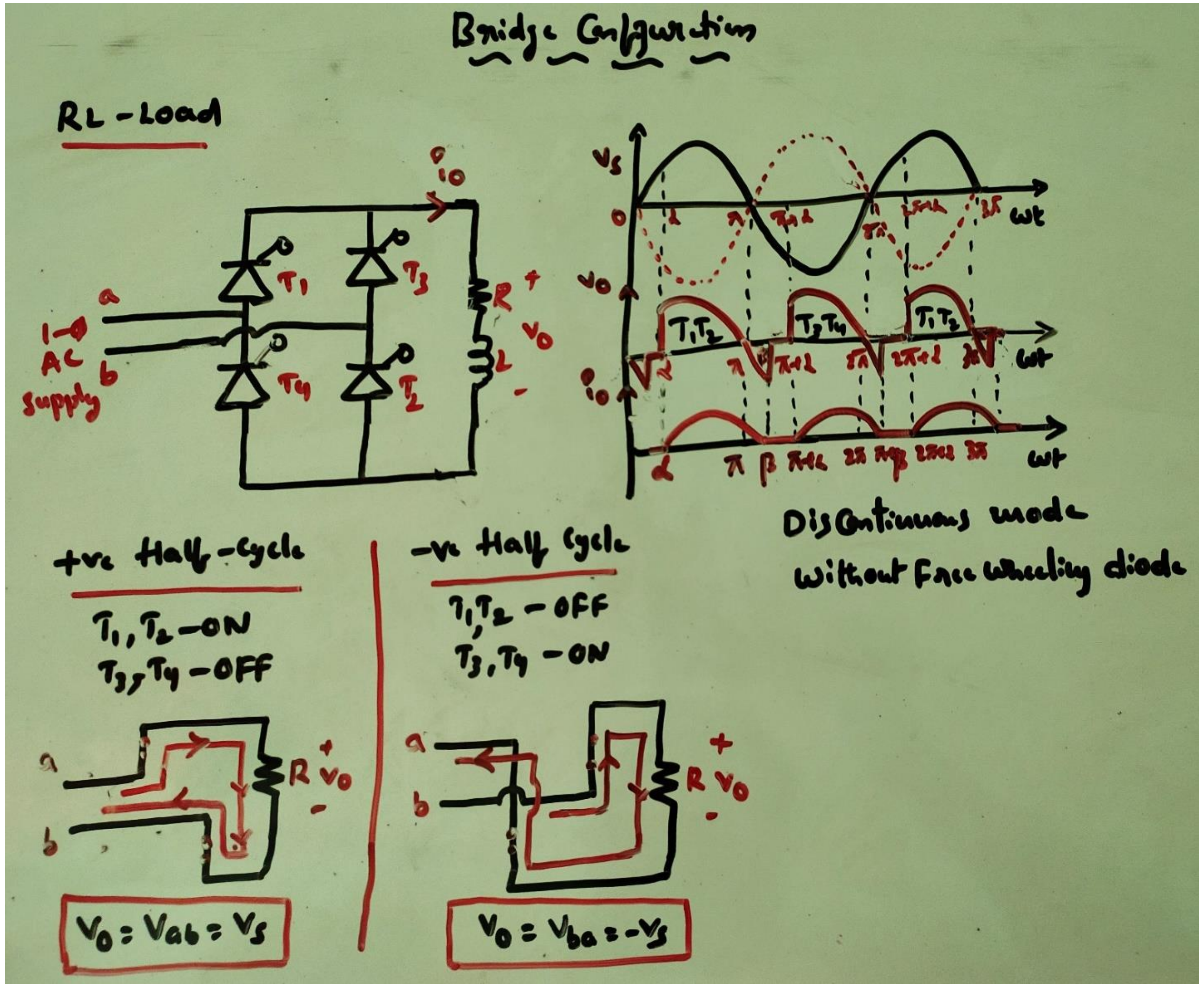
Single Phase full wave controlled rectifier-Bridge Configuration with R-Load



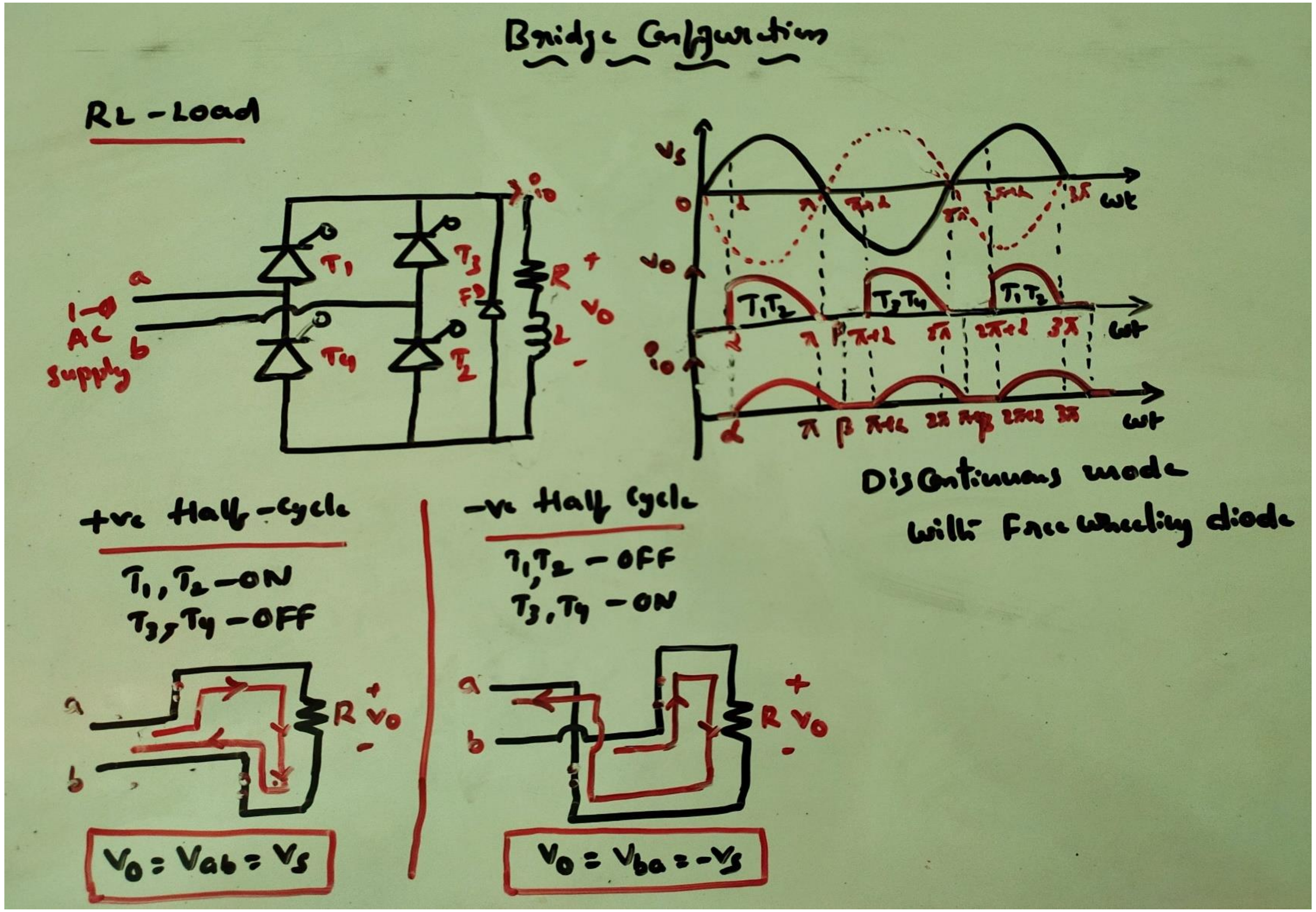
Single Phase full wave controlled rectifier-Bridge Configuration with R-Load



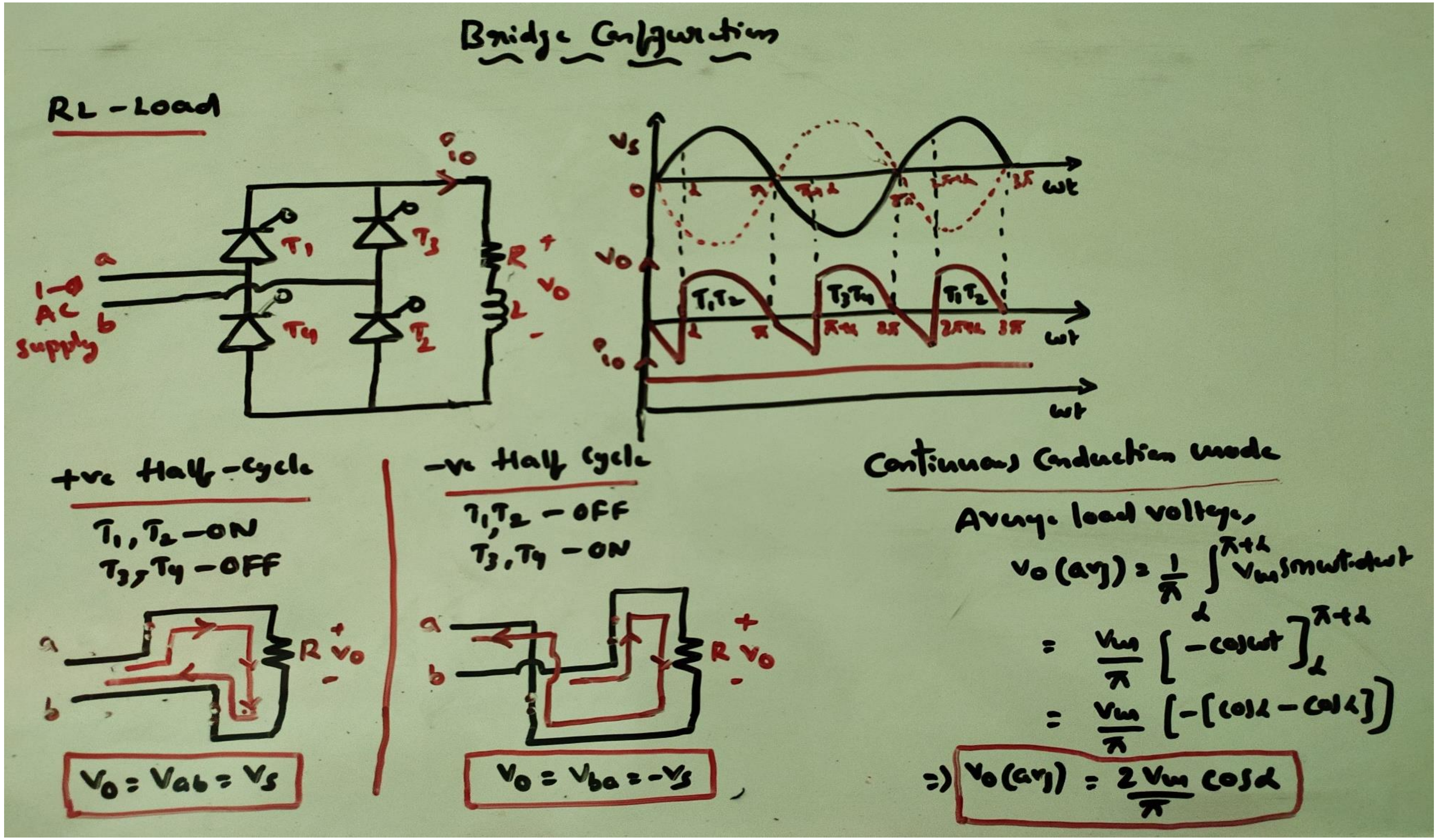
Single Phase full wave controlled rectifier-Bridge Configuration with RL-Load without Free wheeling Diode and Discontinuous Conduction Mode



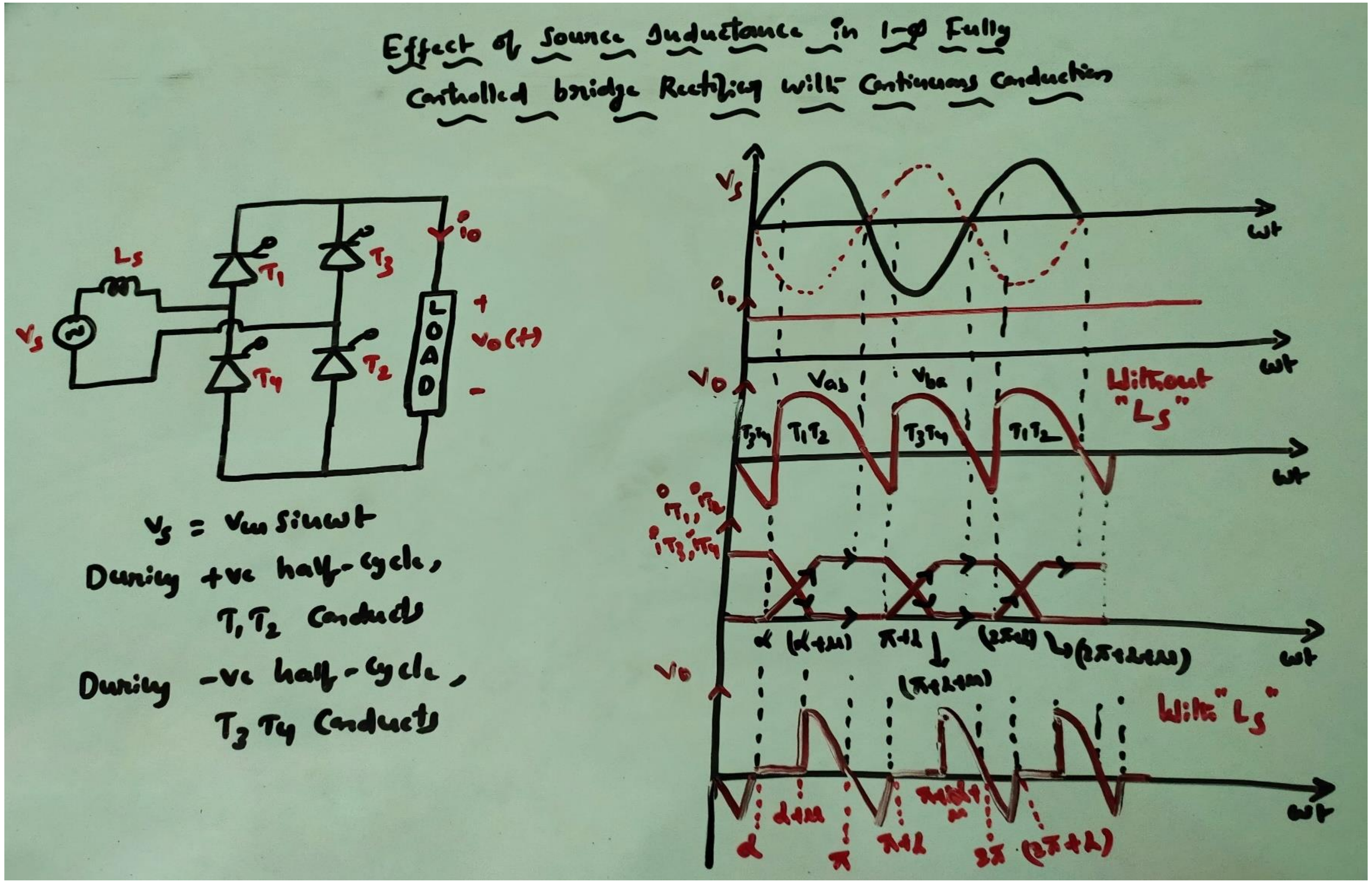
Single Phase full wave controlled rectifier-Bridge Configuration with RL-Load with Free wheeling Diode and Discontinuous Conduction Mode



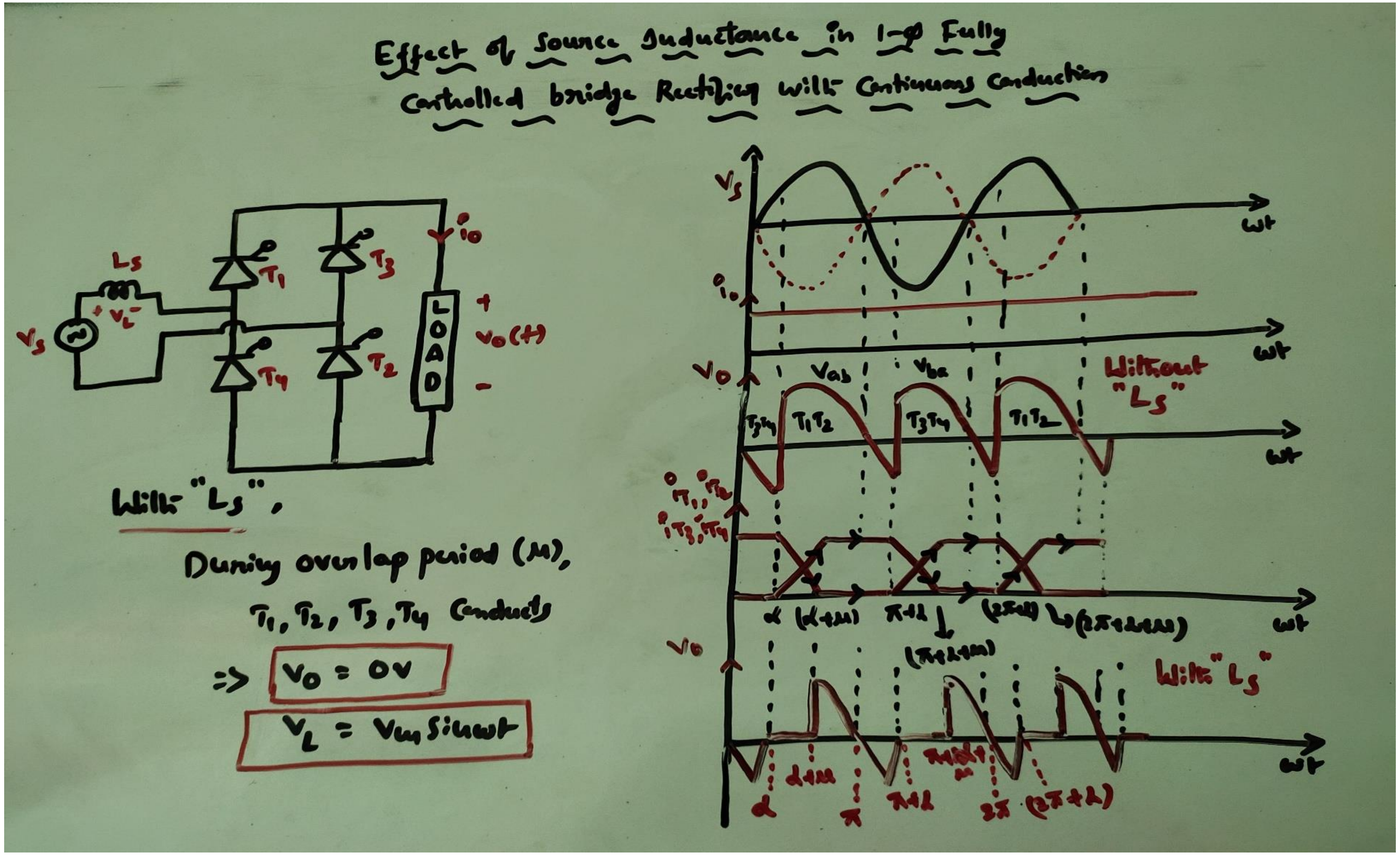
Single Phase full wave controlled rectifier-Bridge Configuration with RL-Load without Free wheeling Diode and Continuous Conduction Mode



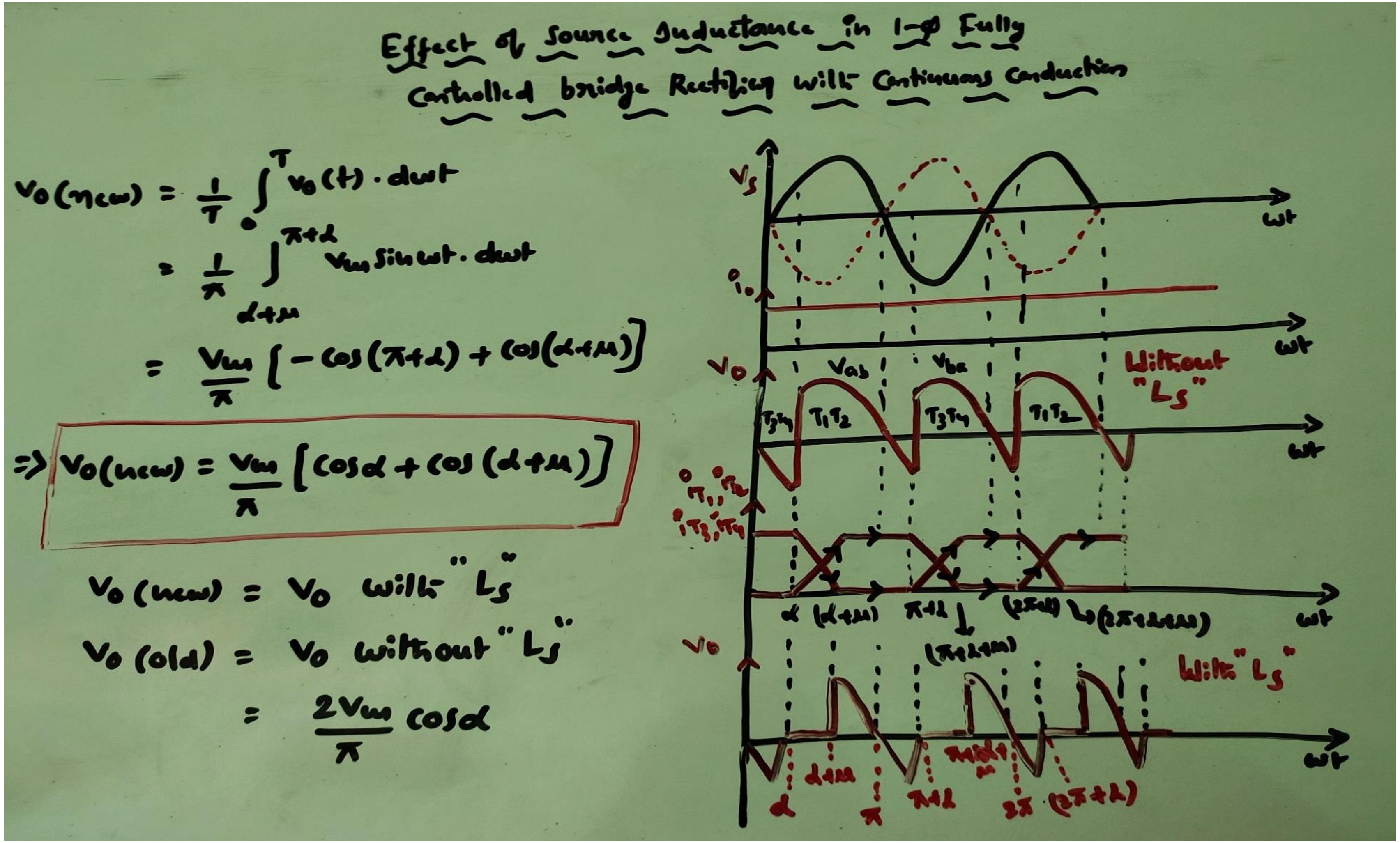
Effect of Source Inductance in single phase Fully controlled bridge Rectifier with Continuous Conduction



Effect of Source Inductance in single phase Fully controlled bridge Rectifier with Continuous Conduction



Effect of Source Inductance in single phase Fully controlled bridge Rectifier with Continuous Conduction



Effect of Source Inductance in single phase Fully controlled bridge Rectifier with Continuous Conduction

Effect of Source Inductance in 1-ϕ Fully Controlled bridge Rectifier with Continuous conduction

$V_0(new)$ (average) $= \frac{1}{T}\int_0^T v_0(t)\cdot d\omega t$

$= \frac{1}{\pi}\int_{\alpha+\mu}^{\pi+\alpha} V_m \sin\omega t \cdot d\omega t$

$= \frac{V_m}{\pi}\left[-\cos(\pi+\alpha)+\cos(\alpha+\mu)\right]$

$\Rightarrow \boxed{V_0(new) = \frac{V_m}{\pi}\left[\cos\alpha + \cos(\alpha+\mu)\right]}$

$V_0(new) = V_{0(avg)}$ with "L_s"

$V_0(old) = V_{0(avg)}$ without "L_s"

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

Reduction in avg output voltage,

$\Delta V_0 = V(old) - V(new)$

$= \frac{2V_m}{\pi}\cos\alpha - \frac{V_m}{\pi}\left[\cos\alpha + \cos(\alpha+\mu)\right]$

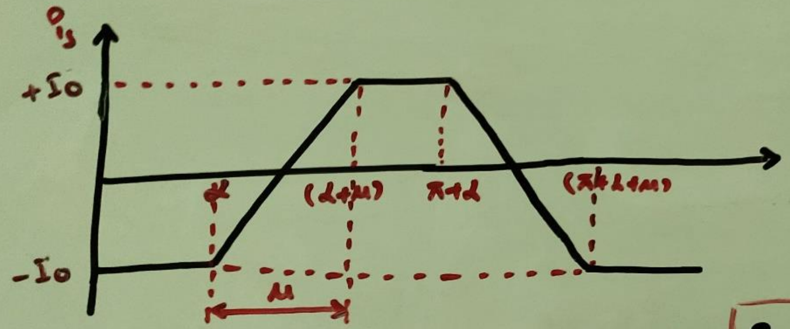
$= \frac{2V_m}{\pi}\cos\alpha - \frac{V_m}{\pi}\cos\alpha - \frac{V_m}{\pi}\cos(\alpha+\mu)$

$= \frac{V_m}{\pi}\cos\alpha - \frac{V_m}{\pi}\cos(\alpha+\mu)$

$\Rightarrow \boxed{\Delta V_0 = \frac{V_m}{\pi}\left[\cos\alpha - \cos(\alpha+\mu)\right]}$

Effect of Source Inductance in single phase Fully controlled bridge Rectifier with Continuous Conduction

Effect of Source Inductance in 1-φ Fully Controlled bridge Rectifier with Continuous Conduction



① During overlapping period, all SCRs will conduct

② Source current, $i_s = i_{T_1} - i_{T_4}$

$$v_L = L\cdot\frac{di}{dt} \Rightarrow V_m \sin\omega t = L\cdot\frac{di}{dt}$$

$$= \int_{-I_0}^{I_0} di = \int_{\alpha/\omega}^{\frac{\alpha+\mu}{\omega}} \frac{V_m}{\omega} \sin\omega t\cdot dt$$

$$\Rightarrow \boxed{I_0 = \frac{V_m}{2\omega L_s}\left[\cos\alpha - \cos(\alpha+\mu)\right]}$$

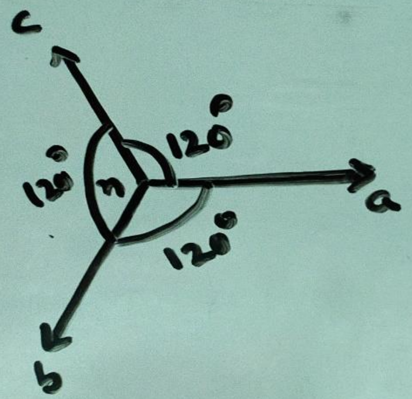
$$\Rightarrow \frac{2\omega L_s}{\pi} = \frac{V_m}{\pi}\left[\cos\alpha - \cos(\alpha+\mu)\right]$$

[∵ Dividing "π" on both sides]

$$\Rightarrow \boxed{\Delta V_0 = \frac{2\omega L_s}{\pi} = 4fL_sI_0}$$

Three Phase Voltages

Three phase Rectifiers



$V_{an}(t) = V_m \sin \omega t$

$V_{bn}(t) = V_m \sin(\omega t - 120^\circ)$

$V_{cn}(t) = V_m \sin(\omega t - 240^\circ)$
$\quad = V_m \sin(\omega t + 120^\circ)$

In a Y-Connection,

$$V_{ph} = \frac{V_L}{\sqrt{3}}$$

$$I_{ph} = I_L$$

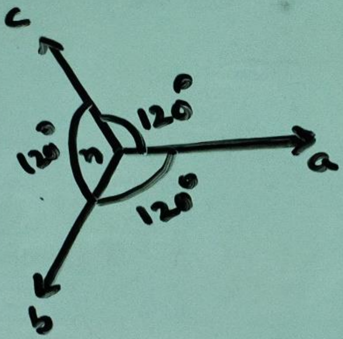
In a Δ Connection,

$$V_{ph} = V_L$$

$$I_{ph} = \frac{I_L}{\sqrt{3}}$$

Three Phase Voltages

Three phase Rectifiers



$$\sin A - \sin B = 2\cos\left(\frac{A+B}{2}\right)\cdot\sin\left(\frac{A-B}{2}\right)$$

$$V_{ab}(t) = V_{an}(t) - V_{bn}(t)$$

$$= V_m \sin\omega t - V_m \sin(\omega t - 120)$$

$$= V_m\left[\sin\omega t - \sin(\omega t - 120)\right]$$

$$= V_m\left[2\cos\left(\frac{A+B}{2}\right)\cdot\sin\left(\frac{A-B}{2}\right)\right]$$

$$= V_m\left[2\cos\left(\frac{2\omega t - 120}{2}\right)\cdot\sin\left(\frac{120}{2}\right)\right]$$

$$= 2V_m \cos(\omega t - 60)\cdot\sin 60$$

$$\Rightarrow \boxed{V_{ab}(t) = \sqrt{3}\,V_m \cos(\omega t - 60)}$$

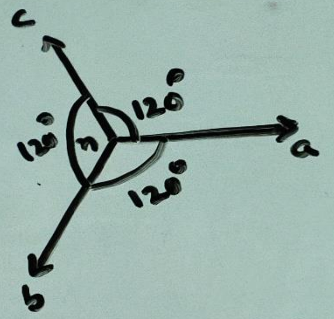
Phase Sequence $ab \rightarrow bc \rightarrow ca$

$$V_{bc}(t) = \sqrt{3}\,V_m \cos(\omega t - 60 - 120^\circ)$$

$$V_{ca}(t) = \sqrt{3}\,V_m \cos(\omega t - 60 - 240^\circ)$$

Three Phase Voltages

Three phase Rectifiers



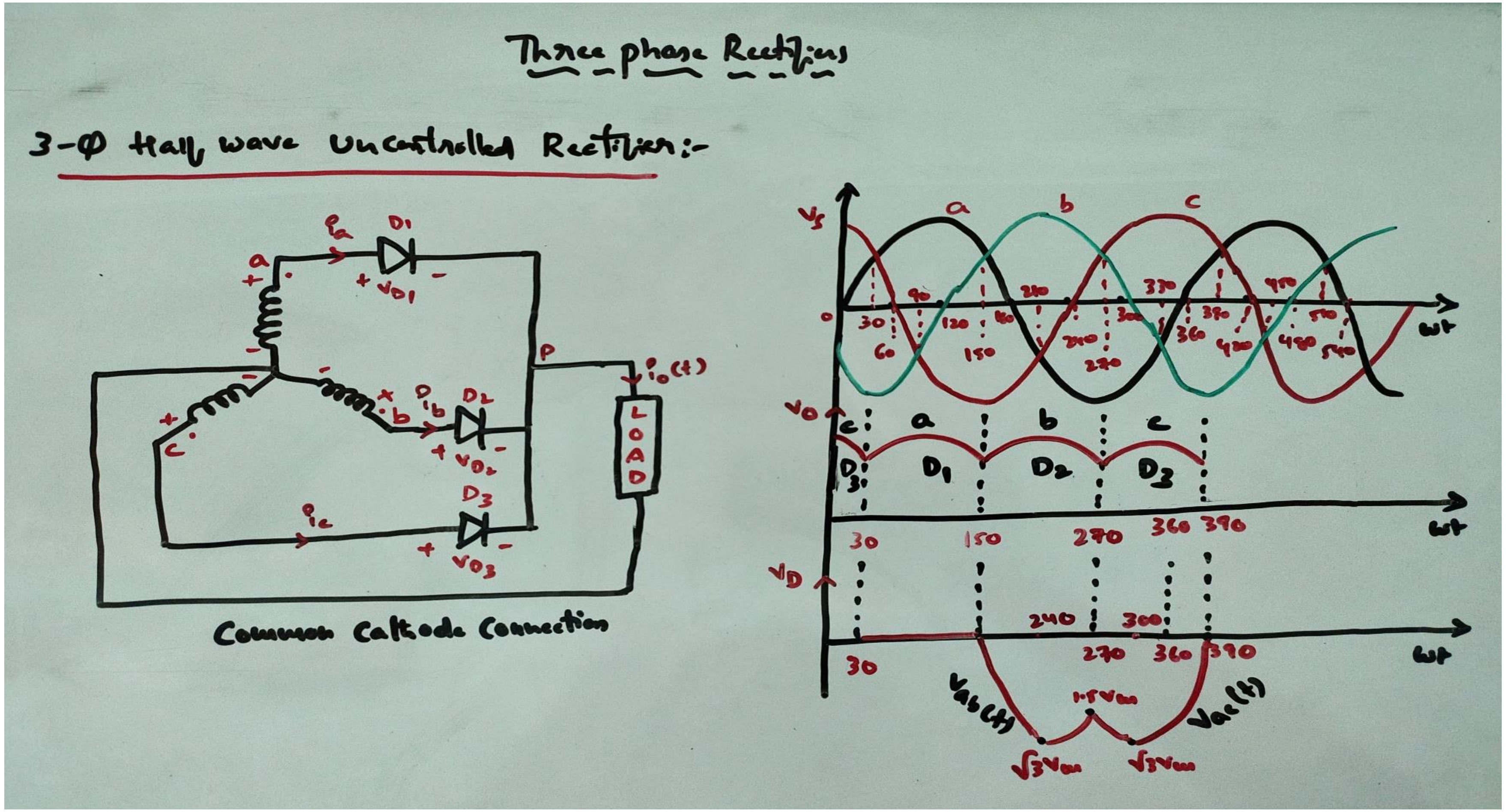
$\sin A - \sin B = 2\cos\left(\frac{A+B}{2}\right)\cdot\sin\left(\frac{A-B}{2}\right)$

$$V_{ab}(t) = V_{an}(t) - V_{bn}(t)$$
$$= V_m \sin\omega t - V_m \sin(\omega t - 120)$$
$$= V_m[\sin\omega t - \sin(\omega t - 120)]$$
$$= V_m\left[2\cos\left(\frac{A+B}{2}\right)\cdot\sin\left(\frac{A-B}{2}\right)\right]$$
$$= V_m\left[2\cos\left(\frac{2\omega t - 120}{2}\right)\cdot\sin\left(\frac{120}{2}\right)\right]$$
$$= 2V_m\cos(\omega t - 60)\cdot\sin 60$$
$$\Rightarrow \boxed{V_{ab}(t) = \sqrt{3}\,V_m\cos(\omega t - 60)}$$

Phase Sequence $ab \rightarrow bc \rightarrow ca$

$$V_{bc}(t) = \sqrt{3}\,V_m\cos(\omega t - 180^\circ)$$
$$V_{ca}(t) = \sqrt{3}\,V_m\cos(\omega t + 60^\circ)$$

Three Phase Half wave Uncontrolled Rectifier



Three Phase Half wave Uncontrolled Rectifier

Three phase Rectifiers

3-φ Half wave Uncontrolled Rectifier:-

Average load voltage,

$$V_o(avg) = \frac{1}{T}\int_0^T v_o(t)\cdot d\omega t$$

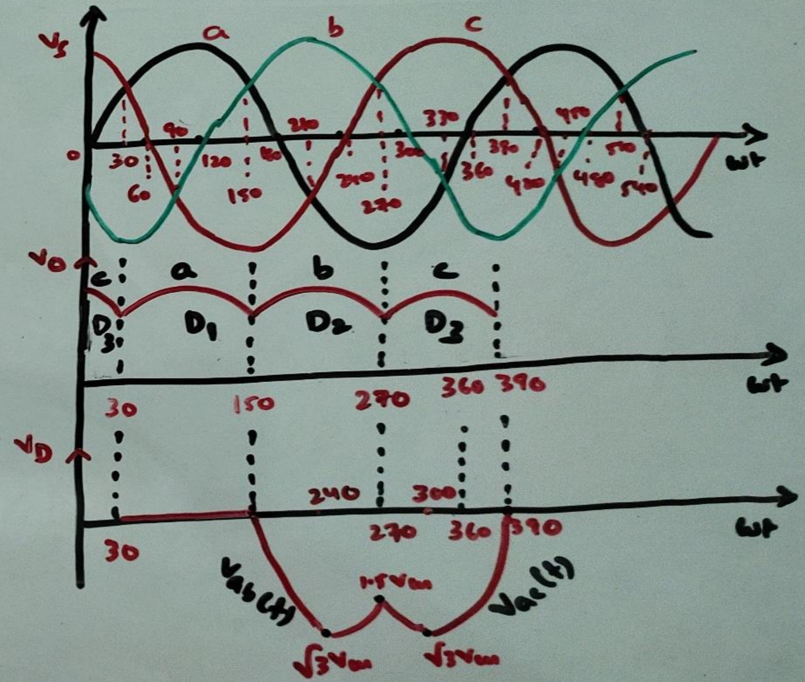
$$= \frac{1}{\left(\frac{2\pi}{3}\right)}\int_{30}^{150} V_m \sin\omega t \cdot d\omega t$$

$$= \frac{3V_m}{2\pi}\left[-\cos\omega t\right]_{30}^{150}$$

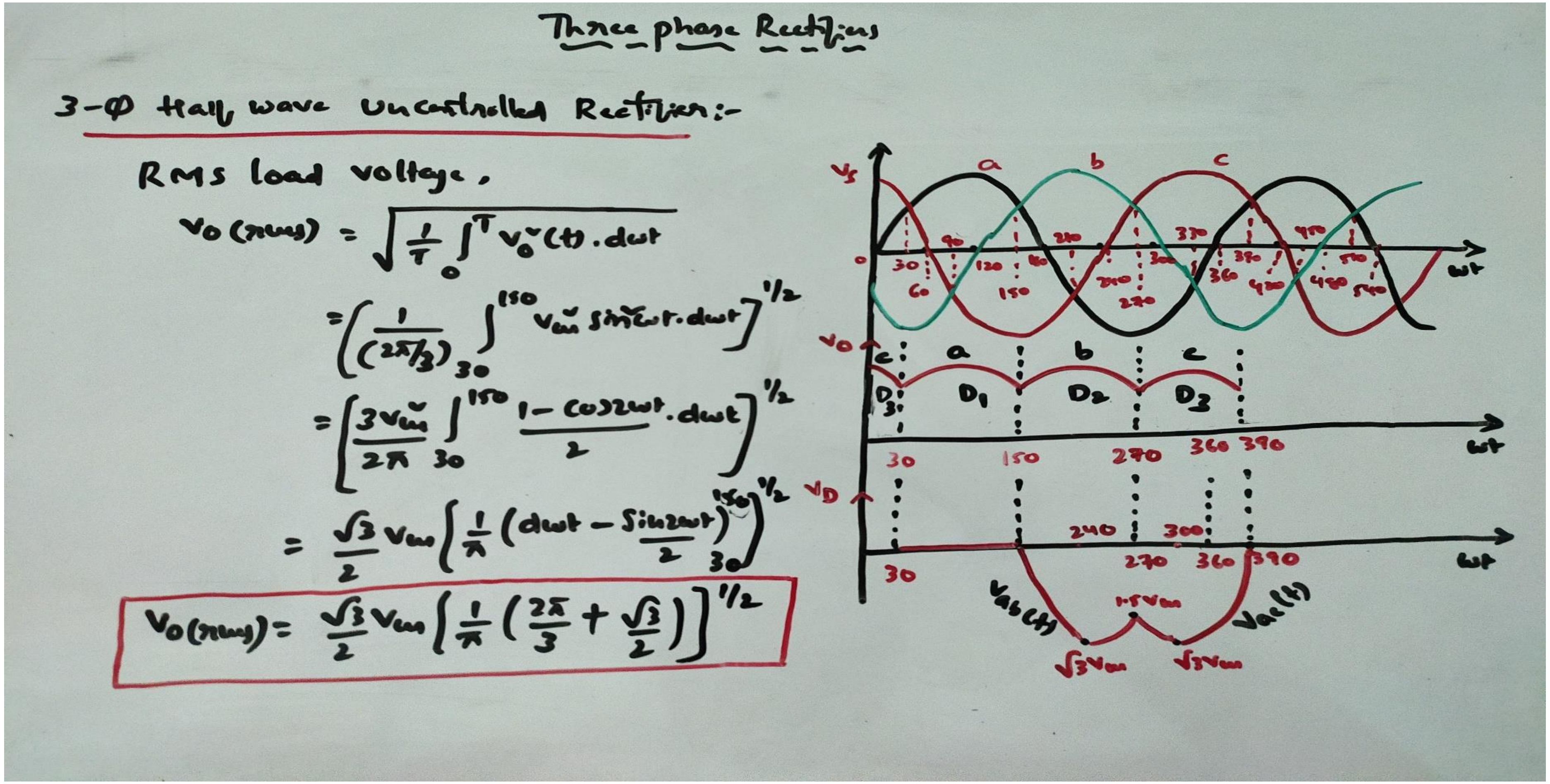
$$= \frac{3V_m}{2\pi}\left[-\left[\cos 150 - \cos 30\right]\right]$$

$$= \frac{3V_m}{2\pi}\left[-\left[-\frac{\sqrt{3}}{2} - \frac{\sqrt{3}}{2}\right]\right]$$

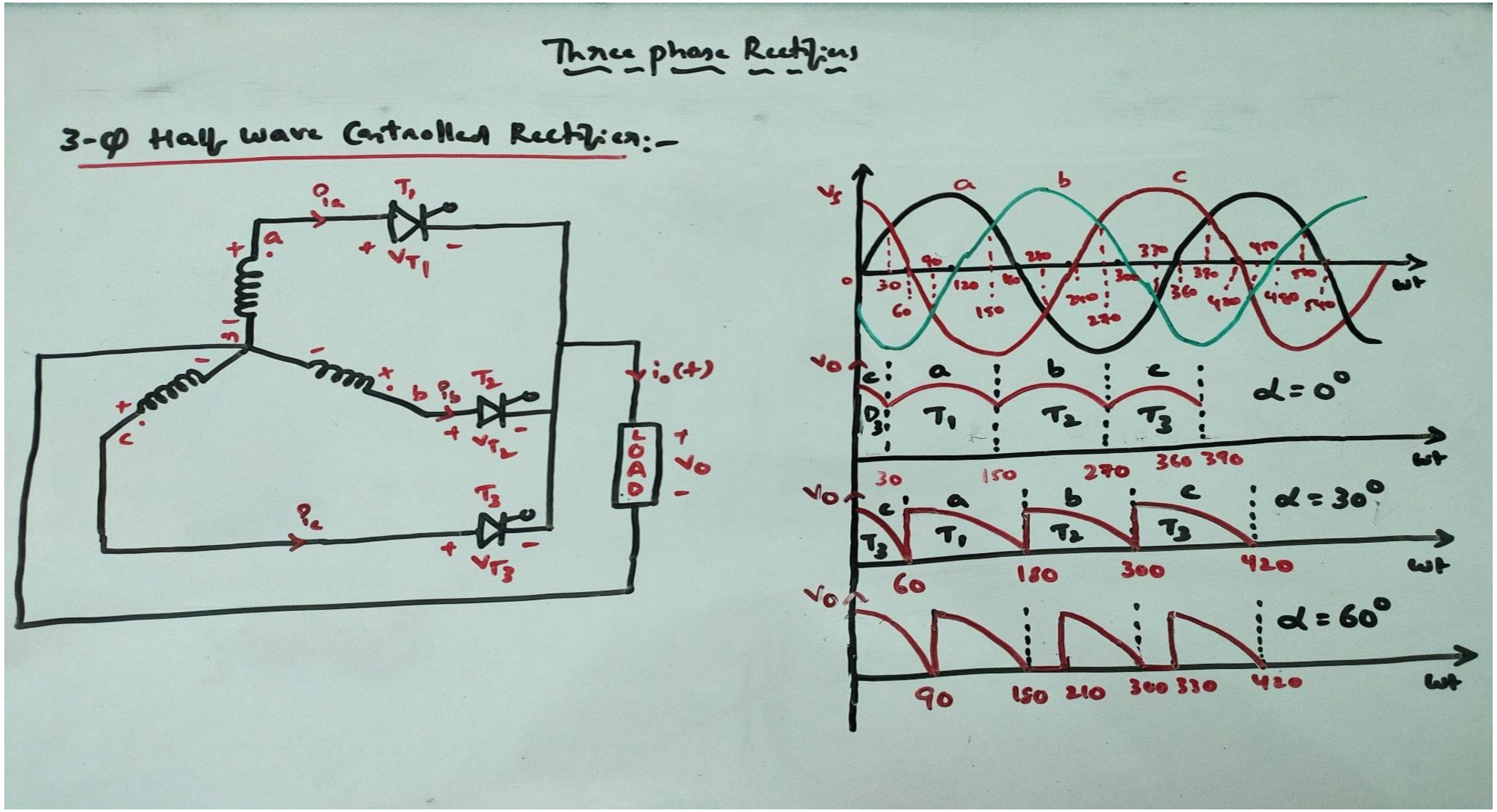
$$\Rightarrow \boxed{V_o(avg) = \frac{3\sqrt{3}V_m}{2\pi}}$$



Three Phase Half wave Uncontrolled Rectifier



Three Phase Half wave Controlled Rectifier



Three Phase Half wave Controlled Rectifier

Three phase Rectifiers

R – Load :-

① Continuous Conduction Mode

(for $0 \le \alpha \le 30^\circ$)

Average load voltage ,

$$V_o(avg) = \frac{1}{\left(\frac{2\pi}{3}\right)} \int_{30+\alpha}^{150+\alpha} V_m \sin\omega t \cdot d\omega t$$

$$= \frac{3V_m}{2\pi} \Big[-\cos\omega t \Big]_{30+\alpha}^{150+\alpha}$$

$$= \frac{3V_m}{2\pi} \Big[-\big[\cos(150+\alpha) - \cos(30+\alpha) \big] \Big]$$

$$\Rightarrow \boxed{V_o(avg) = \frac{3\sqrt{3}}{2\pi} V_m \cos\alpha}$$

$$\boxed{I_o(avg) = \frac{3\sqrt{3}}{2\pi R} V_m \cos\alpha}$$

Three Phase Half wave Controlled Rectifier

Three phase Rectifiers

R-Load :-

$$\cos(A+B) = \cos A \cos B - \sin A \sin B$$

$$\cos(150+\alpha) = \cos 150 \cos\alpha - \sin 150 \sin\alpha$$

$$= -\frac{\sqrt{3}}{2}\cos\alpha - \frac{1}{2}\sin\alpha$$

$$\cos(30+\alpha) = \cos 30 \cos\alpha - \sin 30 \sin\alpha$$

$$= \frac{\sqrt{3}}{2}\cos\alpha - \frac{1}{2}\sin\alpha$$

$$-[\cos(150+\alpha) - \cos(30+\alpha)]$$

$$= -\left[-\frac{\sqrt{3}}{2}\cos\alpha - \cancel{\frac{1}{2}\sin\alpha} - \frac{\sqrt{3}}{2}\cos\alpha + \cancel{\frac{1}{2}\sin\alpha}\right]$$

$$= -\left[-\cancel{2}\cdot\frac{\sqrt{3}}{\cancel{2}}\cos\alpha\right]$$

$$= \sqrt{3}\cos\alpha.$$

Three Phase Half wave Controlled Rectifier

Three phase Rectifiers

R-Load :-

① Continuous Conduction Mode

(for $0 \le \alpha \le 30^\circ$)

RMS load voltage,

$$V_o(rms) = \left[\frac{1}{\left(\frac{2\pi}{3}\right)} \int_{30+\alpha}^{150+\alpha} V_m^2 \sin^2 \omega t \cdot d\omega t \right]^{1/2}$$

$$= V_m \left[\frac{3}{2\pi} \int_{30+\alpha}^{150+\alpha} \left(\frac{1 - \cos 2\omega t}{2} \right) d\omega t \right]^{1/2}$$

$$= V_m \left[\frac{3}{4\pi} \int_{30+\alpha}^{150+\alpha} d\omega t - \frac{3}{4\pi} \int_{30+\alpha}^{150+\alpha} \cos 2\omega t \cdot d\omega t \right]^{1/2}$$

$$= V_m \left(\frac{3}{4\pi} \left[150+\alpha - 30 - \alpha \right] - \frac{3}{8\pi} \left[\sin 2(150+\alpha) - \sin 2(30+\alpha) \right] \right]^{1/2}$$

$$= \boxed{V_o(rms) = V_m \left[\frac{1}{2} + \frac{3\sqrt{3}}{8\pi} \cos 2\alpha \right]^{1/2}}$$

Three Phase Half wave Controlled Rectifier

Three phase Rectifiers

R – Load :-

② Discontinuous Conduction mode

(for $30^\circ < \alpha < 150^\circ$)

Average load voltage,

$$V_o(avg) = \frac{1}{\left(\frac{2\pi}{3}\right)} \int_{30+\alpha}^{180} V_m \sin\omega t \cdot d\omega t$$

$$= \frac{3V_m}{2\pi} \left[-\cos\omega t \right]_{30+\alpha}^{180}$$

$$= \frac{3V_m}{2\pi} \left[-\left[\cos 180 - \cos(30+\alpha) \right] \right]$$

$$= \boxed{V_o(avg) = \frac{3V_m}{2\pi} \left[1 + \cos(30+\alpha) \right]}$$

$$\boxed{I_o(avg) = \frac{3V_m}{2\pi R} \left[1 + \cos(30+\alpha) \right]}$$

Three Phase Half wave Controlled Rectifier

Three phase Rectifiers

R – Load :-

② Discontinuous Conduction mode

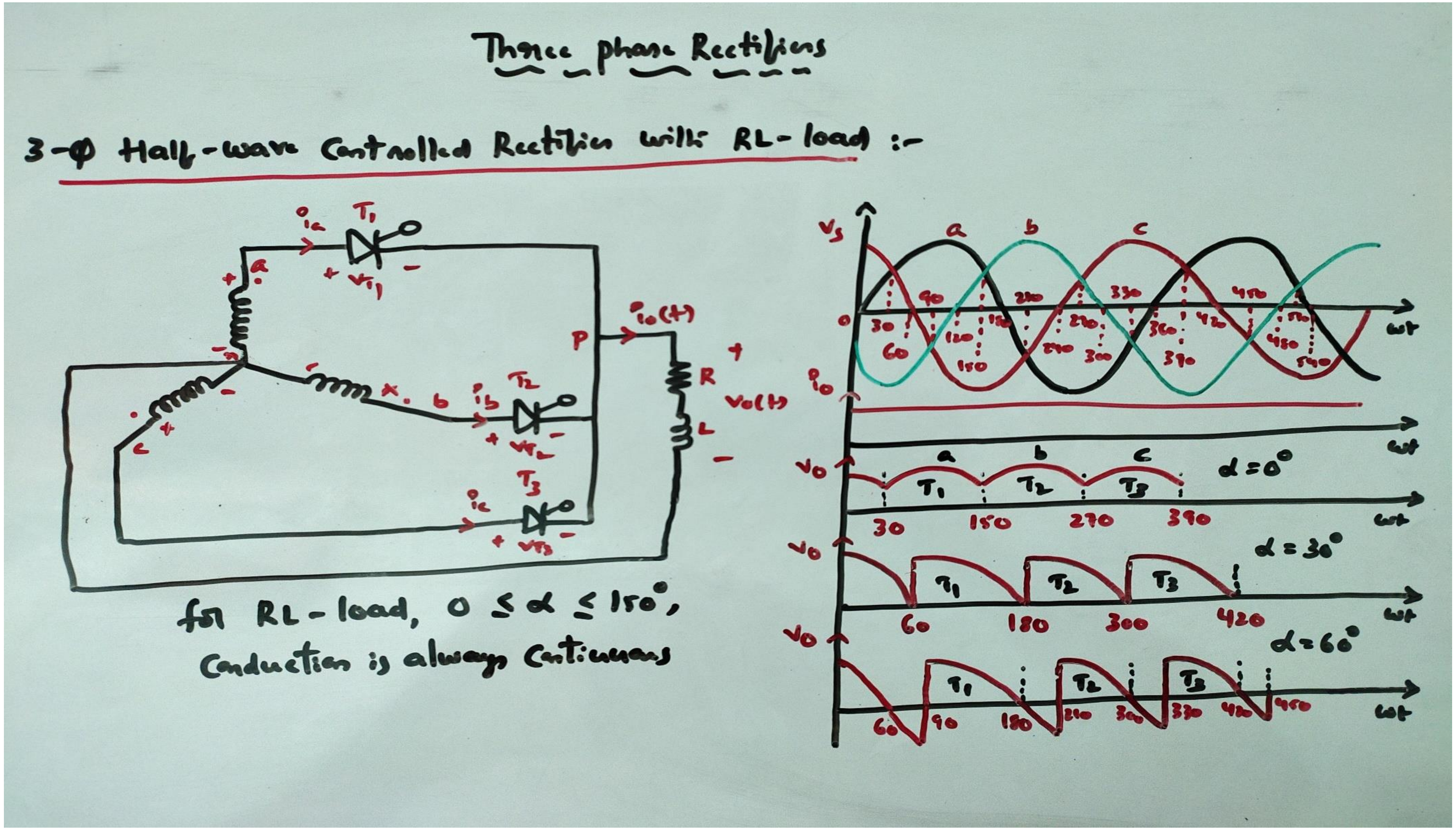
(for $30^\circ < \alpha < 150^\circ$)

RMS load voltage,

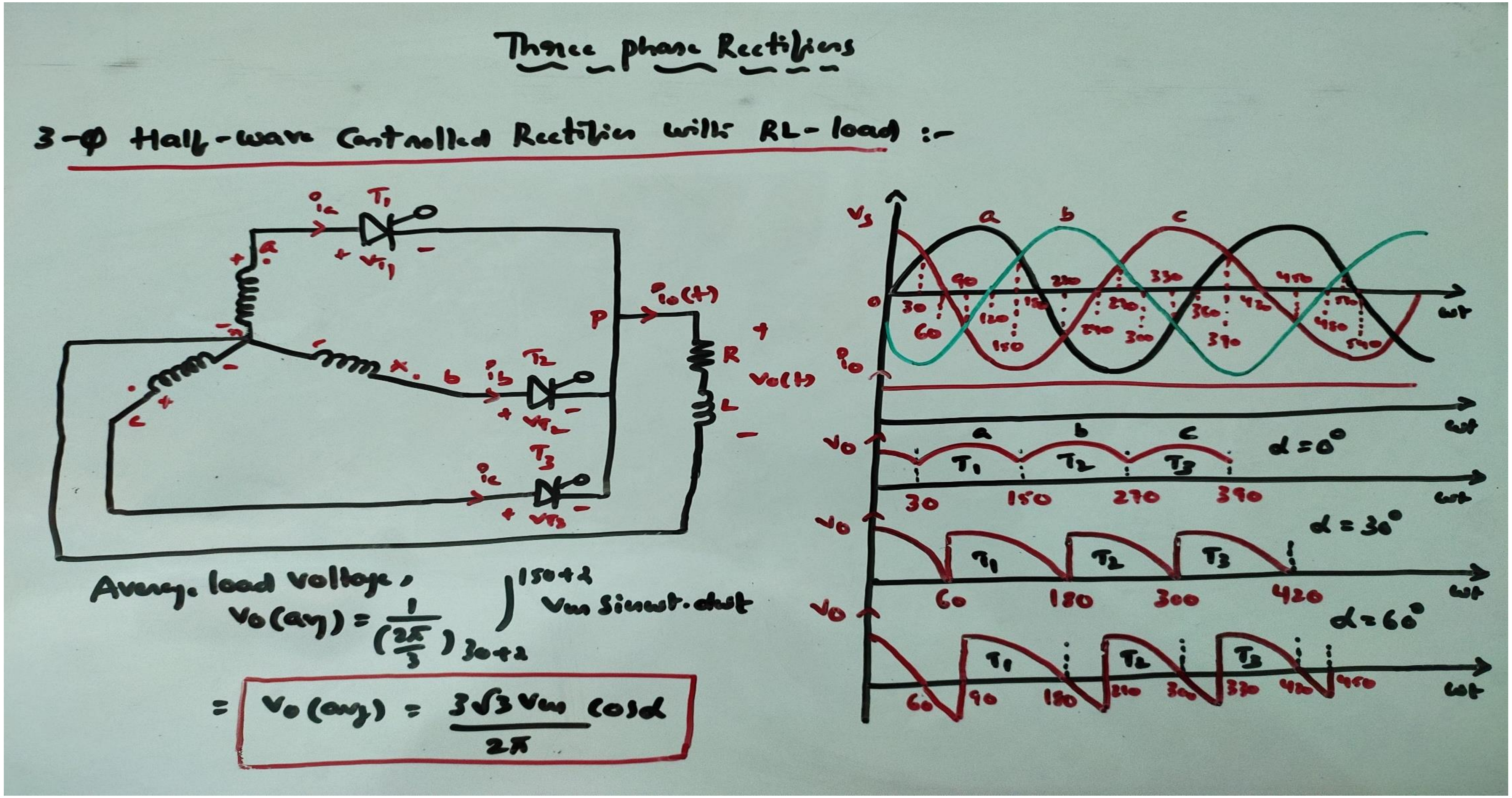
$$V_{o(rms)} = \left[\frac{1}{(2\pi/3)} \int_{30+\alpha}^{180} V_m^2 \sin^2 \omega t \cdot d\omega t \right]^{1/2}$$

$$= \boxed{V_{o(rms)} = \frac{\sqrt{3}\, V_m}{2\sqrt{2}} \left[\frac{5\pi - 3\alpha}{3\pi} + \frac{\sin\left(2\alpha + \frac{\pi}{3}\right)}{\pi} \right]^{1/2}}$$

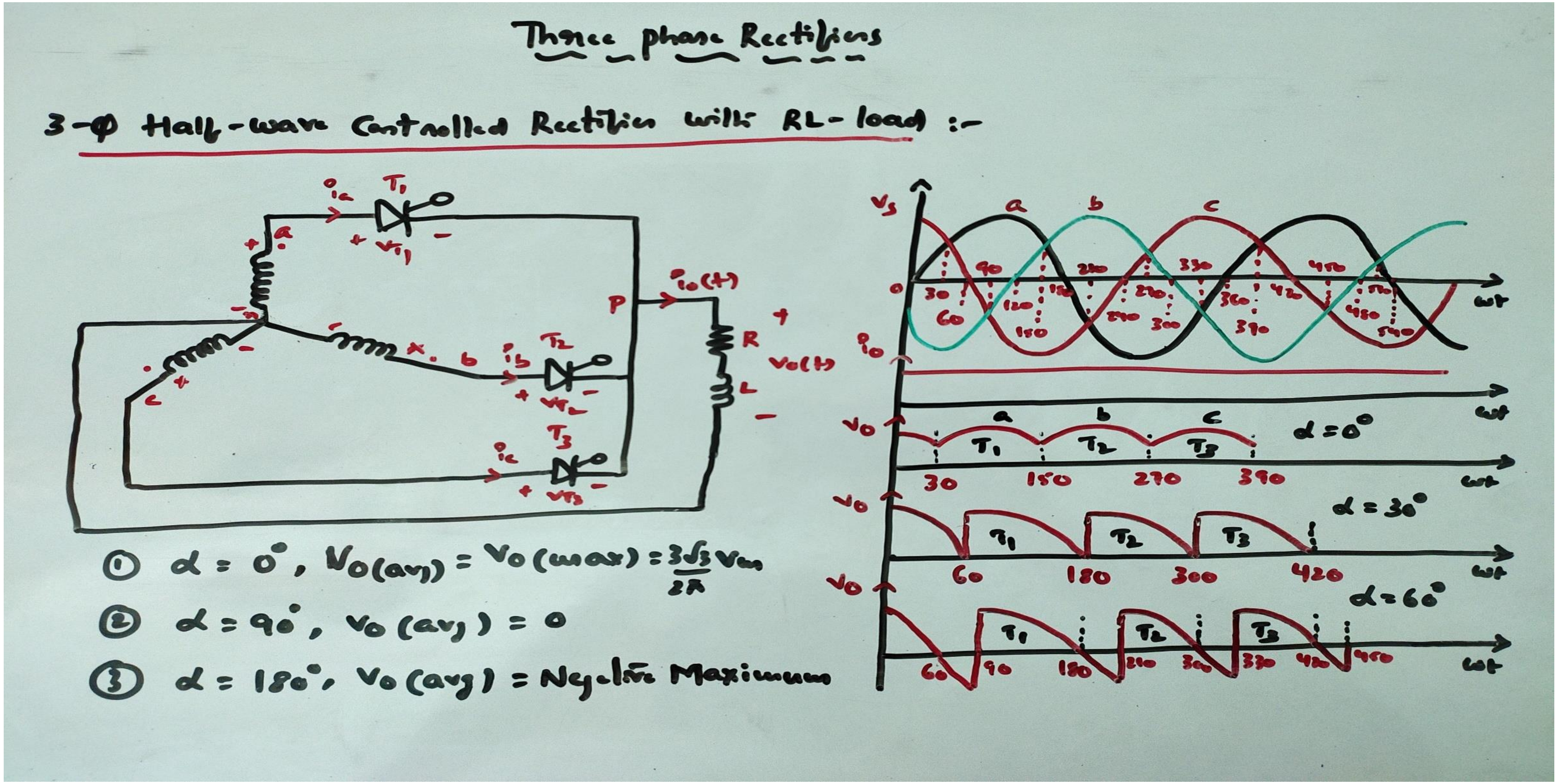
Three Phase Half wave Controlled Rectifier with RL Load



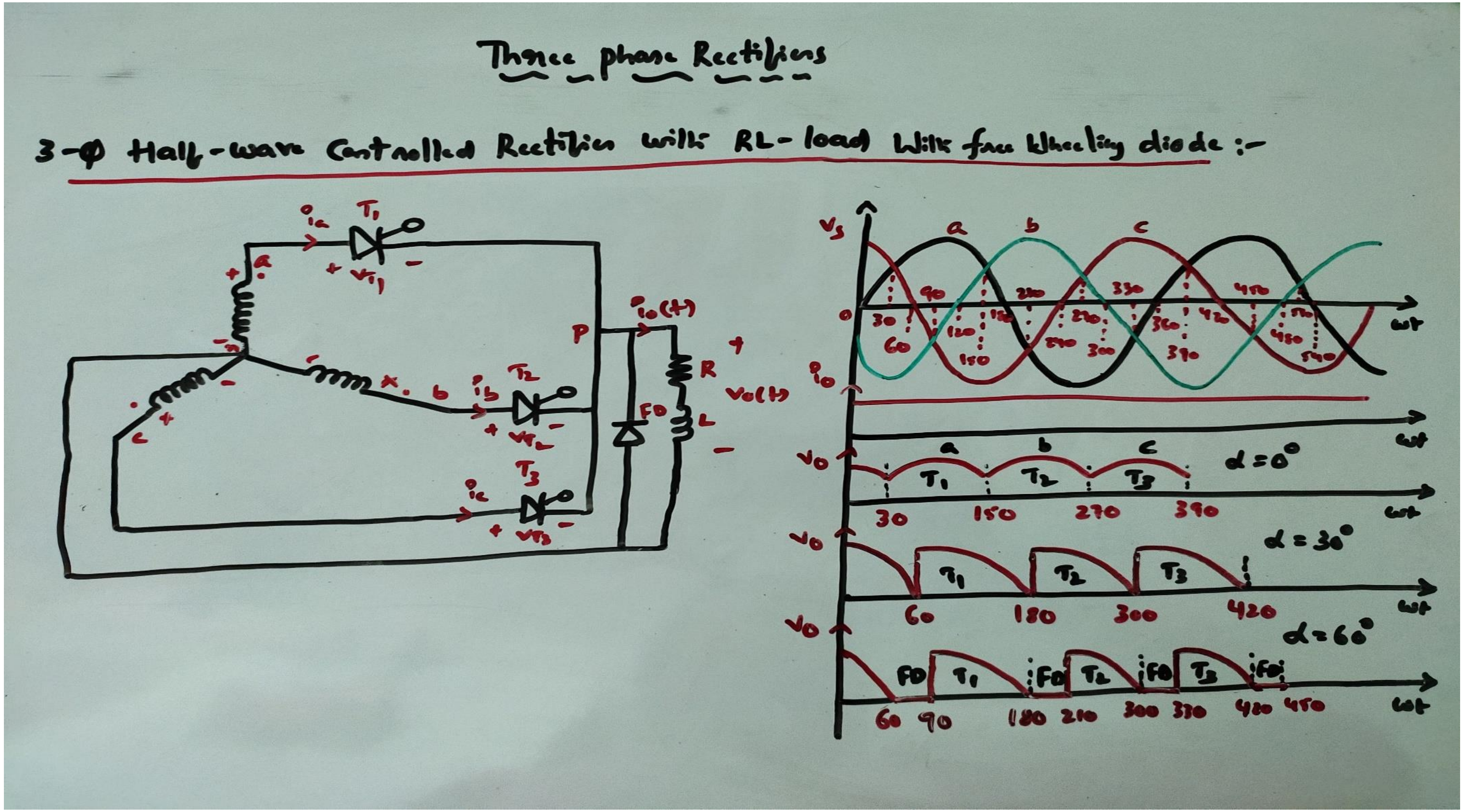
Three Phase Half wave Controlled Rectifier with RL Load



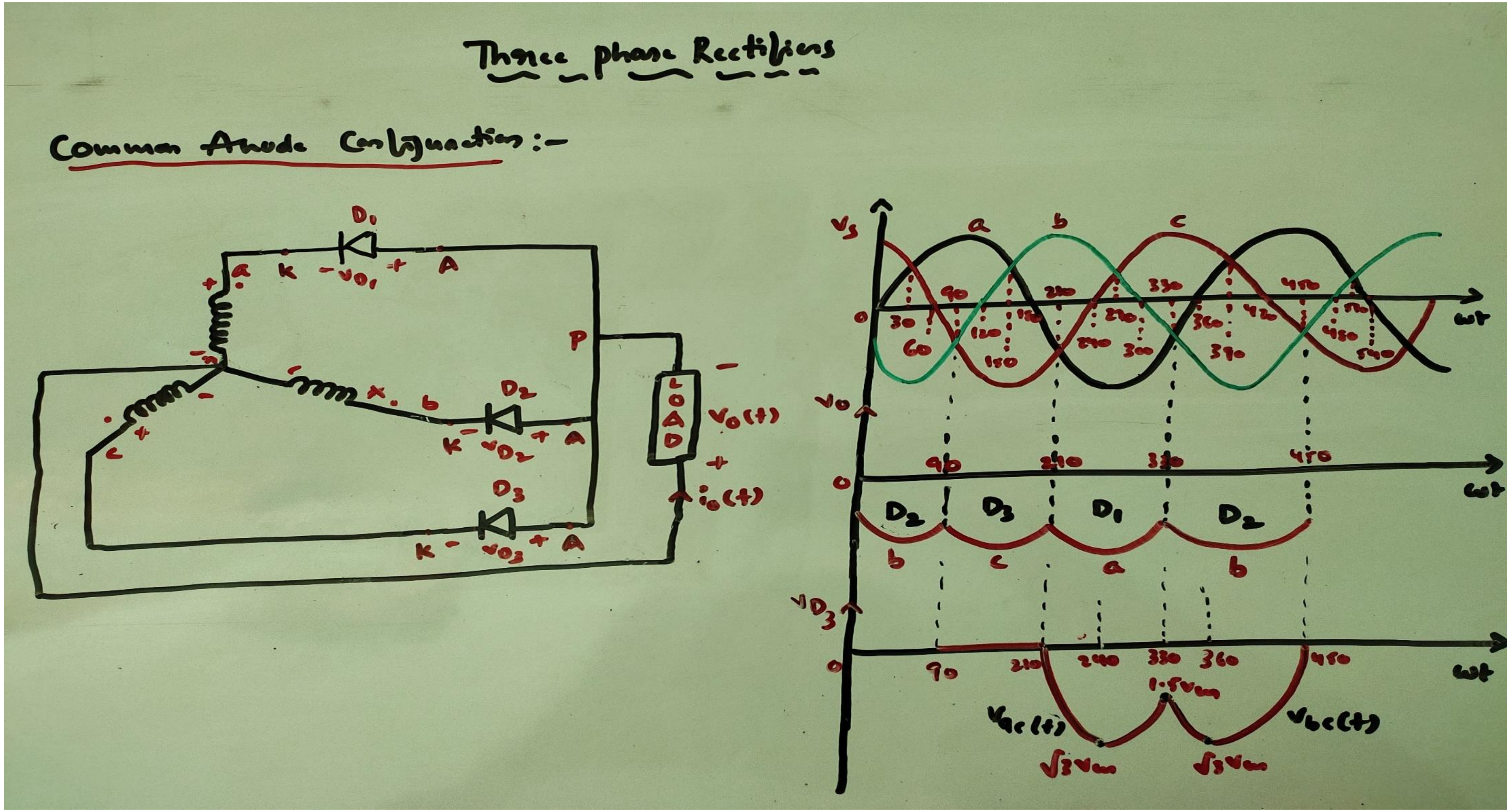
Three Phase Half wave Controlled Rectifier with RL Load



Three Phase Half wave Controlled Rectifier with RL Load with Free Wheeling Diode

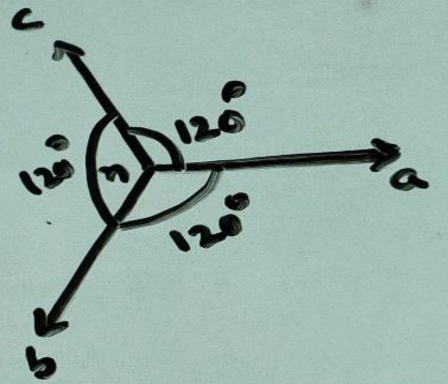


Common Cathode Configuration



Three Phase Voltages

Three phase Rectifiers



$$v_{ab}(t) = v_{an}(t) - v_{bn}(t)$$

$$= V_m \sin\omega t - V_m \sin(\omega t - 120)$$

$$= V_m[\sin\omega t - \sin(\omega t - 120)]$$

$$= V_m\left[2\cos\left(\frac{A+B}{2}\right)\cdot\sin\left(\frac{A-B}{2}\right)\right]$$

$$= V_m\left[2\cos\left(\frac{2\omega t - 120}{2}\right)\cdot\sin\left(\frac{120}{2}\right)\right]$$

$$= 2V_m\cos(\omega t - 60)\cdot\sin 60$$

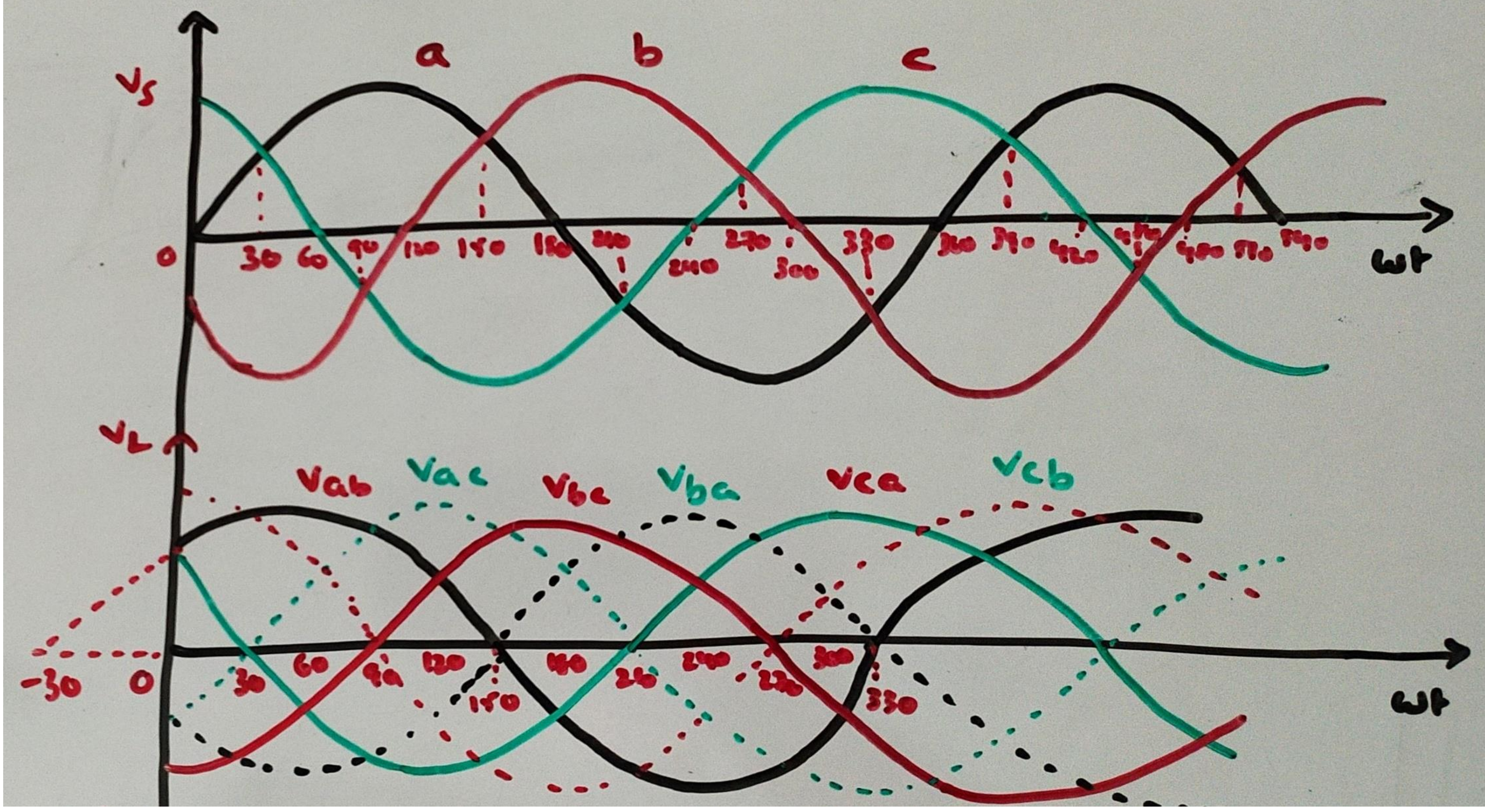
$$\sin A - \sin B = 2\cos\left(\frac{A+B}{2}\right)\cdot\sin\left(\frac{A-B}{2}\right)$$

$$\Rightarrow \boxed{V_{ab}(t) = \sqrt{3}\,V_m\cos(\omega t - 60)}$$

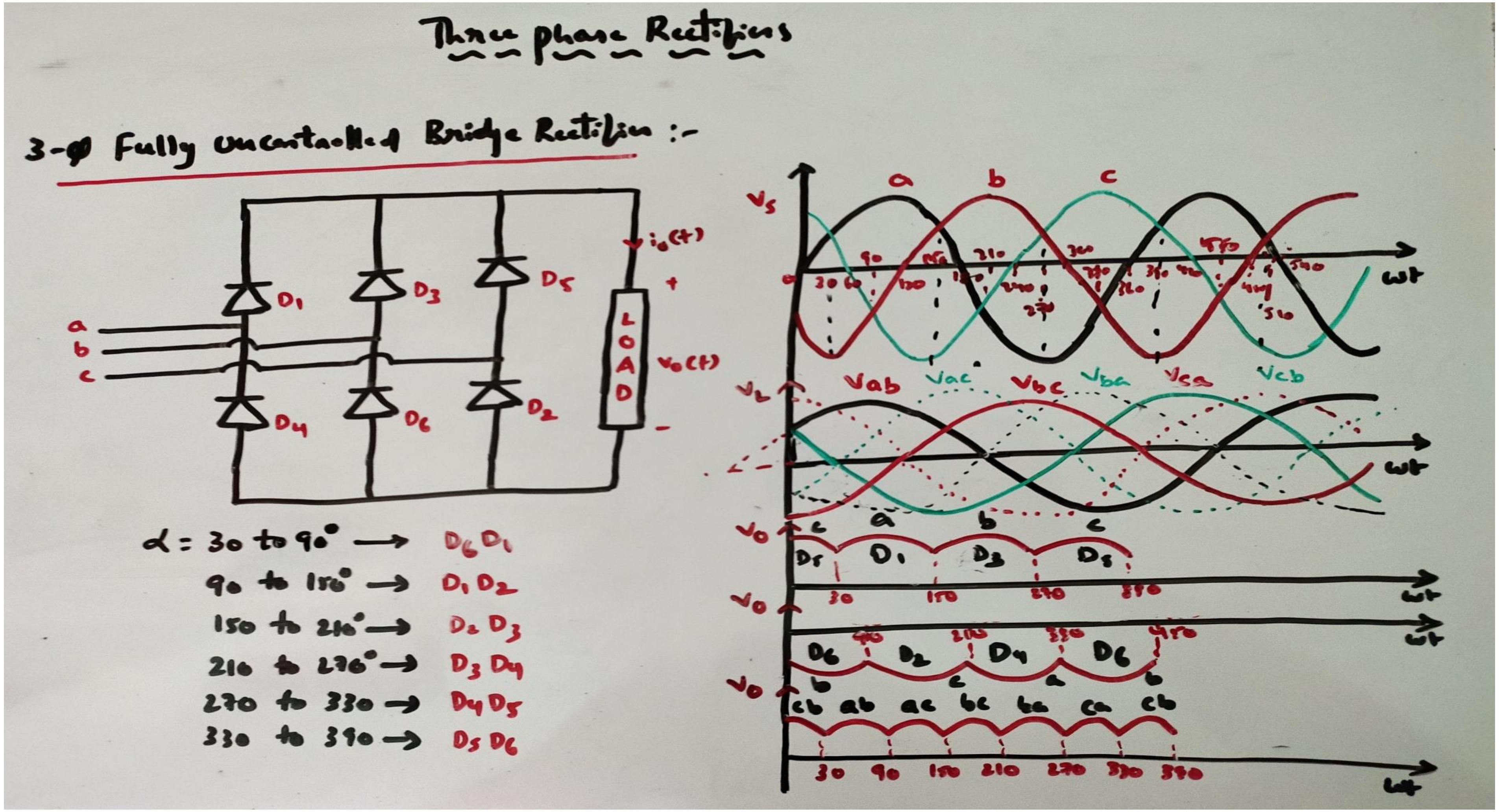
Phase Sequence $ab \rightarrow bc \rightarrow ca$

$$V_{bc}(t) = \sqrt{3}\,V_m\cos(\omega t - 180^\circ)$$

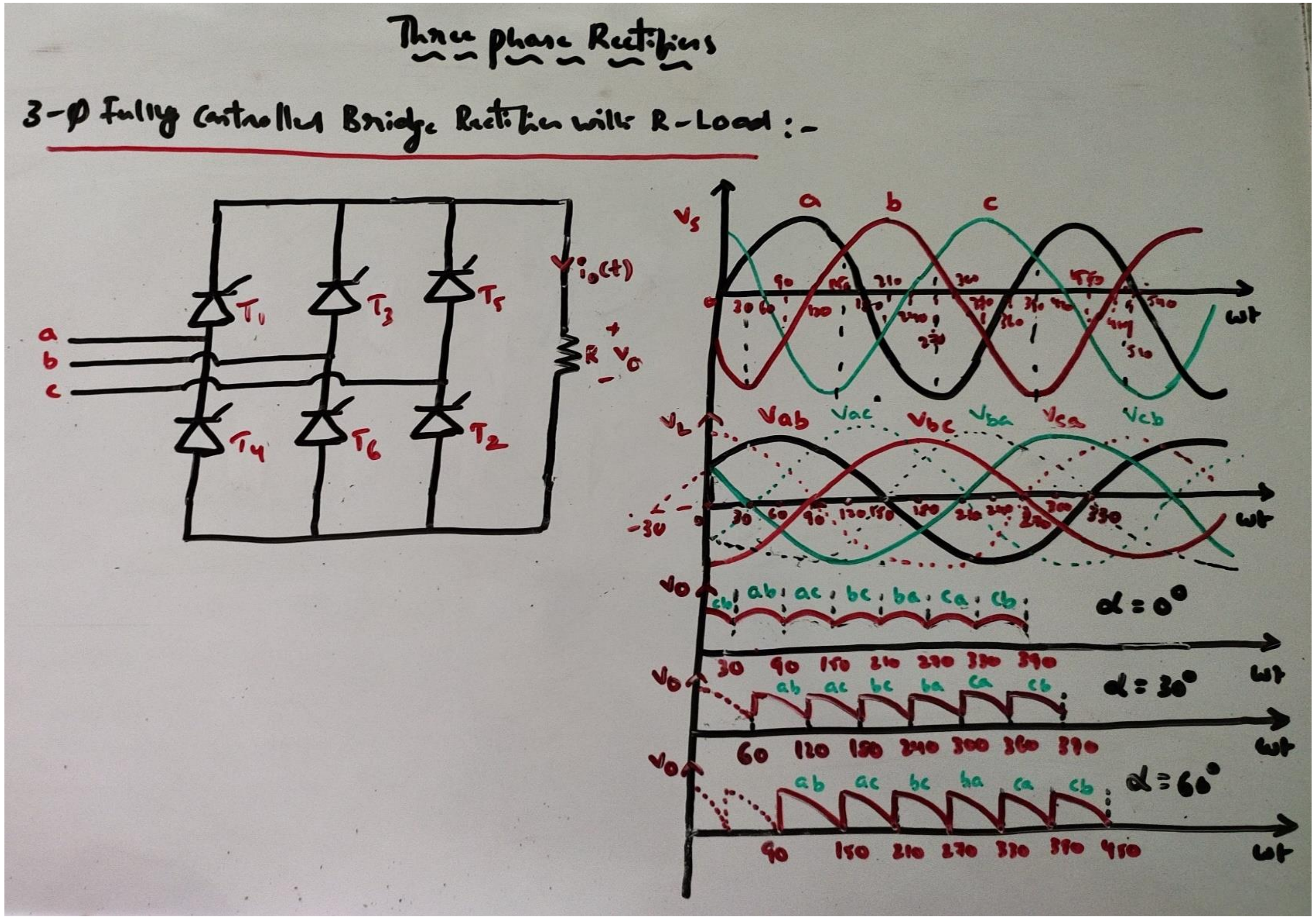
$$V_{ca}(t) = \sqrt{3}\,V_m\cos(\omega t + 60^\circ)$$


a
b
c
Vs
0
30
60
90
120
150
180
210
240
270
300
330
360
ωt
VL
Vab
Vac
Vbc
Vba
Vca
Vcb
-30
0
30
60
90
120
150
180
210
240
270
300
330
ωt

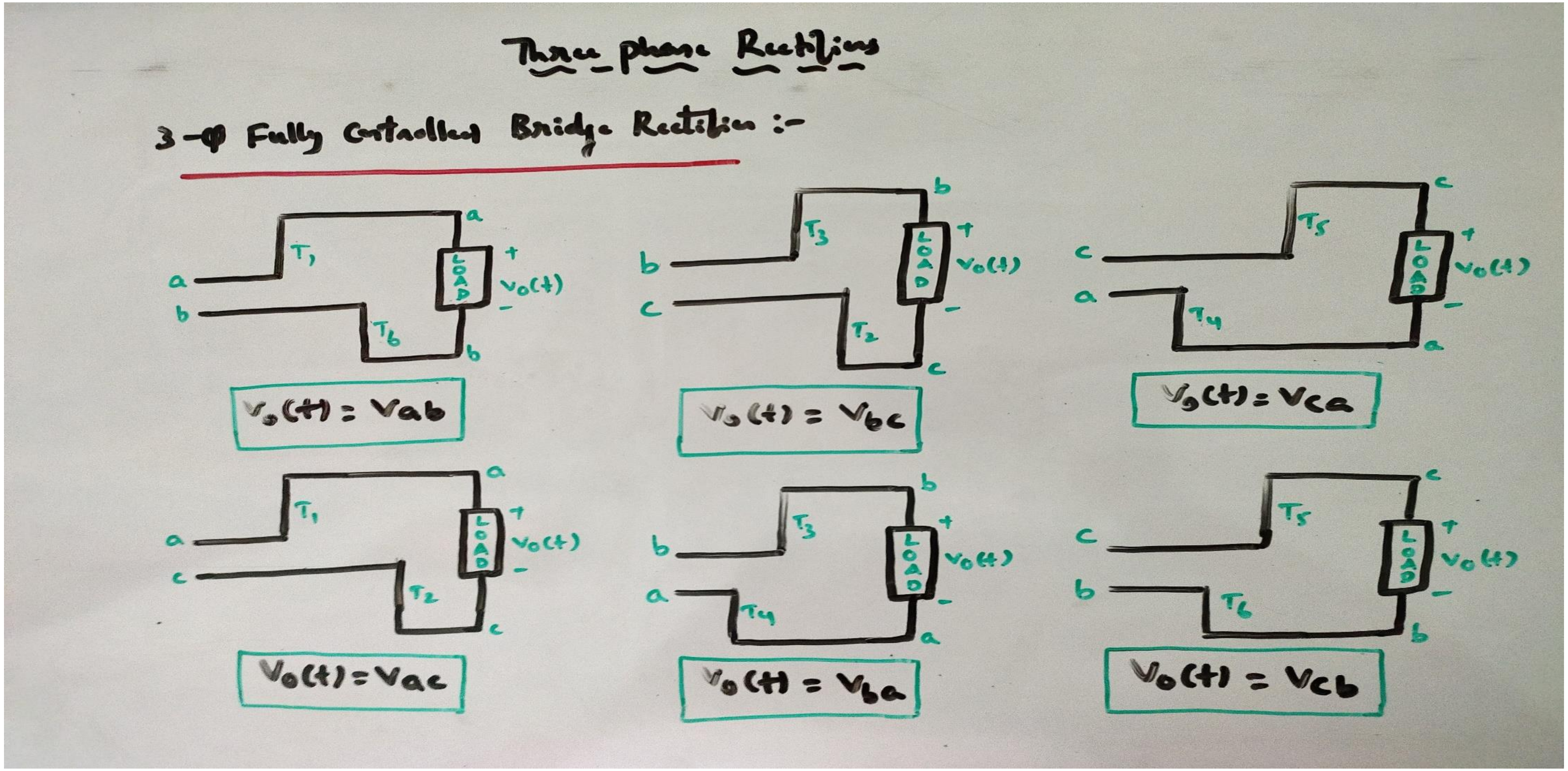
Three Phase Fully Uncontrolled Bridge Rectifier



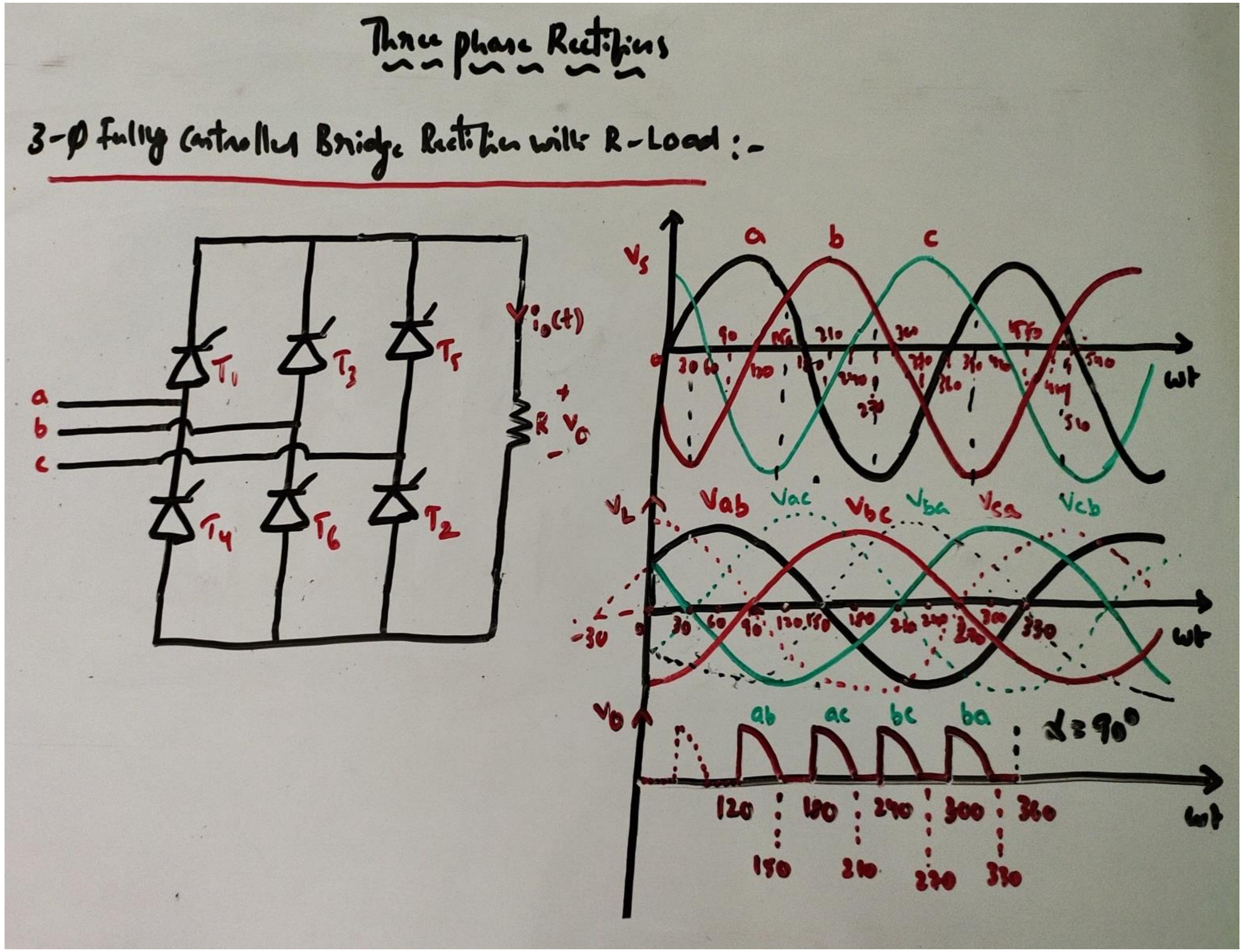
Three Phase Fully Controlled Bridge Rectifier with R-Load



Three Phase Fully Controlled Bridge Rectifier with R-Load



Three Phase Fully Controlled Bridge Rectifier with R-Load



Three Phase Fully Controlled Bridge Rectifier with R-Load

Three phase Rectifiers

R-Load :-

Continuous Conduction Mode ($\alpha < 60^\circ$)

Average load voltage,

$$V_{o(avg)} = \frac{1}{T}\int_0^T v_o(t)\cdot d\omega t$$

$$= \frac{1}{\left(\frac{2\pi}{6}\right)}\int_{\pi/6+\alpha}^{\pi/2+\alpha} v_{ab}(t)\cdot d\omega t$$

$$= \frac{6}{2\pi}\int_{\pi/6+\alpha}^{\pi/2+\alpha} \sqrt{3}\,V_m \sin\left(\omega t + \frac{\pi}{6}\right) d\omega t$$

$$= \frac{3\sqrt{3}\,V_m}{\pi}\Big[-\cos\left(\omega t + \pi/6\right)\Big]_{\pi/6+\alpha}^{\pi/2+\alpha}$$

Three Phase Fully Controlled Bridge Rectifier with R-Load

Three phase Rectifiers

R-Load :-

Continuous Conduction Mode ($\alpha < 60^\circ$)

$$= V_0(avg) = \frac{3\sqrt{3}V_m}{\pi}\left[\cos\left(\frac{\pi}{3}+\alpha\right) - \cos\left(\frac{2\pi}{3}+\alpha\right)\right]$$

$$= \frac{3\sqrt{3}V_m}{\pi}\left[\left[\cos\frac{\pi}{3}\cos\alpha - \sin\frac{\pi}{3}\sin\alpha\right] - \left[\cos\frac{2\pi}{3}\cos\alpha - \sin\frac{2\pi}{3}\sin\alpha\right]\right]$$

$$= \frac{3\sqrt{3}V_m}{\pi}\left[\left[\left(\frac{1}{2}\right)\cos\alpha - \left(\frac{\sqrt{3}}{2}\right)\sin\alpha\right] - \left[\left(-\frac{1}{2}\right)\cos\alpha - \left(\frac{\sqrt{3}}{2}\right)\sin\alpha\right]\right]$$

$$= \frac{3\sqrt{3}V_m}{\pi}\left[\frac{1}{2}\cos\alpha - \cancel{\frac{\sqrt{3}}{2}\sin\alpha} + \frac{1}{2}\cos\alpha + \cancel{\frac{\sqrt{3}}{2}\sin\alpha}\right]$$

$$= \boxed{V_0(avg) = \frac{3\sqrt{3}V_m}{\pi}\cos\alpha}$$

Three Phase Fully Controlled Bridge Rectifier with R-Load

Three phase Rectifiers

R-Load :-

Continuous Conduction Mode ($\alpha < 60^\circ$)

$$V_{o(avg)} = \frac{3\sqrt{3}\,V_m}{\pi} \cos\alpha$$

$$\boxed{I_{o(avg)} = \frac{3\sqrt{3}\,V_m}{\pi R} \cos\alpha}$$

Three Phase Fully Controlled Bridge Rectifier with R-Load

Three phase Rectifiers

R-Load :-

Continuous Conduction Mode ($\alpha < 60^\circ$)

$$V_{o(rms)} = \sqrt{\frac{1}{T}\int_0^T v_o^2(t)\cdot d\omega t}$$

$$= \left[\frac{1}{\left(\frac{2\pi}{6}\right)}\int_{30+\alpha}^{90+\alpha} v_{ab}^2(t)\cdot d\omega t\right]^{1/2}$$

$$= \left[\frac{3}{\pi}\int_{30+\alpha}^{90+\alpha}\left[\sqrt{3}V_m \sin(\omega t+30)\right]^2 d\omega t\right]^{1/2}$$

$$= \left[\frac{9V_m^2}{2\pi}\left[\int_{30+\alpha}^{90+\alpha} 1-\cos 2(\omega t+30)\, d\omega t\right]\right]^{1/2}$$

Three Phase Fully Controlled Bridge Rectifier with R-Load

Three phase Rectifiers

R - Load :-

Continuous Conduction Mode ($\alpha < 60^\circ$)

$$= V_{o(rms)} = \left[\frac{9V_m^2}{2\pi} \left[60 - \frac{1}{2} \left[\sin 2(90+\alpha+30) - \sin 2(30+\alpha+30) \right] \right] \right]^{1/2}$$

$$= \left[\frac{9V_m^2}{2\pi} \left(\frac{\pi}{3} - \frac{1}{2} \left[\sin(240+2\alpha) - \sin(120+2\alpha) \right] \right) \right]^{1/2}$$

$$= \left[\frac{9V_m^2}{2\pi} \left[\frac{\pi}{3} - \frac{1}{2} \left[\sin 240 \cos 2\alpha + \cos 240 \sin 2\alpha - \left[\sin 120 \cos 2\alpha + \cos 120 \sin 2\alpha \right] \right] \right] \right]^{1/2}$$

$$= \left[\frac{9V_m^2}{2\pi} \left(\frac{\pi}{3} - \frac{1}{2} \left(-\frac{\sqrt{3}}{2} \cos 2\alpha - \cancel{\frac{1}{2} \sin 2\alpha} - \frac{\sqrt{3}}{2} \cos 2\alpha + \cancel{\frac{1}{2} \sin 2\alpha} \right) \right) \right]^{1/2}$$

$$= \left[\frac{9V_m^2}{2\pi} \left(\frac{\pi}{3} + \frac{1}{2} \sqrt{3} \cos 2\alpha \right) \right]^{1/2}$$

$$= \boxed{V_{o(rms)} = \frac{3V_m}{2} \left(\frac{\frac{2\pi}{3} + \sqrt{3} \cos 2\alpha}{\pi} \right)^{1/2}}$$

Three Phase Fully Controlled Bridge Rectifier with R-Load

Three phase Rectifiers

R- Load :-

Discontinuous Conduction Mode ($\alpha > 60^\circ$)

Average load voltage .

$$V_{o(avg)} = \frac{1}{T}\int_0^T v_o(t)\cdot d\omega t$$

$$= \frac{1}{\left(\frac{2\pi}{6}\right)}\int_{\pi/6+\alpha}^{5\pi/6} V_{ab}(t)\cdot d\omega t$$

$$= \frac{6}{2\pi}\int_{\pi/6+\alpha}^{5\pi/6}\sqrt{3}\,V_m \sin\left(\omega t+\frac{\pi}{6}\right)d\omega t$$

$$= \frac{3\sqrt{3}V_m}{\pi}\left[-\cos\left(\omega t+\frac{\pi}{6}\right)\right]_{\pi/6+\alpha}^{5\pi/6}$$

$$= \frac{3\sqrt{3}V_m}{\pi}\left[\cos\left(\frac{\pi}{6}+\alpha+\frac{\pi}{6}\right)-\cos\left(\frac{5\pi}{6}+\frac{\pi}{6}\right)\right]$$

Three Phase Fully Controlled Bridge Rectifier with R-Load

Three phase Rectifiers

R-Load :-

Discontinuous Conduction Mode $(\alpha > 60^\circ)$

$$= V_o(avg) = \frac{3\sqrt{3}V_m}{\pi}\left[\cos\left(\frac{\pi}{3}+\alpha\right) - \cos\left(\frac{6\pi}{6}\right)\right]$$

$$= \frac{3\sqrt{3}V_m}{\pi}\left[\cos\left(\frac{\pi}{3}+\alpha\right) - \cos\pi\right]$$

$$= \boxed{V_o(avg) = \frac{3\sqrt{3}V_m}{\pi}\left[1+\cos\left(\frac{\pi}{3}+\alpha\right)\right]}$$

$$\boxed{I_o(avg) = \frac{3\sqrt{3}V_m}{\pi R}\left[1+\cos\left(\frac{\pi}{3}+\alpha\right)\right]}$$

Three Phase Fully Controlled Bridge Rectifier with R-Load

Three phase Rectifiers

R - Load :-

Discontinuous Conduction Mode ($\alpha > 60^\circ$)

RMS output voltage,

$$v_{o(rms)} = \sqrt{\frac{1}{T}\int_0^T v_o^2(t)\cdot d\omega t}$$

$$= \left[\frac{1}{\left(\frac{2\pi}{6}\right)}\int_{30+\alpha}^{150} v_{ab}^2(t)\cdot d\omega t\right]^{1/2}$$

$$= \left[\frac{3}{\pi}\int_{30+\alpha}^{150}\left[\sqrt{3}\,V_m \sin(\omega t+30)\right]^2\right]^{1/2}$$

$$= \left[\frac{9V_m^2}{\pi}\left[\int_{30+\alpha}^{150} 1 - \cos 2(\omega t+30)\right]\right]^{1/2}$$

Three Phase Fully Controlled Bridge Rectifier with R-Load

Three phase Rectifiers

R - Load :-

Discontinuous Conduction Mode ($\alpha > 60°$)

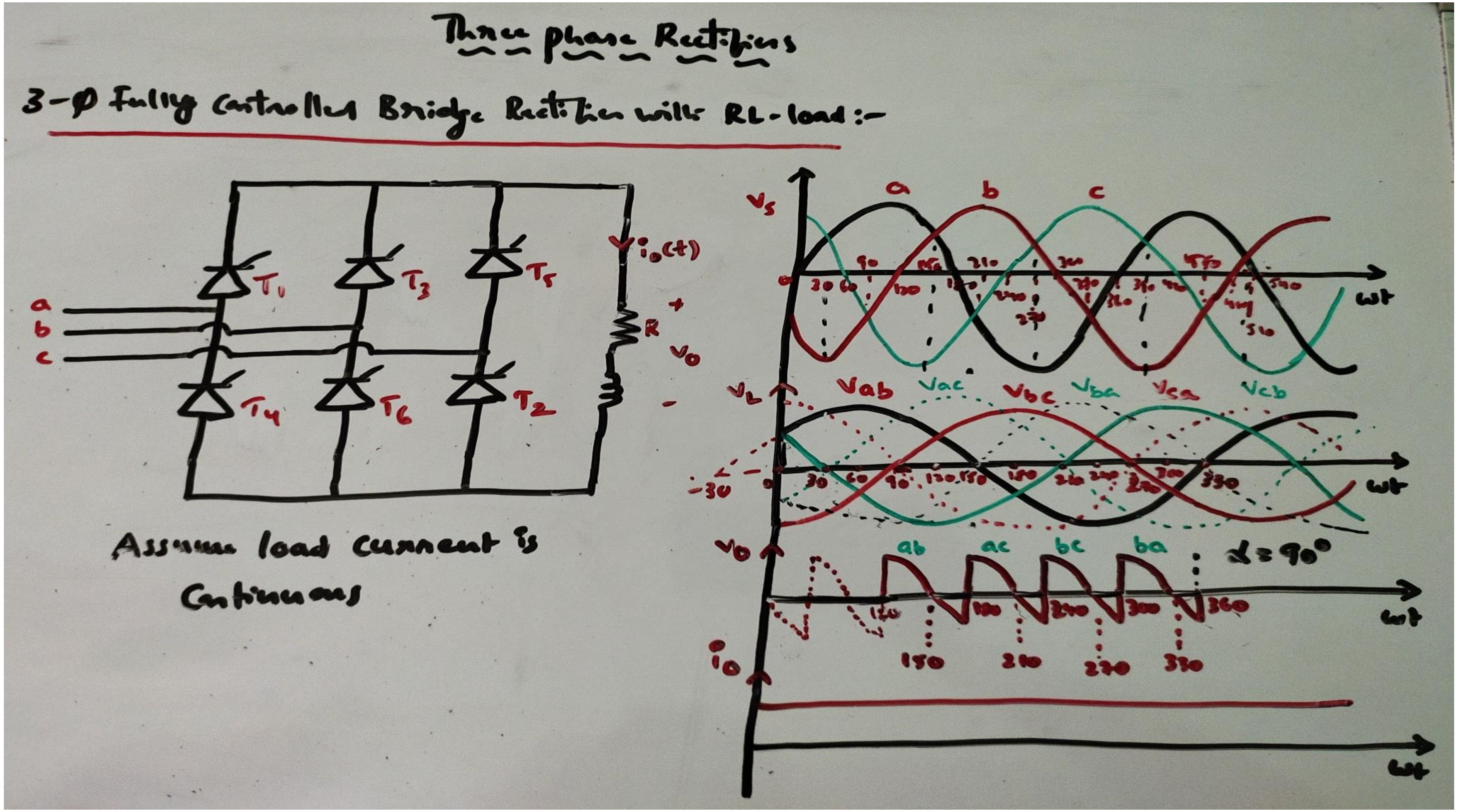
$$= V_{o(rms)} = \left[\frac{9V_m^2}{\pi}\left[(150-30-\alpha) - \frac{1}{2}\left[\sin 2(150+30) - \sin 2(30+\alpha+30)\right]\right]\right]^{1/2}$$

$$= \left[\frac{9V_m^2}{\pi}\left[120-\alpha - \frac{1}{2}\left[\sin 360 - \sin(120+2\alpha)\right]\right]\right]^{1/2}$$

$$= \left[\frac{9V_m^2}{\pi}\left[\frac{2\pi}{3}-\alpha+\frac{1}{2}\sin(120+2\alpha)\right]\right]^{1/2}$$

$$= \boxed{V_{o(rms)} = \frac{3}{2}V_m\left(\frac{\frac{4\pi}{3}-\alpha+\sin(120+2\alpha)}{\pi}\right)^{1/2}}$$

Three Phase Fully Controlled Bridge Rectifier with RL-Load



Three Phase Fully Controlled Bridge Rectifier with RL-Load

Three phase Rectifiers

RL-load :-

Average load voltage,

$$v_0(avg) = \frac{1}{T}\int_0^T v_0(t)\cdot d\omega t$$

$$= \frac{1}{\left(\frac{2\pi}{6}\right)}\int_{30+\alpha}^{90+\alpha} V_{ab}(t)\cdot d\omega t$$

$$= \frac{3}{\pi}\int_{30+\alpha}^{90+\alpha} \sqrt{3}V_m \sin(\omega t+30^\circ)\cdot d\omega t$$

$$= \frac{3\sqrt{3}V_m}{\pi}\Big[-\cos(\omega t+30)\Big]_{30+\alpha}^{90+\alpha}$$

$$= \frac{3\sqrt{3}V_m}{\pi}\Big[\cos(60+\alpha)-\cos(120+\alpha)\Big]$$

$$= \frac{3\sqrt{3}V_m}{\pi}\Big[[\cos 60\cos\alpha - \sin 60\sin\alpha] - [\cos 120\cos\alpha - \sin 120\sin\alpha]\Big]$$

$$= \frac{3\sqrt{3}V_m}{\pi}\Big[\frac{1}{2}\cos\alpha - \frac{\sqrt{3}}{2}\sin\alpha - \Big[\Big(-\frac{1}{2}\cos\alpha\Big) - \frac{\sqrt{3}}{2}\sin\alpha\Big]\Big]$$

$$= \frac{3\sqrt{3}V_m}{\pi}\Big[\cos\alpha\Big]$$

$$= \boxed{v_0(avg) = \frac{3\sqrt{3}V_m}{\pi}\cos\alpha}$$

Three Phase Fully Controlled Bridge Rectifier with RL-Load

Three phase Rectifiers

RL-load :-

$$V_o(rms) = \sqrt{\frac{1}{T}\int_0^T v_o^2(t)\cdot d\omega t}$$

$$= \left[\frac{1}{\left(\frac{2\pi}{6}\right)}\int_{30+\alpha}^{90+\alpha} v_{ab}^2(t)\cdot d\omega t\right]^{1/2}$$

$$= \left[\frac{3}{\pi}\int_{30+\alpha}^{90+\alpha} 3V_m^2 \sin^2(\omega t+30)\right]^{1/2}$$

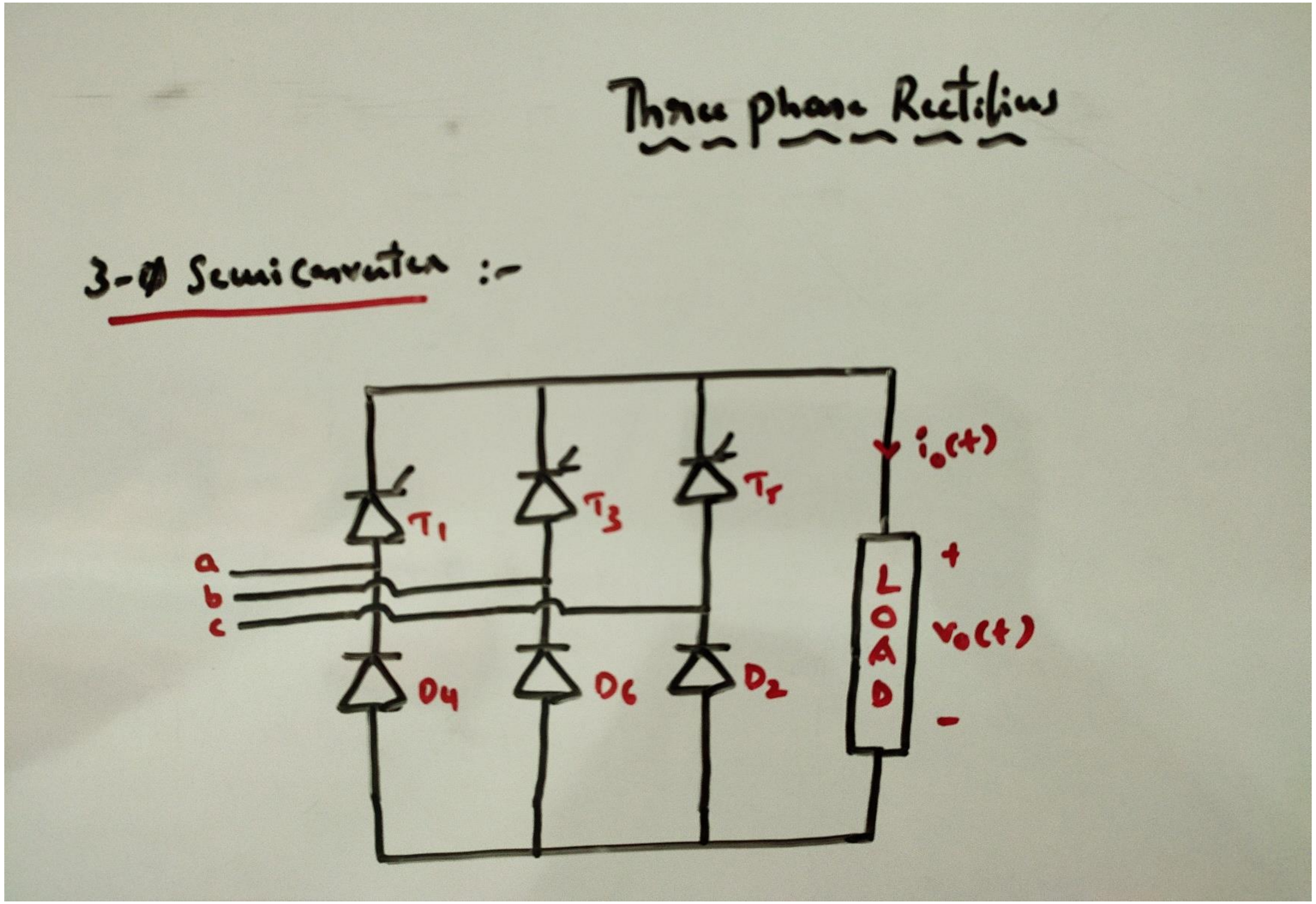
$$= \left[\frac{9V_m^2}{\pi}\left[\int_{30+\alpha}^{90+\alpha}\frac{1-\cos 2(\omega t+30)}{2}\right]\right]^{1/2}$$

$$= \left[\frac{9V_m^2}{2\pi}\left[(90+\alpha-30-\alpha) - \frac{1}{2}\left[\sin(120+2\alpha) - \sin(240+2\alpha)\right]\right]\right]^{1/2}$$

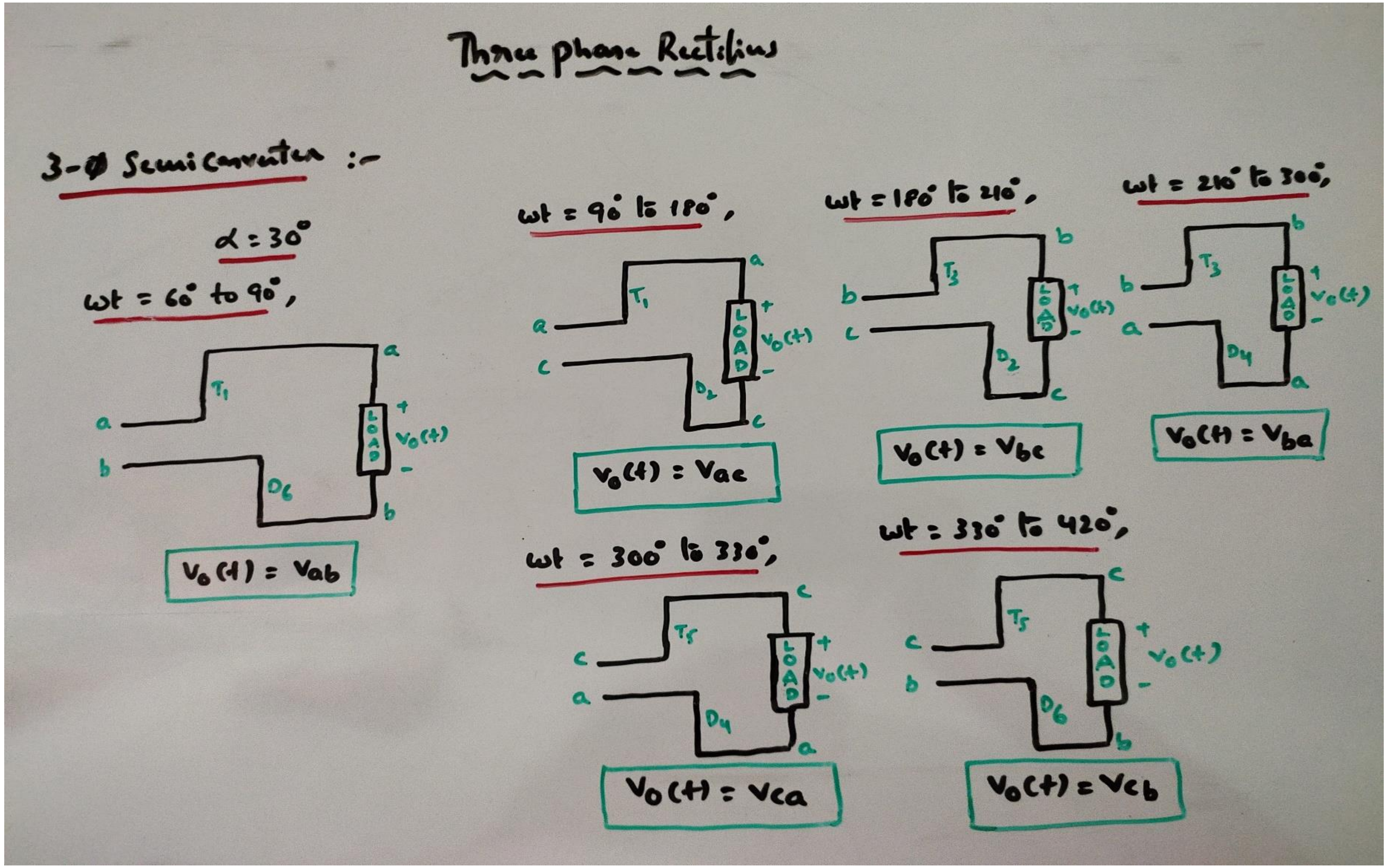
$$= \left[\frac{9V_m^2}{2\pi}\left[60+\frac{1}{2}\left(\sqrt{3}\cos 2\alpha\right)\right]\right]^{1/2}$$

$$= \boxed{V_o(rms) = \frac{3V_m}{2}\left[\frac{2\pi}{3}+\frac{\sqrt{3}}{\pi}\cos 2\alpha\right]^{1/2}}$$

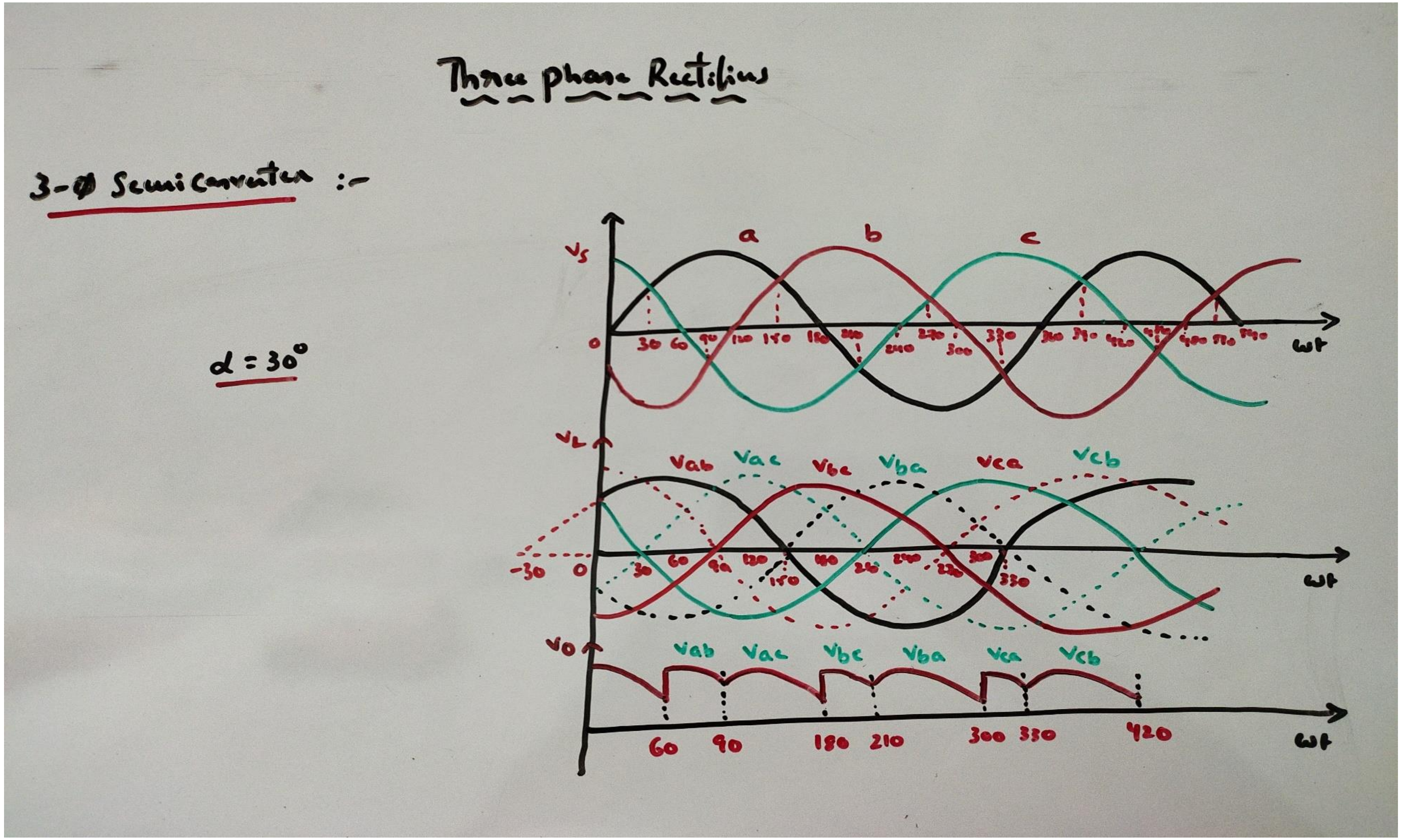
Three Phase Semi Converter



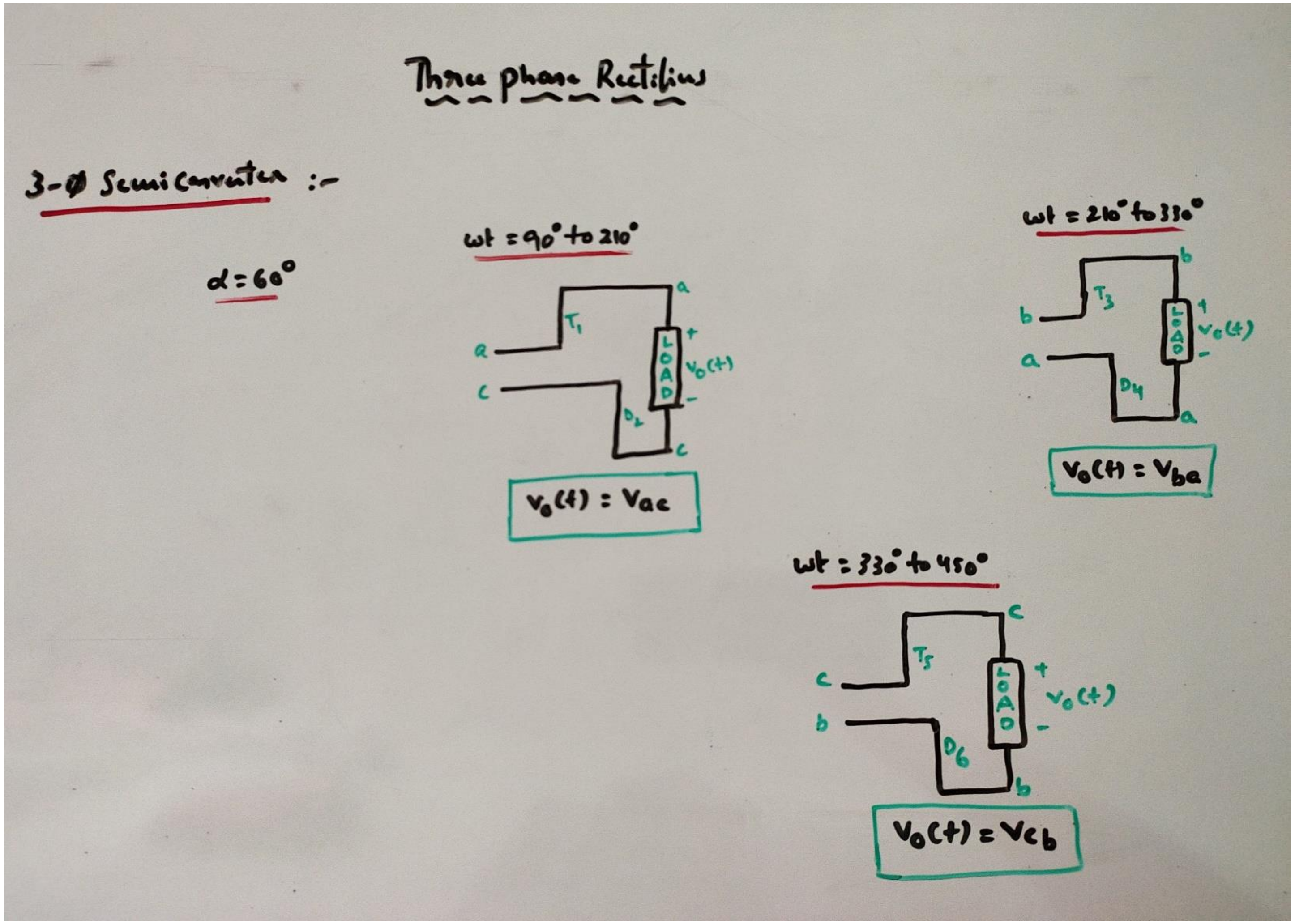
Three Phase Semi Converter



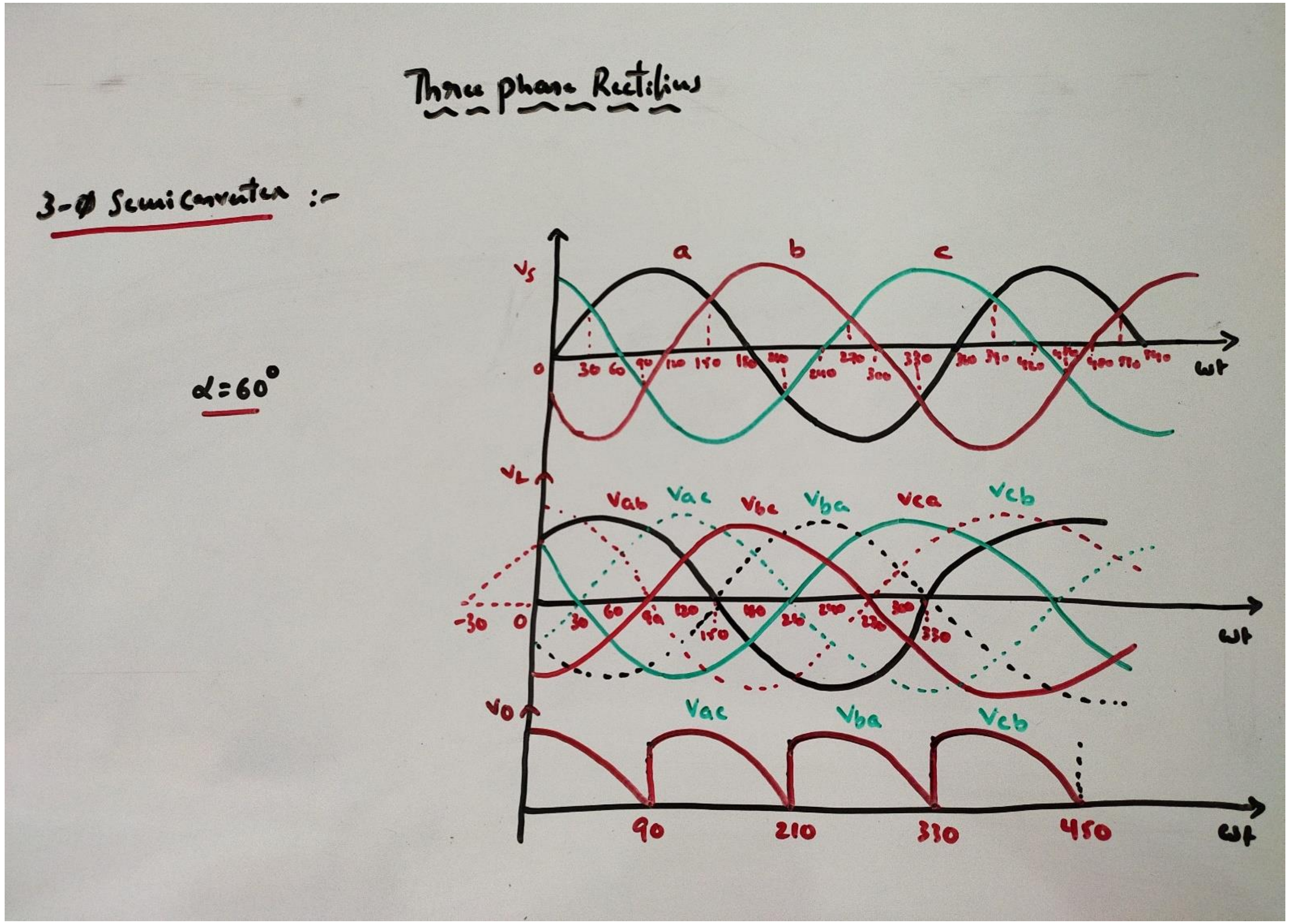
Three Phase Semi Converter



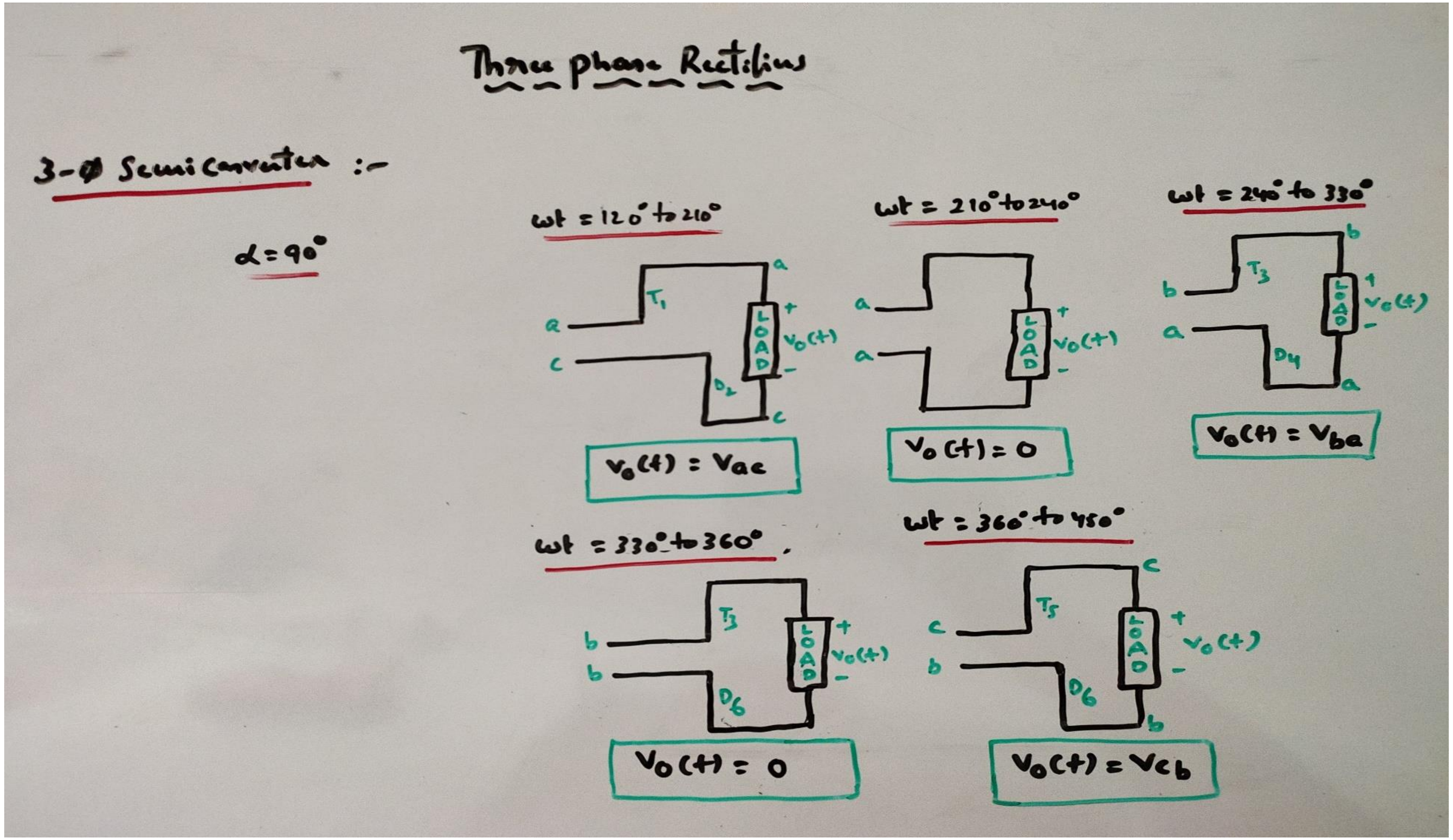
Three Phase Semi Converter



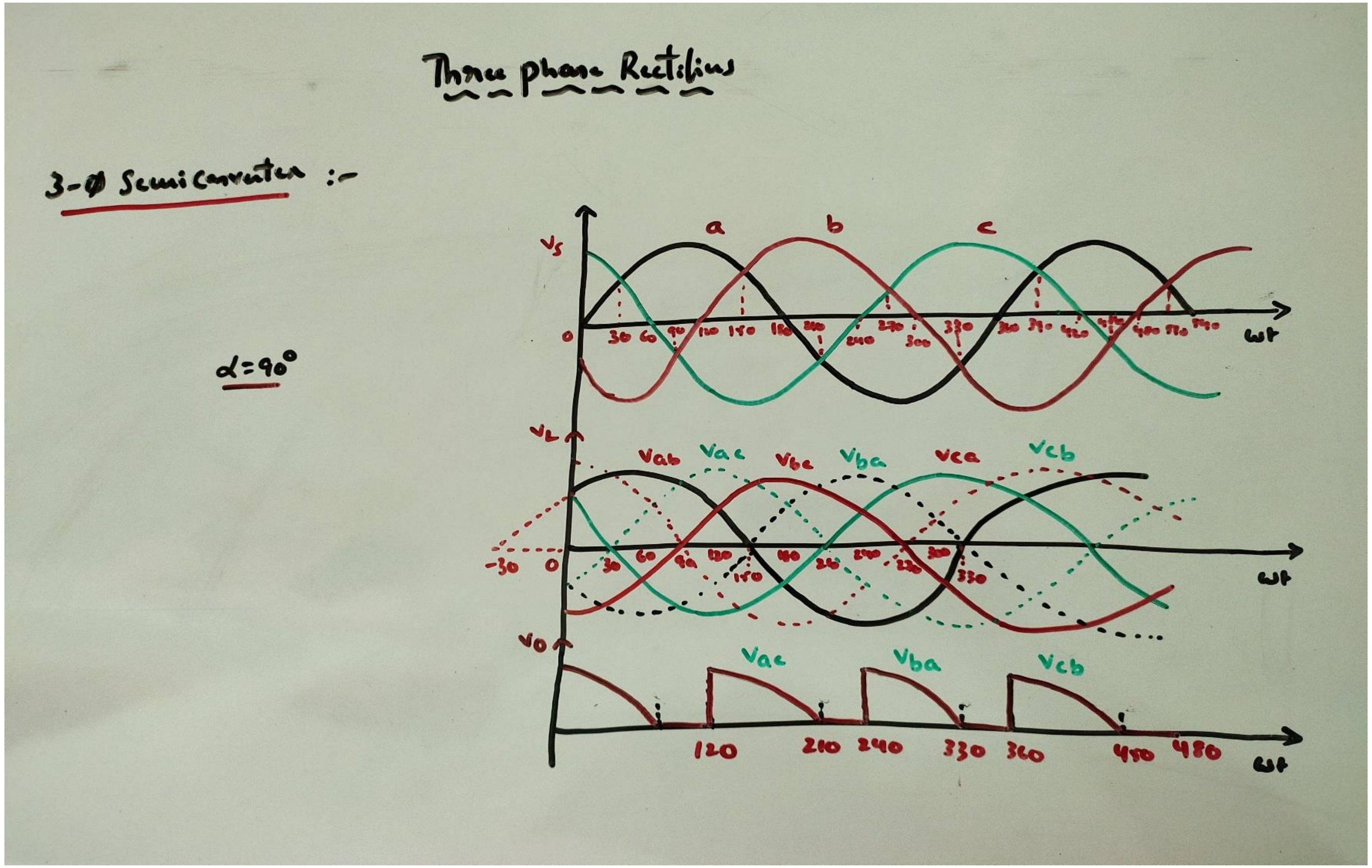
Three Phase Semi Converter



Three Phase Semi Converter



Three Phase Semi Converter



Three Phase Semi converter

Three phase Rectifiers

3-φ Semi Converter :-

$\alpha < 60^\circ$,

$$v_0(avg) = \frac{1}{\left(\frac{2\pi}{3}\right)} \left[\int_{30+\alpha}^{90} V_{ab}(t)\cdot d\omega t + \int_{90}^{150+\alpha} V_{ac}(t)\cdot d\omega t \right]$$

$$= \frac{3}{2\pi} \left[\int_{30+\alpha}^{90} \sqrt{3} V_m \sin(\omega t + 30)\cdot d\omega t + \int_{90}^{150+\alpha} \sqrt{3} V_m \sin(\omega t - 30^\circ)\cdot d\omega t \right]$$

$$= \frac{3\sqrt{3} V_m}{2\pi} \left[\left[-\cos(\omega t + 30) \right]_{30+\alpha}^{90} + \left[-\cos(\omega t - 30) \right]_{90}^{150+\alpha} \right]$$

Three Phase Semi converter

Three phase Rectifiers

3-ϕ Semiconverter :-

$$= V_o(avg) = \frac{3\sqrt{3}V_m}{2\pi}\Big[-[\cos(90+30) - \cos(30+\alpha+30)] + [-[\cos(150+\alpha-30) - \cos(90-30)]]\Big]$$

$$= \frac{3\sqrt{3}V_m}{2\pi}\Big[\cos(60+\alpha) - \cos(120) + \cos(60) - \cos(120+\alpha)\Big]$$

$$= \frac{3\sqrt{3}V_m}{2\pi}\Big\{[\cos 60\cos\alpha - \sin 60\sin\alpha] + \frac{1}{2} + \frac{1}{2} - [\cos 120\cos\alpha - \sin 120\sin\alpha]\Big\}$$

$$= \frac{3\sqrt{3}V_m}{2\pi}\Big[1 + \frac{1}{2}\cos\alpha - \frac{\sqrt{3}}{2}\cancel{\sin\alpha} + \frac{1}{2}\cos\alpha + \frac{\sqrt{3}}{2}\cancel{\sin\alpha}\Big]$$

$$= \boxed{V_o(avg) = \frac{3\sqrt{3}V_m}{2\pi}[1+\cos\alpha]}$$

Three Phase Semi converter

Three phase Rectifiers

3-φ Semi Converter :-

$\alpha \geq 60^\circ,$

$$V_o(avg) = \frac{1}{\left(\frac{2\pi}{3}\right)}\left[\int_{30+\alpha}^{210} V_{ac}(t)\cdot d\omega t\right]$$

$$= \frac{3}{2\pi}\left[\int_{30+\alpha}^{210} \sqrt{3}V_m \sin(\omega t - 30^\circ)\, d\omega t\right]$$

$$= \frac{3\sqrt{3}V_m}{2\pi}\Big[-\cos(\omega t - 30)\Big]_{30+\alpha}^{210}$$

$$= \frac{3\sqrt{3}V_m}{2\pi}\Big(-\big[\cos(210-30) - \cos(\cancel{30}+\alpha-\cancel{30})\big]\Big) = \frac{3\sqrt{3}V_m}{2\pi}\Big[-\big(\cos(180) - \cos\alpha\big)\Big]$$

$$= \boxed{V_o(avg) = \frac{3\sqrt{3}V_m}{2\pi}\left[1+\cos\alpha\right]}$$

Three Phase Semi converter

Three phase Rectifiers

3-φ Semi Converter :-

$\alpha \leq 60^\circ$;

$$V_{0(rms)} = \sqrt{\frac{1}{\left(\frac{2\pi}{3}\right)}\left[\int_{30+\alpha}^{90} v_{ab}^2(t)\cdot d\omega t + \int_{90}^{150+\alpha} v_{ac}^2(t)\cdot d\omega t\right]}$$

$$= \left\{\frac{3}{2\pi}\left[\int_{30+\alpha}^{90}\left[\sqrt{3}V_m \sin(\omega t+30)\right]^2 d\omega t + \int_{90}^{150+\alpha}\left[\sqrt{3}V_m \sin(\omega t-30)\right]^2 d\omega t\right]\right\}^{1/2}$$

$$= \left[\frac{9V_m^2}{2\pi}\left(\int_{30+\alpha}^{90}\sin^2(\omega t+30)\,d\omega t + \int_{90}^{150+\alpha}\sin^2(\omega t-30)\,d\omega t\right)\right]^{1/2}$$

$$= \left[\frac{9V_m^2}{2\pi}\left(\int_{30+\alpha}^{90}\frac{1-\cos 2(\omega t+30)}{2}\cdot d\omega t + \int_{90}^{150+\alpha}\frac{1-\cos 2(\omega t-30)}{2}\cdot d\omega t\right)\right]^{1/2}$$

Three Phase Semi converter

Three phase Rectifiers

3-φ Semi Converter :-

$$= V_{o(rms)} = \left[\frac{9V_m^2}{4\pi} \left[(60-\alpha) - \frac{1}{2}\left[\sin 240 - \sin 2(60+\alpha)\right] + (60+\alpha) - \frac{1}{2}\left[\sin 2(120+\alpha) - \sin(0)\right] \right] \right]^{1/2}$$

$$= \left[\frac{9V_m^2}{4\pi} \left[120 - \frac{1}{2}\left(-\frac{\sqrt{3}}{2} - \sin(120+2\alpha)\right] - \frac{1}{2}\left(\sin(240+2\alpha) - \frac{\sqrt{3}}{2} \right] \right) \right]^{1/2}$$

$$= \left[\frac{9V_m^2}{4\pi} \left[120 + \frac{\sqrt{3}}{4} + \frac{(\sin 120 \cos 2\alpha + \cos 120 \sin 2\alpha)}{2} - \frac{\left[\sin 240 \cos 2\alpha + \cos 240 \sin 2\alpha)\right]}{2} + \frac{\sqrt{3}}{4} \right) \right]^{1/2}$$

Three Phase Semi converter

Three phase Rectifiers

3-φ Semi Converter :-

$$= V_{O(rms)} = \left[\frac{9V_m^2}{4\pi}\left[120 + \frac{\sqrt{3}}{2} + \frac{1}{2}\left[\frac{\sqrt{3}}{2}\cos 2\alpha - \frac{1}{2}\sin 2\alpha \right] - \frac{1}{2}\left[-\frac{\sqrt{3}}{2}\cos 2\alpha - \frac{1}{2}\sin 2\alpha \right] \right] \right]^{1/2}$$

$$= \left[\frac{9V_m^2}{4\pi}\left[120 + \frac{\sqrt{3}}{2} + \frac{\sqrt{3}}{4}\cos 2\alpha - \cancel{\frac{1}{4}\sin 2\alpha} + \frac{\sqrt{3}}{4}\cos 2\alpha + \cancel{\frac{1}{4}\sin 2\alpha} \right] \right]^{1/2}$$

$$= \left[\frac{9V_m^2}{4\pi}\left[\frac{2\pi}{3} + \frac{\sqrt{3}}{2} + \frac{\sqrt{3}}{2}\cos 2\alpha \right] \right]^{1/2}$$

$$= \boxed{V_{O(rms)} = \frac{3V_m}{2}\left[\frac{2}{3} + \frac{\sqrt{3}}{2\pi}\left[1 + \cos 2\alpha\right) \right]^{1/2}}$$

Three Phase Semi converter

Three phase Rectifiers

3-φ Semi Converter :-

$\alpha \geq 60°,$

$$V_{o(rms)} = \sqrt{\frac{1}{\left(\frac{2\pi}{3}\right)}\left[\int_{30+\alpha}^{210} v_{ac}^2(t)\cdot d\omega t\right]}$$

$$= \left[\frac{3}{2\pi}\left(\int_{30+\alpha}^{210}\left[\sqrt{3}V_m \sin(\omega t-30)\right]^2\cdot d\omega t\right]^{1/2}$$

$$= \left(\frac{9V_m^2}{2\pi}\left[\int_{30+\alpha}^{210}\frac{1-\cos 2(\omega t-30)}{2}\right]\right]^{1/2}$$

$$= \left[\frac{9V_m^2}{4\pi}\left[(210-30-\alpha) - \frac{1}{2}\left[\sin 2(210-30) - \sin 2(30+\alpha-30)\right]\right]\right]^{1/2}$$

Three Phase Semi converter

Three phase Rectifiers

3-ϕ Semi Converter :-

$\alpha \geq 60°$,

$$V_0(rms) = \left[\frac{9V_m^2}{4\pi} \left\{ (180-\alpha) - \frac{1}{2}\left[\sin 360 - \sin 2\alpha\right]\right\}\right]^{1/2}$$

$$= \left[\frac{9V_m^2}{4\pi} \left[(\pi-\alpha) - \frac{1}{2}\left[-\sin 2\alpha\right]\right]\right]^{1/2}$$

$$= \boxed{V_0(rms) = \frac{3V_m}{2}\left[\frac{(\pi-\alpha) + \frac{1}{2}\sin 2\alpha}{\pi}\right]^{1/2}}$$

Three Phase Semi converter

Three phase Rectifiers

① A 3-φ half-wave controlled rectifier has a supply of 220V/ph. Determine the average load voltage for firing angles of 0°, 30°, 60° assuming a thyristor voltage drop of 1.5V and continuous load current.

$$\boxed{\begin{array}{l} V_s = \frac{V_m}{\sqrt{2}} \Rightarrow V_m = \sqrt{2}\,V_s \\ \pi = 3.14 \end{array}}$$

$$V_o(avg) = \frac{3\sqrt{3}\,V_m}{2\pi}\cos\alpha - \text{Drop across SCR}$$

$$= \frac{3\sqrt{3}}{2\pi} \times 200\sqrt{2} \times \cos\alpha - 1.5$$

$\underline{\alpha = 0°}$, $$V_o(avg) = \frac{3\sqrt{3}}{2\pi} \times 200\sqrt{2} \times \cos 0° - 1.5$$

$$= \frac{3\sqrt{3} \times 200\sqrt{2} \times 1}{2 \times 3.14} - 1.5$$

$$= \underline{\underline{232.41\,V.}}$$

$\underline{\alpha = 30°}$, $$V_o(avg) = \frac{3\sqrt{3}}{2\pi} \times 200\sqrt{2} \times \cos 30° - 1.5$$

$$= \underline{\underline{201.07\,V.}}$$

$\underline{\alpha = 60°}$, $$V_o(avg) = \frac{3\sqrt{3}}{2\pi} \times 200\sqrt{2} \times \cos 60° - 1.5$$

$$= \underline{\underline{115.45\,V.}}$$

Three Phase Semi converter

Three phase Rectifiers

② A 3-φ half-wave converter is operated from a 3-φ Y connected 220V, 50Hz supply and load resistance is $R = 10\Omega$. If the average output voltage is 25% of the maximum possible average voltage, then determine,

i. Delay Angle

$$V_L = 220V, \quad V_{ph} = \frac{V_L}{\sqrt{3}} = \frac{220}{\sqrt{3}} = 127.01 \approx \underline{127V}.$$

$$V_{ph} = \frac{V_m}{\sqrt{2}} \Rightarrow V_m = \sqrt{2}\cdot V_{ph} = \sqrt{2}\times 127 = \underline{179.63V}$$

$$\boxed{V_{O(avg)} = \frac{3\sqrt{3}V_m}{2\pi}\cos\alpha}$$

$$\alpha = 0, \quad V_{O(avg)} = V_{O(avg)max.} = \frac{3\sqrt{3}V_m}{2\pi} = \frac{3\sqrt{3}\times 179.63}{2\pi} = \underline{148.55V}.$$

Three Phase Semi converter

Three phase Rectifiers

② A 3-φ half-wave converter is operated from a 3-φ Y connected 220V, 50 Hz supply and load resistance is $R = 10\Omega$. If the average output voltage is 25% of the maximum possible average voltage, then determine,

i. Delay Angle

$$V_{o(avg)} = 25\% \, V_{o(avg)max}.$$

$$= 0.25 \times 148.55 = \underline{37.14\,V}.$$

Normalized $V_{o(avg)}$,

$$V_{o(avg)n} = \frac{V_{o(avg)}}{V_{o(avg)max}}.$$

$$= \frac{\frac{3\sqrt{3}V_m}{2\pi}\cos\alpha}{\frac{3\sqrt{3}V_m}{2\pi}} = \underline{\cos\alpha}$$

For $\alpha \le \pi/6$, the load current is continuous.

i.e., $V_{o(avg)n} \ge \cos(\pi/6) = 86.6\%$.

In the sum, $V_{o(avg)n} = 25\% < 86.6\%$.

=> load current is discontinuous

For a R-load, $\alpha \geq \pi/6$,

$$V_{o(avg)} = \frac{3V_m}{2\pi}\left[1+\cos(30+\alpha)\right]$$

$$= 37.14 = \frac{3 \times 179.63}{2\pi}\left[1+\cos(30+\alpha)\right]$$

$$= \underline{\alpha = 94.5^\circ}.$$

Three Phase Semi converter

Three phase Rectifiers

② A 3-φ half-wave Converter is operated from a 3-φ Y Connected 220V, 50 Hz Supply and load resistance is $R = 10\Omega$. If the average output voltage is 25% of the maximum possible average voltage, then determine,

ii. Average output current

$$I_{o(av)} = \frac{V_{o(av)}}{R} = \frac{37.14}{10} = 3.714 \text{ Amp}$$

iii. Thyristor Average current

$$I_{T(avg)} = \frac{I_{o(av)}}{3} = \frac{3.714}{3} = 1.24 \text{ Amp}$$

$$V_{o(rms)} = \frac{\sqrt{3}\,V_m}{2\sqrt{2}}\left[\frac{5\pi - 3\alpha}{3\pi} + \frac{\sin(2\alpha + \pi/3)}{\pi}\right]^{1/2}$$

$$= 62.12V$$

$$I_{o(rms)} = \frac{V_{o(rms)}}{R} = \frac{62.12}{10} = 6.212 \text{ Amp}$$

$$I_{T(rms)} = \frac{I_{o(rms)}}{\sqrt{3}} = \frac{6.21}{\sqrt{3}} = 3.59 \text{ Amp}$$

iv. Rectification efficiency, η

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{37.14 \times 3.714}{62.1 \times 6.21} = 35.75\%$$

v. Transformer utilization factor

$$TUF = \frac{P_{dc}}{3 \cdot V_{ph} \cdot I_{T(rms)}}$$

$$= \frac{37.14 \times 3.714}{3 \times 127 \times 3.59}$$

$$= 10.09\%$$

vi. Input power factor,

$$\frac{P_{out}}{\text{Input VA}} = \frac{I_{o(rms)}^2 \times R}{3 \times 127 \times 3.59}$$

$$= 0.28 \text{ (lagging)}$$

Three Phase Semi converter

Three phase Rectifiers

③ For the 3-φ converter operating from 3-φ, 415V, 50Hz supply, find out the SCR rating if the load resistance is 100Ω in series with a large smoothing inductor.

$$I_{T(avg)} = \frac{I_{O(avg)}}{3}$$

$$I_{T(rms)} = \frac{I_{O(avg)}}{\sqrt{3}}$$

$$I_{O(avg)} = \frac{V_{O(avg)}}{R} = \frac{3\sqrt{3} \times \frac{415}{\sqrt{3}} \times \sqrt{2} \times \frac{1}{\pi} \cdot \cos\alpha}{100}$$

for $\alpha = 0°$, $I_{O(avg)} = \frac{560.5}{100} = \underline{5.605 \text{ Amp}}.$

$$I_{T(avg)} = \frac{I_{O(avg)}}{3} = \frac{5.605}{3} = \underline{1.868 \text{ Amp}}$$

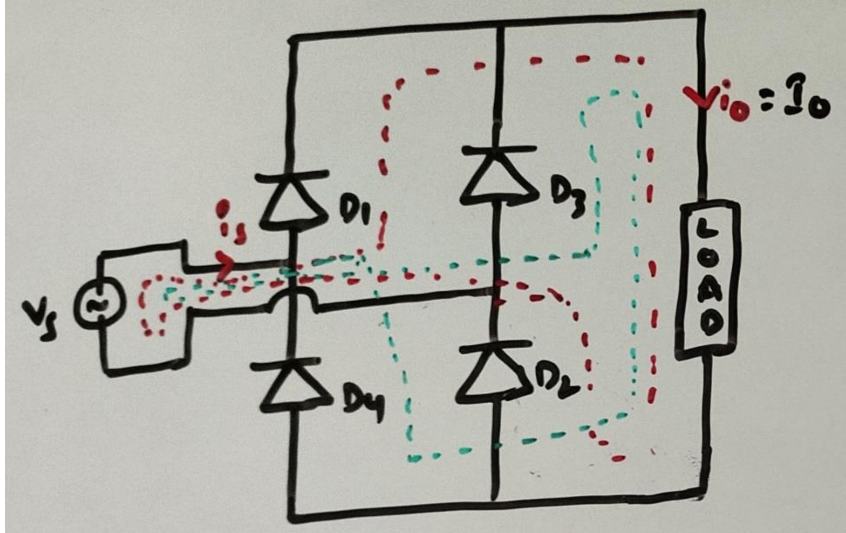
$$I_{T(rms)} = \frac{I_{O(avg)}}{\sqrt{3}} = \frac{5.605}{\sqrt{3}} = \underline{3.235 \text{ Amp}}$$

$$I_{T(peak)} = I_{O(avg)} = \underline{5.605 \text{ Amp}}$$

① A 1-Φ diode bridge rectifier supplies a highly inductive load. The load current can be assumed to be ripple free. The ac supply side current waveform will be —

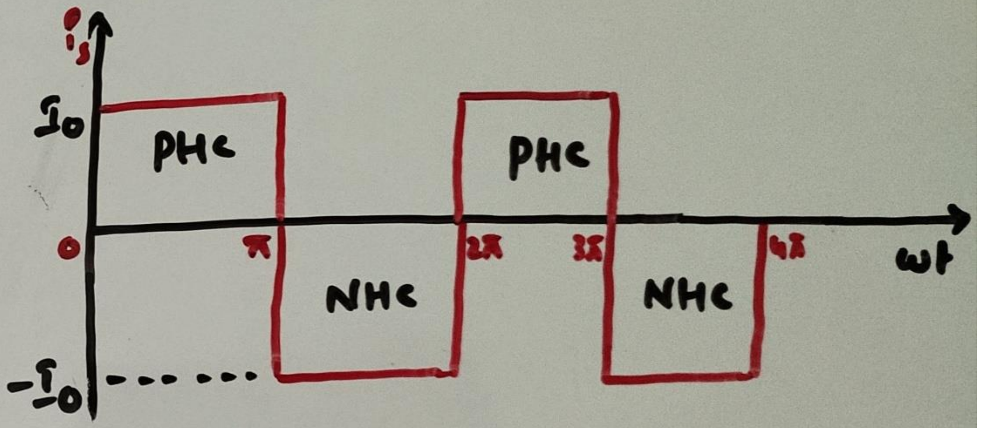
(a) Sinusoidal (b) Constant dc

(c) Square (d) Triangular

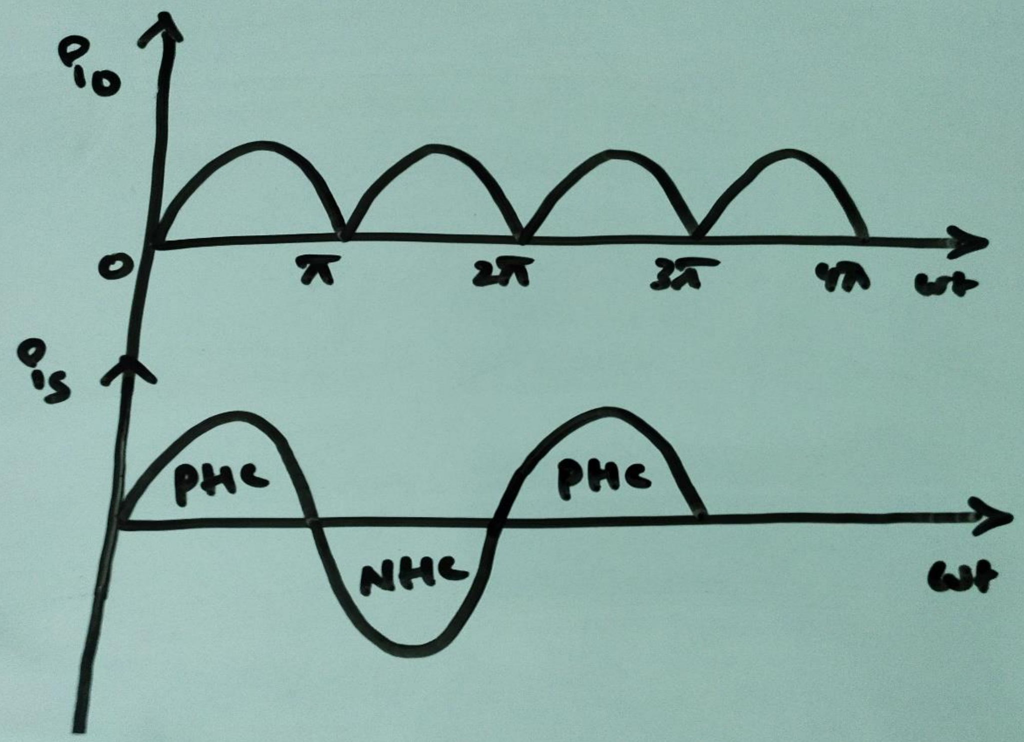


PHC → $I_s = I_0$

NHC → $I_s = -I_0$



Square Waveform



e_{10}
0
π
2π
3π
4π
ωt
e_{1S}
PHC
NHC
PHC
ωt

(2) In a 1-ϕ diode bridge rectifier shown below, the load resistance is 50Ω. $V_s(t) = 200 \sin(\omega t)$, where $\omega = 2\pi \times 50$ rad/sec. The power dissipated in the load resistance "R" is ___

(a) $\frac{3200}{\pi}$ (b) $\frac{400}{\pi}$ (c) 400 (d) 800

$$P_o = I_o^2(\text{rms}) \cdot R$$

(or)

$$P_o = \frac{V_o^2(\text{rms})}{R}$$

$v(t) = 200 \sin(\omega t)$

where, $\omega = 2\pi \times 50$ rad/sec

$R = 50\Omega$

For a full wave bridge rectifier,

$$V_o(\text{rms}) = \frac{V_m}{\sqrt{2}} = \frac{200}{\sqrt{2}} \text{ V}$$

$$P_o = \frac{V_o^2(\text{rms})}{R} = \frac{\left(\frac{200}{\sqrt{2}}\right)^2}{50} = \frac{\left(\frac{400}{2}\right)}{50} = \underline{400 \text{ W}}$$

③ $V_i = 100\sqrt{2}\sin(100\pi t)$ V,

$i = (10\sqrt{2}\sin(100\pi t - \pi/3) +$

$5\sqrt{2}\sin(300\pi t + \pi/4) +$

$2\sqrt{2}\sin(500\pi t - \pi/6)$ Amp.

(i) The Input power factor is ——

(a) 0.31 (b) 0.44 (c) 0.5 (d) 0.71

(ii) The active power drawn by the Converter is ——

(a) 181 W (b) 500 W

(c) 707 W (d) 887 W

$$P = V_{srms} \cdot I_{srms} \cdot \cos\phi$$

V_{srms} = RMS Source voltage

I_{srms} = RMS Source current

$$P = V_{srms} \cdot I_{1\,srms} \cdot \cos\phi_1$$

V_{srms} = RMS Source voltage

$I_{1(srms)}$ = RMS value of fundamental current

$\cos\phi_1$ = Angle between V_{srms} and $I_{1(srms)}$

$\cos\phi$ = Input power factor (or) Supply power factor

$\cos\phi_1$ = Fundamental Input PF (or) Fundamental Supply PF

$$P = V_{rms} \cdot I_{rms} \cdot \cos\phi \longrightarrow (1)$$

$$P = V_{rms} \cdot I_{1(rms)} \cdot \cos\phi_1 \longrightarrow (2)$$

$(1) = (2),$

$$\cancel{V_{rms}} \cdot I_{rms} \cdot \cos\phi = \cancel{V_{rms}} \cdot I_{1(rms)} \cdot \cos\phi_1$$

$$\Rightarrow \cos\phi = \frac{I_{1(rms)}}{I_{rms}} \cdot \cos\phi_1$$

$$\Rightarrow \boxed{\text{Input PF} = \frac{I_{1(rms)}}{I_{rms}} \cdot \text{Fundamental input PF}}$$

$$\Rightarrow \boxed{\text{Input PF} = CDF \times FDF}$$

$$I_{1(rms)} = \frac{10\sqrt{2}}{\sqrt{2}} = 10 \text{ Amp}$$

$$I_{rms} = \sqrt{I_1^2(rms) + I_3^2(rms) + I_5^2(rms)}$$

$$= \sqrt{\left(\frac{10\sqrt{2}}{\sqrt{2}}\right)^2 + \left(\frac{5\sqrt{2}}{\sqrt{2}}\right)^2 + \left(\frac{2\sqrt{2}}{\sqrt{2}}\right)^2}$$

$$= \sqrt{10^2 + 5^2 + 2^2}$$

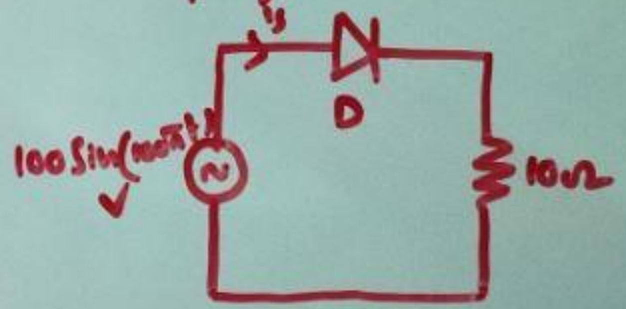
$$= 11.35 \text{ Amp}$$

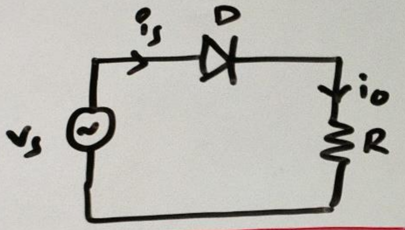
$$\text{Input PF} = \text{CDF} \times \text{FDF}$$

$$= \frac{I_{1(rms)}}{I_{rms}} \cdot \cos\phi_1 = \frac{10}{11.35} \times \cos\left(\frac{\pi}{3}\right)$$

$$= \underline{0.44}$$

④ In the circuit shown, the diode is ideal. The input pf is ____





$$\boxed{i_s = i_o = \frac{V_o}{R}}$$

Source RMS voltage = Load RMS voltage

$$\Rightarrow \boxed{V_{rms} = V_{o(rms)}}$$

$$P = V_{rms} \cdot I_{rms} \cdot \cos\phi$$

$$P = \frac{V_{rms}^2}{R} = \frac{V_o^2(rms)}{R} = \frac{(V_m/2)^2}{R}$$

$$\Rightarrow P = \frac{(100/2)^2}{10} = \frac{2500}{10} = \underline{250\,W}$$

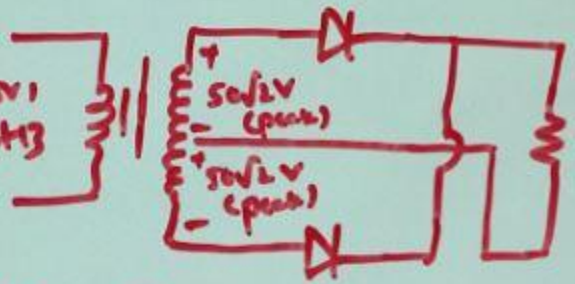
$$250 = \frac{100}{\sqrt{2}} \times I_{o(rms)} \times \cos\phi$$

$$\Rightarrow 250 = \frac{100}{\sqrt{2}} \times \frac{V_{o(rms)}}{R} \times \cos\phi$$

$$\Rightarrow 250 = \frac{100}{\sqrt{2}} \times \frac{100}{2\times 50} \times \cos\phi$$

$$\Rightarrow \boxed{\cos\phi = 0.707}$$

(5) The peak reverse voltage across the diodes D_1 and D_2 is —



(a) $100\sqrt{2}$ V (b) 100V (c) $50\sqrt{2}$ V (d) 50V

- PIV or PRV = 2* V_m ; Center Tapped Rectifier

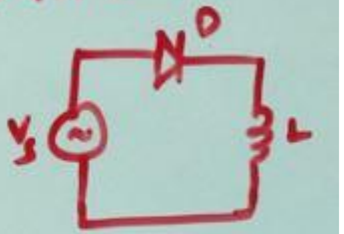
  = 2*50*sqrt(2)

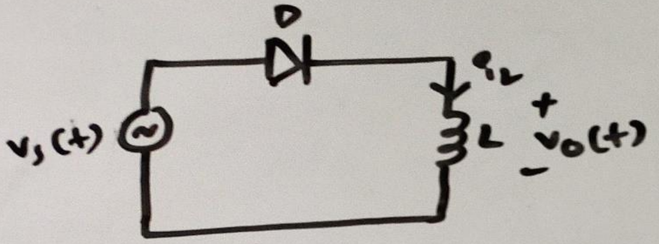
  = 100*sqrt(2).

⑥ The diode Conducts for —

(a) 90° (b) 180°

(c) 270° (d) 360°





+ve Half cycle,

D - ON

$v_o(t) = v_L(t)$

Apply KVL,

$V_o(t) = v_s(t) = v_L(t).$

$$\Rightarrow L \cdot \frac{di(t)}{dt} = V_m \sin\omega t$$

$$\Rightarrow \frac{di(t)}{dt} = \frac{V_m}{L} \sin\omega t$$

$$\Rightarrow i(t) = \int_0^t \frac{V_m}{L} . \sin\omega t . dt$$

$$\Rightarrow i_L(t) = \frac{V_m}{L}\left[-\frac{\cos\omega t}{\omega}\right]_0^t dt$$

$$\Rightarrow \boxed{i_L(t) = \frac{V_m}{\omega L}\left[1 - \cos\omega t\right]}$$

At $\omega t = 0^\circ$,

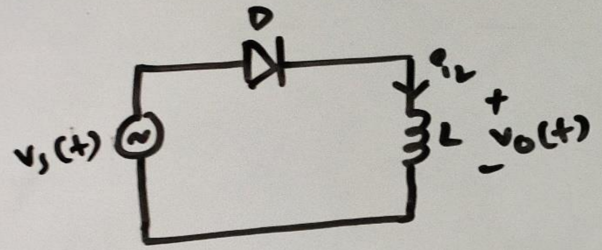
$i_L(t) = \frac{V_m}{\omega L}[1-1] = 0$ Amp

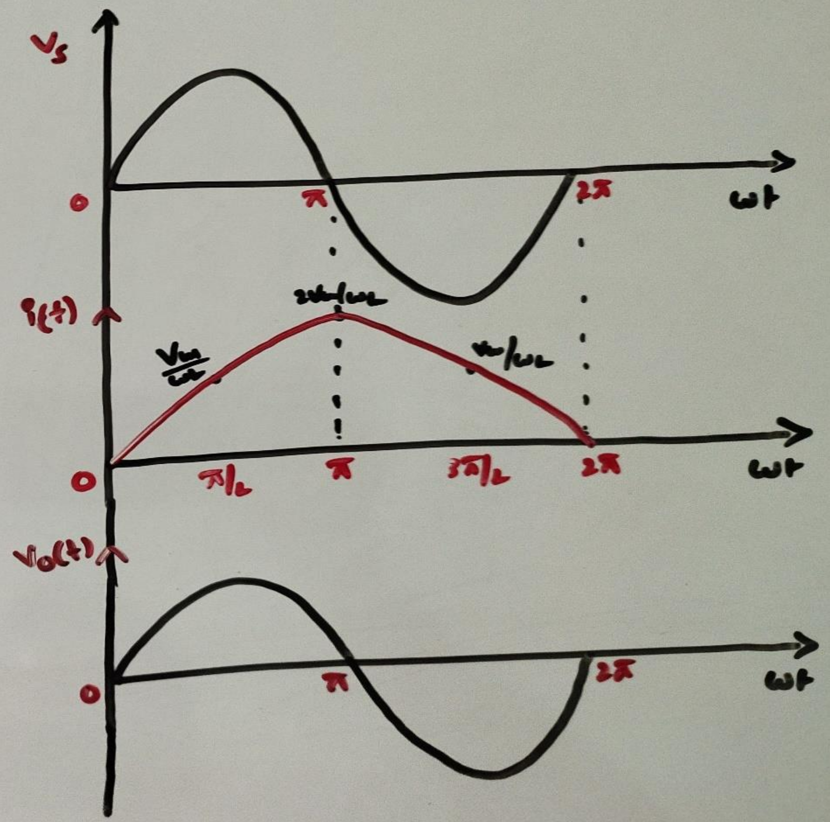
$\omega t = \pi/2$, $i_L(t) = \frac{V_m}{\omega L}$

$\omega t = \pi$, $i_L(t) = \frac{2V_m}{\omega L}$

$\omega t = \frac{3\pi}{2}$, $i_L(t) = \frac{V_m}{\omega L}$

$\omega t = 2\pi$, $i_L(t) = 0$ Amp





Diode Conduction Angle,

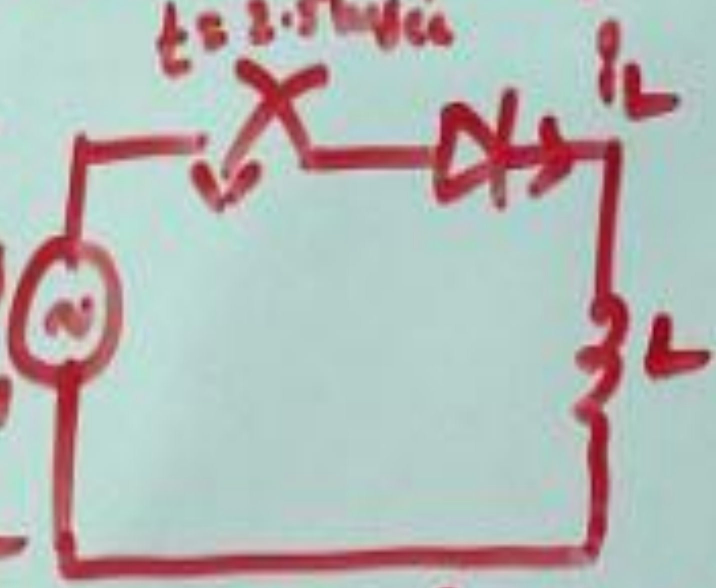
$= 2\pi - 0$

$= 2\pi = \underline{360^\circ}$

$$\boxed{V_o(avg) = 0}$$

(7) $V_s = 100 \sin(\omega t)$, $\omega = 100\pi$ rad/sec,

$L = 31.83$ mH. The Initial Current in "L" is zero. Switch is closed at $t = 2.5$ msec. The Peak Value of Inductor Current in first cycle is —



$t \geq 0,$

$$i_L = \frac{V_m}{\omega L}\left[1 - \cos\omega t\right]$$

$t \geq 2.5\,msec,$

$$i_L = \frac{V_m}{L}\int_{2.5\times10^{-3}sec}^{t} \sin\omega t \cdot dt$$

$$= \frac{V_m}{\omega L}\left[-\cos\omega t\right]_{2.5\times10^{-3}}^{t}$$

$$= \frac{V_m}{\omega L}\left[\cos\omega(2.5\times10^{-3}) - \cos\omega t\right]$$

$$= \frac{V_m}{\omega L}\left[\cos\left(100\pi\times\frac{2.5}{1000}\right) - \cos\omega t\right]$$

$$\Rightarrow i_L = \frac{V_m}{\omega L}\left[\cos\frac{\pi}{4} - \cos\omega t\right]$$

$V_m = 100,\ \omega = 100\pi,$

$L = 31.83\ mH$

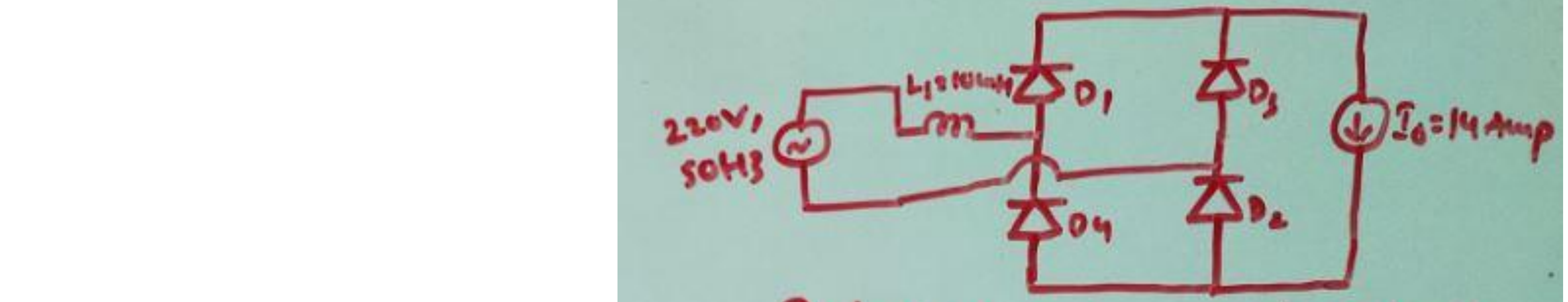
$$\Rightarrow i_L = \frac{\cancel{100}}{\cancel{100}\pi\times31.83\times10^{-3}}\left[\frac{1}{\sqrt{2}} - \cos\omega t\right]$$

At $\omega t = \pi$, $i_L = i_L(max)$

$$\Rightarrow i_L(max) = \frac{1000}{3.14\times31.83}\left[0.707 + 1\right]$$

$$= \underline{17\ Amp}$$

(8) The Conduction angle of the diode "D_1" in degrees shown in the figure is —



The load current draws constant current of 14 Amp.

Without "L_s",

$$V_o = \frac{2V_m}{\pi}\cos\alpha$$; Controlled Rectifier

$$V_o = \frac{2V_m}{\pi}$$; uncontrolled Rectifier

With "L_s",

$$V_o = \frac{V_m}{\pi}\left[\cos\alpha + \cos(\alpha+\mu)\right]$$

(or) $$V_o = \frac{2V_m}{\pi}\cos\alpha - 4fL_s I_o$$

Controlled Rectifier

$$V_o = \frac{V_m}{\pi}\left[1 + \cos\mu\right]$$

$$V_o = \frac{2V_m}{\pi} - 4fL_s I_o$$

uncontrolled Rectifier

$$V_0 = \frac{2V_m}{\pi} - 4fL_sI_0$$

$$= \frac{2 \times 220\sqrt{2}}{3.14} - 4 \times 50 \times 10 \times 10^{-3} \times 14$$

$$= 184.07\,V.$$

$$V_0 = \frac{V_m}{\pi}[1 + \cos\mu]$$

$$\Rightarrow 184.07 = \frac{220\sqrt{2}}{3.14}[1 + \cos\mu]$$

$$\Rightarrow 1 + \cos\mu = 184.07 \times \frac{3.14}{220\sqrt{2}}$$

$$\Rightarrow \mu = 44.2^\circ$$

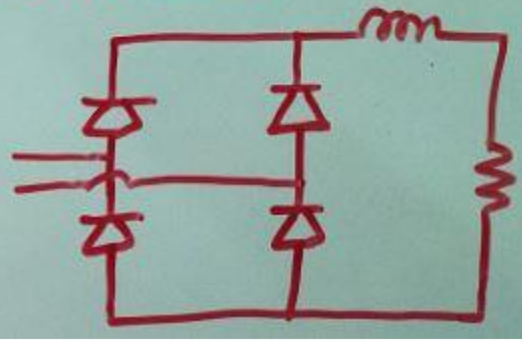
Conduction Angle of Diode "D_1",

$$= \gamma = 180 + \mu$$

$$= 180 + 44.2$$

$$= 224.2^\circ.$$

(9) When $\alpha = 0°$, $V_0 = 300V$. Assume CCM, the output voltage for a firing angle of $60°$ will be ——



$$V_0 = \frac{2V_m}{\pi} \cos\alpha \quad ; \alpha \neq 0$$

$$V_0 = \frac{2V_m}{\pi} \quad ; \alpha = 0$$

At $\alpha = 0^\circ$, $V_0 = 300V$

$$\Rightarrow \quad 300 = \frac{2V_m}{\pi} \longrightarrow ①$$

At $\alpha = 60^\circ$,

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

$$= 300 \cos(60^\circ)$$

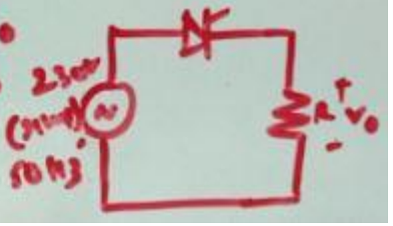
$$= 300 \times \frac{1}{2}$$

$$\Rightarrow V_0 = \underline{150V}$$

(10) The thyristor in the figure is fired at an angle of "α" in every +ve half cycle of the input voltage. If the peak value of the instantaneous output voltage equals 230V, then the firing angle "α" is close to —

(a) 45° (b) 135°

(c) 90° (d) 83.6°



Instantaneous value,

$$V_m \sin\alpha = 230$$

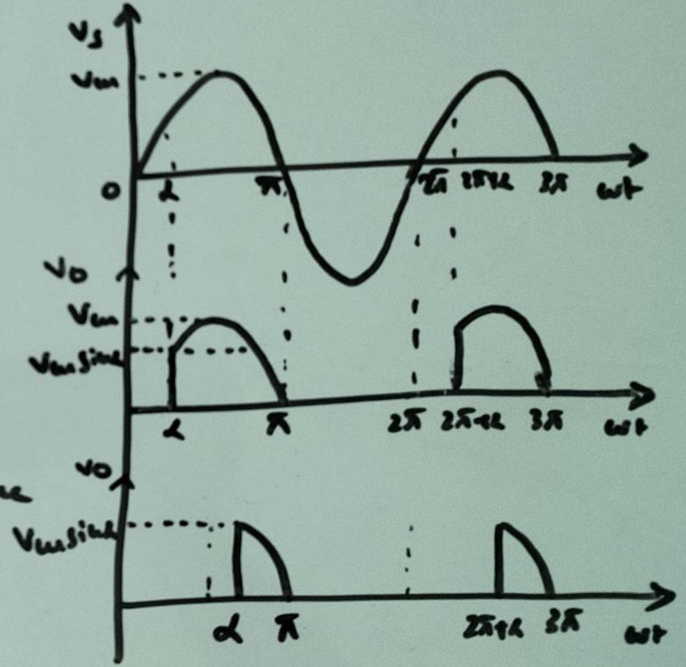
$$\Rightarrow 230\sqrt{2}\,\sin\alpha = 230$$

$$\Rightarrow \sin\alpha = \frac{1}{\sqrt{2}}$$

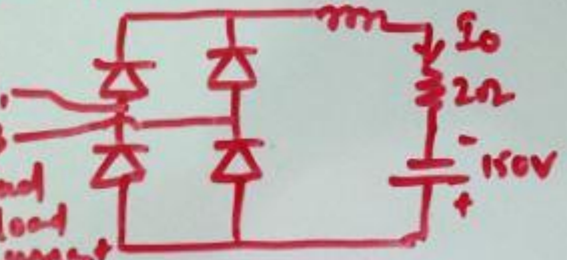
$$\Rightarrow \alpha = 45^\circ \text{ (or) } 135^\circ$$

If $\alpha \geq 90^\circ$, then the instantaneous output voltage will be the peak value

$$\Rightarrow \underline{\alpha = 135^\circ}$$



(11) The firing angle of the bridge for a load current of $I_0 = 10$ Amp is —



Continuous and ripple free load current

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

$$V_0 = 10\times 2 - 150$$

$$= -130V$$

$$\Rightarrow -130 = \frac{2\times 230\sqrt{2}}{3.14}\cos\alpha$$

$$\Rightarrow \cos\alpha = -0.6275$$

$$\Rightarrow \alpha = 128.86^\circ.$$

$\alpha < 90^\circ$; Converter Mode

(or)

Motoring Mode

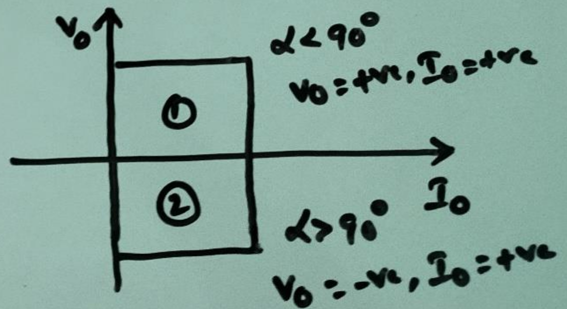
Source $\xrightarrow{\text{Power flow}}$ Load

$\alpha > 90^\circ$; Inverter Mode

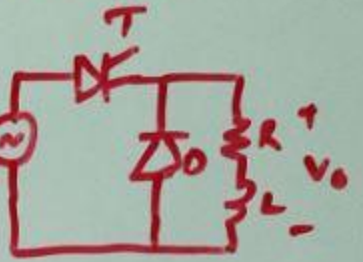
(or)

Breaking Mode

Load $\xrightarrow{\text{Power flow}}$ Source



(12) The thyristor firing angle (α) in degrees needed to obtain an average load voltage of 70V is ____



$V_s = 325 \sin(314t)$

$R = 10\Omega$,
$L = 0.05H$

$$V_0 = \frac{V_m}{2\pi}\left[1+\cos\alpha\right]$$

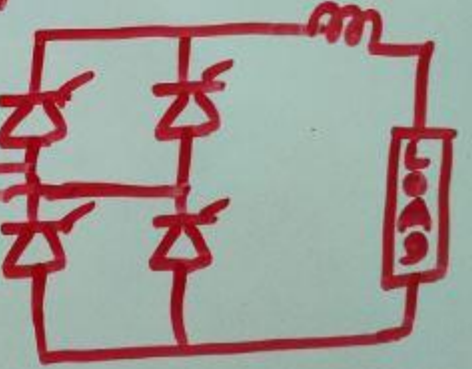
$$\Rightarrow 70 = \frac{325}{2\times 3.14}\left[1+\cos\alpha\right]$$

$$\Rightarrow 1+\cos\alpha = 1.3526$$

$$\Rightarrow \cos\alpha = 1.3526-1 = 0.3526$$

$$\Rightarrow \alpha = 69.35^\circ.$$

(14) A fully Controlled Converter bridge feeds a highly Inductive load with ripple free load Current. The Input Supply (v_s) to the bridge is a Sinusoidal Source. $\alpha = 30^\circ$. The Input power factor of the bridge is —



Input PF = CDF × FDF

$$= \frac{2\sqrt{2}}{\pi} \times \cos\phi_1$$

$$= 0.9 \times \cos\alpha$$

$$= 0.9 \times \cos(60^\circ)$$

$$= \underline{\underline{0.7794}}.$$

$$i_{sn}(t) = \sum_{n=1,3,5} \frac{4 \cdot I_0}{n\pi} \cdot \sin(n\omega t - n\alpha)$$

$$\cos\phi = \frac{I_{s1}}{I_s} \cdot \cos\phi_1 \quad ; \phi_n = -n\alpha$$

$$\phi_1 = -\alpha$$

$$= \frac{\frac{4 I_0}{\pi\sqrt{2}}}{I_0} \cdot \cos\phi_1$$

$$= \frac{4}{\pi\sqrt{2}} \times \frac{\sqrt{2}}{\sqrt{2}} \cdot \cos\phi_1$$

$$= \frac{2\sqrt{2}}{\pi} \cos\phi_1$$

$$\Rightarrow \cos\phi = \underline{\underline{0.9\cos\alpha}}$$

(15) A 1-φ fully-Controlled thyristor Converter is used to obtain an average voltage of 180V with 10 Amp Constant Current to feed a dc load. It is fed from 1-φ AC Supply of 230v, 50Hz. Neglect the Source Impedance. The power factor (round off to two decimal places) of AC mains is ____

$V_{avg} = V_0 = 180V$, $V_s = 230V$

For a 1-φ fully Controlled thyristor,

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

$$\Rightarrow 180 = \frac{2 \times 230\sqrt{2}}{\pi}\cos\alpha$$

$$\Rightarrow \cos\alpha = 0.869$$

$$\text{Input PF} = \frac{2\sqrt{2}}{\pi}\cos\alpha$$

$$= 0.9\cos\alpha$$

$$= 0.9 \times 0.869$$

$$= \underline{\underline{0.786 \text{ lag}}}$$

(16) A 1-ϕ, full-bridge diode rectifier fed from a 230V, 50Hz sinusoidal source supplies a series combination of finite resistance "R", and a very large inductance "L". The two most dominant frequency components in the source current are

(a) 50Hz, 0Hz (b) 50Hz, 100Hz

(c) 50Hz, 150Hz (d) 150Hz, 250Hz

$$I_{sn}(t) = \sum_{n=1,3,5..} \frac{4I_0}{n\pi} \sin(n\omega t - n\alpha)$$

for a diode bridge rectifier,

$$\alpha = 0$$

$$\Rightarrow I_{sn}(t) = \sum_{n=1,3,5..} \frac{4I_0}{n\pi} \sin(n\omega t)$$

Dominant frequencies,

$$n=1 \Rightarrow \frac{4I_0}{\pi}$$

$$n=3 \Rightarrow \frac{4I_0}{3\pi}$$

$$n=5 \Rightarrow \frac{4I_0}{5\pi}$$

$\Rightarrow f = 50Hz, 3\times50, 5\times50$

$\Rightarrow$ 50Hz, 150Hz, 250Hz

(17) A 1-φ, full bridge, fully controlled thyristor rectifier feeds a load comprising a low resistance in series with a very large inductance. The rectifier is fed from an ideal 230V, 50Hz sinusoidal source through cables which have negligible internal resistance and a total inductance of 2.28 mH. If the thyristors are triggered at an angle $\alpha = 45°$, the commutation overlap angle in degree (round off to 2 decimal places) is —

With "L_s",

$$V_0 = \frac{2V_m}{\pi}\cos\alpha - 4fL_sI_0$$

$$\Rightarrow I_0 \times R = \frac{2V_m}{\pi}\cos\alpha - 4fL_sI_0$$

$$\Rightarrow I_0 \times 10 = \frac{2 \times 230\sqrt{2} \times \cos 45}{\pi} - 4 \times 50 \times 2.28 \times 10^{-3} \times I_0$$

$$\Rightarrow I_0 = 14 \text{ Amp}$$

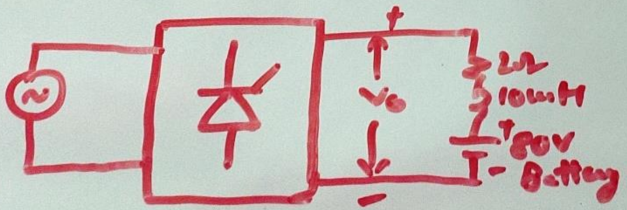
Voltage drop due to "L_s",

$$2\omega L_s I_0 = V_m[\cos\alpha - \cos(\alpha+\mu)]$$

$$\Rightarrow 14 = \frac{230\sqrt{2}}{2 \times 100\pi \times 2.28 \times 10^{-3}} \times [\cos 45 - \cos(45+\mu)]$$

$$\Rightarrow \mu = 4.8°$$

(18) A phase controlled 1-ϕ rectifier, supplied by an AC source, feeds power to an RLE load as shown in the figure. The rectifier output voltage has an average value given $V_0 = \frac{V_m}{2\pi}(3+\cos\alpha)$, where $V_m = 80\pi$ volts and "α" is the firing angle. If the power delivered to the lossless battery is 1600 W, "α" in degree is ___ (upto 2 decimal places)



Power transfers to the 80v battery,

$$E \cdot I_0 = 1600$$

$$\Rightarrow I_0 = \frac{1600}{80} = 20 \text{ Amp}$$

$$V_0 = I_0 R + E = 20 \times 2 + 80$$

$$= 120V$$

from the sum,

$$V_0 = \frac{V_m}{2\pi}(3+\cos\alpha), \quad V_m = 80\pi$$

$$\Rightarrow 120 = \frac{80\pi}{2\pi}(3+\cos\alpha)$$

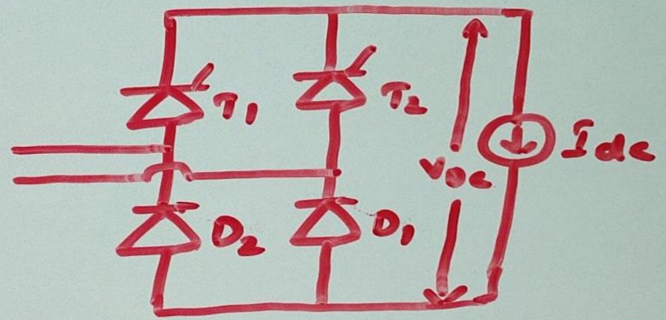
$$\Rightarrow \cos\alpha = \frac{120}{40} - 3 = 0$$

$$\Rightarrow \alpha = \cos^{-1}(0)$$

$$\Rightarrow \alpha = 90^\circ$$

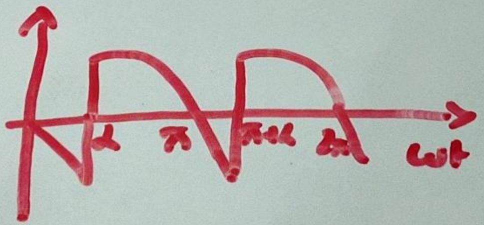
1-φ Semi Converters

(19) A half-Controlled 1-φ Converter is shown in below figure. $\alpha = 30^\circ$

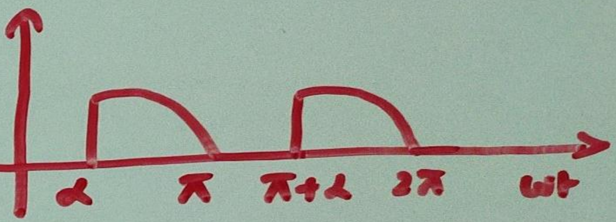


The output dc voltage wave shape will be as shown in

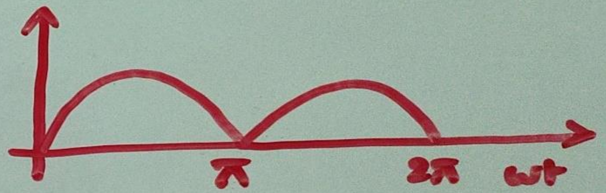
(a)



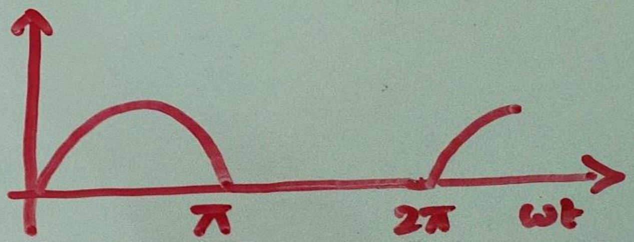
(b)



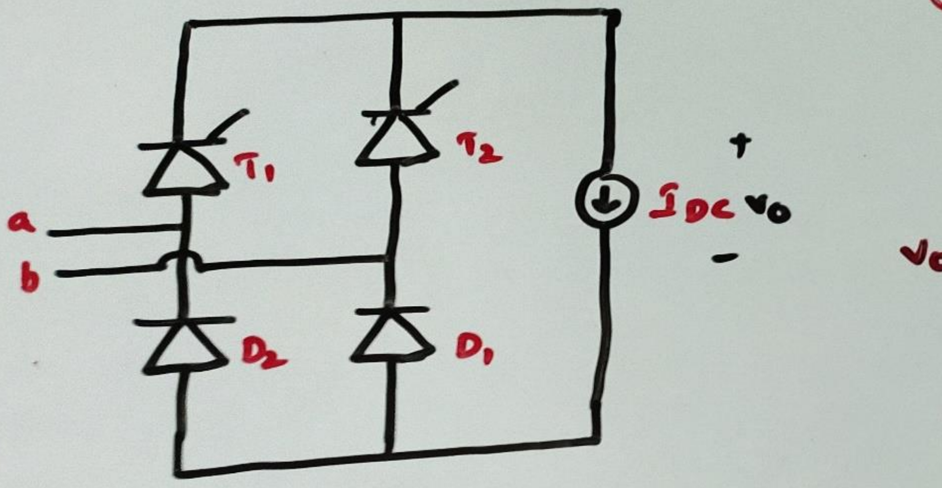
(c)

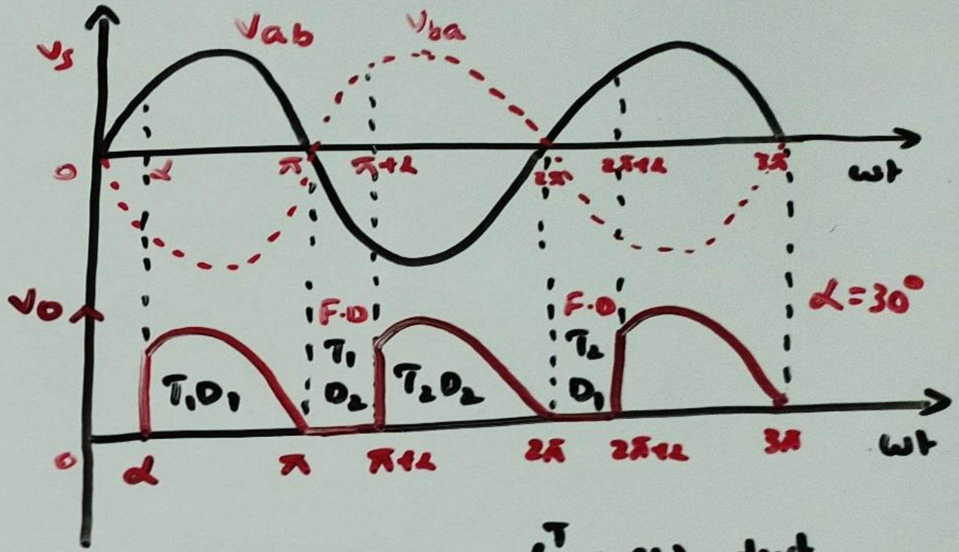


(d)



1-ϕ SemiConverter :-





PHC → $T_1 D_1$ conducts → $V_0 = V_{ab}$

NHC → $T_2 D_2$ conducts → $V_0 = -V_{ab}$

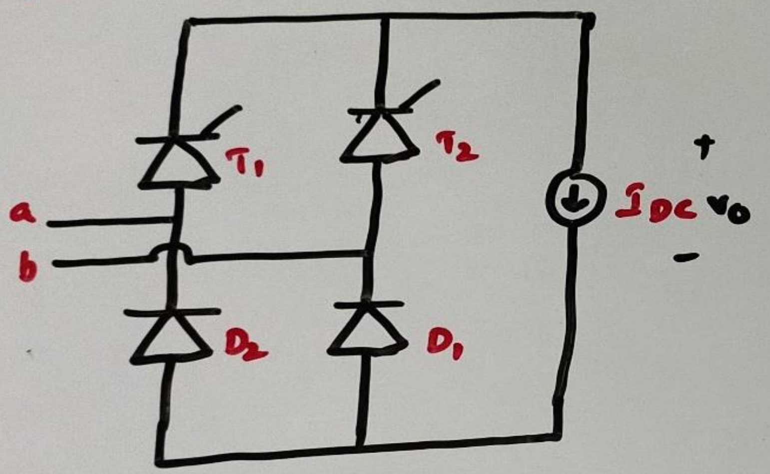
$$V_{0(avg)} = \frac{1}{T}\int_0^T V_0(t)\cdot d\omega t$$

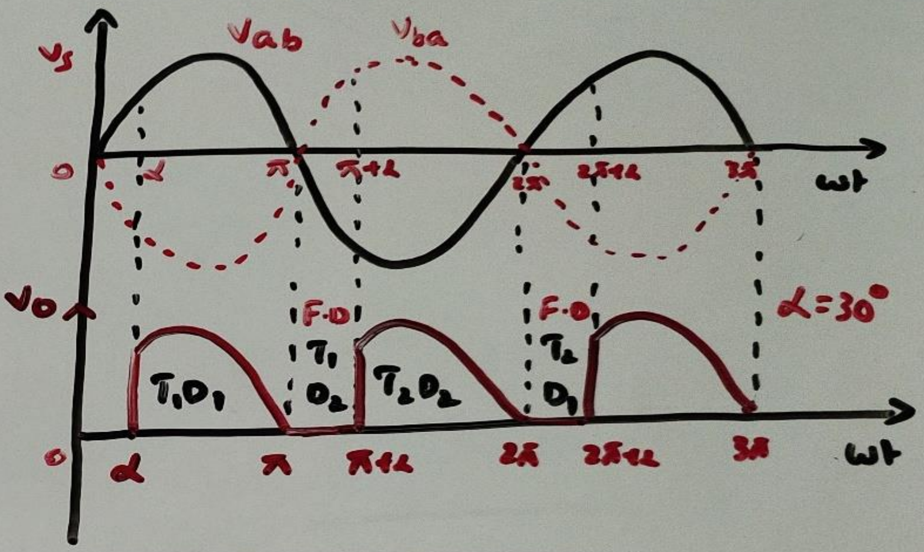
$$= \frac{1}{\pi}\left[\int_\alpha^\pi V_m \sin\omega t\cdot d\omega t\right]$$

$$= \frac{V_m}{\pi}\left[-\cos\omega t\right]_\alpha^\pi$$

$$= \boxed{V_{0(avg)} = \frac{V_m}{\pi}\left[1+\cos\alpha\right]}$$

1-ϕ Semiconverter :-





ωt	T_1	T_2	D_1	D_2	V_o
$0<\omega t<\alpha$	OFF	ON	ON	OFF	0(VFA)
$\alpha<\omega t<\pi$	ON	OFF	ON	OFF	V_{ab}
$\pi<\omega t<\pi+\alpha$	ON	OFF	OFF	ON	0(VFA)
$\pi+\alpha<\omega t<2\pi$	OFF	ON	OFF	ON	$-V_{ab}$

1-ϕ Semi Converters

(20) A half - Controlled 1-ϕ diode bridge rectifier is supplying an RL-load. It is operated at a firing angle "α" and the load Current is Continuous. The fraction of cycle that the free wheeling diode Conducts is

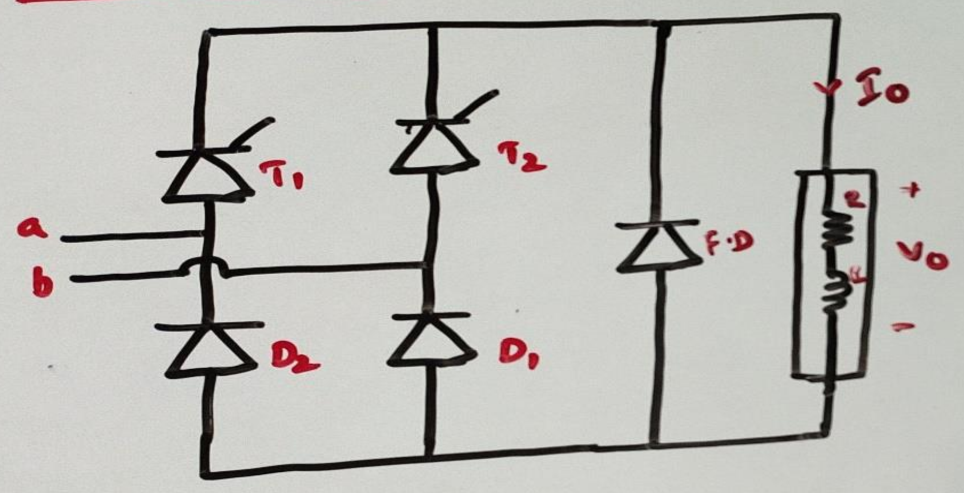
(a) $\frac{1}{2}$

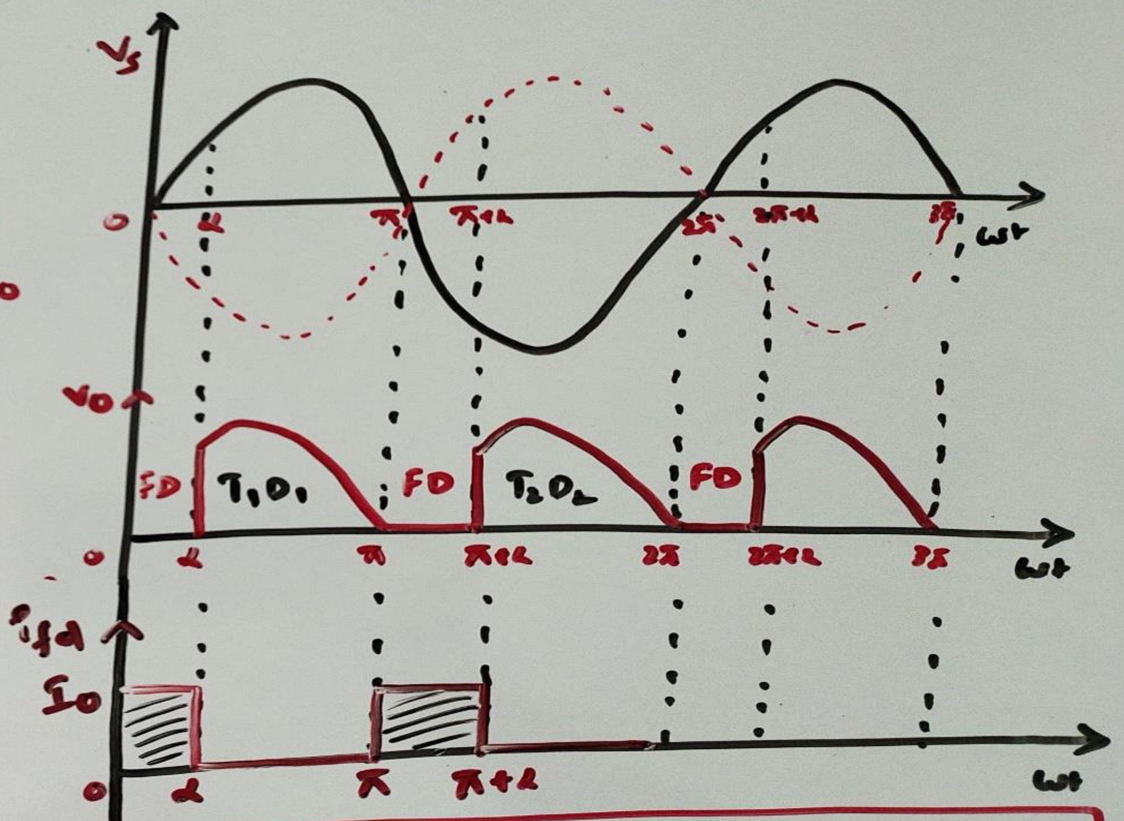
(b) $\left(\frac{1-\alpha}{\pi}\right)$

(c) $\frac{\alpha}{2\pi}$

(d) $\frac{\alpha}{\pi}$

1-ϕ Semi Converter :-





Time period of F.D. : π

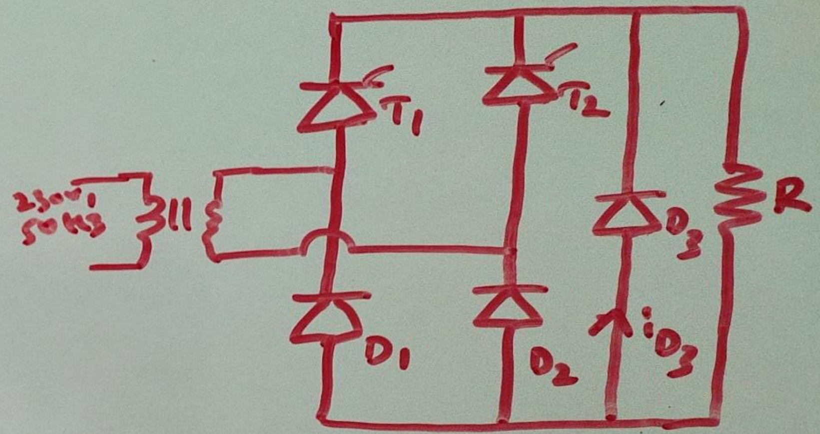
Fraction of cycle,

$$\delta = \frac{T_{ON}}{T} = \frac{\alpha}{\pi}$$

$$\boxed{\text{Circuit turn-off time, } t_c = \frac{\pi - \alpha}{\omega} \text{ sec}}$$

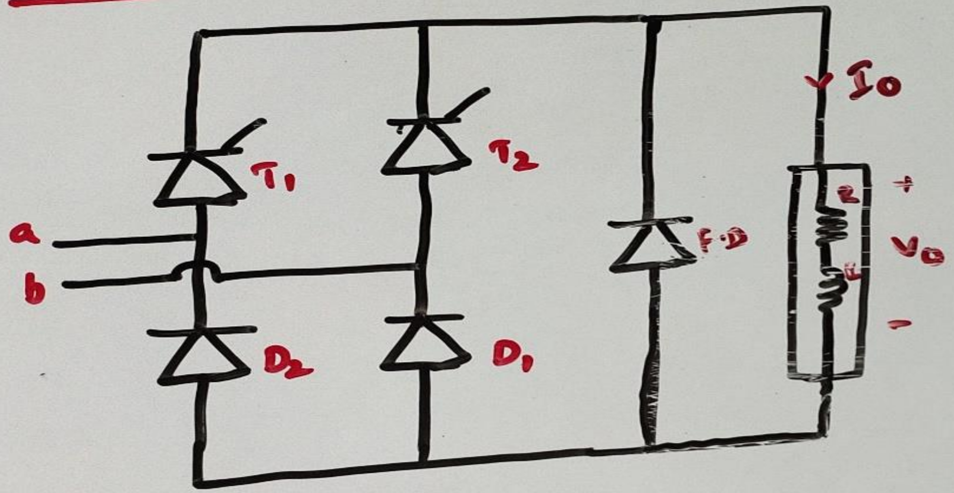
1-φ Semi Converters

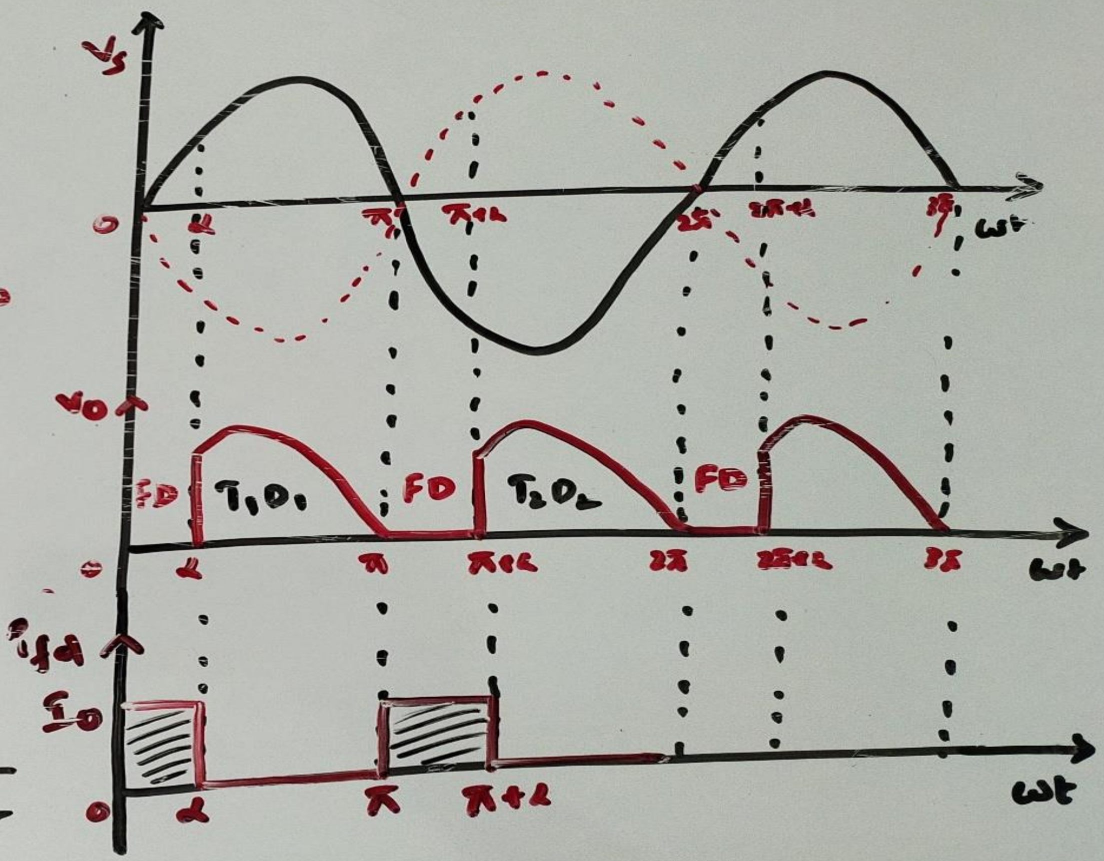
(21) The figure below shows the circuit diagram of a controlled rectifier supplied from a 230 V, 50 Hz, 1-φ voltage source and a 10 : 1 ideal transformer. Assume that all devices are ideal. The firing angles of the thyristors T_1 and T_2 are 90° and 270° respectively.



The RMS value of the current through diode "D_3" in amperes is —

1-ϕ Semiconverter :-





$$i_{fd\,(avg)} = \left(\frac{\text{Area}}{T}\right)$$

$$= \frac{\alpha \cdot I_0}{\pi}$$

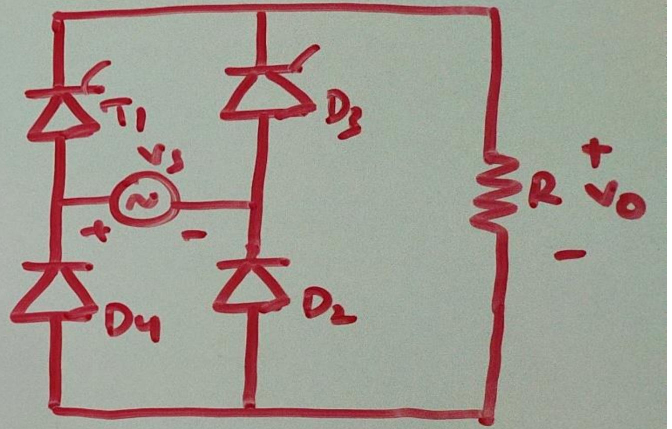
$$i_{fd\,(rms)} = \sqrt{\frac{1}{\pi}\int_0^{\alpha} I_0^2 \cdot d\omega t}$$

$$= \sqrt{I_0^2 \cdot \frac{\alpha}{\pi}} = I_0\sqrt{\frac{\alpha}{\pi}}$$

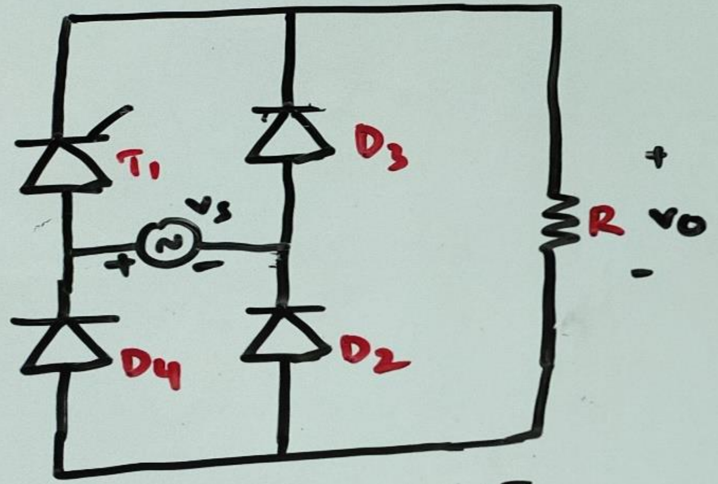
For a Resistive load, the RMS current through the Free wheeling diode is **0 Amp**.

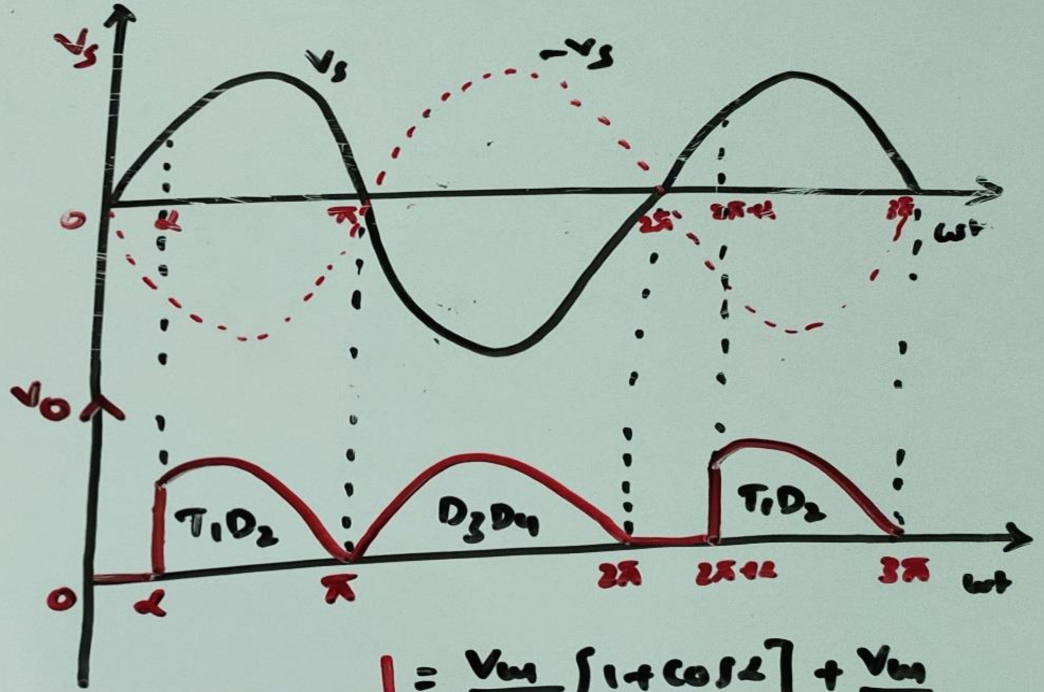
1-φ Semi Converters

(22) In the given rectifier, the delay angle of the thyristor "T_1" measured from the positive going zero crossing of V_s is 30°. If the input voltage V_s is $100 \sin(100\pi t)$ V, the average voltage across "R" (in volt) under steady-state is __



1-ϕ Semiconverter :-





$$V_{0(avg)} = \frac{1}{2\pi}\left[\int_{\alpha}^{\pi} V_m \sin\omega t \cdot d\omega t + \int_{\pi}^{2\pi} -V_m \sin\omega t \cdot d\omega t\right]$$

$$= \frac{V_m}{2\pi}\Big[-\cos\omega t\Big]_{\alpha}^{\pi} + \frac{V_m}{2\pi}\Big[\cos\omega t\Big]_{\pi}^{2\pi}$$

$$= \frac{V_m}{2\pi}\left[1+\cos\alpha\right] + \frac{V_m}{2\pi}\left[1+1\right]$$

$$= \frac{V_m}{2\pi}\left[1+\cos\alpha\right] + \frac{V_m}{\pi}$$

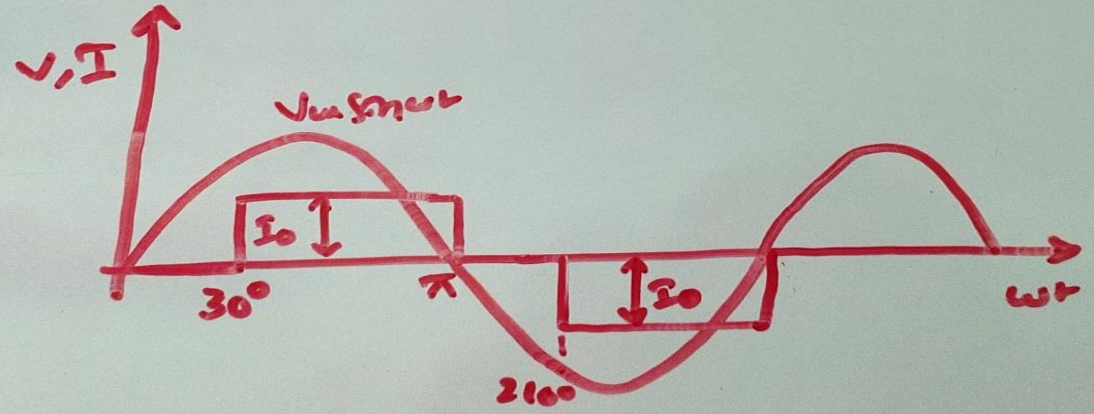
At $\alpha = 30^\circ$,

$$= \frac{100}{2\times 3.14}\left[1+\cos 30^\circ\right] + \frac{100}{3.14}$$

$$= 61.5\,V.$$

1-φ Semi Converters

(23) The waveform of the current drawn by a Semi-Converter from a Sinusoidal AC voltage Source is shown in the figure. If $I_0 = 20$ Amp, the rms value of fundamental component of the current is ___ Amp (upto 2 decimal places)



$$I_{sn}(t) = \sum_{n=1,3,5\ldots}^{\infty} \frac{4I_0}{n\pi} \cos\left(\frac{n\alpha}{2}\right) \cdot \sin\left(n\omega t - \frac{n\alpha}{2}\right)$$

$$I_{1(rms)} = \frac{\frac{4I_0}{\pi} \times \cos\left(\frac{\alpha}{2}\right)}{\sqrt{2}}$$

$$= \frac{4 \times 20}{\pi\sqrt{2}} \times \cos(15^\circ)$$

$$= \underline{\underline{17.39 \text{ Amp}}}$$

① A 3-ϕ diode bridge rectifier is feeding a constant dc current of 100 Amp to a highly inductive load. If 3-ϕ, 415V, 50Hz ac source is supplying to this bridge rectifier, then the rms value of the current in each diode in ampere, is ____

In a 3-ϕ full wave Controlled Converter at $\alpha = 0°$ (or) 3-ϕ full wave uncontrolled rectifier,

1. Each SCR Conducts for 120°
2. Each SCR pair Conducts for 60°
3. Each phase Conducts for 240°
4. Average value of thyristor Current, $I_{o(avg)} = \frac{I_o}{3}$ Amp
5. Average value of Source Current, $I_{s(avg)} = 0$ Amp
6. RMS value of thyristor Current, $I_{o(rms)} = \frac{I_o}{\sqrt{3}}$ Amp
7. RMS value of Source Current, $I_{s(rms)} = I_o \sqrt{\frac{2}{3}}$
8. In a 3-ϕ fully Controlled Converter (RL/RLE load), with Continuous Conduction and Constant Current,

$$V_{o(avg)} = \frac{3 V_{mL}}{\pi} \cos\alpha$$

$$V_{mL} = \sqrt{2} V_{rms}$$

9. $\alpha < 90° \rightarrow$ Motoring mode
10. $\alpha > 90° \rightarrow$ Inverting mode ($V_o = -V_c$)

In a 3-φ full wave controlled converter at $\alpha = 0°$ (or) 3-φ full wave uncontrolled rectification,

(11) $i_{sn}(t) = \sum_{n=1,3,5..} \frac{4 I_0}{n\pi} \sin\left(\frac{n\pi}{3}\right) \sin(n\omega t - n\alpha)$

I_{sr_1} = Fundamental rms current

$$\Rightarrow I_{sr_1} = \frac{\frac{4 I_0}{\pi} \sin\left(\frac{\pi}{3}\right)}{\sqrt{2}} \quad ; n = 1$$

(12) Current distortion factor, $CDF = \frac{I_{sr_1}}{I_{sr}}$

$$I_{sr} = I_{s(rms)} = I_0 \times \sqrt{\frac{2}{3}}$$

(13) Distortion factor,

$$DF = \cos\alpha$$

(14) Input power factor (or) Supply power factor,

$$= CDF \times DF$$

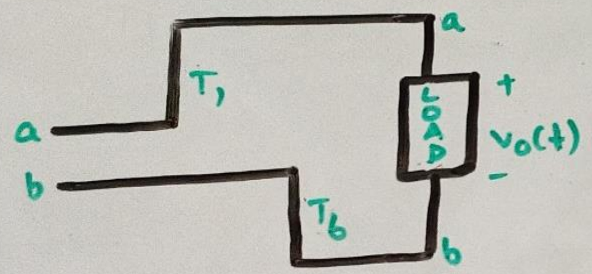
(15) The ripple frequency at the output,

$$f_0(\text{ripple}) = n \cdot f_s$$

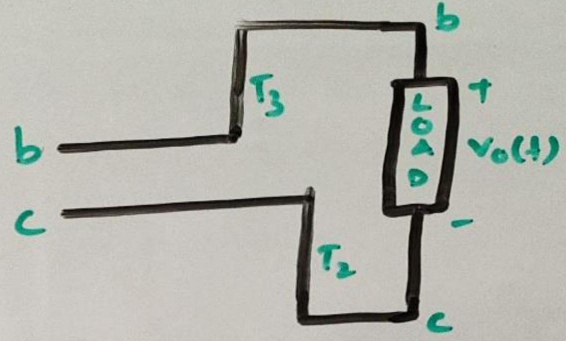
f_s = Supply frequency

Three phase Rectifiers

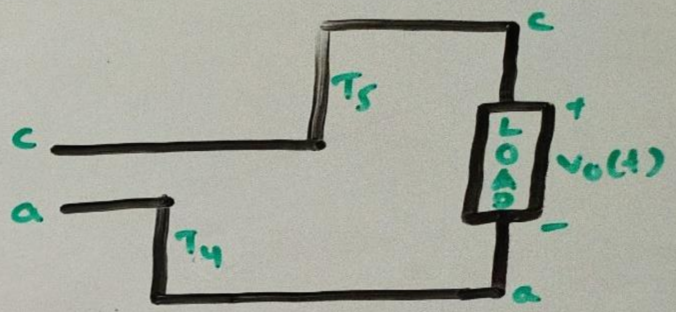
3-φ Fully Controlled Bridge Rectifier :-



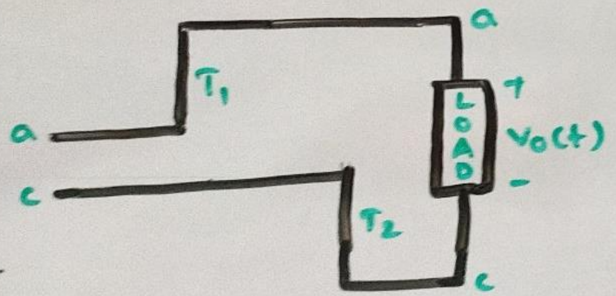
$V_o(t) = V_{ab}$



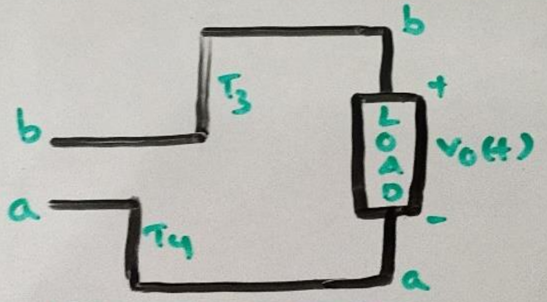
$V_o(t) = V_{bc}$



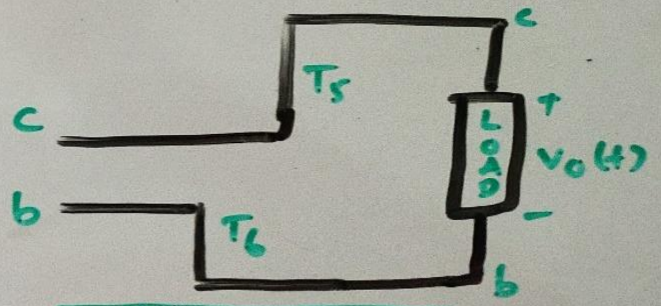
$V_o(t) = V_{ca}$



$V_o(t) = V_{ac}$

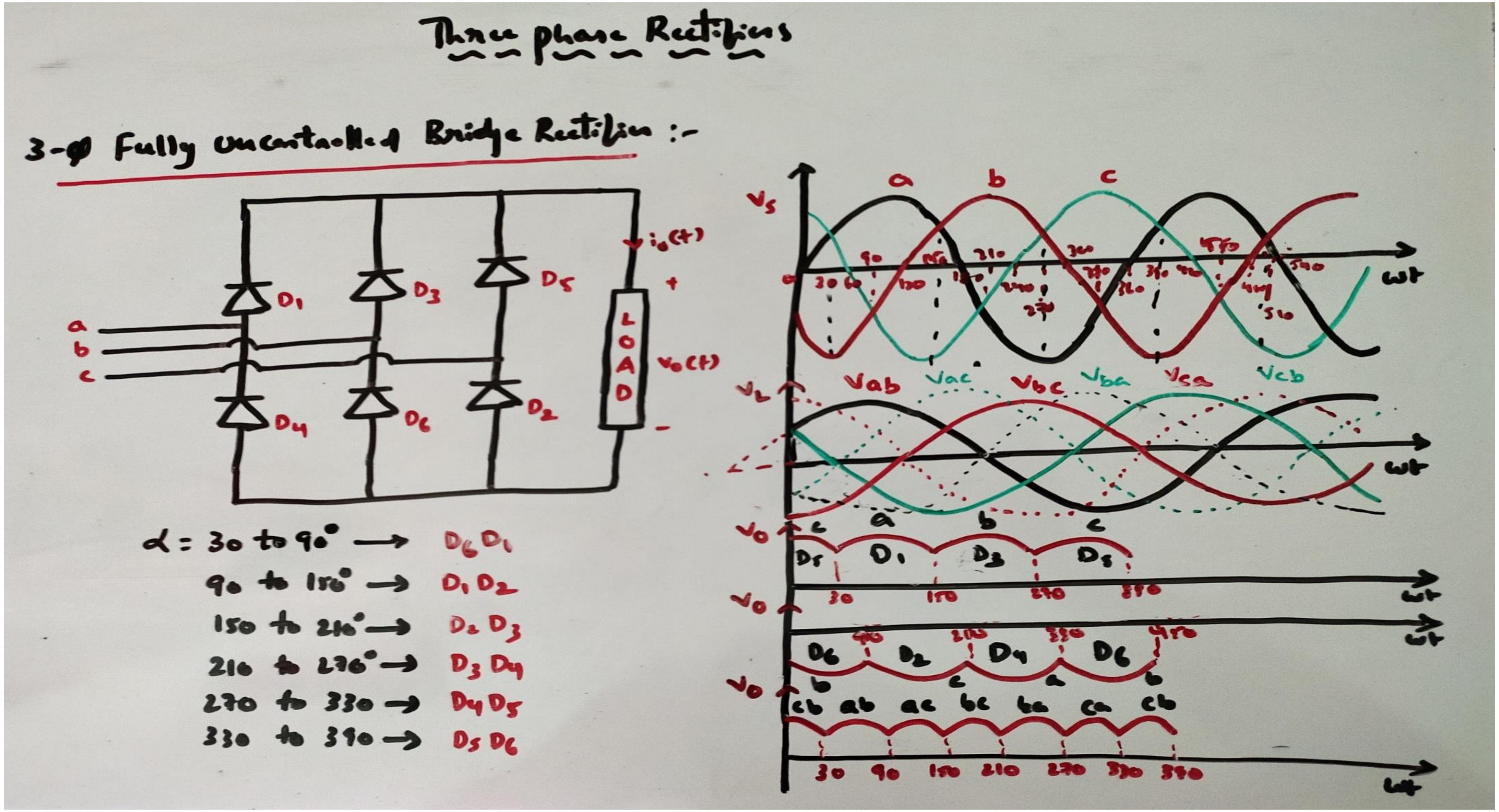


$V_o(t) = V_{ba}$

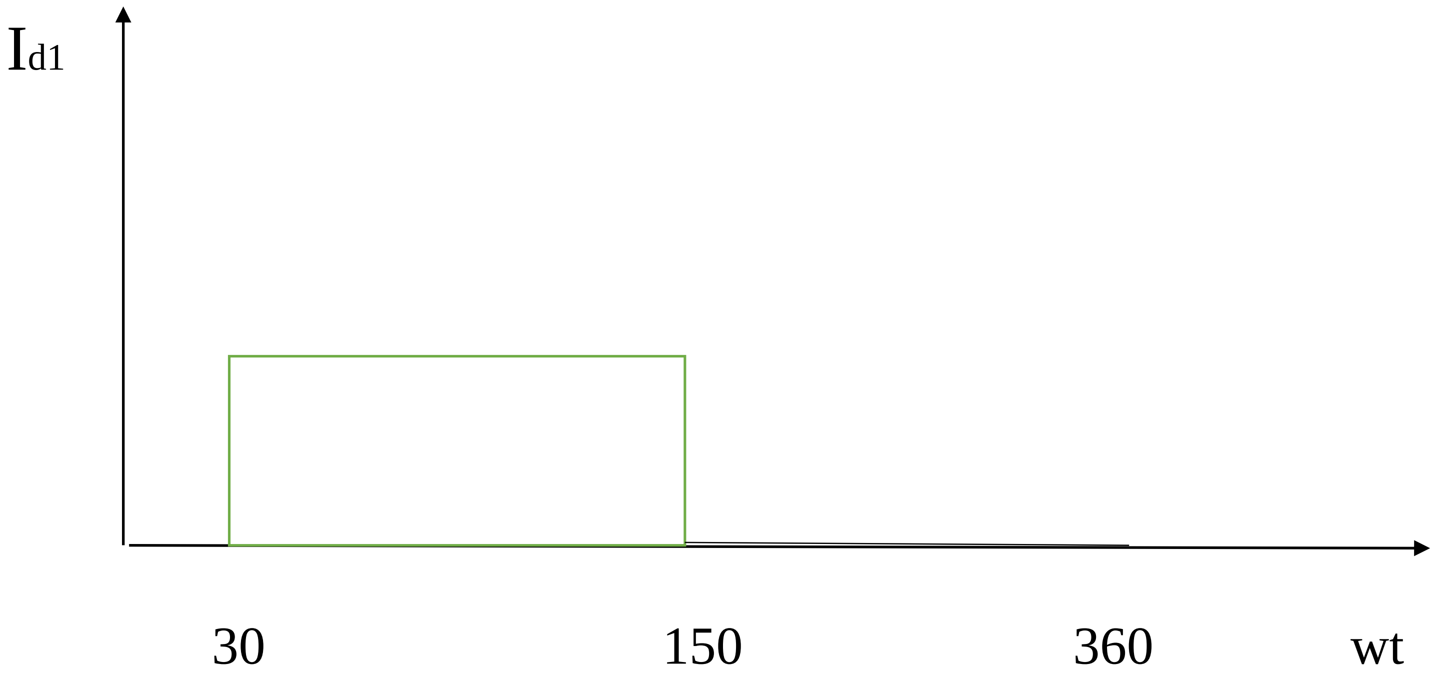


$V_o(t) = V_{cb}$

Three Phase Fully Uncontrolled Bridge Rectifier



- Each SCR conducts for 120 degree
- Each SCR pair conducts for 60 degree
- Each Phase conducts for 240 degree
- Average value of Thyristor current, I_o(Avg)=Peak value*(120/360)= I_o/3 Amperes
- RMS value of Thyristor current, I_o(rms)=Peak value*Sqrt(120/360)=I_o/sqrt(3) Amperes
- Average value of Source current, I_s(Avg)= 0 Amperes
- RMS value of Source current, I_s(rms)=I_o*sqrt(120/180)= I_o*sqrt(2/3) Amperes



Id1
30
150
360
wt

- Average value of Thyristor current, $\mathbf{I_o(Avg)}$=Peak value*(120/360)

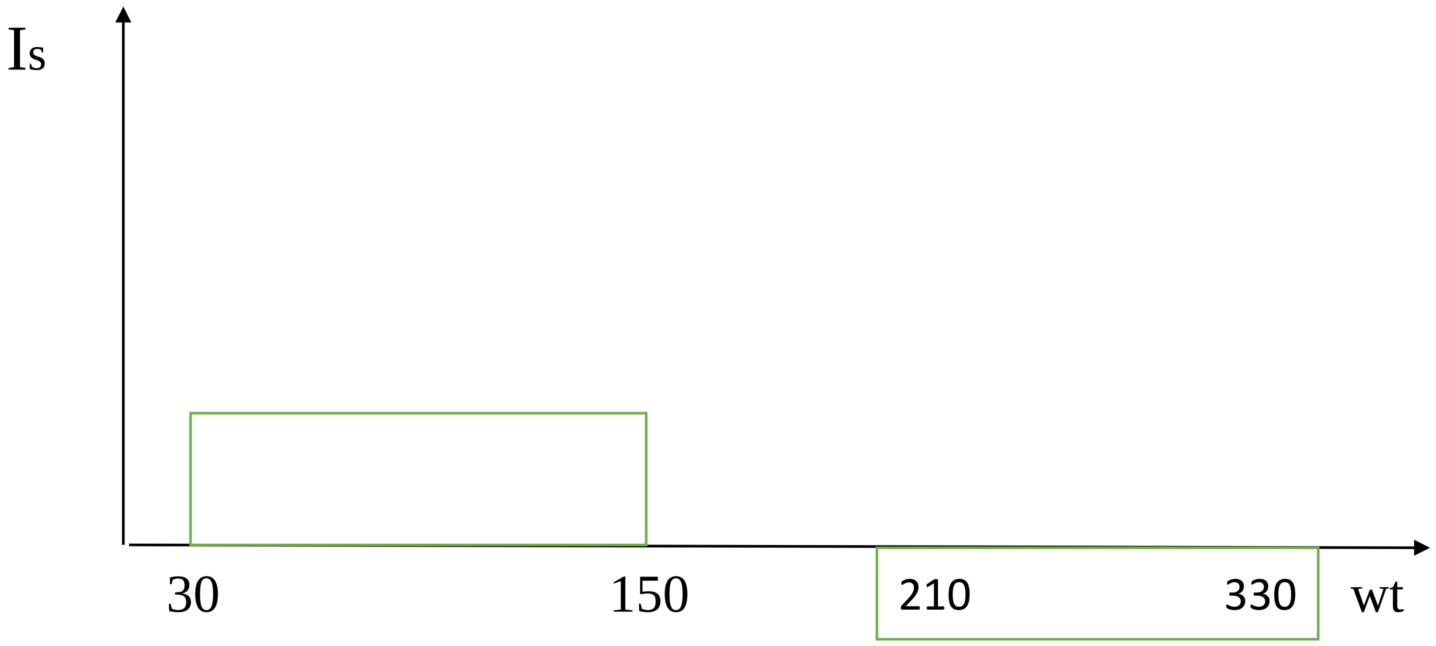
  = $\mathbf{I_o/3}$ **Amp** =

  = 100/3 = 33.33 **Amp**

- RMS value of Thyristor current, $\mathbf{I_o(rms)}$=Peak value*Sqrt (120/360)

  =$\mathbf{I_o/\sqrt{3}}$ **Amp**

  = 100/$\sqrt{\mathbf{3}}$ **= 57.73 Amp**


Is
30
150
210
330
wt

- Average value of Source current, **$I_{s(Avg)}$= 0 Amp**

The wave is a symmetrical waveform. The average value will be equal to Zero.

- RMS value of Source current, $\mathbf{I_{s(rms)}} = \mathbf{I_o} * \sqrt{(\mathbf{120}/\mathbf{180})}$

$= \mathbf{I_o} * \sqrt{(\mathbf{2}/\mathbf{3})}$ **Amp**

$= 100 * \sqrt{(\mathbf{2}/\mathbf{3})}$ Amp.

(2) A 3-ϕ fully controlled thyristor bridge converter is used as line commutated inverter to feed 50kw power, 420v dc to a 3-ϕ, 415v (line), 50 Hz ac mains. Consider dc link current to be constant, The rms current of the thyristor is ___

P output = 50 kw= 50*1000 watts

Output voltage = 420 v

$P_O = V_O * I_o$

$50 * 1000 = 420 * I_o$

I_o= (50*1000)/420 = 119.05 Amps

$I_{T(rms)}$= I_o*(1/sqrt(3)) = (119.05)/1.732 = 68.73 Amps.

$I_{T(Avg)}$= I_o/3 = 119.05/3= 39.68 Amps

I_o= (50*1000)/420 = 119.05 Amps

$I_{T(rms)}$= I_o*(1/sqrt(3)) = (119.05)/1.732 = 68.73 Amps.

$I_{T(Avg)}$= I_o/3 = 119.05/3= 39.68 Amps

$I_s(Avg)$ = 0 Amps

$I_{s(rms)}$ = I_o*sqrt(2/3)= 119.05*(1.414/1.732) = 97.19 Amps

For a Three Phase fully controlled Thyristor bridge converter (R, RL/RLE load) with continuous conduction and constant current,

$$Vo(avg) = \frac{3*Vml}{\pi}\cos\alpha$$

$$= \frac{3*\sqrt{2}*Vl(rms)}{\pi}\cos\alpha$$

$$= \frac{3*\sqrt{2}*\sqrt{3}*Vph}{\pi}\cos\alpha$$

$$= \frac{3*\sqrt{2}*\sqrt{3}*Vmp}{\sqrt{2}*\pi}\cos\alpha$$

$$= \frac{3*\sqrt{3}*Vmp}{\pi}\cos\alpha$$

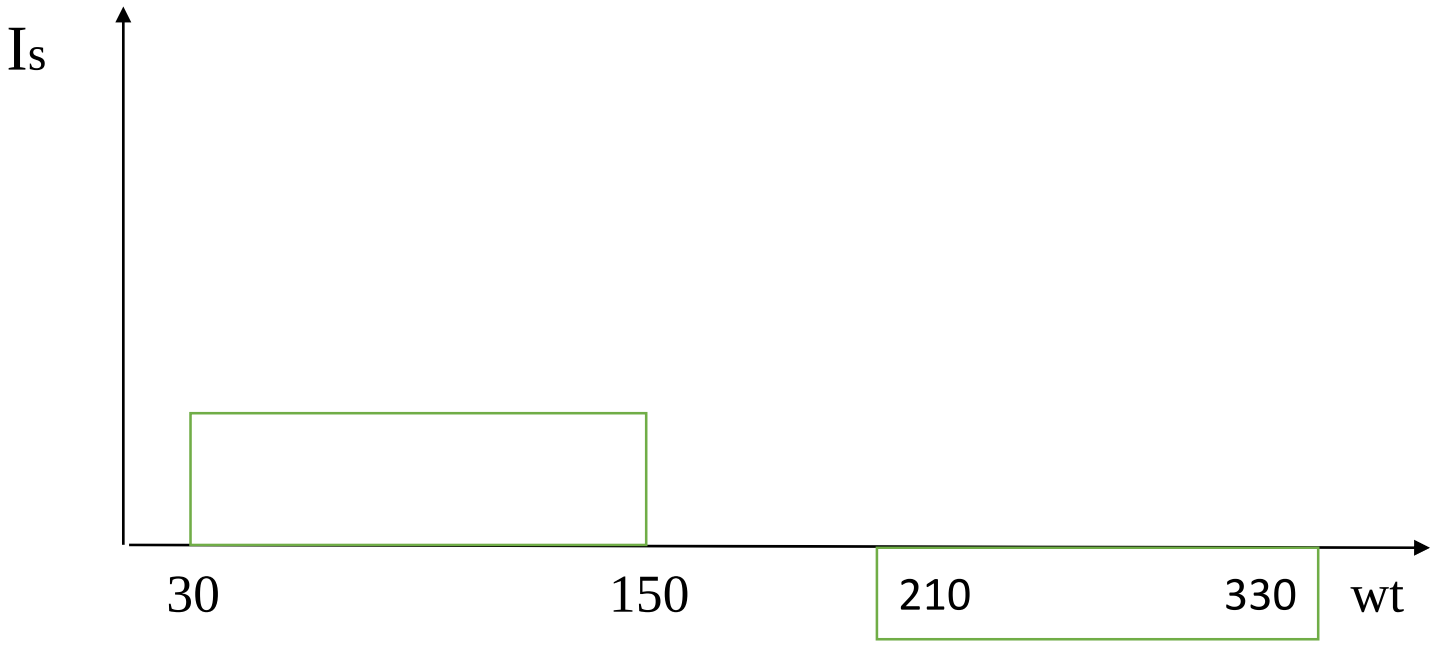
In the given sum, it is a line commutated inverter

i.e., α=90° and Vo = Negative = -420 V

$$Vo(avg) = \frac{3*Vml}{\pi}\cos\alpha$$

$$= -420 = \frac{3*415*\sqrt{2}}{3.14}\cos\alpha$$

$$= \alpha = -138.5^{o}$$


Is
30
150
210
330
wt

$$i_{sn}(t) = \sum_{n=1,3,5..} \frac{4*I_o}{n\pi} * \sin(\frac{n\pi}{3}) * \sin(nwt - n\alpha)....(1)$$

$$i_{sn}(t) = \sum_{n=1,3,5..} \frac{4*I_o}{n\pi} * \sin(\frac{n\pi}{3}) * \sin(nwt)....(2)$$

Equation (1) represents the fourier series representation for a controlled rectifier and Equation(2) represents the the fourier series representation for a Unontrolled rectifier

$$I_{sr1} = \frac{\frac{4 * I_o}{\pi} * \sin(\frac{\pi}{3})}{\sqrt{2}}$$

Isr1= Fundemental RMS source current

$$= I_{sr1} = \frac{4 * \frac{\sqrt{3}}{2} * I_o}{\pi * \sqrt{2}} = \frac{2 * \sqrt{3} * I_o}{\pi * \sqrt{2}} * \frac{\sqrt{2}}{\sqrt{2}}$$

$$= I_{sr1} = \frac{\sqrt{6}}{\pi} * I_o Amp = \frac{\sqrt{6}}{\pi} *119.05 = \frac{2.4494}{3.14} *119.05 = 92.82 Amp$$

Current Distortion Factor,

$$CDF = \frac{I_{sr1}}{I_{sr}}$$

$$where$$

$$I_{sr} = I_{s(rms)} = I_o * \sqrt{\frac{2}{3}} = 119.05 * \sqrt{\frac{2}{3}} = 97.19\,Amp$$

$$CDF = \frac{92.82}{97.19} = 0.95$$

Distortion Factor,

$$DF = \cos\alpha$$

$$= DF = \cos(-138.5)$$

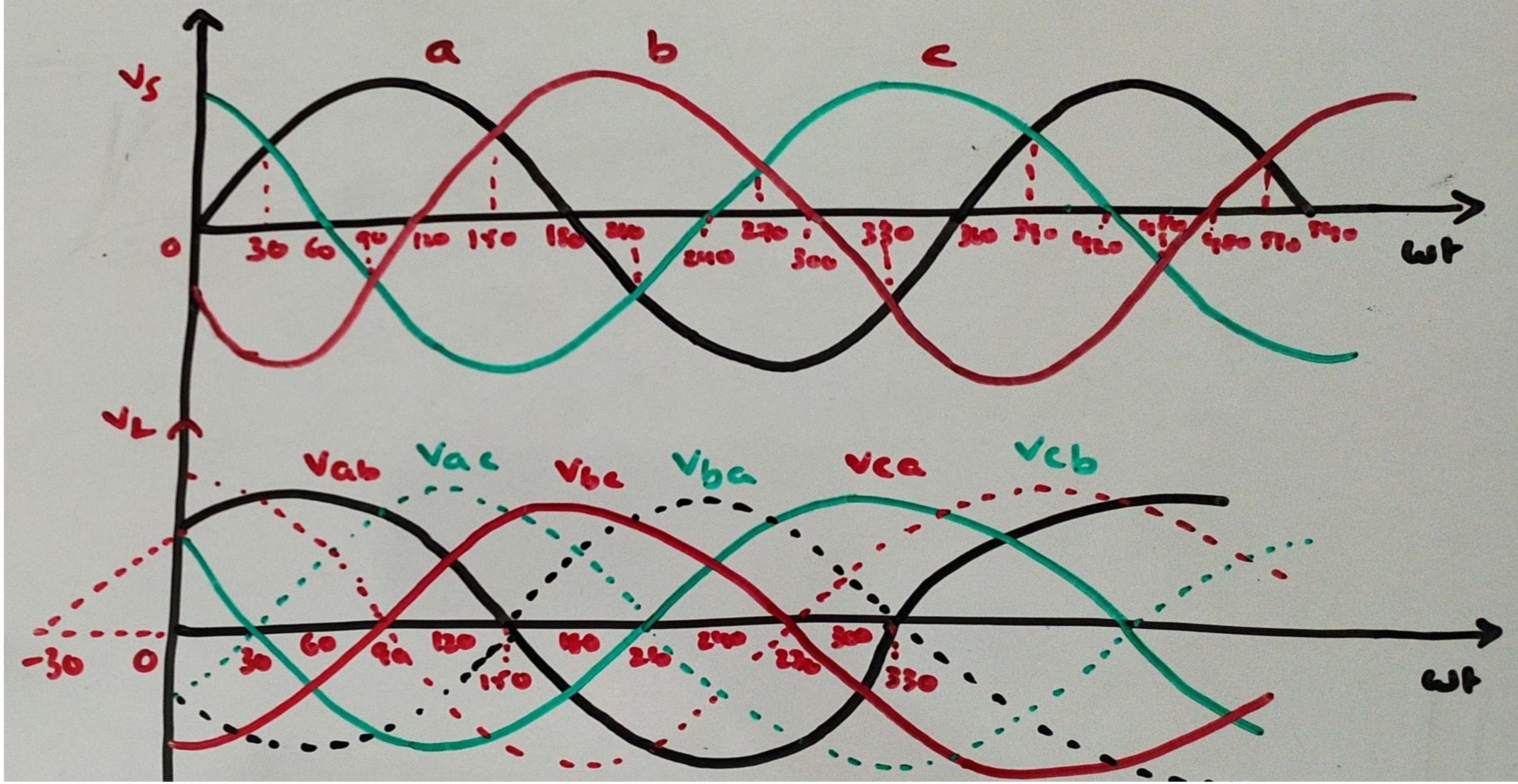
$$= 0.7489$$

Input Power Factor or Supply Power Factor = CDF*DF

= 0.95*0.7489

= **0.7114**

(3) A 3-ϕ diode bridge rectifier is fed from a 400 V rms, 50 Hz, 3-ϕ ac source, If the load is purely resistive, then the peak instantaneous output voltage is equal to ___



Vs
a
b
c
0
30
60
90
120
150
180
210
240
270
300
330
360
390
420
480
510
540
wt
VL
Vab
Vac
Vbc
Vba
Vca
Vcb
-30
0
30
60
90
120
150
180
210
240
270
300
330
wt

$$V_{ab}(t) = V_{ml} * \sin(wt + 30)$$

(Refer waveforms)

The peak instantaneous output voltage can be obtained when **wt= 60°**

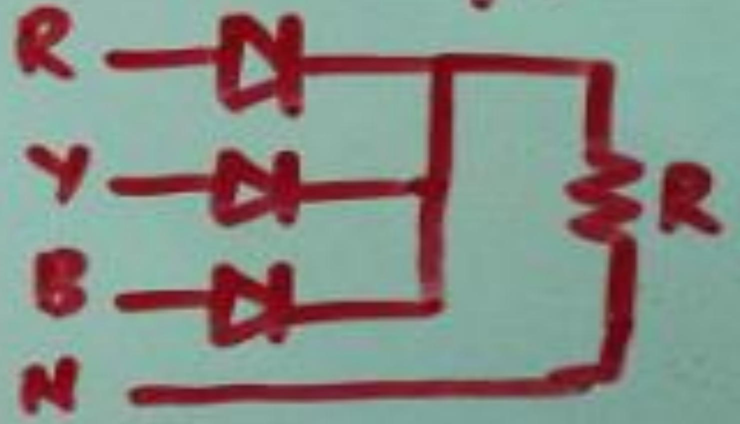
Vml= Maximum line voltage

At **wt = 60°**,

$$V_{ab}(t) = V_{ml} * \sin(60 + 30) = V_{ml} * \sin(90) = V_{ml}$$

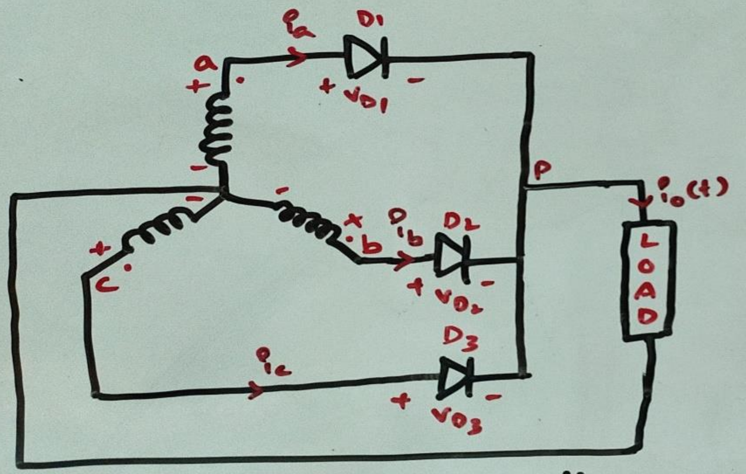
$$V_{ml} = \sqrt{2} * V_{rms} = 400\sqrt{2}V$$

(4) The Circuit shown is a 3-ϕ half-wave rectifier. The Source is a symmetrical, 3-ϕ, 4-wire System. The line to line voltage of the Source is 100V. The supply frequency is 400Hz. The ripple frequency at the output is ___

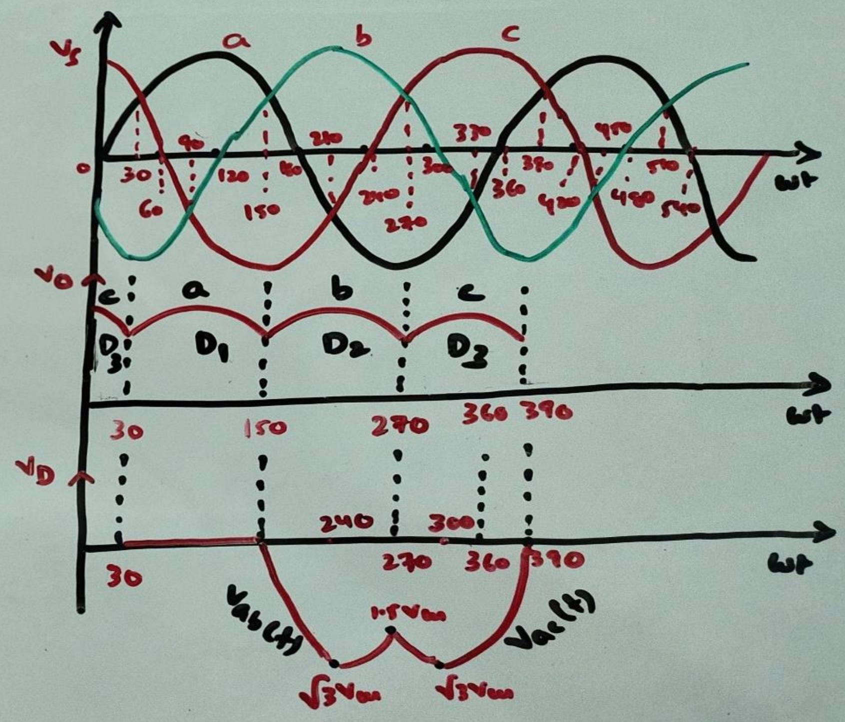


Three phase Rectifiers

3-Φ Half wave Uncontrolled Rectifier:-



Common Cathode Connection



Number of pulses in a cycle = 3

The ripple frequency at the output = $f_o = n*f_s$

Where $f_s = 400$ Hz

$f_o = 3*400 = 1200$ Hz.

Number of pulses in a cycle = 3

Output Time period, $T_o = (2*pi)/n=(2*pi)/3$

Supply Time period, $T= 2*pi$

$T_o/T=1/3$

$T_o= T/3$ $f=1/T$ $f_o=3/T=3*fs=3*400=1200$ Hz

⑤ A fully-Controlled 3-φ bridge Converter is working from a 415V, 50Hz ac supply. It is supplying constant current of 100 Amp at 400V to DC load. Assume large inductive smoothing and neglect overlap. The rms value of the AC line current in Amperes (round off to two decimal place) is—

$I_0 = 100$ Amp

For a fully controlled 3-φ bridge Converter,

$$I_{s(rms)} = I_0 \times \sqrt{\frac{2}{3}}$$

$$= 100 \times \sqrt{\frac{2}{3}}$$

$$= 81.65 \text{ Amp}$$

(6) A Six pulse thyristor bridge rectifier is connected to a balanced 3-ϕ, 50 Hz ac source. Assuming that the dc output current of the rectifier is constant, the lowest harmonic component in the AC input current is

(a) 300 Hz (b) 250 Hz

(c) 150 Hz (d) 100 Hz

$$i_{sn}(t) = \sum_{n=1,3,5} \frac{4 I_0}{n\pi} \cdot \sin\left(\frac{n\pi}{3}\right) \cdot \sin(n\omega t - n\alpha)$$

$n = 1 \longrightarrow$ Fundamental

$n = 3 \Rightarrow i_{sn}(t) = 0$

$n = 5 \Rightarrow i_{sn}(t)$ have some Value

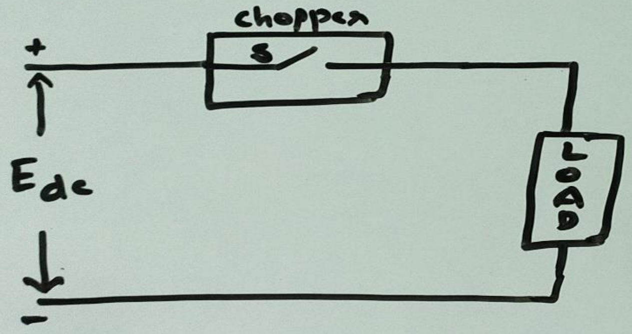
Lowest harmonic component in the AC Input current is,

$5 \times 50 = \underline{\underline{250\ Hz}}$

DC-DC Converters

DC-DC power Converters

① A dc chopper is a static device (switch) used to obtain variable dc voltage from a source of constant dc voltage.



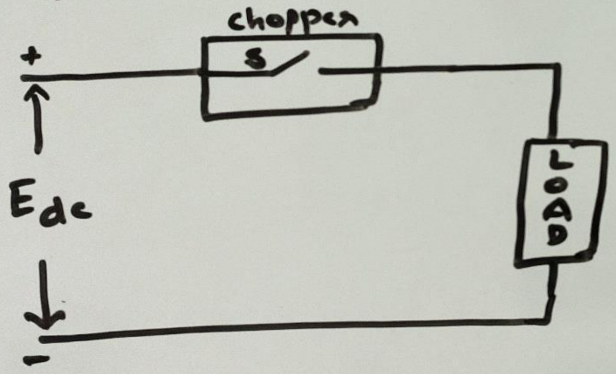
② Therefore chopper may be called as dc equivalent of ac Transformer.

③ Besides, the saving in power, the dc chopper offers greater efficiency, faster response, lower maintainance, small size, smooth control and for many applications, lower cost than Motor-Generator sets (or) Gas tubes approaches.

DC-DC Converters

DC-DC power Converters

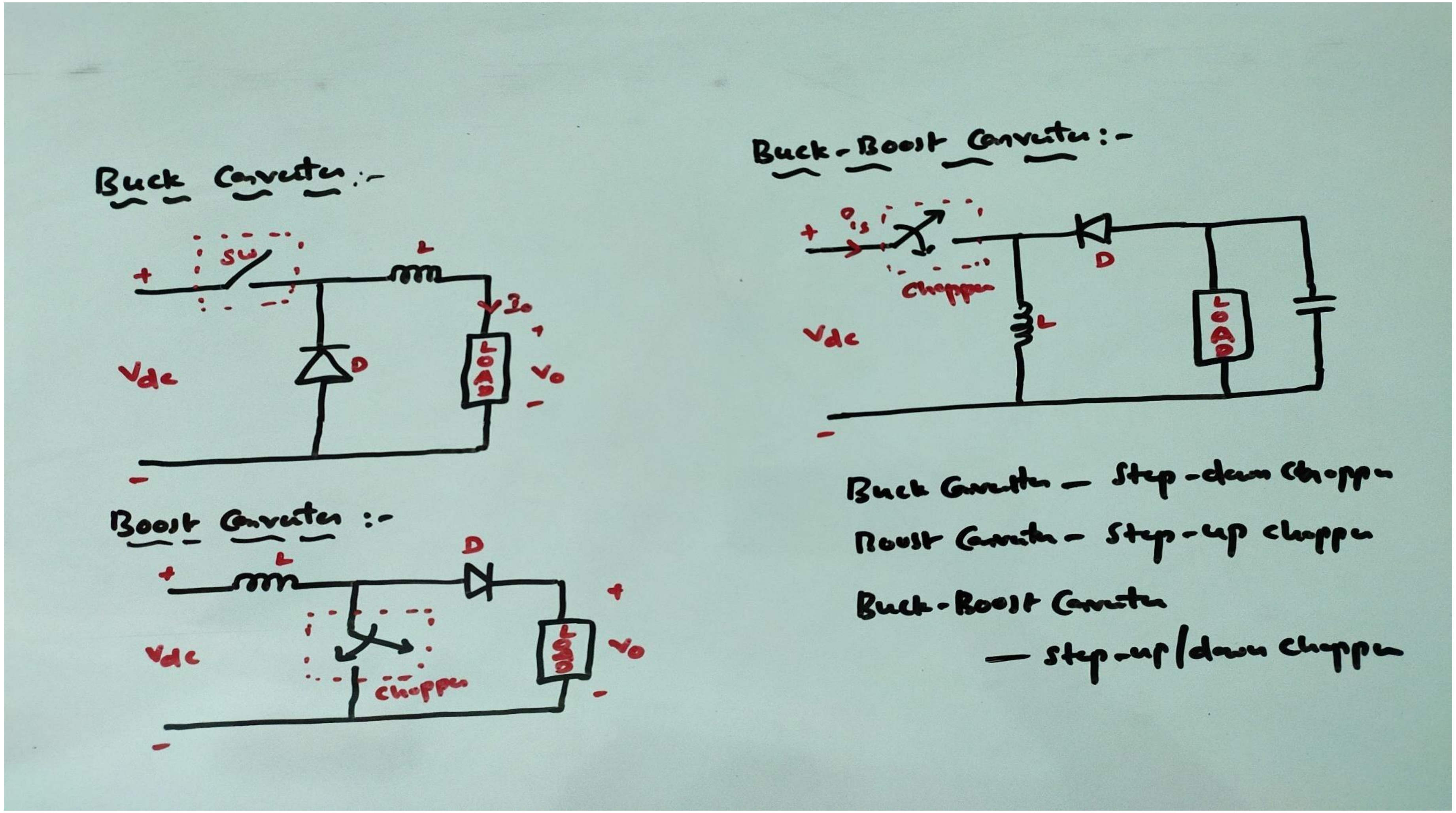
A dc chopper is a static device (switch) used to obtain variable dc voltage from a source of constant dc voltage.



Applications :-

1. Trolly cars
2. Battery operated vehicles
3. Traction-Motor control
4. Control of dc motors from a common bus
5. Control of Induction motors
6. Marine hoists
7. Fork lift trucks
8. Mine haulers

DC-DC Converters



DC-DC Converters

Control Strategies :-

The average value of the output voltage, "V_0" can be controlled by periodic opening and closing of the switches.

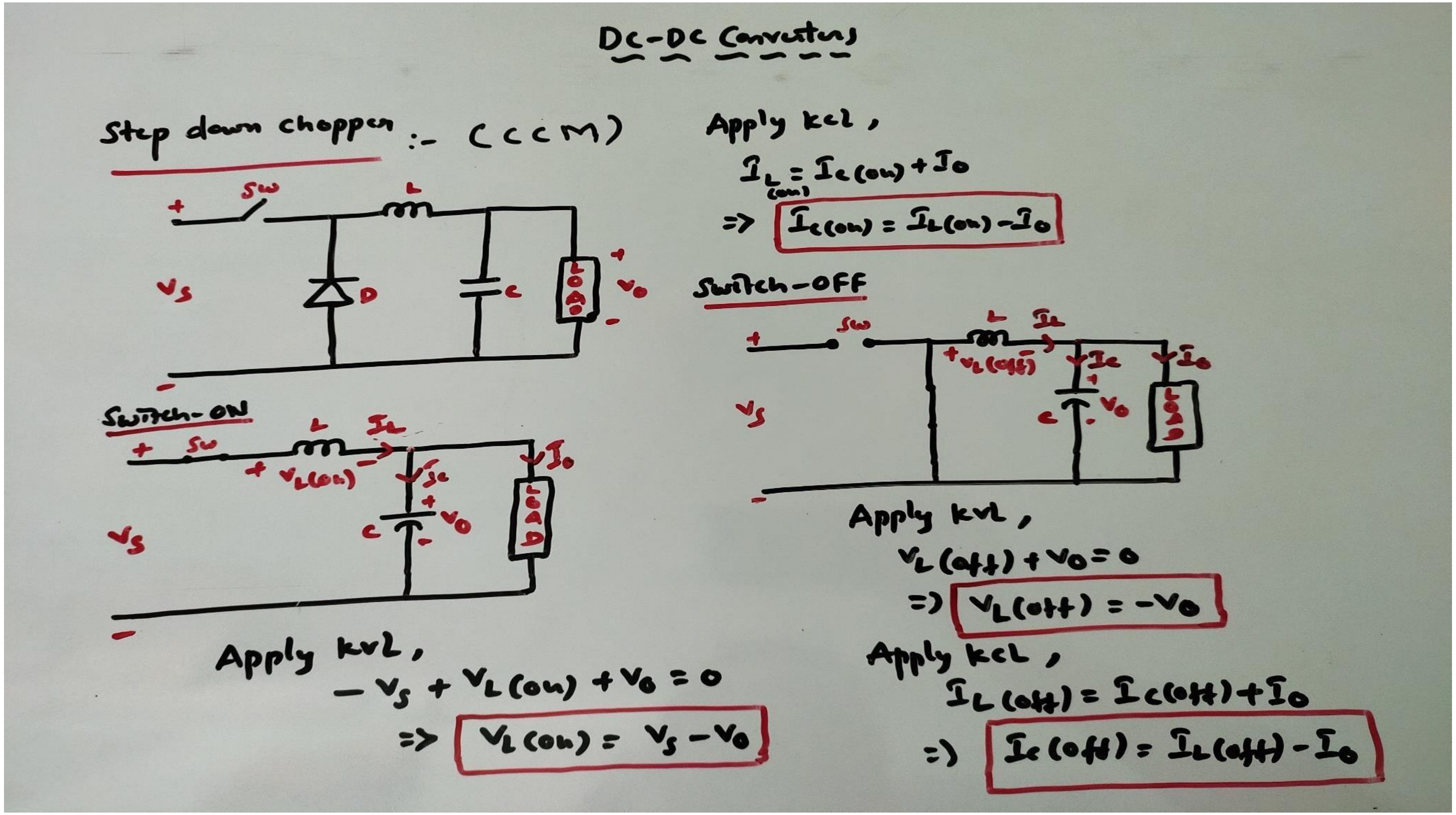
The two types of control strategies for operating the switches are employed in dc choppers are

1. Time ratio Control (TRC)
2. Current limit Control (CLC)

Time Ratio Control (TRC)

1. Constant frequency System
2. Variable frequency System

Step down Converter



Step down Converter

DC-DC Converters

Volt-sec Balance :-

$$V_L(on)\cdot T_{on} + V_L(off)\cdot T_{off} = 0$$

$$\Rightarrow (V_s - V_0)\cdot DT - V_0(1-D)T = 0$$

$$\Rightarrow \boxed{V_0 = D\cdot V_s}$$

Ampere-sec Balance :-

$$I_c(on)\cdot T_{on} + I_c(off)\cdot T_{off} = 0$$

$$\Rightarrow (I_L - I_0)\cdot DT + (I_L - I_0)(1-D)T = 0$$

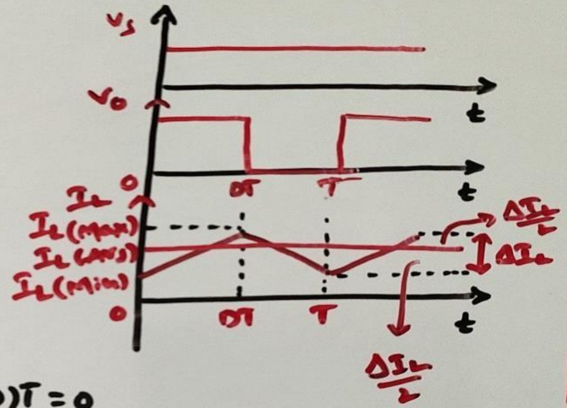
$$\Rightarrow \boxed{I_L = I_0}$$

Ripple in the Inductor current, ΔI_L :-

During T_{on},

$$V_L(on) = V_s - V_0$$

$$\Rightarrow L\cdot \frac{di(on)}{dt} = V_s - D\cdot V_s$$



$$\Rightarrow L\cdot\frac{\Delta I_L}{DT} = V_s(1-D)$$

$$\Rightarrow \Delta I_L = \frac{V_s(1-D)DT}{L}$$

$$\Rightarrow \boxed{\Delta I_L = \frac{V_s\cdot D\cdot(1-D)}{fL}}$$

$$I_L(max) = I_L(avg) + \frac{\Delta I_L}{2} = I_0 + \frac{\Delta I_L}{2}$$

$$I_L(min) = I_L(avg) - \frac{\Delta I_L}{2} = I_0 - \frac{\Delta I_L}{2}$$

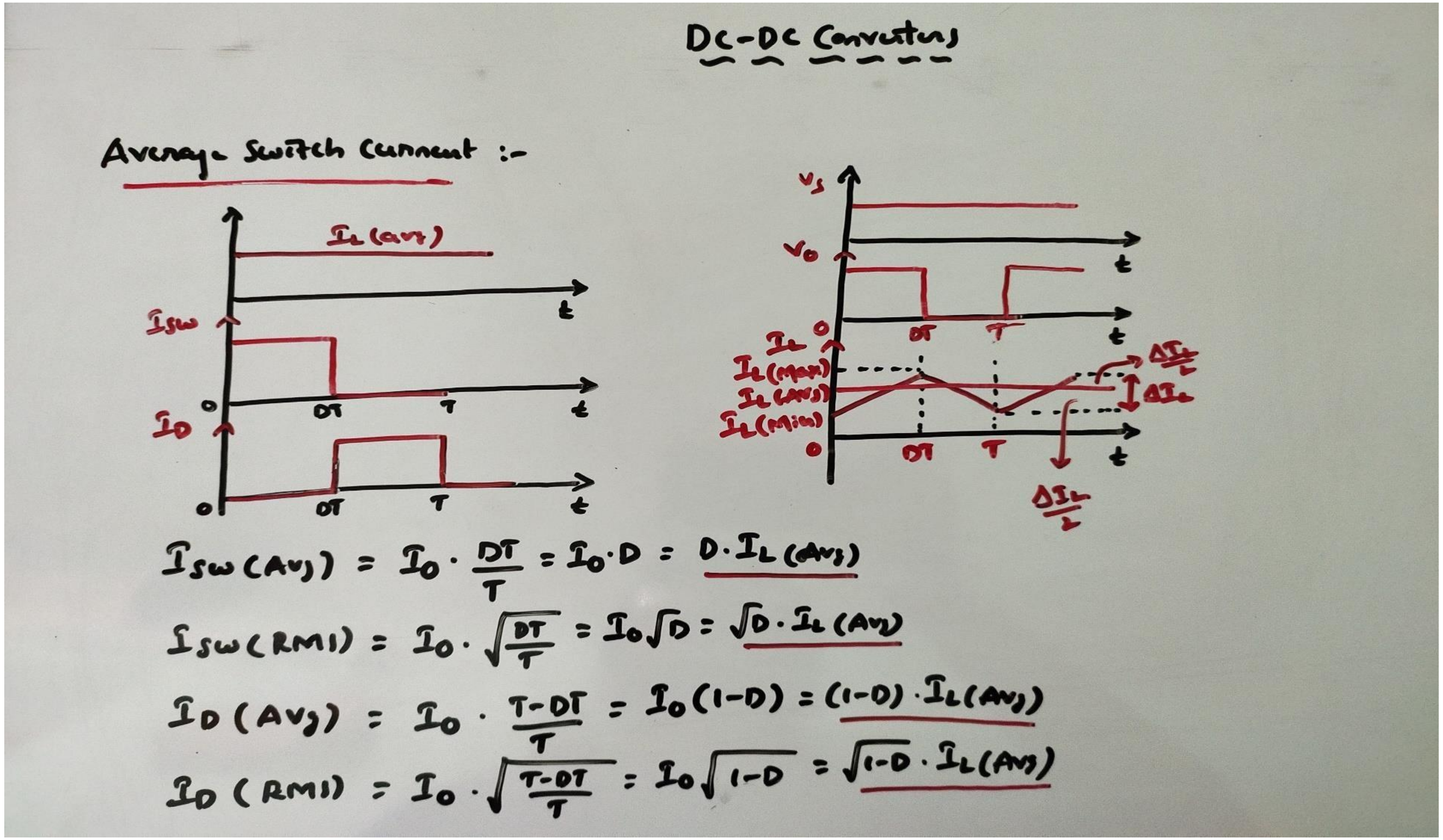
Source current, I_s :-

Input power = output power

$$\Rightarrow V_s\cdot I_s = V_0 I_0$$

$$\Rightarrow \boxed{I_s = \frac{V_0 I_0}{V_s}}$$

Step down Converter



Step down Converter

DC-DC Converters

Ripple in the Capacitor voltage, ΔV_c :-

$$I_C = I_L - I_O$$

$$Q = CV$$

$$\Rightarrow \Delta Q = C \cdot \Delta V_C$$

$$\boxed{\Delta V_C \approx \Delta V_O}$$

$$\Rightarrow \Delta V_C = \frac{\Delta Q}{C} \longrightarrow (1)$$

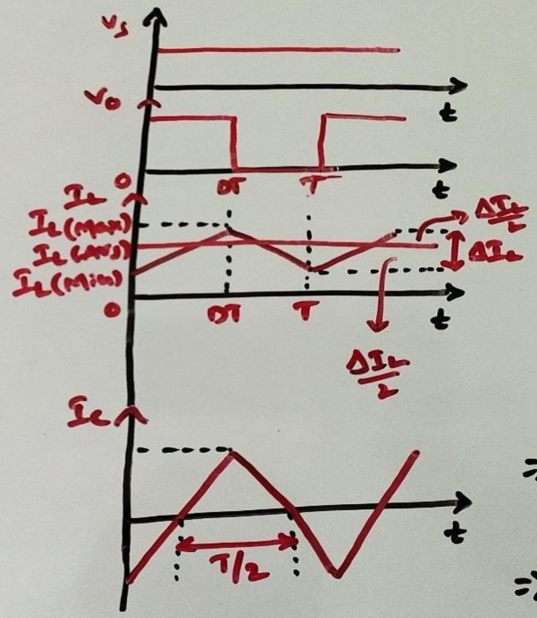
Area,

$$\Delta Q = \frac{1}{2} \times \frac{\Delta I_L}{2} \times \frac{T}{2}$$

$$= \frac{\Delta I_L}{8f}$$

from eqn (1),

$$\Delta V_C = \frac{\Delta I_L}{8fC}$$



Where,

$$\Delta I_L = \frac{V_S \cdot D \cdot (1-D)}{fL}$$

$$\Rightarrow \Delta V_C = \frac{V_S \cdot D \cdot (1-D)}{fL} \cdot \frac{1}{8fC}$$

$$\Rightarrow \boxed{\Delta V_C = \frac{V_S \cdot D \cdot (1-D)}{8f^2 LC}}$$

Step down Converter

DC-DC Converters

$$\Delta V_c = \frac{V_s \cdot D \cdot (1-D)}{8f^2LC}$$

$$\frac{d\,\Delta V_c}{dD} = 0$$

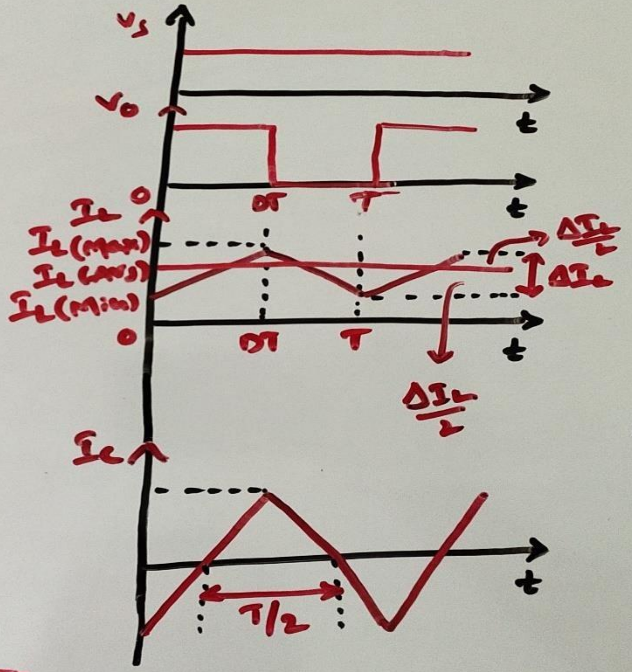
$$\Rightarrow \frac{8f^2LC\left[(1-2D)V_s\right] - \left(D(1-D)V_s\right)\times 0}{(8f^2LC)^2} = 0$$

$$\Rightarrow \quad 1-2D = 0$$

$$\Rightarrow \quad \boxed{D = 0.5}$$

At $D = 0.5$, $\Delta V_c = \Delta V_c(\text{max.})$

$$\boxed{\Delta V_c(\text{max.}) = \frac{V_s}{32f^2LC}}$$



At $D = 0.5$,

$$\boxed{\Delta I_L(\text{max.}) = \frac{V_s}{4fL}}$$

Step down Converter

DC-DC Converters

Critical Inductance, L_c :-

It is the minimum value of Inductor for which Inductor current is just continuous.

(or)

$$I_L(min) = 0$$

$$\Rightarrow I_L(avg) - \frac{\Delta I_L}{2} = 0$$

$$\Rightarrow I_O - \frac{\Delta I_L}{2} = 0$$

$$\Rightarrow \frac{V_O}{R} = \frac{V_s \cdot D \cdot (1-D)}{2 f L_c}$$

$$\Rightarrow \frac{D V_s}{R} = \frac{V_s \cdot D \cdot (1-D)}{2 f L_c}$$

$$\Rightarrow \boxed{L_c = \frac{R(1-D)}{2f}}$$

Critical capacitance, C_c :-

It is the minimum value of capacitor for which the output voltage is just continuous.

(or)

$$V_c(min) = 0$$

$$\Rightarrow V_c - \frac{\Delta V_c}{2} = 0$$

$$\Rightarrow V_O = \frac{\Delta V_c}{2}$$

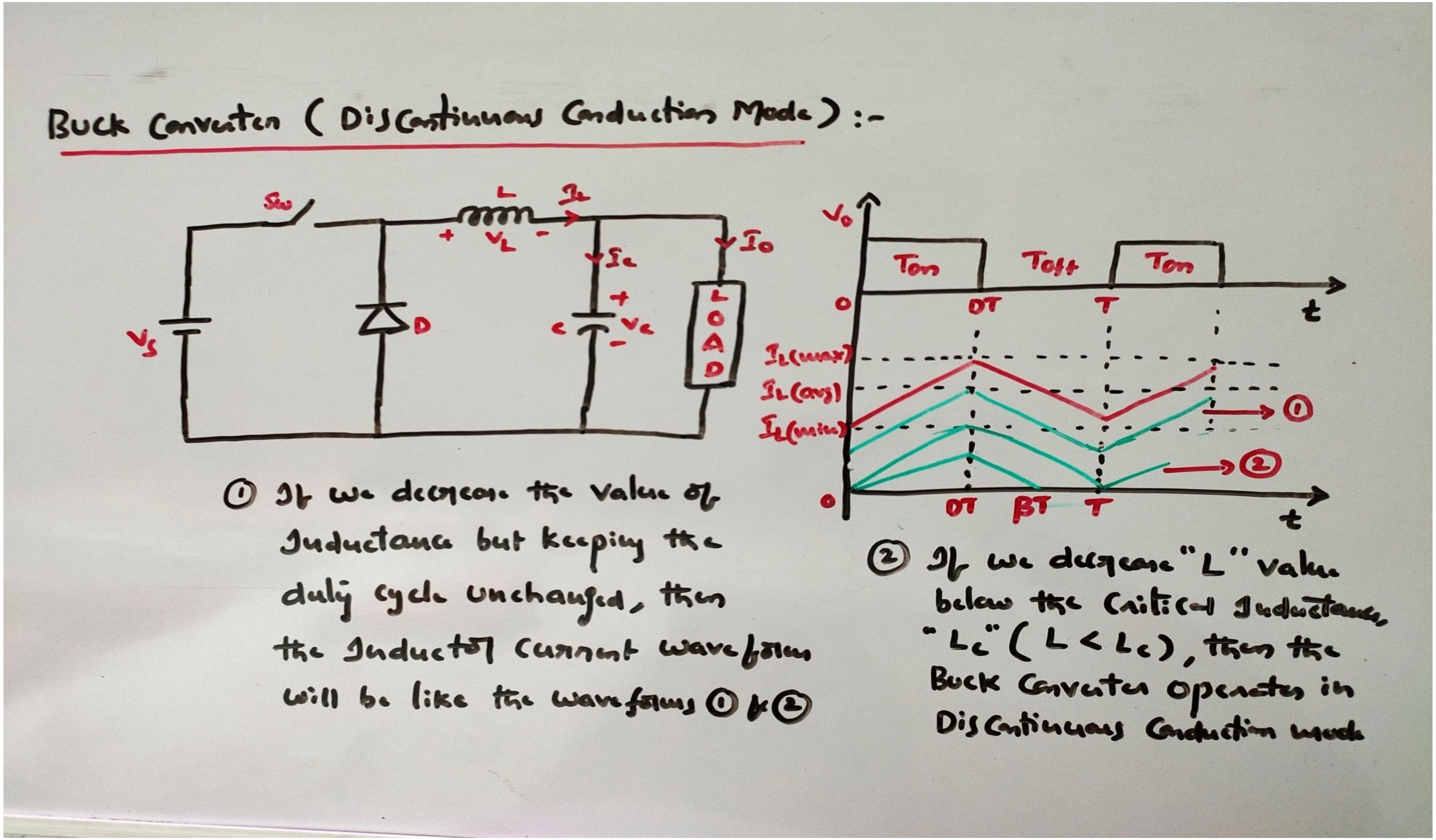
$$\Rightarrow D V_s = \frac{1}{2}\left[\frac{V_s D(1-D)}{8 f^2 L_c C_c}\right]$$

$$\Rightarrow \boxed{C_c = \frac{(1-D)}{16 f^2 L_c}}$$

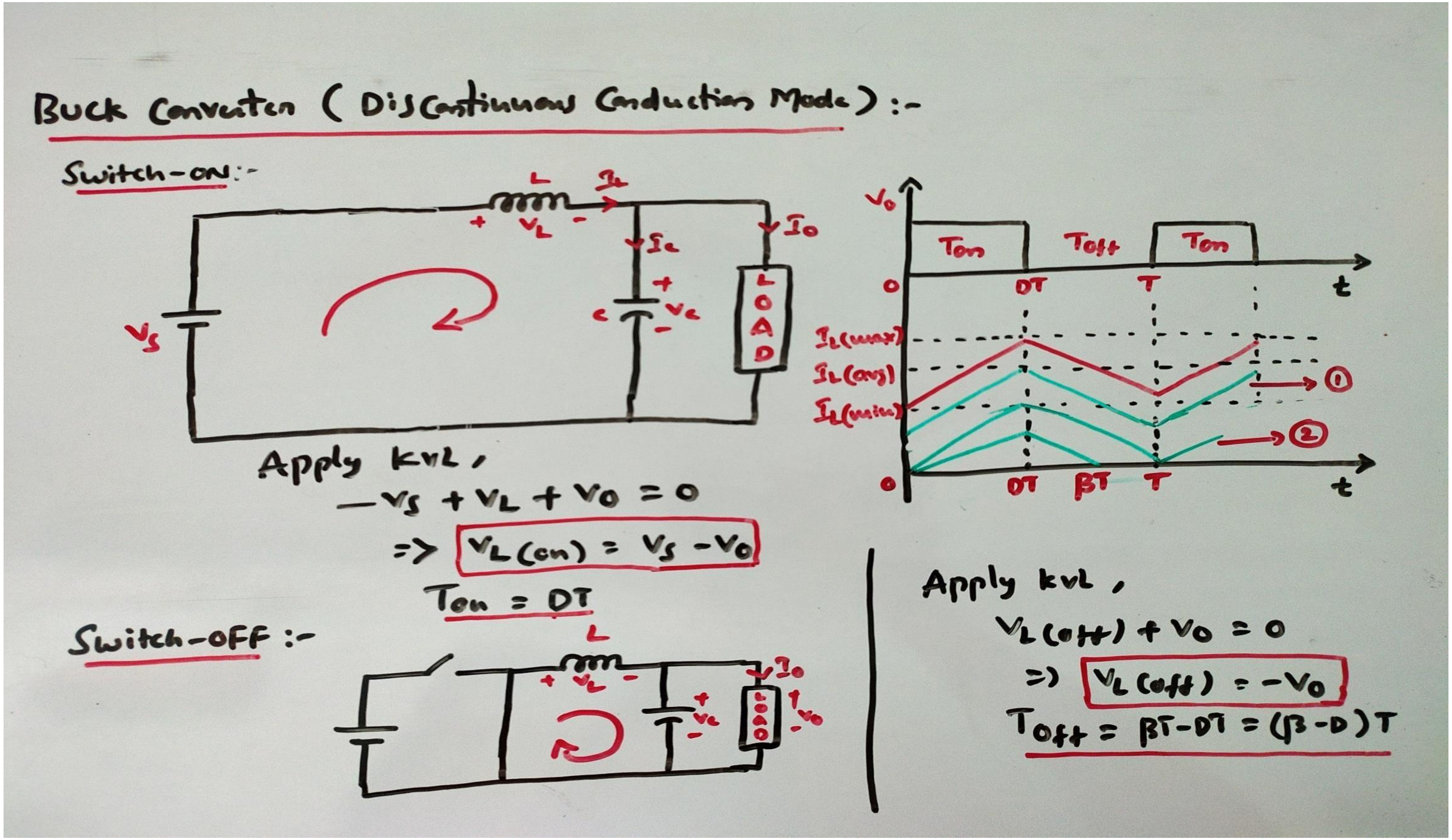
Substitute "L_c",

$$\boxed{C_c = \frac{1}{8 f R}}$$

Step down Converter(DCM)



Step down Converter(DCM)



Step down Converter(DCM)

Buck Converter (Discontinuous Conduction Mode):-

Volt-sec balance theory ,

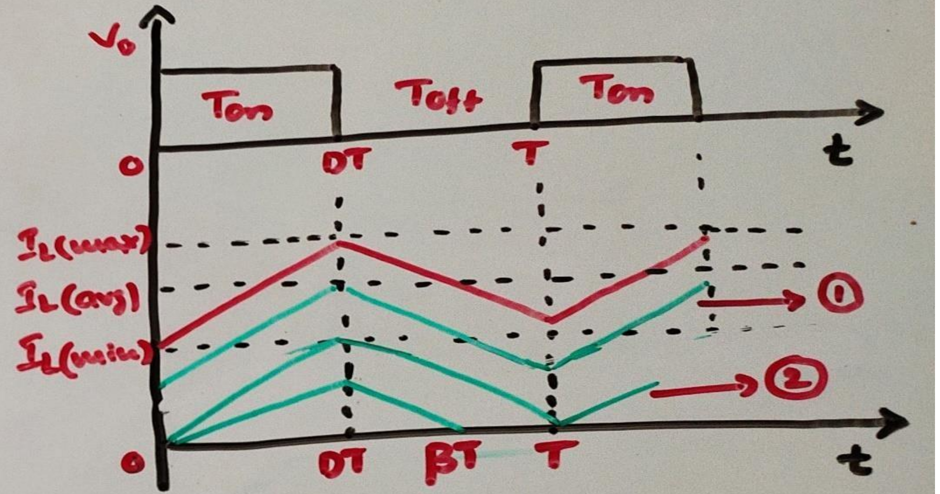
$$V_L(on)\, T_{on} + V_L(off)\, T_{off} = 0$$

$$\Rightarrow (V_s - V_0)\, DT - V_0(\beta - D)T = 0$$

$$\Rightarrow V_s DT - \cancel{V_0 DT} - V_0 \beta T + \cancel{V_0 DT} = 0$$

$$\Rightarrow V_s DT = V_0 \beta T$$

$$\Rightarrow \boxed{V_0 = \frac{V_s D}{\beta}} \quad ; \beta < 1$$



In DCM, $V_0(avg) > V_0(avg)\, CCM$

Step down Converter(DCM)

Buck Converter (Discontinuous Conduction Mode) :-

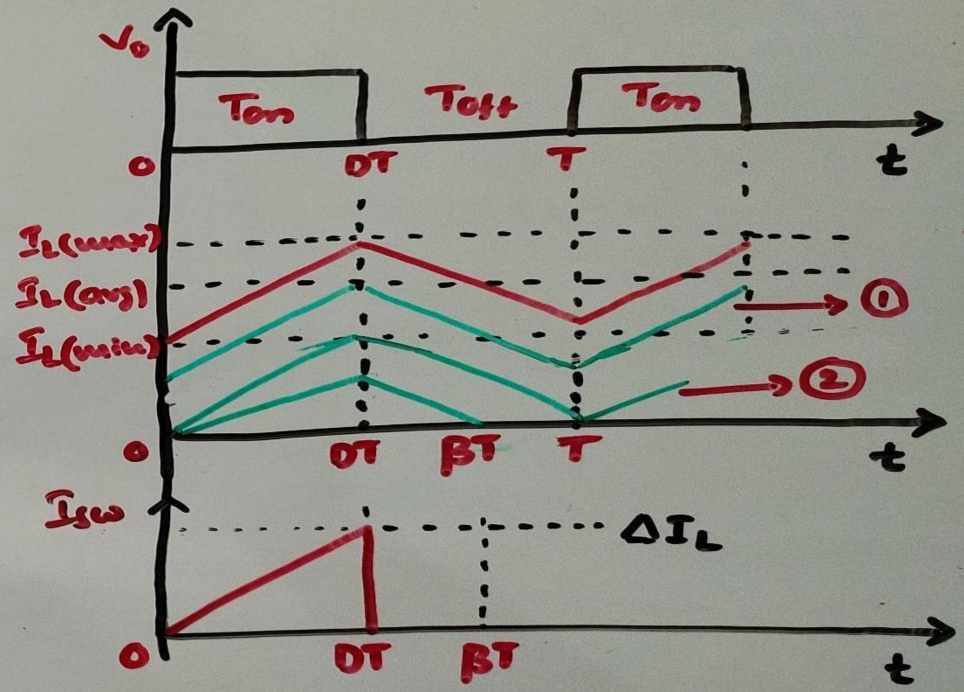
In a DCM, the change in the Inductor current $= \Delta I_L$.

$\Rightarrow$ peak current, $I_{L(max)} = \Delta I_L$

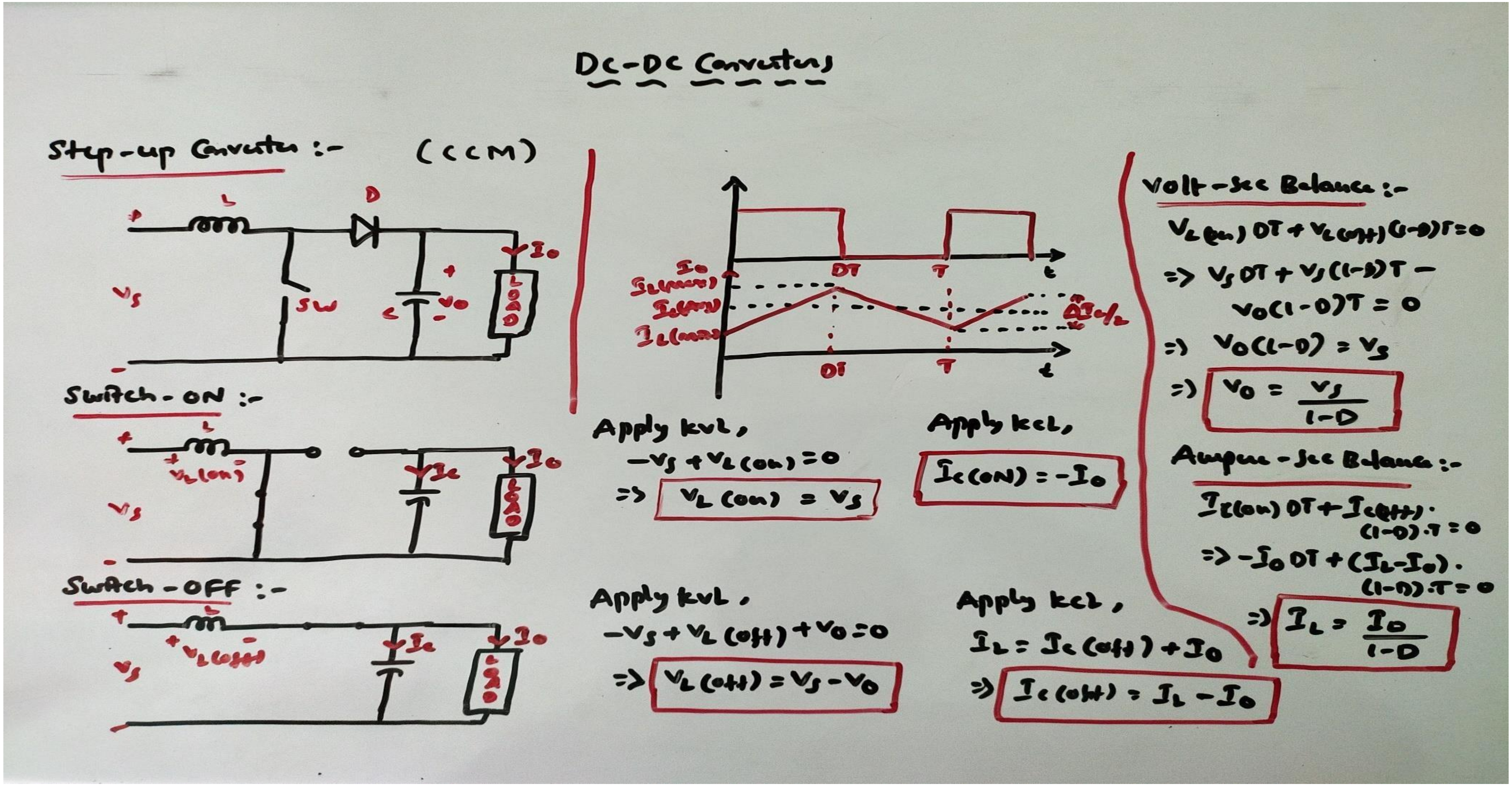
Average switch current,

$$I_{s(avg)} = \frac{\frac{1}{2} \times DT \times \Delta I_L}{T}$$

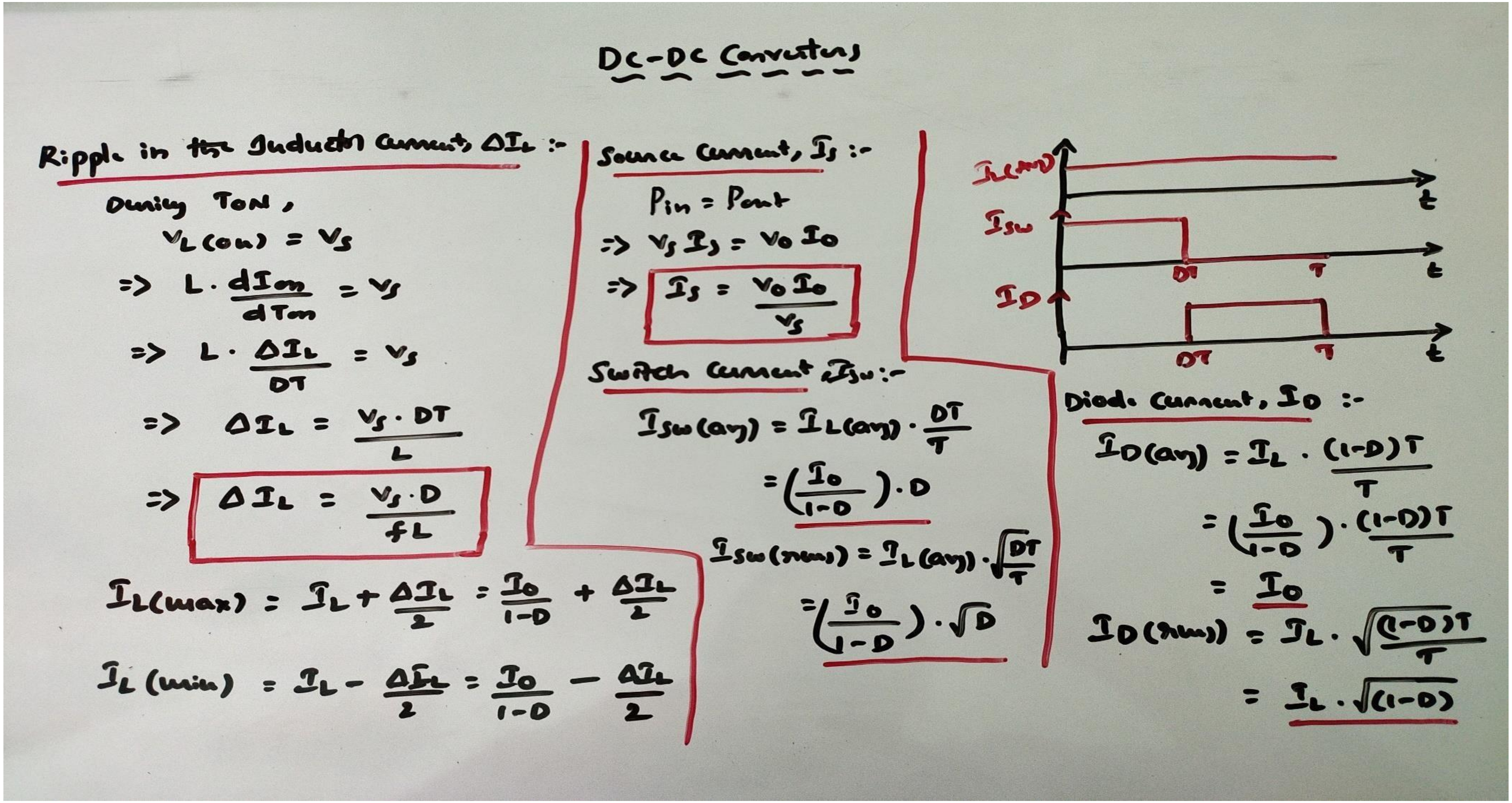
$$\Rightarrow \boxed{I_{s(avg)} = \frac{D \times \Delta I_L}{2}}$$



Step up Converter(CCM)



Step up Converter(CCM)



Step up Converter(CCM)

DC-DC Converters

Ripple in the output voltage, $\Delta V_C \approx \Delta V_o$:-

During T_{ON}, the capacitor is delivering power to the load.

$$I_C = -I_o$$

$$\Rightarrow C\frac{dV_C}{dt} = -I_o \Rightarrow \int_{V_{max}}^{V_{min}} dV_C = \int_0^{DT} -\frac{I_o}{C}\cdot dt$$

$$\Rightarrow V_{min} - V_{max} = -\frac{I_o}{C}\cdot DT$$

$$\Rightarrow -\Delta V_C = -\frac{I_o}{C}\cdot DT$$

$$\Rightarrow \boxed{\Delta V_C = \frac{I_o \cdot D}{fC}}$$

Critical Inductance, L_C :-

$$I_L(min) = 0 \Rightarrow I_L - \frac{\Delta I_L}{2} = 0$$

$$\Rightarrow \frac{I_o}{1-D} = \frac{V_s\cdot D}{2fL_C}$$

$$\Rightarrow \frac{V_o}{R(1-D)} = \frac{V_s\cdot D}{2fL_C} \Rightarrow \frac{V_s}{(1-D)}\cdot\frac{1}{R(1-D)} = \frac{V_s\cdot D}{2fL_C}$$

$$\Rightarrow \boxed{L_C = \frac{D(1-D)^2 R}{2f}}$$

Critical capacitance, C_C :-

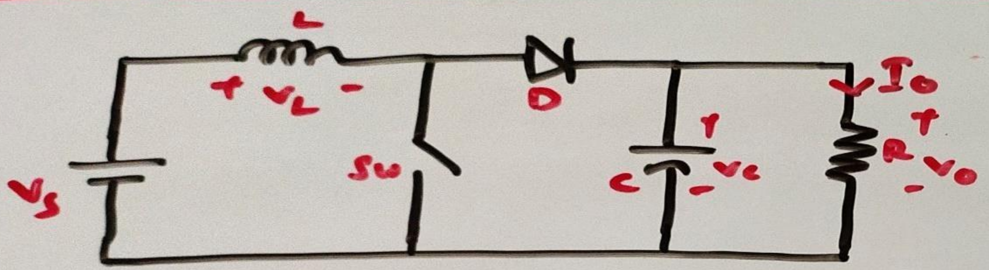
$$V_C(min) = 0 \Rightarrow V_C - \frac{\Delta V_C}{2} = 0$$

$$\Rightarrow V_o = \frac{1}{2}\left(\frac{I_o D}{fC}\right) = \frac{DV_o}{2RfC}$$

$$\Rightarrow \boxed{C_C = \frac{D}{2fR}}$$

Step up Converter(DCM)

Boost Converter (Discontinuous Conduction Mode) :-



Switch-ON

$$V_L(on) = V_s$$
$$T_{on} = DT$$

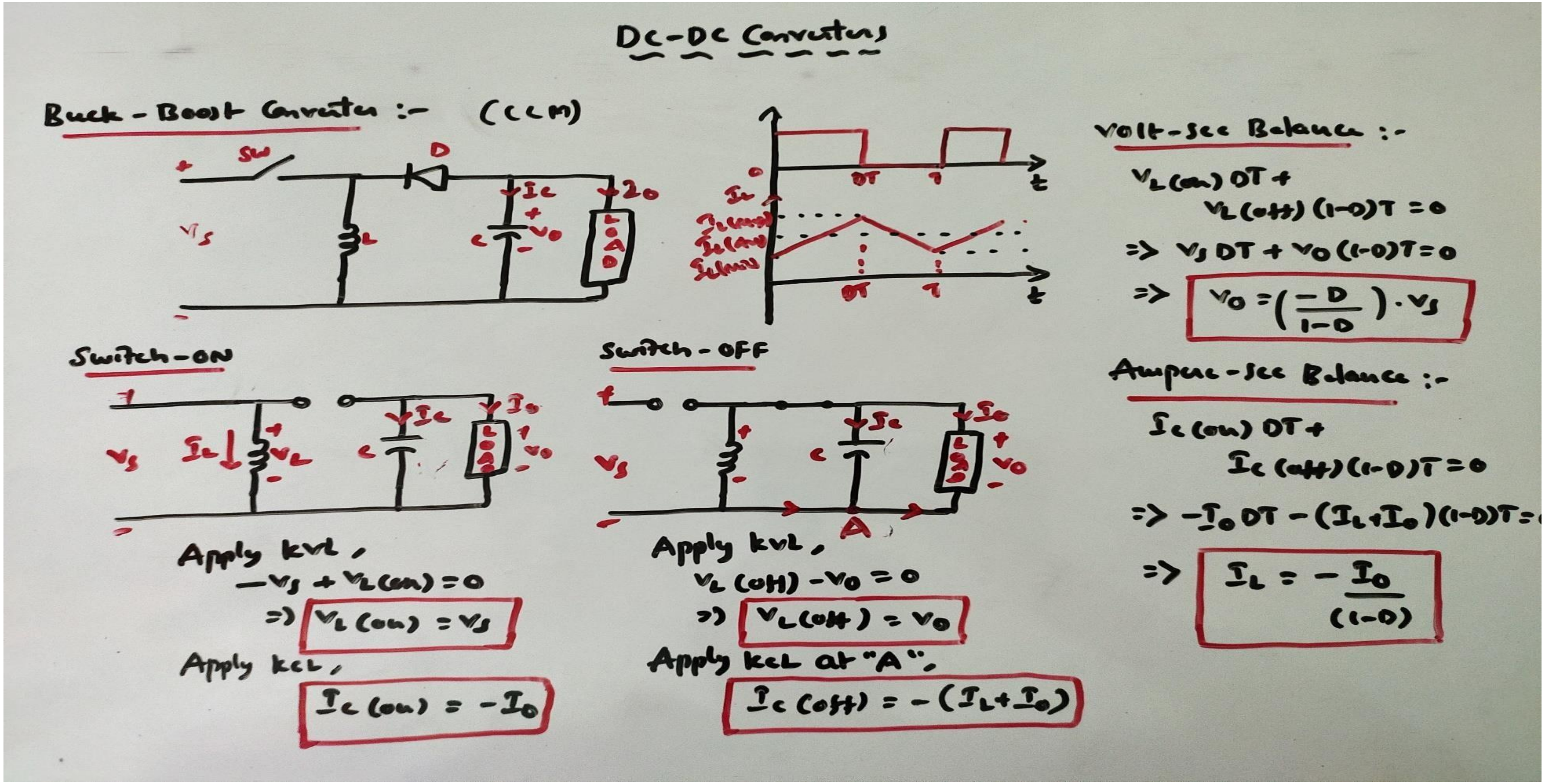
Switch-off

$$V_L(off) = V_s - V_o$$
$$T_{off} = \beta T - DT = (\beta - D)T$$

Volt-sec balance theory,

$$V_L(on)T_{on} + V_L(off)T_{off} = 0$$
$$\Rightarrow V_s DT + (V_s - V_o)(\beta - D)T = 0$$
$$\Rightarrow V_s DT + (V_s - V_o)(\beta T - DT) = 0$$
$$\Rightarrow V_s \cancel{DT} + V_s \cdot \beta T - V_s \cancel{DT} - V_o \beta T + V_o DT = 0$$
$$\Rightarrow V_s \cdot \beta T = V_o \cdot \beta T - V_o DT$$
$$\Rightarrow V_s \cdot \beta \cancel{T} = V_o \cancel{T} (\beta - D)$$
$$\Rightarrow \boxed{V_o = \frac{V_s \beta}{(\beta - D)}}$$

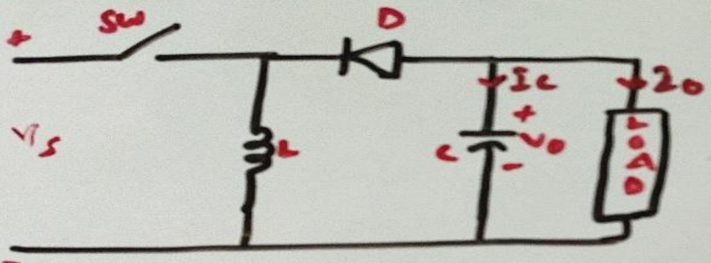
Buck-Boost Converter(CCM)

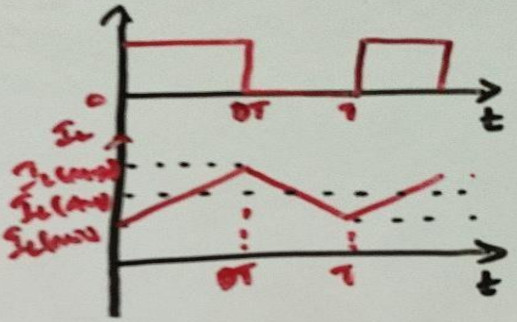


Buck-Boost Converter(CCM)

Dc-Dc Converters

Buck-Boost Converter :- (CCM)





Ripple in Inductor current, ΔI_L :-

During Ton,

$V_{L(on)} = V_s$

$\Rightarrow L \cdot \frac{di_{L(on)}}{dT_{on}} = V_s$

$\Rightarrow L \cdot \frac{\Delta I_L}{DT} = V_s$

$\Rightarrow \Delta I_L = \frac{V_s \cdot DT}{L}$

$\Rightarrow \boxed{\Delta I_L = \frac{V_s \cdot D}{fL}}$

Ripple in capacitor voltage, ΔV_c :-

During Ton,

$I_{c(on)} = -I_o$

$\Rightarrow C \cdot \frac{dv_c}{dt} = -I_o$

$\Rightarrow \int_{V_{min}}^{V_{max}} dv_c = \int_0^{DT} \frac{-I_o}{C} \cdot dt$

$\Rightarrow \boxed{\Delta V_c = \frac{I_o \cdot D}{fC}}$

Critical Inductance, L_c :-

$I_{L(min)} = 0$

$\Rightarrow I_L - \frac{\Delta I_L}{2} = 0$

$\Rightarrow \frac{-I_o}{1-D} = \frac{V_s \cdot D}{2fL_c}$

$\Rightarrow \frac{-V_o}{R(1-D)} = \frac{V_s \cdot D}{2fL_c}$.

$\Rightarrow \frac{V_s \cdot D}{R(1-D)^2} = \frac{V_s \cdot D}{2fL_c}$

$\Rightarrow \boxed{L_c = \frac{R(1-D)^2}{2f}}$

Critical Capacitance, C_c :-

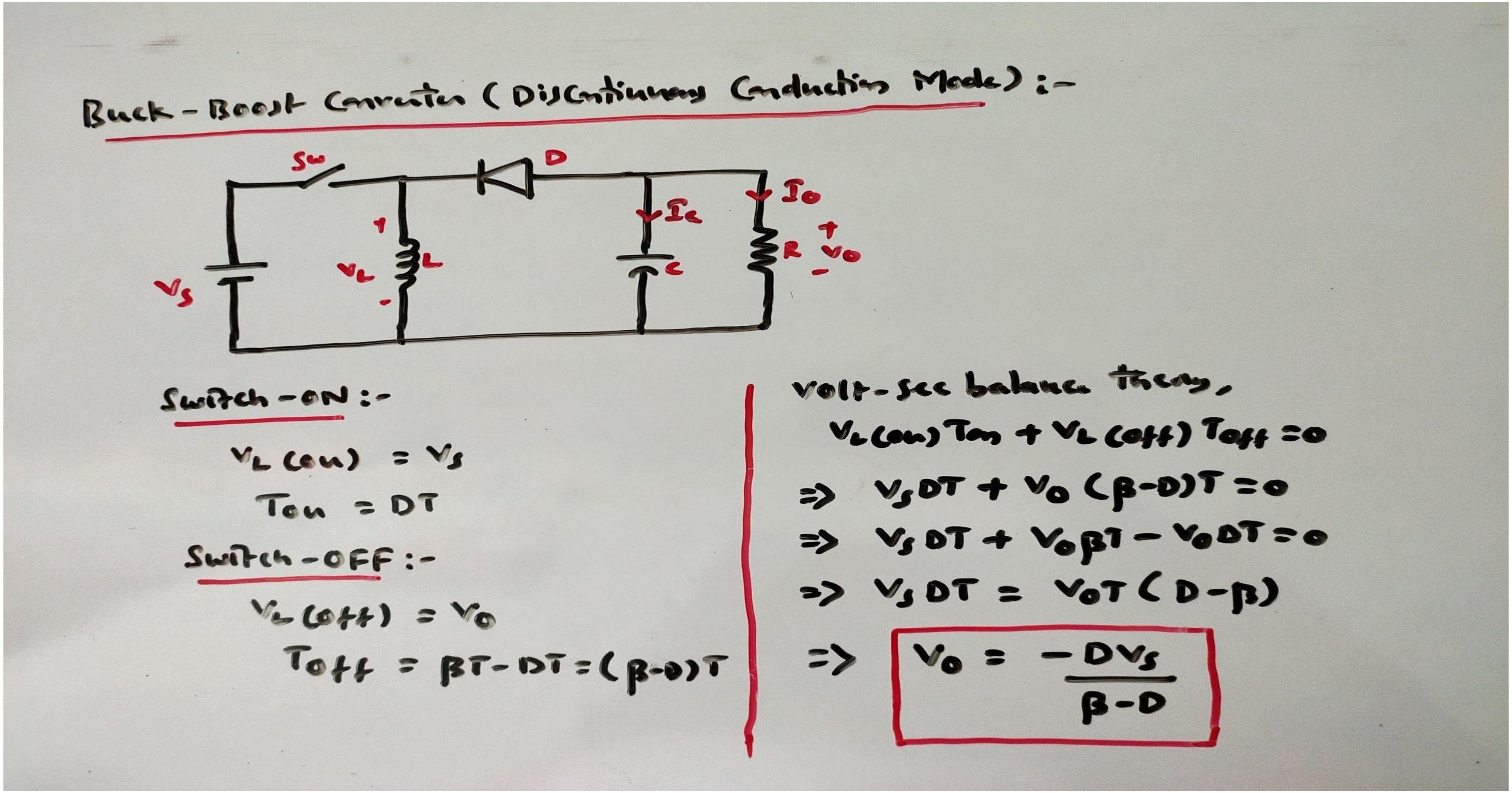
$V_{c(min)} = 0$

$\Rightarrow V_c - \frac{\Delta V_c}{2} = 0$ $[\because V_c = V_o]$

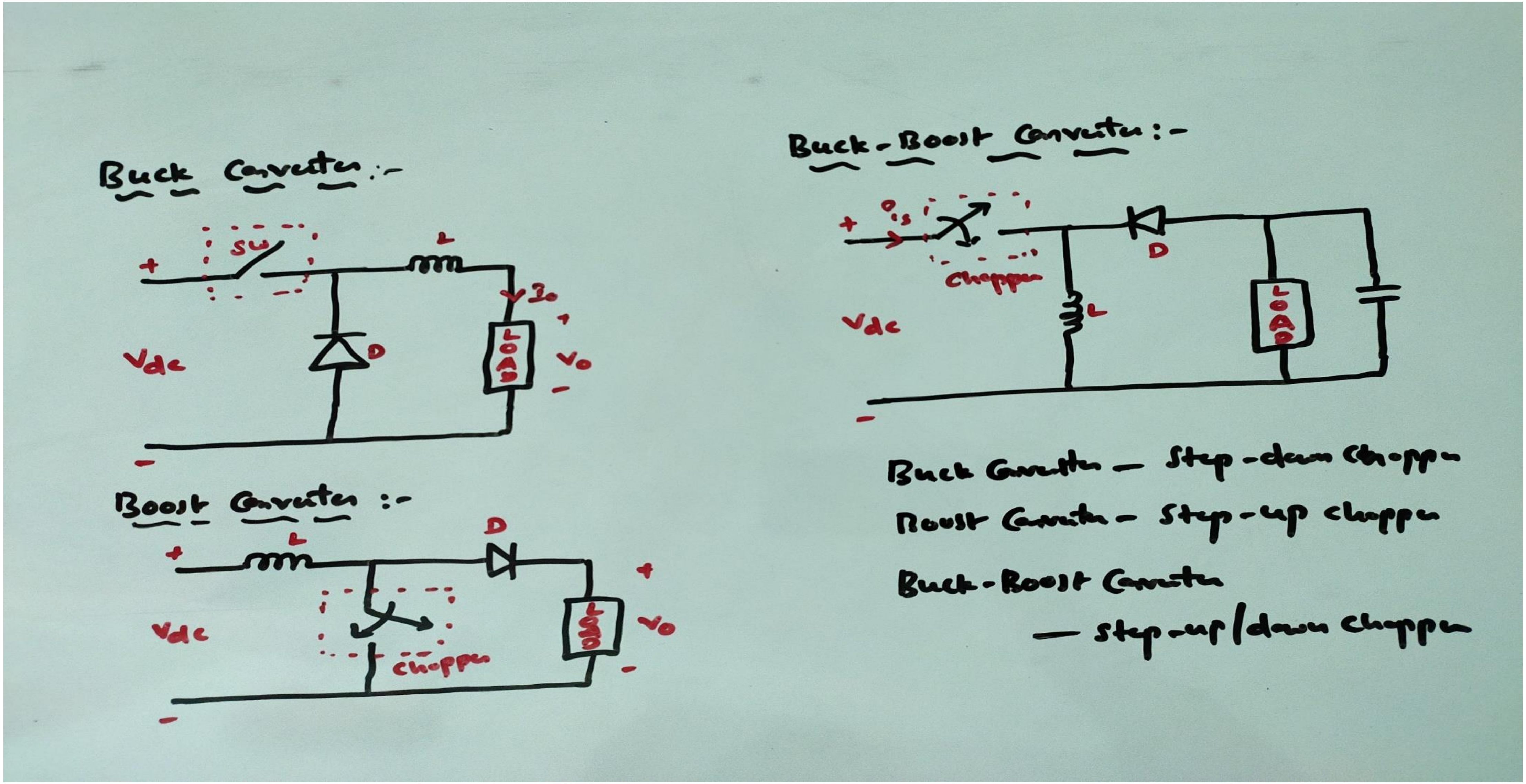
$\Rightarrow V_o = \frac{1}{2}\left(\frac{I_o \cdot D}{fC}\right) = \frac{1}{2}\left(\frac{V_o \cdot D}{fCR}\right)$

$\Rightarrow \boxed{C_c = \frac{D}{2fR}}$

Buck-Boost Converter(DCM)

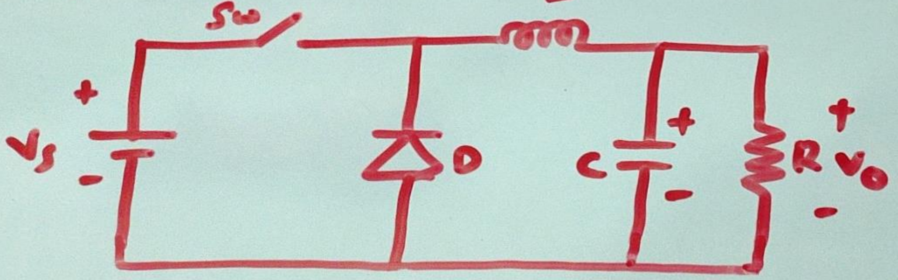


DC-DC Converters



Buck Converter :-

① In the chopper circuit shown in the figure, the input dc voltage has a constant value "V_s". The output voltage "V_o" is assumed ripple-free. The switch "S" is operated with a switching time period "T" and a duty ratio "D". What is the value of "D" at the boundary of continuous and discontinuous conduction of inductor current, "i_L"?



At the boundary condition of continuous and discontinuous conduction,

$$I_L(min) = 0$$

$$\Rightarrow I_L(avg) - \frac{\Delta I_L}{2} = 0$$

$$\Rightarrow I_o = \frac{\Delta I_L}{2} \Rightarrow \frac{V_o}{R} = \frac{V_s(1-D)DT}{2L}$$

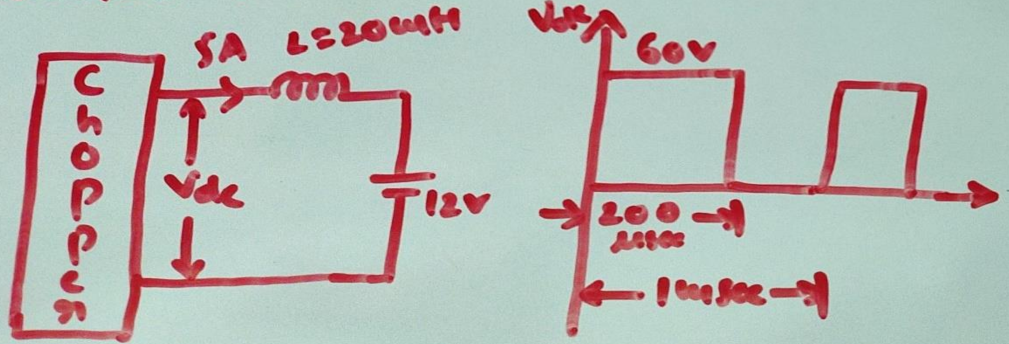
$$\Rightarrow \frac{DV_s}{R} = \frac{V_s(1-D)DT}{2L}$$

$$\Rightarrow (1-D) = \frac{2L}{RT}$$

$$\Rightarrow \boxed{D = 1 - \frac{2L}{RT}}$$

Buck Converter :-

② A chopper is employed to charge a battery as shown in the figure. The charging current is 5 Amp, the duty ratio is 0.2. The chopper output voltage is also shown in below figure. The peak to peak ripple current in the charging current is —



Peak to peak ripple current,

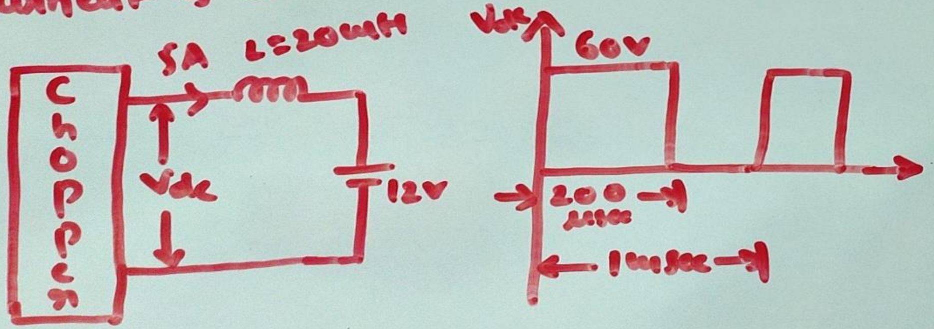
$$\Delta I_L = \frac{V_s (1-D) DT}{L}$$

$$= \frac{60 \times (1-0.2) 0.2 \times 1 \times 10^{-3}}{20 \times 10^{-3}}$$

$$= 0.48 \text{ Amp.}$$

Buck Converter :-

(2) A chopper is employed to charge a battery as shown in the figure. The charging current is 5 Amp, the duty ratio is 0.2. The chopper output voltage is also shown in below figure. The peak to peak ripple current in the charging current is ——



Extra Questions :-

(1) $V_{avg} = \text{Peak value} \times \dfrac{\text{Conduction Period}}{\text{Time period}}$

$$= 60 \times \frac{200\times10^{-6}}{1\times10^{-3}}$$

$$= 60 \times 0.2$$

$$\Rightarrow V_{avg} = 12\,V.$$

(2) Battery power $= 12 \times 5 = 60$ watts.

(3) Input power = output power (always)

$= 60$ watts.

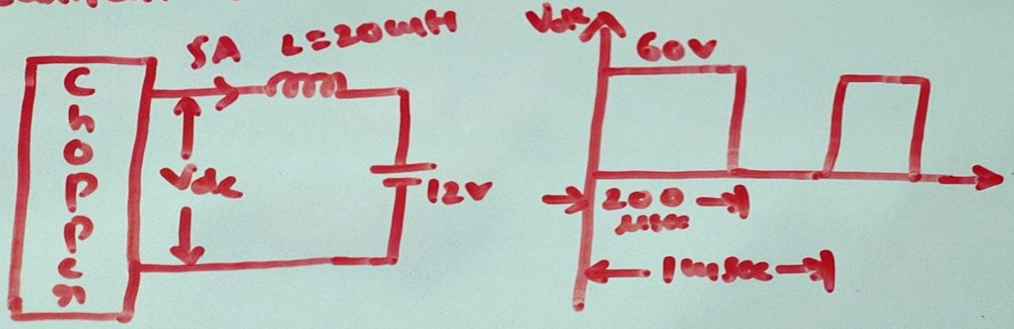
(4) $V_s I_s = V_o I_o \Rightarrow I_s = \dfrac{V_o I_o}{I_s}$

$$\Rightarrow I_s = \frac{12\times5}{60}$$

$$= 1\ \text{Amp.}$$

Buck Converter :-

(2) A chopper is employed to charge a battery as shown in the figure. The charging current is 5 Amp, the duty ratio is 0.2. The chopper output voltage is also shown in below figure. The peak to peak ripple current in the charging current is —



Extra Questions :-

(5) Maximum possible Inductor current,

$$I_L(max) = I_L(avg) + \frac{\Delta I_L}{2}$$

$$= 5 + \frac{0.48}{2}$$

$$= 5.24 \text{ Amp.}$$

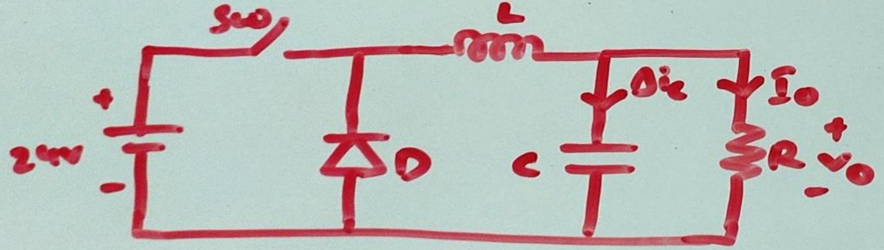
$$I_L(min) = I_L(min) - \frac{\Delta I_L}{2}$$

$$= 5 - \frac{0.48}{2}$$

$$= 4.76 \text{ Amp.}$$

Buck Converter :-

(3) In the circuit shown, an ideal switch "S" is operated at 100 kHz with a duty ratio of 50%. Given that Δi_c is 1.6 Amp peak to peak and "I_o" is 5 Amp dc, the peak current in switch "S" is ——



$$V_o(avg) = D \cdot V_s$$
$$= 0.5 \times 24$$
$$= 12V.$$

Peak current in switch "S" can be obtained only during "T_{on}".

Imp

$$\boxed{I_{sw}|_{peak} = I_L(max)}$$

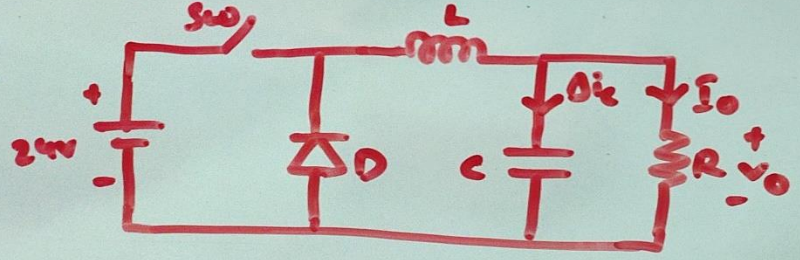
Imp

$$\boxed{\Delta i_c = \Delta I_L}$$

$$I_{sw}|_{peak} = I_L(max) = I_L(avg) + \frac{\Delta I_L}{2}$$
$$= I_o + \frac{\Delta I_L}{2}$$
$$= 5 + \frac{1.6}{2}$$
$$= 5.8 \text{ Amp.}$$

Buck Converter :-

(3) In the circuit shown, an Ideal Switch "S" is operated at 100 kHz with a duty ratio of 50%. Given that Δi_c is 1.6 Amp peak to peak and "I_o" is 5 Amp dc, the peak current in Switch "S" is ——



Extra Question :-

At which duty cycle, "D", change in ripple current is maximum?

$$\boxed{\begin{array}{l}\text{At } D = 0.5, \\ \Delta I_L = \Delta I_{L(max.)}\end{array}}$$

Buck Converter :-

(4) figure (i) shows the circuit diagram of a chopper. The switch "S" in the circuit in the figure (i) is switched such that the voltage "V_D" across the diode has the waveshape as shown in the figure (ii). The capacitance "C" is large so that the voltage across it is constant. If the switch "S" and the diode "D" are ideal, then the peak to peak ripple (in Amp) in the inductor current is ______

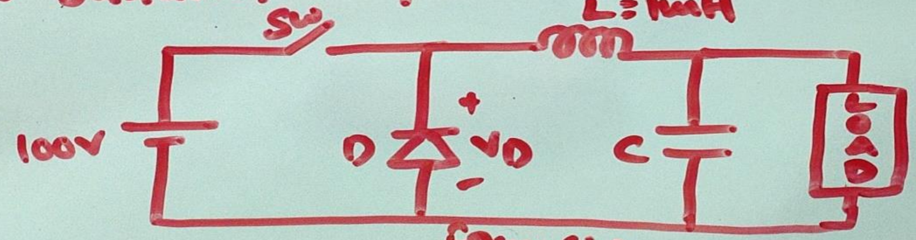


figure (i)

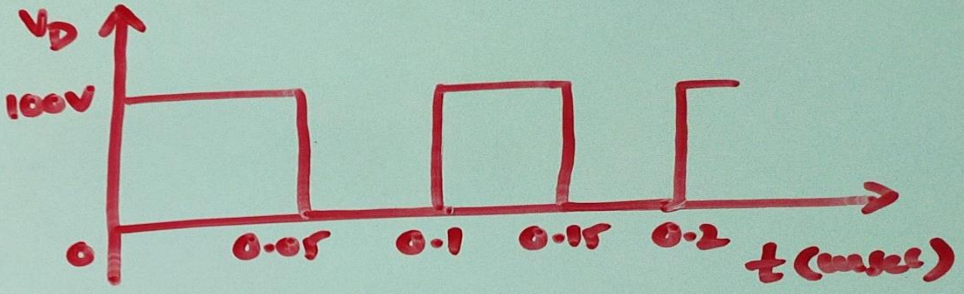


figure (ii)

Peak to peak ripple,

$$\Delta I_L = \frac{V_s(1-D)D \cdot T}{L}$$

$$D = \frac{T_{on}}{T} = \frac{0.05}{0.1} = 0.5$$

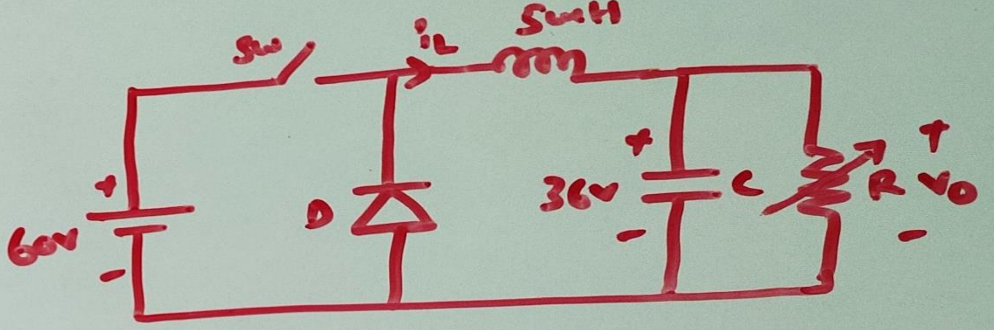
$$\Delta I_L = \frac{100 \times (1-0.5)\, 0.5 \times 0.1 \times 10^{-3}}{1 \times 10^{-3}}$$

$$= 100 \times 0.5 \times 0.5 \times 0.1$$

$$= \underline{\underline{2.5 \text{ Amp.}}}$$

Buck Converter :-

(5) A buck converter feeding a variable resistive load is shown in the figure. The switching frequency of the switch "S" is 100 kHz and the duty ratio is 0.6. The output voltage, $V_0 = 36$ V. Assume that all the components are ideal, and that the output voltage is ripple free. The value of "R" (in ohms) that will make the inductor current (i_L) just continuous is ______



$$\boxed{D = 1 - \frac{2L}{RT}}$$

$$\Rightarrow \frac{2L}{RT} = 1 - D$$

$$\Rightarrow RT = \frac{2L}{1-D}$$

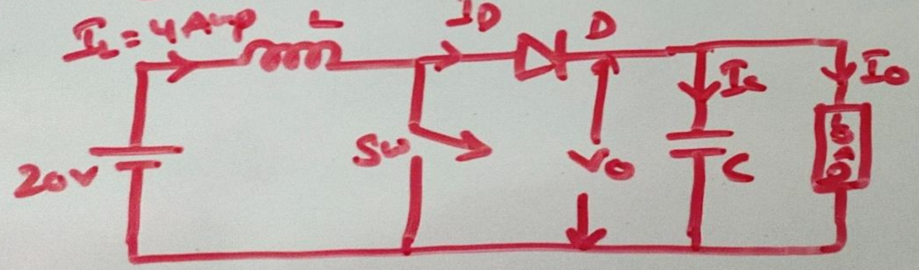
$$\Rightarrow R = \frac{2L}{(1-D)T} = \frac{2L \cdot f}{(1-D)}$$

$$= \frac{2 \times 5 \times 10^{-3} \times 100 \times 1000}{1 - 0.6}$$

$$= 2500\,\Omega.$$

Boost Converter

(6) In the circuit shown in the figure, the switch is operated at a duty cycle of 0.5. A large capacitor is connected across the load. The inductor current is assumed to be continuous. The average voltage across the load and the average current through the diode will respectively be —



$$V_0(avg) = \frac{V_s}{1-D} = \frac{20}{1-0.5} = \frac{20}{0.5}$$

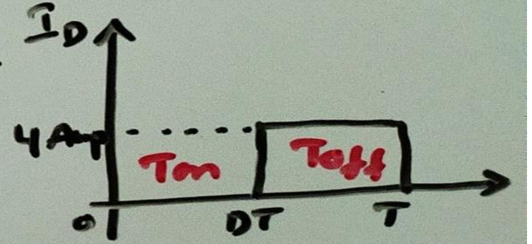
$$= 40\,V.$$

Imp

In a Boost Converter,

Sw – ON ⇒ D – OFF ⇒ $I_D = 0$

Sw – OFF ⇒ D – ON ⇒ $I_D \neq 0$



$$I_{D(avg)} = I_{L(avg)} \times \frac{T-DT}{T}$$

$$= 4 \times 1-D$$

$$= 4 \times (1-0.5)$$

$$= 4 \times 0.5$$

$$= 2\text{ Amp}$$

Boost Converter

6 Extra Questions :-

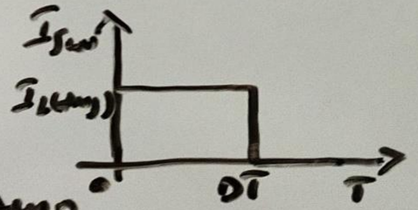
① $I_d(rms) = I_L(avg) \times \sqrt{\frac{T-DT}{T}}$

$= 4 \times \sqrt{1-D}$

$= 4 \times \sqrt{0.5}$

$= 2.828$ Amp

② Switch current, I_{sw}



$I_{sw}(Avg) = I_L(avg) \times \frac{DT}{T}$

$= 4 \times 0.5 = 2$ Amp

$I_{sw}(rms) = I_L(avg) \times \sqrt{\frac{DT}{T}}$

$= 4 \times \sqrt{0.5} = 2.828$ Amp

③ Load current, I_o

$I_L(avg) = \frac{I_o}{1-D}$

$\Rightarrow I_o = I_L(avg) \times (1-D)$

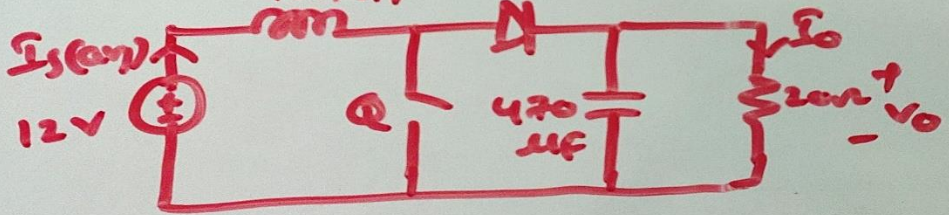
$= 4 \times (1-0.5)$

$= 4 \times 0.5$

$= 2$ Amp

Boost Converter

(7) In the figure shown below, the chopper feeds a resistive load from a battery source. MOSFET "Q_1" is switched at 250 kHz, with a duty ratio of 0.4. All the elements of the circuit are assumed to be ideal



(a) The avg. source current in Amps in steady state is ___

(b) The peak to peak source current ripple in Amps is ___

(a) $I_s(avg) = I_L(avg)$ (Always)

$\Rightarrow I_s(avg) = \dfrac{I_o}{1-D}$

$I_o = \dfrac{V_o}{R}$; $V_o = \dfrac{V_s}{1-D} = \dfrac{12}{1-0.4}$

$\Rightarrow V_o = 20V$

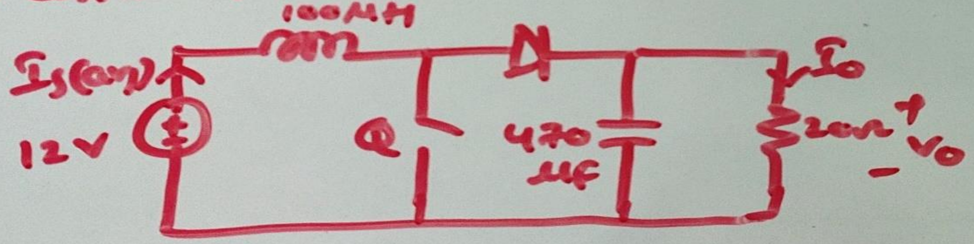
$I_o = \dfrac{20}{20} = 1$ Amp

$\Rightarrow I_s(avg) = \dfrac{1}{1-0.4} = \dfrac{1}{0.6}$

$\Rightarrow I_s(avg) = \dfrac{5}{3}$ Amp

Boost Converter

(7) In the figure shown below, the chopper feeds a resistive load from a battery source. MOSFET "Q_1" is switched at 250 KHz, with a duty ratio of 0.4. All the elements of the circuit are assumed to be ideal



(a) The avg. source current in Amps in steady state is ___

(b) The peak to peak source current ripple in Amps is ___

(b) $$\Delta I_L = \frac{V_s \cdot D}{fL}$$

$$= \frac{12 \times 0.4}{250 \times 1000 \times 100 \times 10^{-6}}$$

$$= 0.192 \text{ Amp}$$

Boost Converter

7. Extra Questions :-

(1) $I_L(max) = I_L(avg) + \frac{\Delta I_L}{2}$

$= \frac{5}{3} + \frac{0.192}{2}$

$= 1.762$ Amp

(2) $I_L(min) = I_L(avg) - \frac{\Delta I_L}{2}$

$= \frac{5}{3} - \frac{0.192}{2}$

$= 1.5706$ Amp

(3) $I_D(avg) = I_L(avg) \times (1-D)$

$= 5/3 \times (1-0.4)$

$= 1$ Amp

(4) $I_D(rms) = I_L(avg) \times \sqrt{1-D}$

$= \frac{5}{3} \times \sqrt{1-0.4}$

$= 1.29091$ Amp

(5) $I_{SW}(Avg) = I_L(avg) \times D$

$= \frac{5}{3} \times 0.4$

$= 0.6664$ Amp

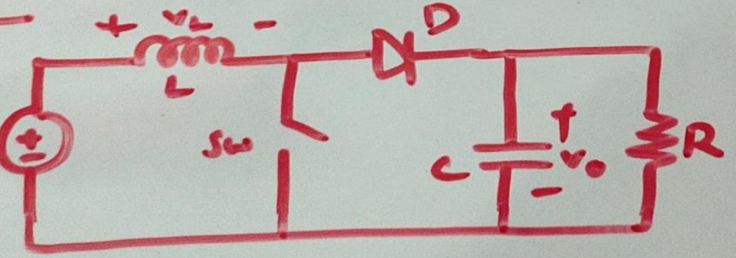
(6) $I_{SW}(rms) = I_L(avg) \times \sqrt{D}$

$= \frac{5}{3} \times \sqrt{0.4}$

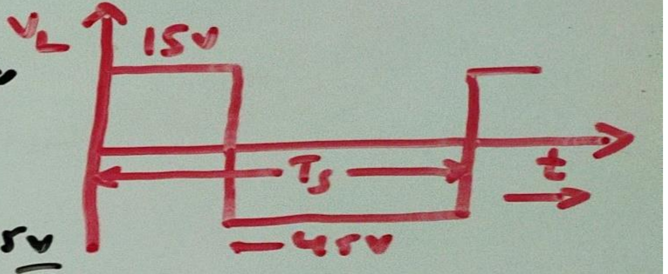
$= 1.05367$ Amp

Boost Converter

(8) For the switching converter shown, assume steady state operation. Also assume that the components are ideal, the inductor current is always positive and continuous and switching period is "T_s". If the voltage "V_L" is as shown, the duty cycle of the switch "S" is ______



In a Boost Converter,



SW-ON,

$$V_L(on) = V_s$$

$$\Rightarrow V_L(on) = V_s = 15V$$

SW-OFF,

$$V_L(off) = V_s - V_o \Rightarrow V_o = V_s - V_L(off)$$

$$\Rightarrow V_o = 15 - (-45) = 60V$$

$$V_o = \frac{V_s}{1-D}.$$

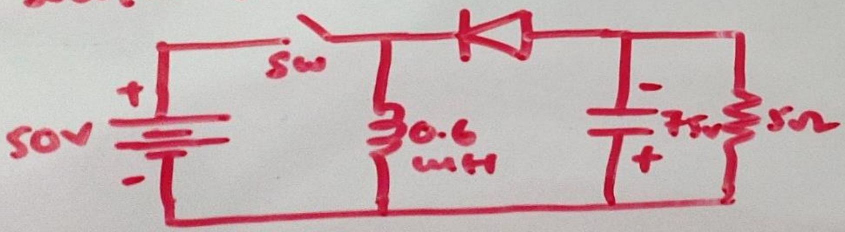
$$\Rightarrow 60 = \frac{15}{1-D}$$

$$\Rightarrow 1-D = \frac{15}{60} = \frac{1}{4} = 0.25$$

$$\Rightarrow D = 0.75$$

Buck - Boost Converter

(9) In the Circuit Shown, all the elements are Ideal and the Switch "S" is operated at 10 kHz and 60% duty ratio. The capacitance is large enough so that the ripple across it is negligible and at Steady State acquires a voltage as shown. The peak current in amperes drawn from the 50V dc Source is ——



$V_0 = \frac{V_s D}{1-D}$, $I_L(\text{avg}) = \frac{I_0}{1-D}$

Imp

Source current = Switch current, I_{sw}

= current through the Inductor, I_L

$\boxed{I_{sw}(\text{peak}) = I_L(\text{max})}$

$\Rightarrow I_L(\text{max}) = I_L(\text{avg}) + \frac{\Delta I_L}{2}$

$V_0 = \frac{V_s D}{1-D} = \frac{50 \times 0.6}{1-0.6} = 75\,V$

$I_0 = \frac{V_0}{R} = \frac{75}{5} = 15$ Amp

$I_L(\text{avg}) = \frac{I_0}{1-D} = \frac{15}{1-0.6} = 37.5$ Amp

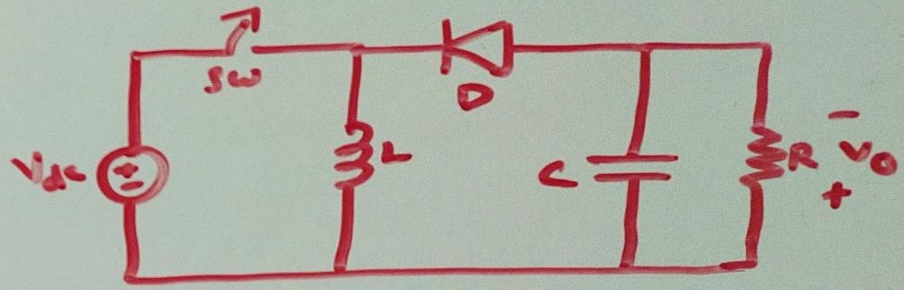
$\Delta I_L = \frac{V_s D}{fL} = \frac{50 \times 0.6}{10 \times 1000 \times 0.6 \times 10^{-3}} = 5$ Amp

$I_{sw}(\text{peak}) = I_L(\text{max}) = 37.5 + 5/2$

$= 40$ Amp

Buck - Boost Converter

(10) The Input voltage V_{dc} of the buck-boost converter shown below varies from 32V to 72V. Assume that all components are ideal, inductor current is continuous, and output voltage is ripple free. The range of duty ratio "D" of the converter for which the magnitude of the steady state output voltage remains at 48V is ——



Case-1 :- $V_s = 32V, V_0 = 48V$

$$V_0 = \frac{V_s D}{1-D} \Rightarrow 48 = \frac{32 \times D_1}{1-D_1}$$

$$\Rightarrow 48 - 48D_1 = 32D_1$$

$$\Rightarrow D_1 = 0.6 \rightarrow (1)$$

Case-2 :- $V_s = 72V, V_0 = 48V$

$$\Rightarrow 48 = \frac{72 \times D_2}{1-D_2}$$

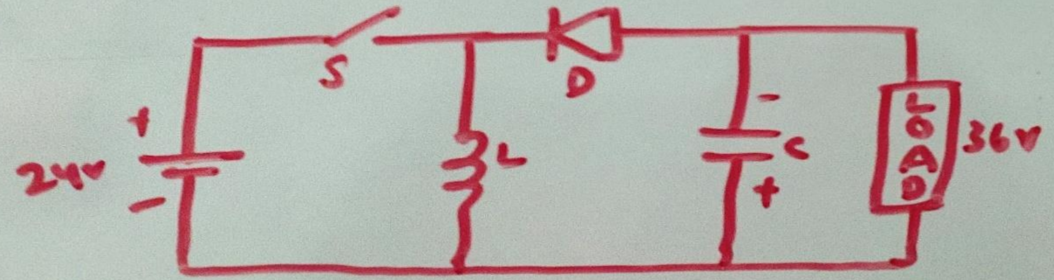
$$\Rightarrow D_2 = \frac{48}{72+48} = \frac{48}{120} = \frac{2}{5} \rightarrow (2)$$

$$D_1 \le D \le D_2$$

$$\Rightarrow 0.6 \le D \le \frac{2}{5}.$$

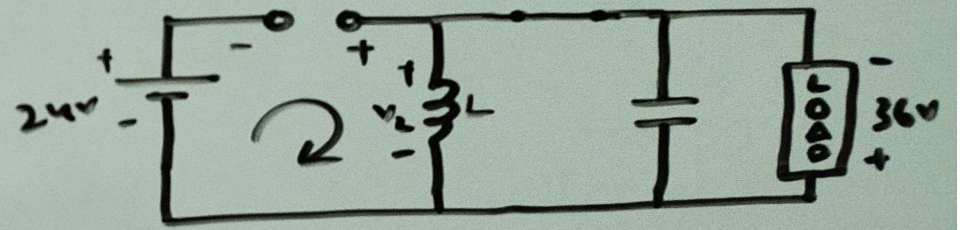
Buck - Boost Converter

(11) A buck-boost dc-dc converter shown is used to convert 24v battery voltage to 36v dc voltage to feed a load of 72W. It is operated at 20 kHz. With an inductor of 2 mH and output capacitance of 1000 μF. All devices are considered to be ideal. The peak voltage across the solid-state switch, (S) in volts is ——



SW-ON => S.C. => $V_{sw} = 0$

voltage across the switch can be obtained only when the switch is off.



Apply KVL,

$$-V_S - V_{sw(off)} + V_L = 0$$

$$\Rightarrow -24 - V_{sw(off)} - 36 = 0$$

$$\Rightarrow V_{sw(off)} = 24 + 36$$

$$\Rightarrow V_{sw(off)} = 60\,\text{v}$$

Buck - Boost Converter

(11) Extra Questions :-

(1) $V_o = \frac{V_s D}{1-D}$

$\Rightarrow 36 = \frac{24 \times D}{1-D}$

$\Rightarrow D = 3/5$

(2) Change in ripple,

$\Delta I_L = \frac{V_s D}{fL} = \frac{24 \times 0.6}{20 \times 10^3 \times 2 \times 10^{-3}}$

$= 0.36$ Amp

(3) $P_L = V_o I_o$

$\Rightarrow I_o = \frac{P_L}{V_o} = \frac{72}{36} = 2$ Amp

(4) $I_L(avg) = \frac{I_o}{1-D} = \frac{2}{1-0.6} = 5$ Amp

(5) $I_L(max) = I_L(avg) + \frac{\Delta I_L}{2}$

$= 5 + \frac{0.36}{2} = 5 + 0.18$

$= 5.18$ Amp

$I_L(min) = I_L(avg) - \frac{\Delta I_L}{2}$

$= 5 - \frac{0.36}{2} = 5 - 0.18$

$= 4.82$ Amp

(6) $V_s I_s = V_o I_o$

$\Rightarrow I_s = \frac{V_o I_o}{V_s} = \frac{72}{24}$

$\Rightarrow I_s = 3$ Amp

Voltage commutated chopper,

① $i_{TM}(peak) = I_o + V_s\sqrt{\frac{C}{L}}$

② $i_{TA}(peak) = I_o$

③ capacitor current $= V_s\sqrt{\frac{C}{L}}$

④ $I_L(peak) = I_D(peak) = V_s\sqrt{\frac{C}{L}}$

⑤ Minimum Turn ON time of main thyristor, $T_M = \pi\sqrt{LC}$

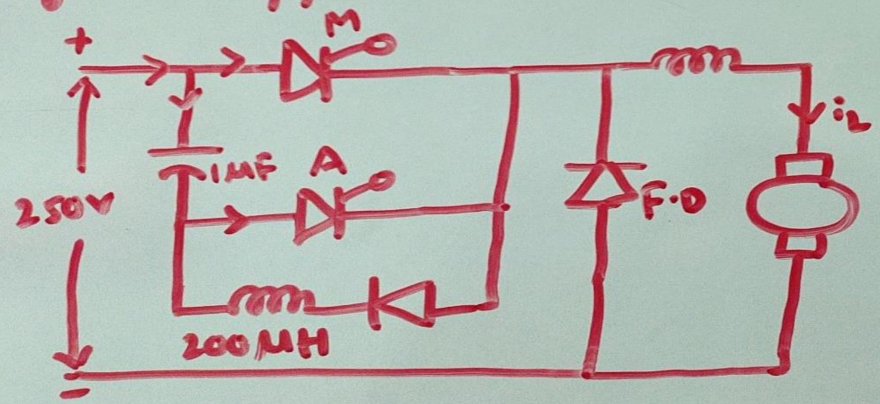
⑥ Commutation time of auxiliary thyristor, $T_A = \frac{\pi}{2}\sqrt{LC}$

⑦ Circuit turn off time (or) commutation time of main thyristor, TM, $t_{cm} = \frac{CV_s}{I_o}$

(12) A voltage commutated chopper operating at 1 KHz is used to control the speed of a dc motor as shown in the figure. The load current is assumed to be constant at 10 Amp.

(a) The minimum time in μsec for which the SCR "M" should be "ON" is ——

(b) The average output voltage of a chopper will be ——



(a) Minimum turn-ON time of "M",

$$T_M = \pi\sqrt{LC}$$
$$= \pi\sqrt{200\times10^{-6}\times1\times10^{-6}}$$
$$= 140\ \mu sec$$

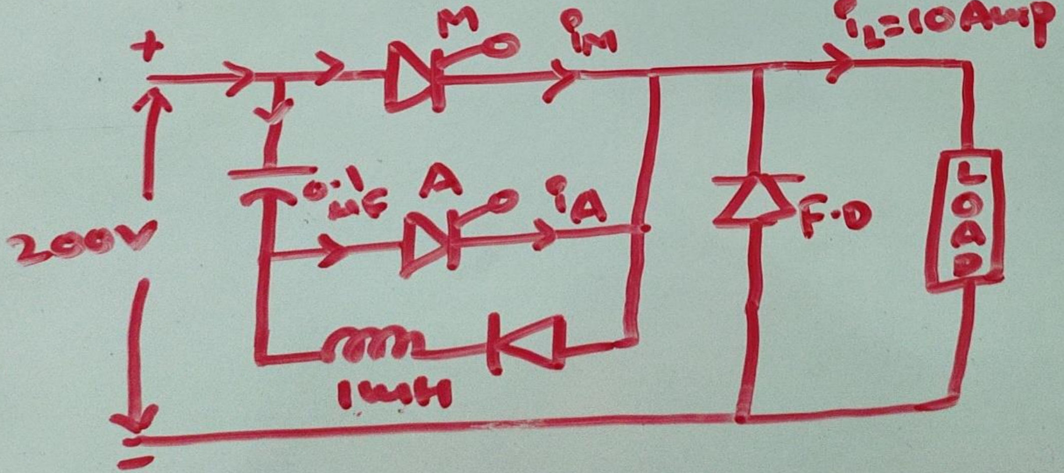
(b) $$V_o(avg) = \frac{V_s \times t_3 + \frac{1}{2}(2V_s)\times 2t_{cm}}{T}$$

Where,

$$t_3 = t_{min} = \pi\sqrt{LC} = 140\ \mu sec$$
$$T = 1/f = 1/1\times1000$$
$$t_{cm} = \frac{C\cdot V_s}{I_o} = \frac{1\times10^{-6}\times250}{10}$$
$$= 25\ \mu sec$$

$$\Rightarrow V_o(avg) = 47.5\ V$$

(13) A Voltage commutated chopper circuit operated at 500 Hz is shown below. If the maximum value of load current is 10 Amp, then the maximum current through the main (M) and Auxiliary (A) thyristor will be ——



$$I_{TM}(max) = I_0 + V_s\sqrt{\frac{C}{L}}$$

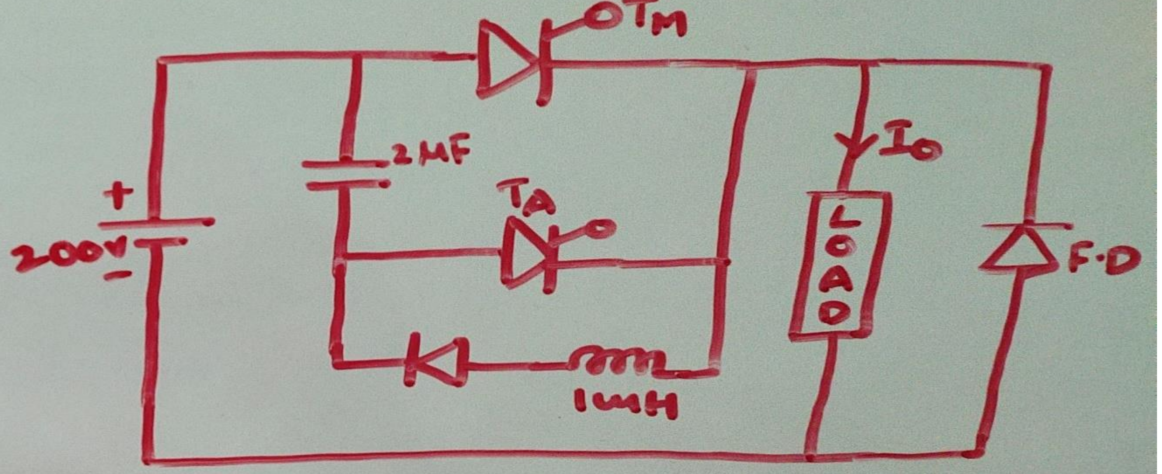
$$= 10 + 200\sqrt{\frac{0.1\times10^{-6}}{1\times10^{-3}}}$$

$$= \underline{\underline{12 \text{ Amp}}}$$

$$I_{TA}(max) = I_0$$

$$= \underline{\underline{10 \text{ Amp}}}$$

(14) Consider the chopper circuit shown in the figure. The chopper operates at 400 Hz and 50% duty cycle. The load current remains almost ripple free at 10 Amp. Assuming the input voltage to be 200 V and the devices to be Ideal, the turn-off time available to the thyristor, T_M is — μsec.

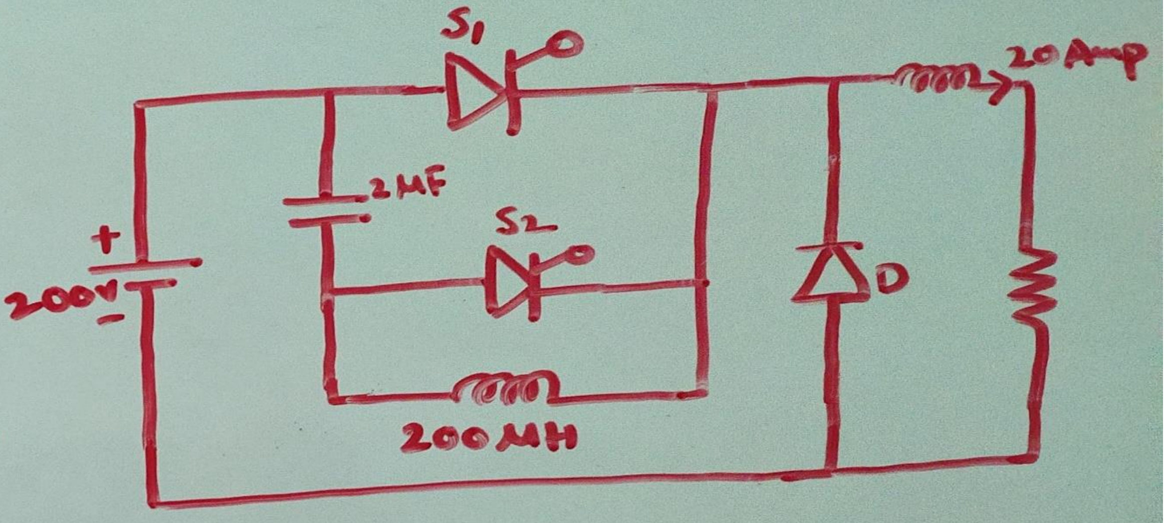


Circuit turn-off time of "M",

$$T_M = t_{cm} = \frac{CV_s}{I_0} = \frac{2 \times 10^{-6} \times 200}{10}$$

$$= 40\,\mu sec$$

(15) Figure shows a Chopper. The device "S_1" is the main switching device. "S_2" is the auxiliary commutation device. "S_1" is rated for 400V, 60 Amp. "S_2" is rated for 400V, 30 Amp. The load current is 20 Amp. The main device operates with a duty ratio of 0.5. The peak current through "S_1" is ——



$$I_{S_1}(\text{peak}) = I_{TM}(\text{peak}) = I_0 + V_s\sqrt{\frac{C}{L}}$$

$$= 20 + 200\sqrt{\frac{2\times10^{-6}}{200\times10^{-6}}}$$

$$= \underline{\underline{40\ \text{Amp}}}$$

$$I_{S_2}(\text{peak}) = I_{TA}(\text{peak}) = I_0$$

$$= \underline{\underline{20\ \text{Amp}}}$$