LECTURE NO. 1

INTRODUCTION TO POWER ELECTRONICS

Definition

• Power electronics refers to control and conversion of electrical power by power semiconductor devices wherein these devices operate as switches.
• Advent of silicon-controlled rectifiers, abbreviated as SCRs, led to the development of a new area of application called the power electronics.
• Prior to the introduction of SCRs, mercury-arc rectifiers were used for controlling electrical power, but such rectifier circuits were part of industrial electronics and the scope for applications of mercury-arc rectifiers was limited.
• Once the SCRs were available, the application area spread too many fields such as drives, power supplies, aviation electronics & high frequency inverters.

Main Task of Power Electronics

• Power electronics has applications that span the whole field of electrical power systems, with the power range of these applications extending from a few VA/Watts to several MVA / MW.
• The main task of power electronics is to control and convert electrical power from one form to another.
• The four main forms of conversion are:
→ **Rectification referring to conversion of AC voltage to DC voltage,**
→ **DC-to-AC conversion,**
→ **DC-to DC conversion,**
→ **AC-to-AC conversion**

• "Electronic power converter" is the term that is used to refer to a power electronic circuit that converts voltage and current from one form to another.
These converters can be classified as:
→ Rectifier converting an ac voltage to a dc voltage,
→ Inverter converting a dc voltage to an ac voltage,
→ Chopper or a switch-mode power supply that converts a dc voltage to another dc voltage, and
→ Cycloconverter converts an ac voltage to another ac voltage.

Rectification

- Rectifiers can be classified as uncontrolled and controlled rectifiers, and the controlled rectifiers can be further divided into semi-controlled and fully controlled rectifiers.

- Uncontrolled rectifier circuits are built with diodes, and fully controlled rectifier circuits are built with SCRs. Both diodes and SCRs are used in semi-controlled rectifier circuits.

- There are several rectifier configurations. The popular rectifier configurations are listed below.

→ Single-phase half wave rectifier,
→ Single-phase full wave rectifier,
→ Single-phase half wave controlled rectifier,
→ Single-phase semi-controlled full wave rectifier,
→ Single-phase fully controlled full wave rectifier,
→ Three-phase half wave rectifier,
→ Three-phase bridge rectifier,
→ Three-phase half wave controlled rectifier,
→ Three-phase semi-controlled bridge rectifier
→ Three-phase fully controlled bridge rectifier

• Power rating of a single-phase rectifier tends to be lower than 10 kW. Three-phase bridge rectifiers are used for delivering higher power output, up to 500 kW at 500 V dc or even more.
• There are many applications for rectifiers. Some of them are:
→ Variable speed dc drives,
→ Battery chargers,
→ DC power supplies and Power supply for a specific application like electroplating

DC-to-AC Conversion

- The converter that changes a dc voltage to an alternating voltage is called an inverter.
- Earlier inverters were built with SCRs.
- Since the circuitry required turning the SCR off tends to be complex, other power semiconductor devices such as bipolar junction transistors, power MOSFETs, insulated gate bipolar transistors (IGBT) and MOS-controlled thyristors (MCTs) are used nowadays.

• Some of the applications of an inverter are listed below:
→ Emergency lighting systems,
→ AC variable speed drives,

→ Uninterrupted power supplies,
→ Frequency converters

DC-to-DC Conversion

- A SCR, power BJT or a power MOSFET is normally used in such a converter and this converter is called a switch-mode power supply.

- A switch-mode power supply can be of one of the types listed below:

→ Step-down switch-mode power supply,
→ Step-up switch-mode power supply,
→ Fly-back converter,
→ Resonant converter

- The typical applications for a switch-mode power supply or a chopper are:

→ DC drive
→ Battery charger
→ DC power supply

AC-to-AC Conversion

- A cycloconverter converts an ac voltage, such as the mains supply, to another ac voltage.
- The amplitude and the frequency of input voltage to a cycloconverter tend to be fixed values, whereas both the amplitude and the frequency of output voltage of a cycloconverter tend to be variable.
- A typical application of a cycloconverter is to use it for controlling the speed of AC traction motor and most of these cycloconverters have a high power output, of the order a few megawatts and SCRs are used in these circuits.

Power electronic devices (part I)

1. The power diode

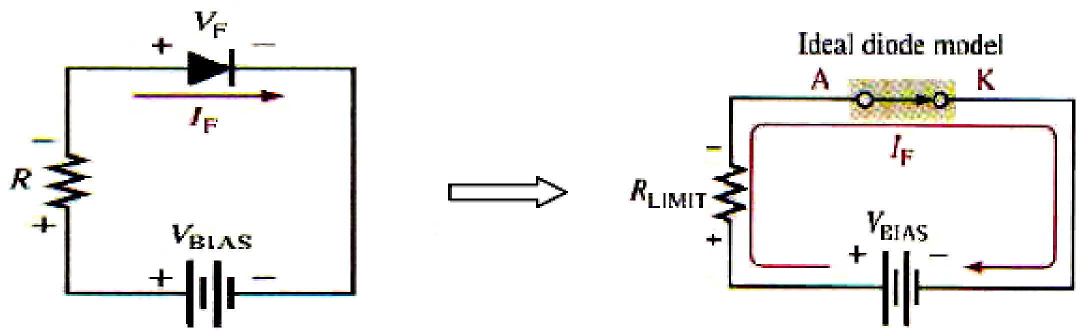
Diode Approximations

i. The Ideal Model

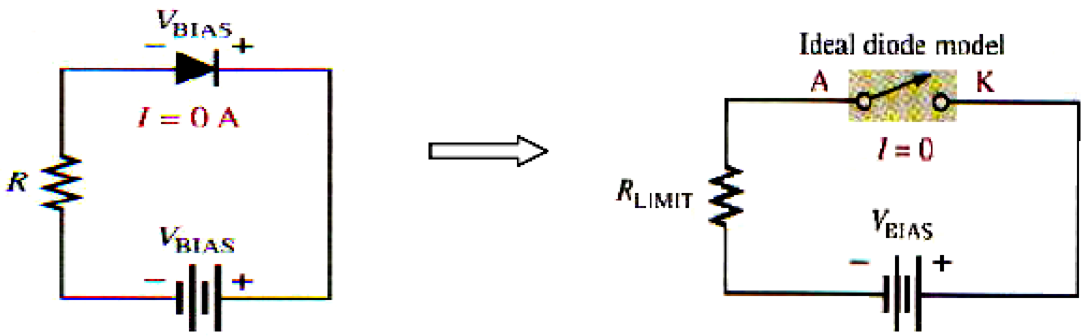
• Think it as switch

• When forward biased, act as a closed (ON) switch

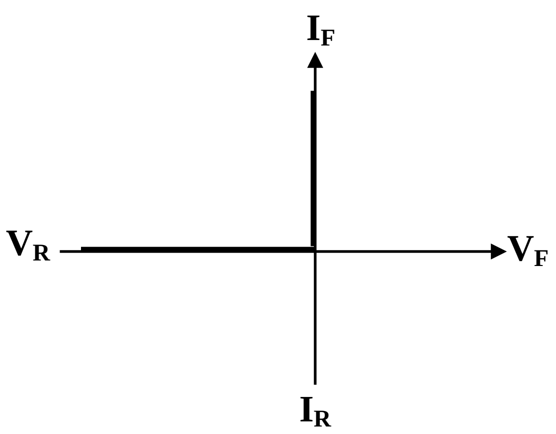
• When reverse biased, act as open (off) switch



Ideal diode model for forward bias



Ideal diode model for reverse bias

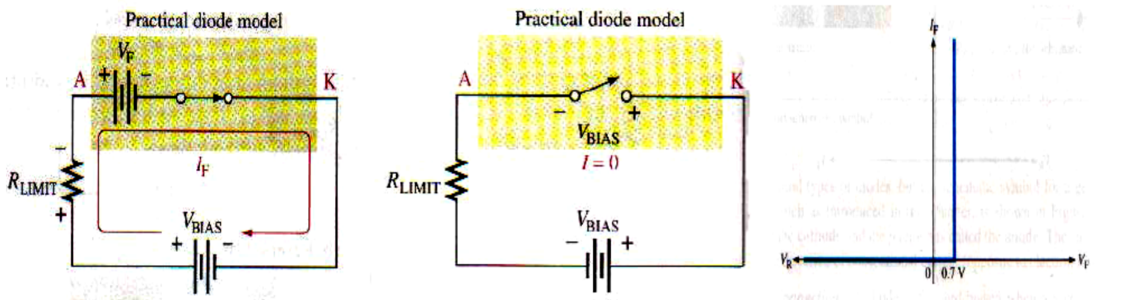


Ideal Characteristic curve (blue) for Ideal model

- This model neglects the effect of the barrier potential, the internal resistance, and other parameters.

ii. The Barrier Potential Model

- The forward biased diode is represented as a closed switch in series with a small ‘battery’ equal to the barrier potential VB (0.7 V for Si and 0.3 V for Ge)
- The positive end of the equivalent battery is toward the anode.
- This barrier potential cannot be measured by using a multimeter, but it has the effect of a battery when forward bias is applied.
- The reverse biased diode is represented by an open switch, because barrier potential does not affect reverse bias.

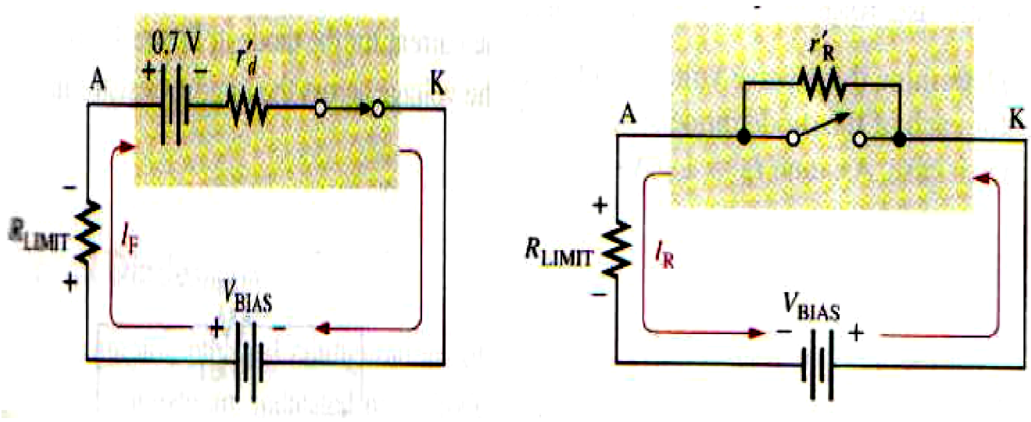


(a) : Forward bias (b) : Reverse bias (c) : Characteristic curve (silicon)

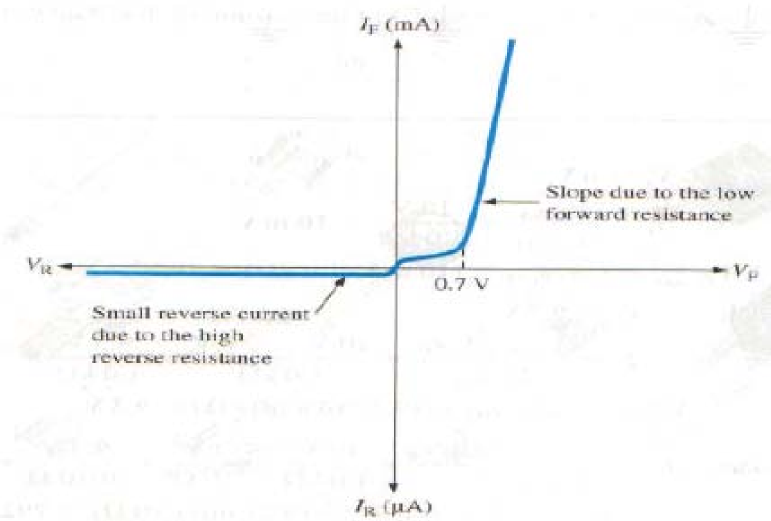
The practical model of a diode

The Complete Diode Model

- More accurate
- The forward biased diode model with both the barrier potential and low forward (bulk) resistance (r'_d)



(a) : Forward bias (b) : Reverse bias



(c) : Characteristic curve (silicon)

Diode Characteristics

• A power diode is a two terminal *pn* – junction device.

• The magnitude of this voltage drop depends on:

a) on the manufacturing process

b) junction temperature

• When the cathode potential is positive with respect to the anode:

⇒ The diode is said to be reverse biased

⇒ A small reverse current (also known as leakage current) in the range of micro or miliampere, flows through it.

⇒ It increases slowly in magnitude with the reverse voltage until the avalanche or zener voltage is reached.

• The *v* – *I* characteristics shown above can be expressed by an equation known as 'Schockley diode equation' and it is given under dc steady state operation by:

$$I_D = I_S\left(e^{V_D / nV_T} - 1\right)$$

• Where:

I_D = Current through the diode, A

V_D = Diode voltage (forward voltage)

I_S = Leakage current (or reverse saturation).

n = emission coefficient

V_T = Thermal Voltage

$$V_T = \frac{kT}{q}$$

q = electron charge : 1.6022×10^{-19} C
T = absolute temperature in Klevin
k = Boltzman's constant : 1.3806×10^{-23} J / K

• The diode characteristics can be divided into three region:
1. Forward – biased region, where VD > 0
2. Reverse – biased region, where VD < 0
3. Breakdown region, where VD < -VBR

Forward – biased region

• VD > 0
• Diode current ID very small if VD is less than a specific value VT (0.7V)
• Diode conducts fully if VD is higher than this value VT, which is referred to as the threshold voltage or the turn-on voltage
• The threshold voltage is a voltage at which the diode conducts fully.

Reverse – biased region

• VD < 0
• If VD is negative and |VD| >> VT, which occurs for VD < -0.1, the exponential term in Schockley equation becomes negligibly small compared to unity and the diode current ID becomes:

$$I_D = I_S\left(e^{V_D / nV_T} - 1\right) \cong -I_S$$

Breakdown region

• Reverse voltage is high.
• Magnitude of reverse voltage exceeds a specified voltage known as the breakdown voltage, VBR
• IR increases rapidly with a small change in reverse voltage beyond VBR.
• The operation in this region will not be destructive provided that the power dissipation is within a 'safe level' that is specified in the manufacture's data sheet.
• But it has to limit I_R in order to limit the power dissipation within a permissible value

Home work :

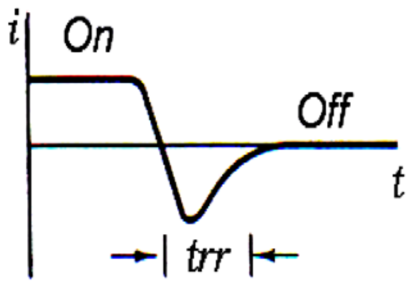
The forward voltage drop of a power diode is V_D = 1.2 V at I_D = 300 A. Assuming that n = 2 and V_T = 25.7 mV, find the reverse saturation current I_S.

LECTURE NO. 2

Reverse Recovery

- An important dynamic characteristic of a non-ideal diode is reverse recovery current
- When a diode turns off, the current in it decreases and momentarily becomes negative before becoming zero as shown in figure below.
- The diode continues to conduct due to minority carries that remain stored in the *pn*-junction.
- The minority carriers require a certain time (trr) to recombine with opposite charges and to be neutralized.

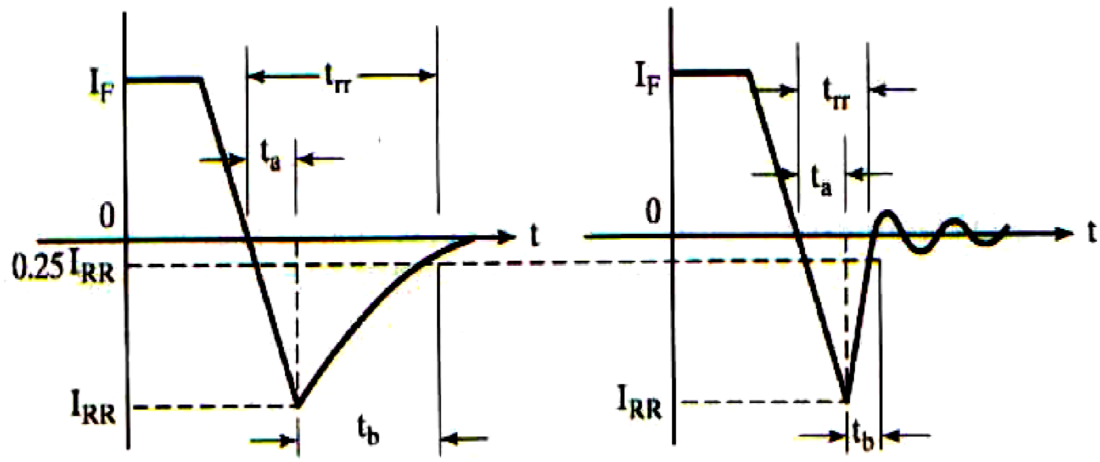
• Effects of reverse recovery:
1. Switching losses increase – especially in high frequency applications,
2. Voltage rating increase,
3. Over voltage (spikes) in inductive loads.



Reverse recovery time

Reverse Recovery Characteristics

• Figure shows two reverse recovery characteristics of junction diodes.



(a) : Soft recovery **(b): Abrupt recovery**

- The reverse recovery time is denoted as t_{rr} and is measured from the initial zero crossing of the diode current to 25% of maximum (peak) reverse current, I_{RR}.
- t_{rr} consists of two components, t_a and t_b .
- t_a is due to charge storage in the depletion region of the junction and represents the time between the zero crossing and the peak reverse current, I_{RR}.
- t_b is due to charge stored in the bulk semiconductor material.
- The ratio t_b / ***ta*** is known as ***softness factor***, ***SF***.
- For practical purposes, need to be concerned with the total recovery time t_{rr} and the peak value of the reverse current I_{RR}.

$$t_{rr} = t_a + t_b$$

- The peak reverse current can be expressed in reverse *di/dt* as:

$$I_{RR} = t_a \times \frac{di}{dt}$$

- ***trr*** is dependent on the *junction temperature*, *rate of fall of forward current*, and the *forward current* prior to commutation.
- ***Reverse recovery charge, QRR***, is amount of charge carriers that flow across the diode in the reverse direction due to changeover from forward conduction to reverse blocking condition.
- ***QRR*** value is determined from the area enclosed by the path of the reverse recovery current.
- The storage charge, which is the area enclosed by the path of the recovery current, is approximately:

$$Q_{RR} \cong \frac{1}{2} I_{RR} t_a + \frac{1}{2} I_{RR} t_b = \frac{1}{2} I_{RR} t_{rr}$$

Or;

$$I_{RR} \cong \frac{2Q_{RR}}{t_{rr}}$$

Then;

$$t_{rr} t_a = \frac{2Q_{RR}}{di/dt}$$

If t_b is negligible as compared to t_a , which usually the case, $t_{rr} \approx t_a$, then;

$$t_{rr} \cong \sqrt{\frac{2Q_{RR}}{di/dt}}$$

And

$$I_{RR} = \sqrt{2Q_{RR}\frac{di}{dt}}$$

- The storage charge is dependent on the forward diode current, $\boldsymbol{I_F}$.
- The ***peak reverse recovery current*** $\boldsymbol{I_{RR}}$, *reverse charge* $\boldsymbol{Q_{RR}}$, and the ***softness factor SF*** are very important parameters for circuit design and are normally included in the diodes specification sheets.
- A diode which is in a reverse-biased, then been forward-biased again. It also requires a certain time known as forward recovery (turn-on) time before all the majority carriers over the whole junction can contribute to the current flow.
- If the rate of rise of the forward current is high and the forward current is concentrated to a small area of the junction, the diode will fail.

Home Work:

The reverse recovery time of a diode is t_{rr} = 3 µs and the rate of fall of the diode current is *di/dt* = 30 A/µs. Determine:
(a) The storage charge $\boldsymbol{Q_{RR}}$
(b) The peak reverse current $\boldsymbol{I_{RR}}$

EXAMPLE (1): The manufacturer of a selected diode gives the rate of fall of the diode current *di/dt* = 20A/µs, and a reverse recovery time of t_{rr}=5 µs. What value of peak reverse current do you expect?

SOLUTION: The peak reverse current is given as:

$$I_{rr} = \sqrt{\frac{di}{dt}2Q_{RR}}$$

The storage charge Q_{RR} calculated as:

$$Q_{RR} = \frac{1}{2}\frac{di}{dt}t_{rr}^{2}$$

$$= 1/2 \times 20\ A/\mu s \times (5 \times 10^{-6})^2 = 50\ \mu C.$$

$$I_{rr} = \sqrt{20\frac{a}{\mu s} \times 2 \times 50\ \mu C} = 44.72\ A$$

2. Thyristor (SCR)

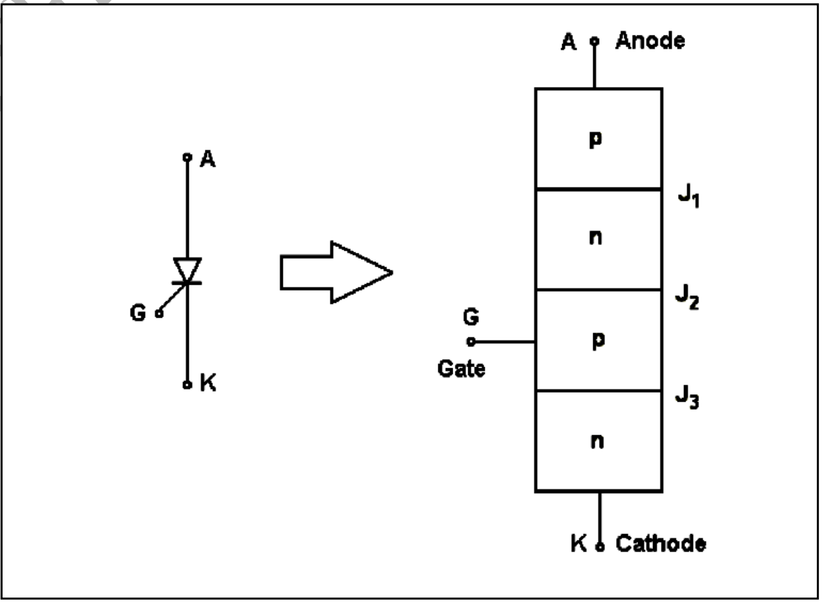
2.1 Introduction

Thyristors are usually three-terminal devices with four layers of alternating p- and n-type material (i.e. three p-n junctions) in their main power handling section. The control terminal of the thyristor, called the gate (G) electrode, may be connected to an integrated and complex structure as part of the device. The other two terminals, anode (A) and cathode (K), handle the large applied potentials and conduct the major current through the thyristor. The anode and cathode terminals are connected in series with the load to which power is to be controlled.

Figure 1.24 : Various thyristor configurations

2. Basic Structure and Operation

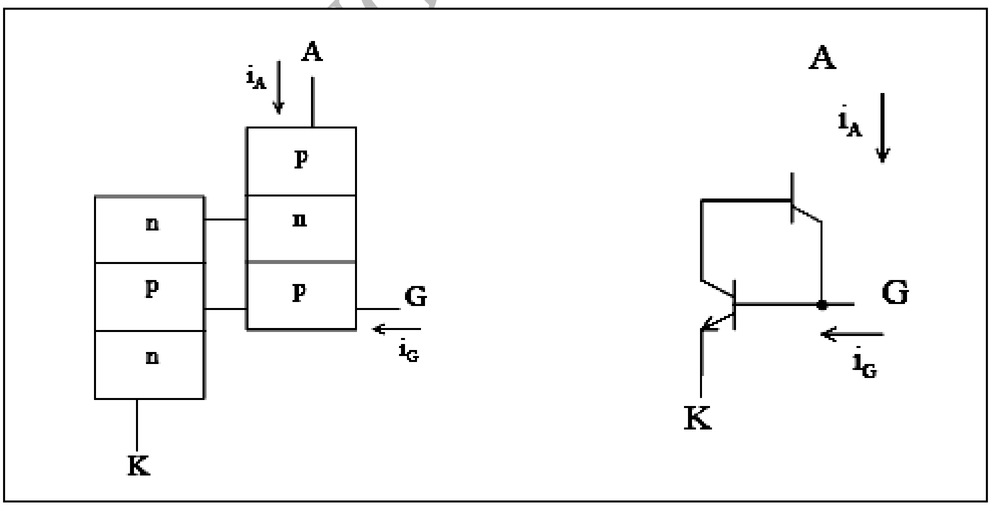
Figure below shows a conceptual view of a typical thyristor with the three p-n junctions and the external electrodes labeled. Also shown in the figure the thyristor circuit symbol used in electrical schematics.



The operation of thyristors is as follows. When a positive voltage is applied to the anode (with respect to a cathode), the thyristor is in its forward-blocking state. The center junction J_2 (see Figure above) is reverse-biased. In this operating mode, the gate current is held to zero (open-circuit). In this condition only thermally generated leakage current flows through the device and can often be approximate as zero in value. When a positive gate current is injected into the device J_3 becomes forward-biased and electrons are injected from the n-emitter into the p-base. The thyristor is latched in its on state (forward-conduction).

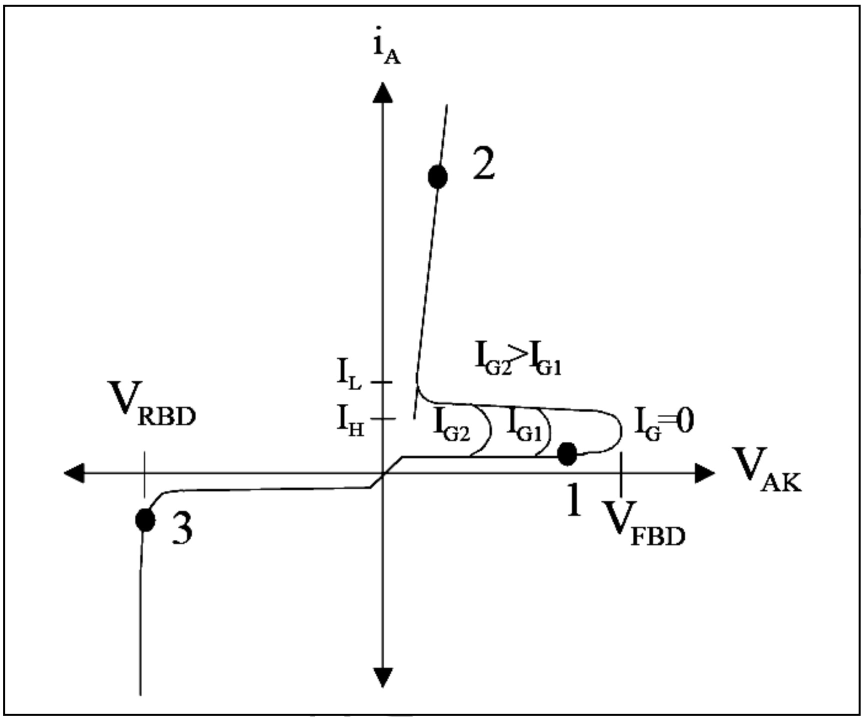
This switching behavior can also be explained in terms of the two-transistor analog shown in Figure below. The two transistors are regenerative coupled so that if the sum of their forward current gains (α's) exceeds unity, each drives the other into saturation. The forward current gain (expressed as the ratio of collector current to emitter current) of the pnp transistor is denoted by α_p, and that of the npn as α_n. The α's are current dependent and increase slightly as the current increases. The center junction J_2 is reverse-biased under forward applied voltage (positive V_{AK}).

When Gate current increases the current in both transistors are increased. Collector current in the npn transistor acts as base current for the pnp, and analogously, the collector current of the pnp acts as base current driving the npn transistor. The thyristor switches to its on-state (latches). This condition can also be reached, without any gate current, by increasing the forward applied voltage so that the internal leakage current increased.



Current-Voltage Curves for Thyristors

A plot of the anode current (i_A) as a function of anode cathode voltage (V_{AK}) is shown in Figure below. The forward blocking mode is shown as the low-current portion of the graph (solid curve around operating point "1"). With zero gate current and positive V_{AK} the forward characteristic in the "off state" or "blocking-state" is determined by the center junction J_2, which is reverse-biased. At operating point "1", very little current flows (I_{co} only) through the device. However, if the applied voltage exceeds the forward-blocking voltage, the thyristor switches to its "on-state" or "conducting-state" (shown as operating point "2") because of carrier multiplication. The effect of gate current is to lower the blocking voltage at which switching takes place.



The thyristor moves rapidly along the negatively sloped portion of the curve until it reaches a stable operating point determined by the external circuit (point ‘‘2"). The portion of the graph indicating forward conduction shows the large values of i_A that may be conducted at relatively low values of V_{AK} , similar to a power diode.

LECTURE NO. 3

AC-DC converter (Rectifiers)

Introduction

Certain terms will be frequently used in this lesson and subsequent lessons while characterizing different types of rectifiers. Such commonly used terms are defined in this section.

Let "f(t)" be the instantaneous value of any voltage or current associated with a rectifier circuit, then the following terms, characterizing the properties of "f(t)", can be defined.

Peak value of f(t) : As the name suggests f_{max}.

Average (DC) value of f(t) is (F_{av}) : Assuming f(t) to be periodic over the time period T

$$F_{av} = \frac{1}{T}\int_0^T f(t)dt$$

RMS (effective) value of f(t) is (F_{RMS}) : For f(t) , periodic over the time period T,

$$F_{RMS} = \sqrt{\frac{1}{T}\int_0^T f^2(t)dt}$$

Form factor of f(t) is (f_{FF}) : Form factor of 'f(t) ' is defined as:

$$f_{FF} = \frac{F_{RMS}}{F_{av}}$$

Ripple factor of f(t) is (f_{RF}) : Ripple factor of f is defined as:

$$f_{RF} = \frac{\sqrt{F_{RMS}^2 - F_{av}^2}}{F_{av}} = \sqrt{f_{FF}^2 - 1}$$

Ripple factor can be used as a measure of the deviation of the output voltage and current of a rectifier from ideal dc.

Peak to peak ripple of f(t) is f_{pp}: By definition

$$f_{pp} = f_{max} - f_{min} \text{ Over period T}$$

Single-Phase Diode Rectifiers

There are two types of single-phase diode rectifier that convert a single-phase ac supply into a dc voltage, namely, single-phase half-wave rectifiers and single-phase full-wave rectifiers.. For the sake of simplicity the diodes are considered to be ideal, that is, they have zero forward voltage drop and reverse recovery time. This assumption is generally valid for the case of diode rectifiers that use the mains, a low-frequency source, as the input, and when the forward voltage drop is small compared with the peak voltage of the mains.

Single-Phase Half-Wave Rectifiers(R-Load)

The simplest single-phase diode rectifier is the single-phase half-wave rectifier. A single-phase half-wave rectifier with resistive load is shown in Figure below. The circuit consists of only one diode that is usually fed with a transformer secondary as shown. During the positive half-cycle of the transformer secondary voltage, diode D conducts. During the negative half-cycle, diode D stops conducting. Assuming that the transformer has zero internal impedance and provides perfect sinusoidal voltage on its secondary winding, the voltage and current waveforms of resistive load R and the voltage waveform of diode D are shown in Figure below.

→It is clear that the peak inverse voltage (PIV) of diode D is equal to V_m.

→Hence the Peak Repetitive Reverse Voltage (V_{RRM}) rating of diode D must be chosen to be higher than V_m to avoid reverse breakdown.

→ The Peak Repetitive Forward Current (I_{FRM}) rating of diode D must be chosen to be higher than the peak load current V_m/R.

The average value of the load voltage v_L is V_{dc} and it is defined as:

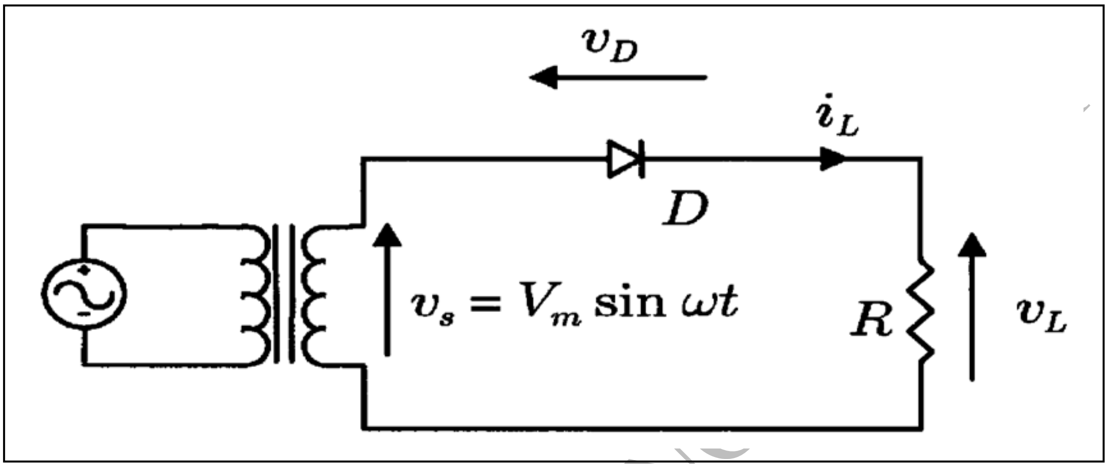
$$V_{dc} = \frac{1}{T}\int_0^T v_L(t)\,dt$$

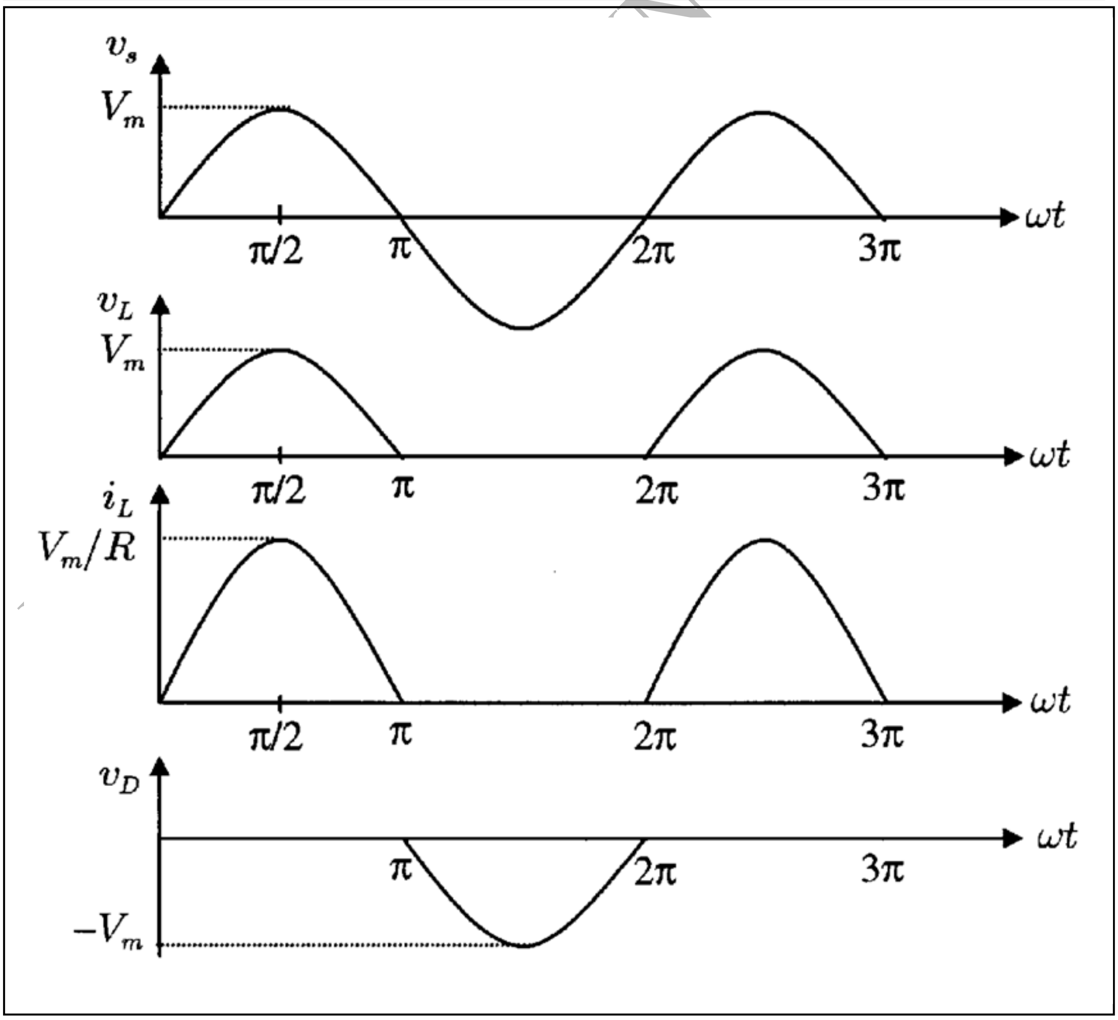
That load voltage $V_L(t)=0$, for the negative half-cycle. Note that the angular frequency of the source $\omega=2\pi/T$. Then:

$$V_{dc} = \frac{1}{2\pi}\int_0^{\pi} V_m \sin \omega t d(\omega t)$$

Therefore,

$$V_{dc} = \frac{V_m}{\pi} = 0.318\, V_m$$





The root-mean-square (rms) value of load voltage v_L is V_L, which is defined as:

$$V_L = \left[\frac{1}{T}\int_0^T v_L^2(t)dt\right]^{1/2}$$

In the case of a half-wave rectifier, $V_L(t)=0$ for the negative half-cycle, therefore,

$$V_L = \sqrt{\frac{1}{2\pi}\int_0^{\pi}(V_m \sin\omega t)^2 d(\omega t)}$$

Or;

$$V_L = \frac{V_m}{2} = 0.5\ V_m$$

The average value of load current $\boldsymbol{i_L}$ is $\mathbf{I_{dc}}$ and because load R is purely resistive it can be found as:

$$I_{dc} = \frac{V_{dc}}{R}$$

The root-mean-square (rms) value of load current i_L is I_L and it can be found as:

$$I_L = \frac{V_L}{R}$$

In the case of a half-wave rectifier,

$$I_{dc} = \frac{0.318\ V_m}{R}$$

And

$$I_L = \frac{0.5\ V_m}{R}$$

→The rectification ratio, which is a figure of merit for comparing the effectiveness of rectification, is defined as:

$$\frac{\mathbf{P_{dc}}}{\mathbf{P_L}} = \frac{\mathbf{V_{dc}I_{dc}}}{\mathbf{V_L I_L}}$$

In the case of a half-wave diode rectifier, the rectification ratio can be determined by:

$$= \frac{(0.318\ V_m)^2}{(0.5\ V_m)^2} = 40.5\%$$

→The form factor (FF) is defined as the ratio of the root-mean square value of a voltage or current to its average value,

$$\mathrm{FF} = \frac{V_L}{V_{dc}} \quad \text{or} \quad \frac{I_L}{I_{dc}}$$

$$\mathrm{FF} = \frac{0.5\ V_m}{0.318\ V_m} = 1.57$$

→The ripple factor (RF), which is a measure of the ripple content, is defined as:

$$\mathrm{RF} = \frac{V_{ac}}{V_{dc}}$$

Where V_{ac} is the effective (rms) value of the ac component of load voltage V_L,

$$V_{ac} = \sqrt{V_L^2 - V_{dc}^2}$$

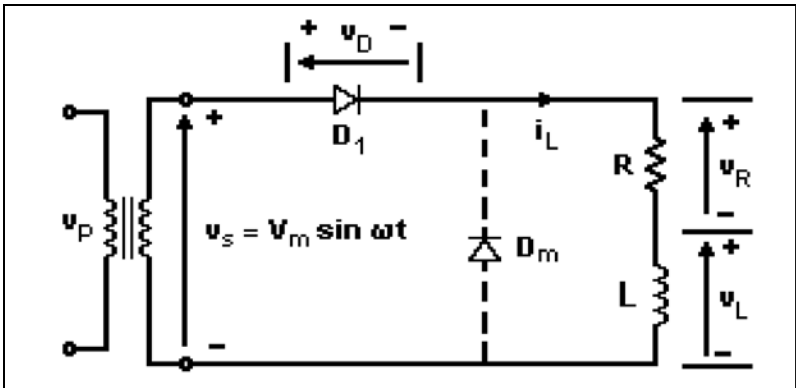
$$\mathrm{RF} = \sqrt{\left(\frac{V_L}{V_{dc}}\right)^2 - 1} = \sqrt{\mathrm{FF}^2 - 1}$$

$$\mathrm{RF} = \sqrt{1.57^2 - 1} = 1.21$$

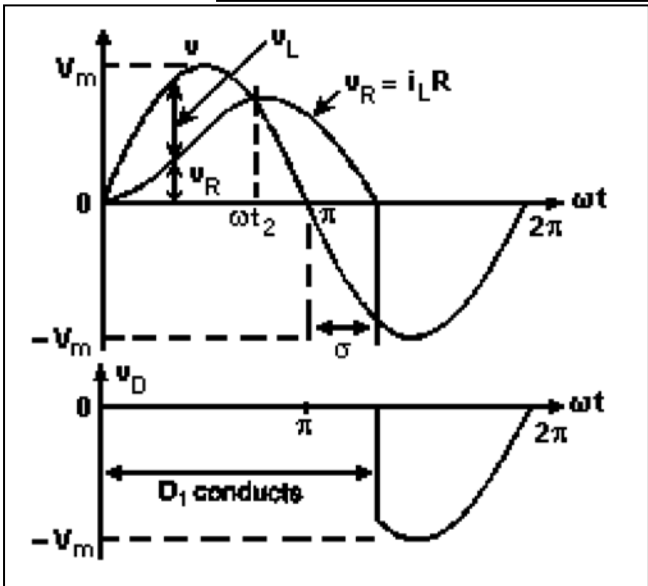
LECTURE NO. 4

Single Phase Half-Wave Rectifier (RL- Load)

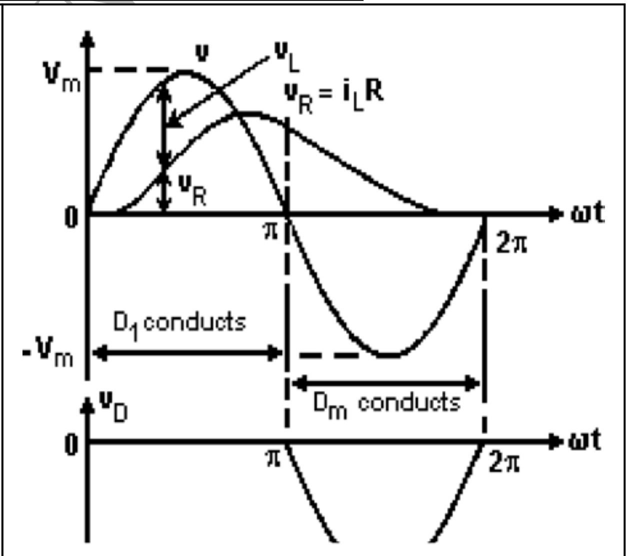
The half wave rectifier with an inductive load (RL) is shown in figure below.



(a) Circuit diagram



Without freewheeling diode



With freewheeling diode

During the interval 0 to π/2

The source voltage **V**s increases from zero to its positive maximum, while the voltage across the inductor $\mathbf{V}_L$ opposes the change of current through the load. It must be noted that the current through an inductor cannot change instantaneously; hence, the current gradually increases until it reaches its maximum value. The current does not reach its peak when the voltage is at its maximum, which is consistent with the fact that the current through an inductor lags the voltage across it. During this time, energy is transferred from the ac source and is stored in the magnetic field of the inductor.

For the interval π/2 and π

The source voltage decreases from its positive maximum to zero. The induced voltage in the inductor reverses polarity and opposes the associated decrease in current, thereby aiding the diode forward current. Therefore, the current starts decreasing gradually at a delayed time, becoming zero when all the energy stored by then inductor is released to the circuit. Again, this is consistent with the fact that current lags voltage in an inductive circuit. Hence, even after the source voltage has dropped past zero volts, there is still load current, which exists a little more than half a cycle.

For the interval greater than π

At π, the source voltage reverses and starts to increase to its negative maximum. However, the voltage induced across the inductor is still positive and will sustain forward conduction of the diode until this induced voltage decreases to zero. When this induced voltage falls to zero, the diode will now be reversed biased, but would have conducted forward current for an angle β, where $\beta = \pi + \sigma$. σ is the extended angle of current conduction due to the energy stored in the magnetic field being returned to the source.

The instantaneous supply voltage $\mathbf{V}_s$ is given by:

$$\mathbf{V}_s = \mathbf{V}_R + \mathbf{V}_L$$

For angles, less than ωt_2 the inductor is storing energy in its magnetic field from the source and the inductor voltage would be such as to oppose the growth of current and the supply voltage. For angles greater than ωt_2 the inductor voltage would have reversed and would aid the supply voltage to prevent the fall of current. Hence, the average inductor voltage is zero.

From the preceding discussion

-For $0 \le \omega t \le \beta$

$$v_D = 0$$

$$v_o = v_i$$

$$i_o = i_i$$

For $\beta \le \omega t \le 2\pi$

$$v_o = 0$$

$$i_o = i_i = 0$$

$$v_D = v_i - v_o = v_i$$

The average output voltage is given by:

$$V_{dc} = \frac{1}{2\pi}\int_0^{2\pi} v_0 d\omega t = \frac{1}{2\pi}\int_0^{\beta} \sqrt{2}V_i \sin\omega t d\omega t$$

$$= \frac{\sqrt{2}V_i}{\pi}\left(\frac{1-\cos\beta}{2}\right)$$

Where, $V_m = \sqrt{2}V_i$

The rms output voltage is given by:

$$V_L = \sqrt{\frac{1}{2\pi}\int_0^{\beta} 2V_i^2 \sin^2\omega t d\omega t}$$

$$= \sqrt{\frac{V_i^2}{2\pi}\left(\beta - \frac{1}{2}\sin 2\beta\right)} = \frac{V_i}{\sqrt{2}}\sqrt{\frac{2\beta - \sin 2\beta}{2\pi}}$$

Form factor of the voltage waveform is:

$$FF = \frac{V_L}{V_{dc}} = \pi\sqrt{\frac{2\beta - \sin 2\beta}{2\pi(1-\cos\beta)^2}}$$

$$RF = \sqrt{FF^2 - 1}$$

$$= \sqrt{\frac{\pi(2\beta - \sin 2\beta)}{2(1-\cos\beta)^2} - 1}$$

All these quantities are functions of β which can be found as follows.

-For $0 \le \omega t \le \beta$

$$v_i = \sqrt{2}V_i \sin\omega t = L\frac{dio}{dt} + Ri_0$$

$$i_0(\omega t = 0) = i_0(\omega t = \beta) = 0$$

The solution is given by:

$$i_0 = I_0 e^{-\frac{\omega t}{\tan\varphi}} + \frac{\sqrt{2}V_i}{Z}\sin(\omega t - \varphi)$$

Where;

$$\tan\varphi = \frac{\omega L}{R}$$

$$Z = \sqrt{R^2 + \omega^2 L^2}$$

The addition of a freewheeling diode

The average dc voltage varies proportionately to [1 - cos(β)]. This can be made to be a maximum, thereby increasing the average dc voltage, by making cos(β) a maximum. The maximum value that this can take is given by $\cos(\pi + \sigma) = 1$, which can be obtained if $\sigma = 0$. We can make $\sigma = 0$ with the addition of a freewheeling diode given by $\mathbf{D}_m$ as shown with the dotted line.

When the supply voltage goes to zero, the current from $\mathbf{D}_1$ is transferred across to diode $\mathbf{D}_m$. This is called commutation of diodes. The result is the charge in the inductor will be used to keep diode $\mathbf{D}_m$ on, instead of previously forcing $\mathbf{D}_1$ to remain in its forward state. This would reduce the value of the extended angle of conduction of the diode $\mathbf{D}_1$, σ to zero.

We can see that if the value of the inductance is high, it will store more charge and therefore be able to keep diode $\mathbf{D}_m$ on for a longer time.

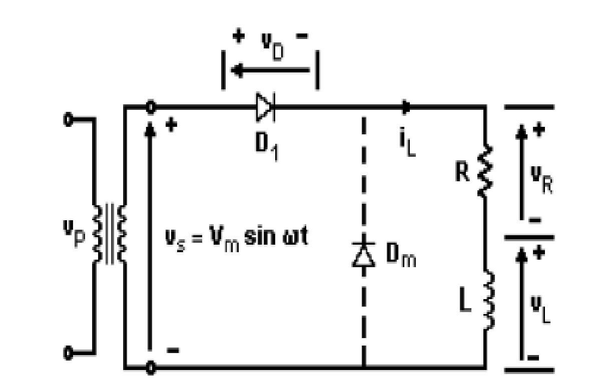
Then the inductor would be able to keep diode $\mathbf{D}_m$ on for the entire duration of the negative half cycle, and by so doing, maintain a continuous load current.

<u>Home work:</u> Consider the circuit shown with:

i) Purely resistive load.
ii) Resistive-inductive load.

Then determine the following factors:

a. The efficiency
b. The ripple factor
c. The peak inverse voltage (PIV) of diode D_1
d. Form factor



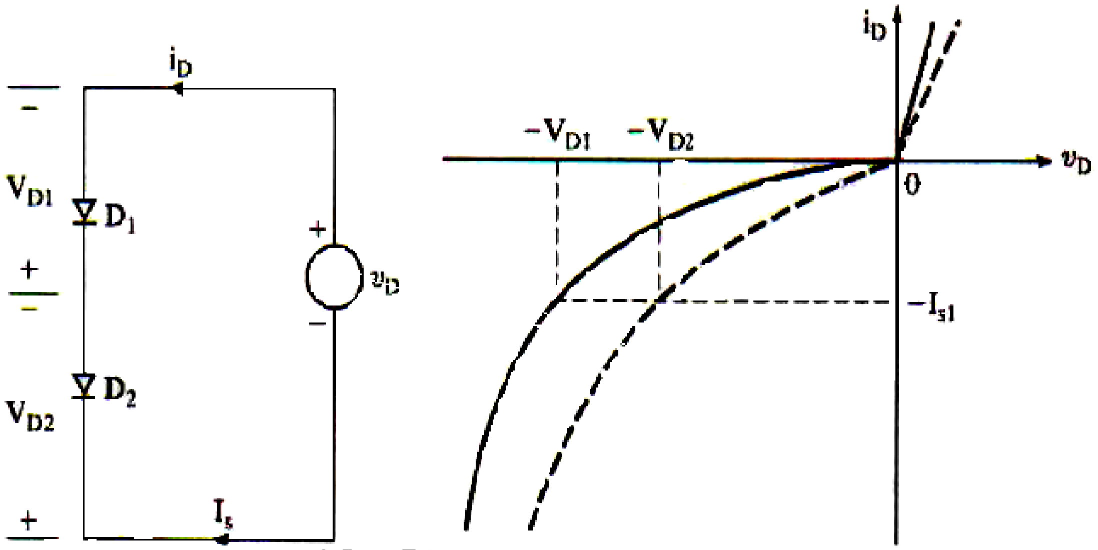
(a) Circuit diagram

R=110Ω, L=100mH, Vs=30V

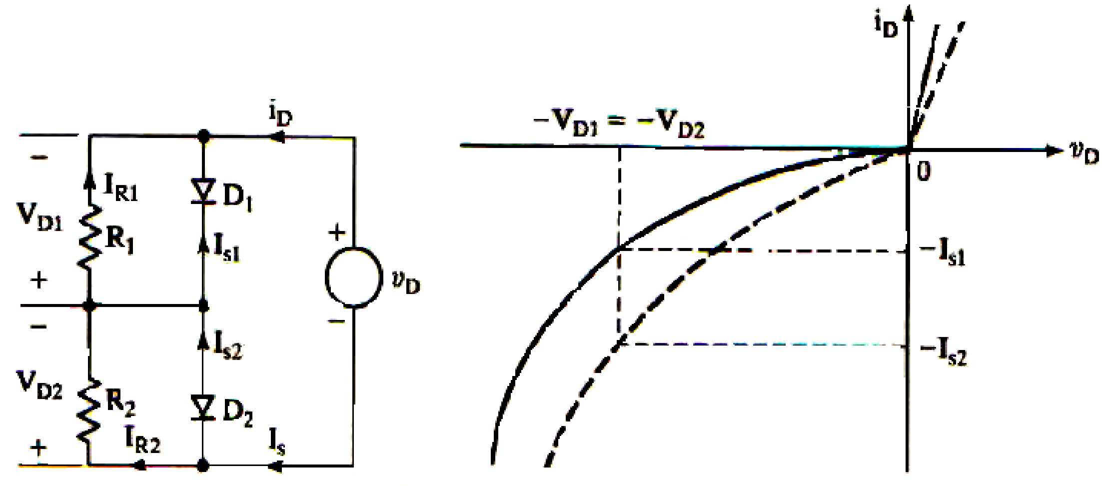
LECTURE NO. 5

<u>High Voltage Series Connected Diodes</u>

- In many high voltage applications, one commercially diode cannot meat the required voltage rating
- Because of this reason, diodes are connected in series to increase the reverse blocking capabilities.



- VD1 and VD2 are the sharing reverse voltages of diodes D1 and D2.
- In practice, the *v-i* characteristics for the same type of diodes differ due to tolerances in their production process.
- Refer to the figure above, for reverse blocking conditions, each diode has to carry the same leakage current. And as a result, the blocking voltage will be different.
- The solution is to force equal voltage sharing by connecting a resistor across each diode as shown in figure below.
- This will make the leakage current of each diode would be different because the total leakage current must be shared by a diode and its resistor.



(a) Circuit diagram (b) $v - i$ characteristics

$$V_{D1} + V_{D2} = V_S$$

$$I_S = I_{S1} + I_{R1} = I_{S2} + I_{R2}$$

$$I_{R1} = \frac{V_{D1}}{R_1} \text{ and } I_{R2} = \frac{V_{D2}}{R_2}$$

$$I_{S1} + \frac{V_{D1}}{R_1} = I_{S2} + \frac{V_{D2}}{R_2}$$

<u>Howe work:</u>

Two diodes are connected in series, shown in figure above to share a total dc reverse voltage of VD = 5kV. The reverse leakage currents of the two diodes are I_{S1}=30mA and I_{S2}=35mA.

a) Find the diode voltages if the voltage sharing resistance are equal, $R_1=R_2=R=100k\Omega$.
b) Find the voltage sharing resistances R1 and R2 if the diode voltages are equal, $V_{D1}=V_{D2}=0.5V_D$

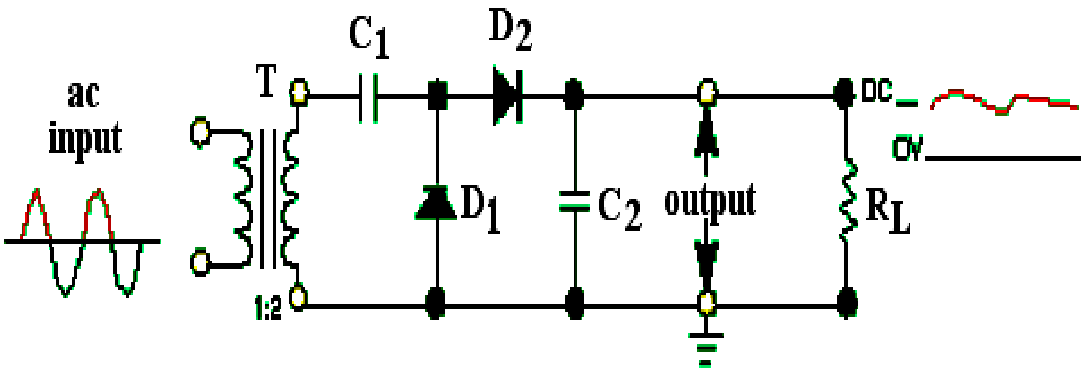
<u>Voltage Multiplier</u>

Voltage multipliers may also be used as primary power supplies where a 177 volt-ac input is rectified to pulsating dc. This dc output voltage may be increased (through use of a voltage multiplier) to as much as 1000 volts dc. This voltage is generally used as the plate or screen grid voltage for electron tubes.

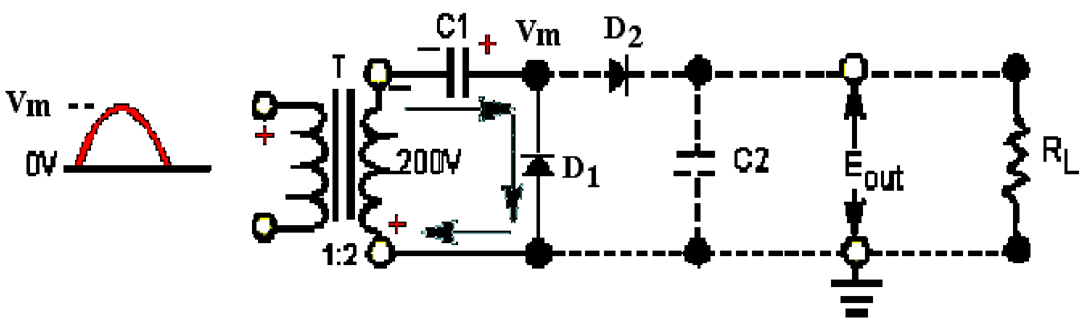
Voltage multipliers may be classified as voltage doublers, triplers, or quadruplers. The classification depends on the ratio of the output voltage to the input voltage. For example, a voltage multiplier that increases the peak input voltage twice is called a voltage doubler. Voltage multipliers increase voltages through the use of series-aiding voltage sources.

Half wave voltage multiplier

Figure below shows the schematic for a half-wave voltage doubler. Notice the similarities between this schematic and those of half-wave voltage rectifiers. In fact, the doubler shown is made up of two half-wave voltage rectifiers. C_1 and D_1 make up one half-wave rectifier, and C_2 and D_2 make up the other. The schematic of the first half-wave rectifier is indicated by the dark lines in figure below. The dotted lines and associated components represent the other half-wave rectifier and load resistor.

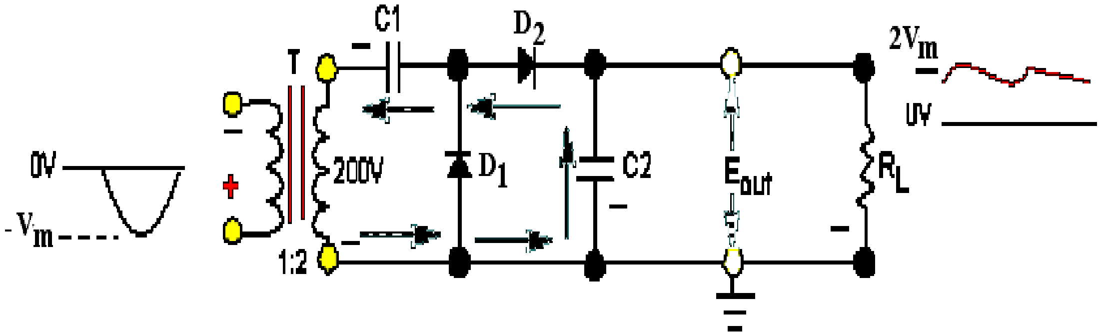


Notice that C_1 and D_1 work exactly like a half-wave rectifier. During the positive alternation of the input cycle, the polarity across the secondary winding of the transformer is make the top of the secondary is negative. At this time D_1 is forward biased (cathode negative in respect to the anode). This forward bias causes D_1 to function like a closed switch and allows current to follow the path indicated by the arrows. At this time, C_1 charges to the peak value of the input voltage.



During the period when the input cycle is negative, the polarity across the secondary of the transformer is reversed. Note specifically that the top of the secondary winding is now positive. This condition now forward biases D_2 and reverse biases D_1. A series circuit now exists consisting of

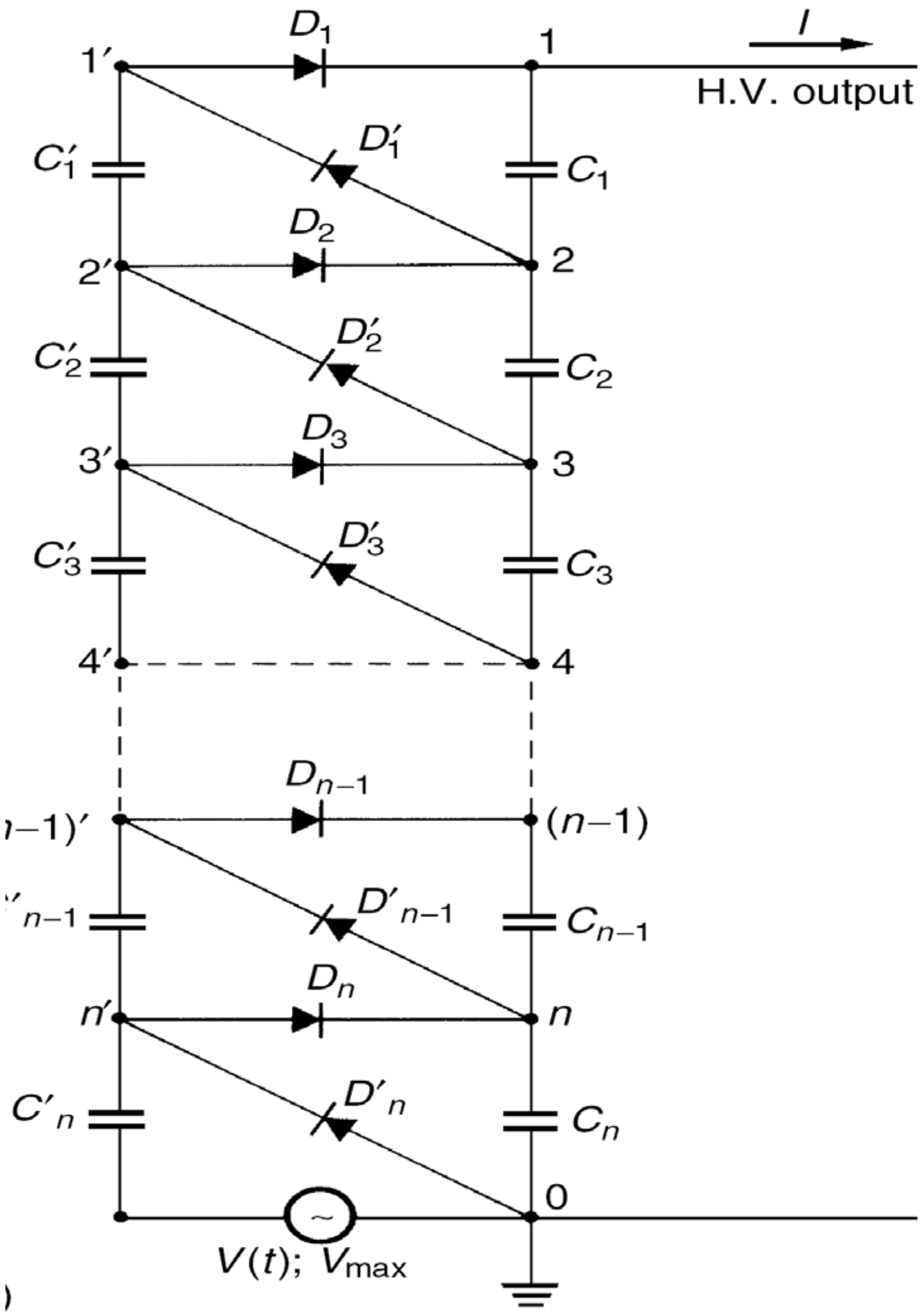
C_1, D_2, C_2, and the secondary of the transformer. The secondary voltage of the transformer now aids the voltage on C_1. This results in a pulsating dc voltage with $2V_m$, as shown by the waveform. The effect of series aiding is comparable to the connection of two batteries in series. As shown in figure C_2 charges to the sum of these voltages.



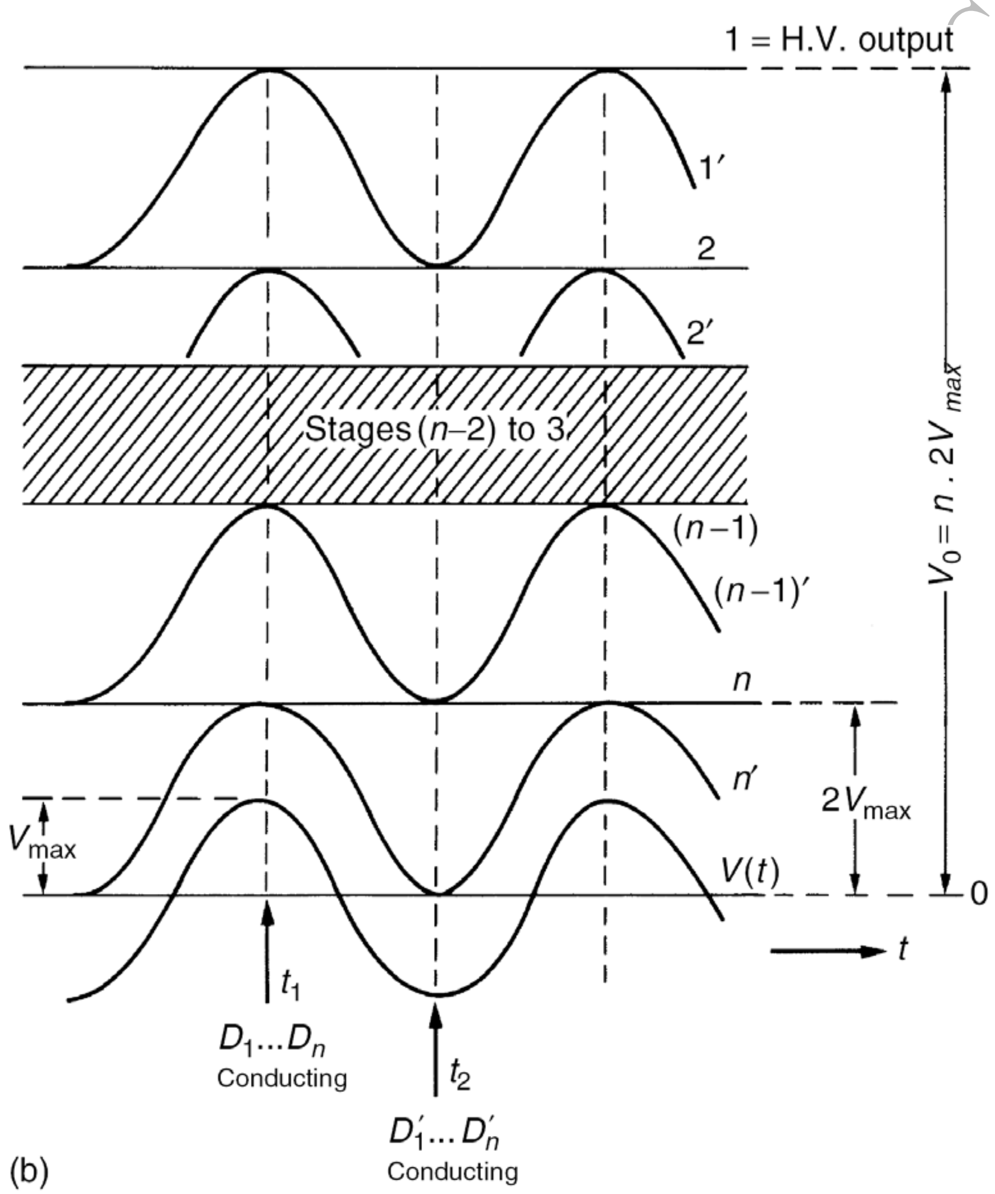
LECTURE NO. 6

Cascade Voltage Multiplier

To demonstrate the principle only, an n-stage single-phase cascade circuit of the 'Cockcroft–Walton type', shown in figure below, will be presented.



HV output open-circuited: **I = 0**. The portion (0 -n' -V(t)) is a half-wave rectifier circuit in which C'_n charges up to a voltage of $+V_{max}$ if V(t) has reached the lowest potential, $-V_{max}$. If C_n is still uncharged, the rectifier D_n conducts as soon as V(t) increases. As the potential of point n' swings up to $+V_{2max}$ during the period T = 1/f, point **n** attains further on a steady potential of $+2V_{max}$ if V(t) has reached the highest potential of $+V_{max}$. The part (n' - n – 0) is therefore a half-wave rectifier, in which the voltage across D'_n can be assumed to be the a.c. voltage source.

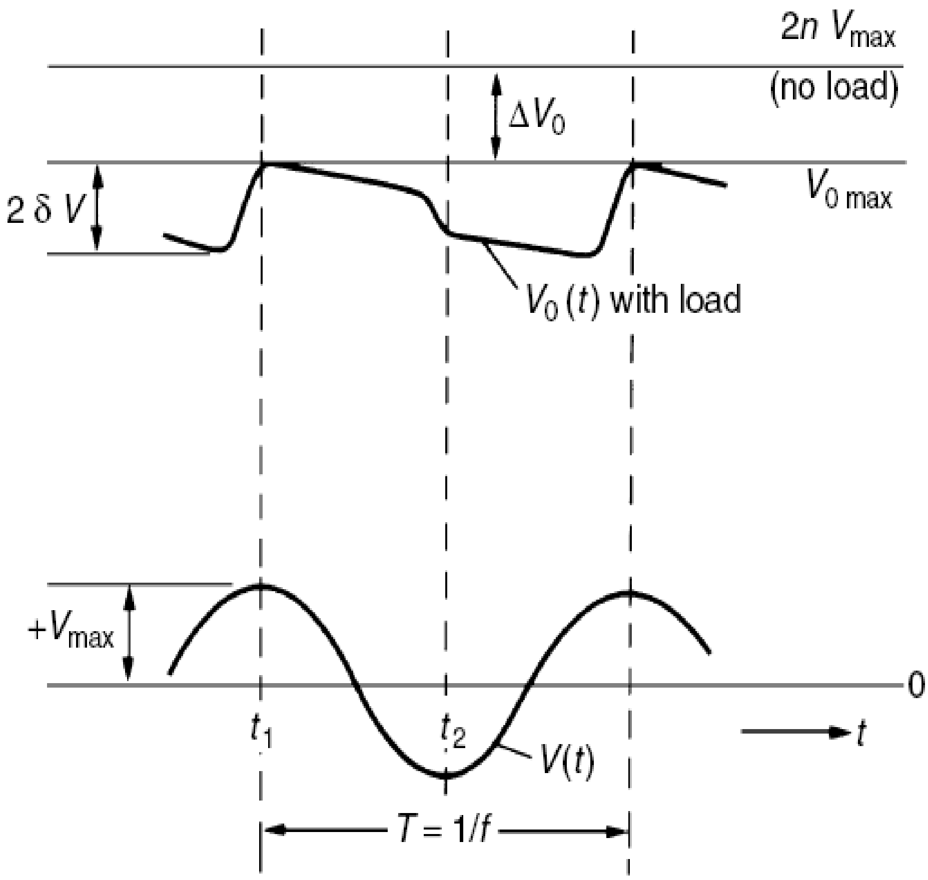


The current through D_n that charged the capacitor C_n was not provided by D'_n, but from V(t) and C'_n. We can assume that the voltage across C_n is not reduced if the potential n' oscillates between zero and $+2V_{max}$. If the potential of n', however, is zero, the capacitor C'_{n-1} is also charged to the potential of n, i.e. to a voltage of +2Vmax. The next voltage oscillation of V(t) from -Vmax to +Vmax will force the diode D_{n-1} to conduct, so that also C_{n-1} will be charged to a voltage of $+2V_{max}$.

The steady state potentials at all nodes of the circuit are sketched for the circuit for zero load conditions. From this it can be seen, that:

1- The potentials at the nodes **(1', 2' . . . n')** are oscillating due to the voltage oscillation of V(t);
2- The potentials at the nodes **(1, 2 . . . n)** remain constant with reference to ground potential;
3- The voltages across all capacitors are of d.c. type, the magnitude of which is 2Vmax across each capacitor stage, except the capacitor C'_n which is stressed with V_{max} only;
4- Every rectifier $\mathbf{D_1, D'_1 \ldots D_n, D'_n}$ is stressed with $2V_{max}$ or twice a.c. peak voltage; and
5- The HV output will reach a maximum voltage of $2nV_{max}$.

H.V. output loaded: **I > 0.** If the generator supplies any load current I, the output voltage will never reach the value $2nV_{max}$.There will also be a ripple on the voltage, and therefore we have to deal with two quantities: the voltage drop ΔV_o and the peak-to-peak ripple $2\delta V$. The sketch in figure below shows the shape of the output voltage and the definitions of ΔV_o and $2\delta V$.



Let a charge q be transferred to the load per cycle, which is obviously q = I x T. This charge comes from the smoothing column, the series connection of $C_1 \ldots C_n$. If no charge would be transferred during **T** from this stack via $D'_1 \ldots D'_n$ to the oscillating column. However, just before the time instant t2 every diode $D'_1 \ldots D'_n$ transfers the same charge q, and each of these charges discharges all capacitors on the smoothing column between the relevant node and ground potential, the ripple will be:

$$\delta V = \frac{I}{2f}\left(\frac{1}{C_1} + \frac{2}{C_2} + \frac{3}{C_3} + \ldots \frac{n}{C_n}\right)$$

Thus in a cascade multiplier the lowest capacitors are responsible for most ripple and it would be desirable to increase the capacitance in the lower stages. This is, however, very inconvenient for H.V. cascades, as a voltage breakdown at the load would completely overstress the smaller capacitors within the column. Therefore, equal capacitance values are usually provided, and with $C = C_1 = C_2 = C_3 \ldots C_n$,

$$\delta V = \frac{I}{fC} \times \frac{n(n+1)}{4}$$

To calculate the total voltage drop ΔV_o, we will first consider the stage n. Although the capacitor C'_n at time t_1 will be charged up to the full voltage V_{max}, if ideal rectifiers and no voltage drop within the a.c.-source are assumed,

$$\Delta V_0 = \frac{I}{fC}\left(\frac{2n^3}{3} + \frac{n^2}{2} - \frac{n}{6}\right)$$

For a given number of stages, this maximum voltage or also the mean value $V_o = V_{omax} - \delta V$ will decrease linearly with the load current **I** at constant

Where $\mathbf{V_{o\,max} = 2nV_{max} - \Delta V_o}$

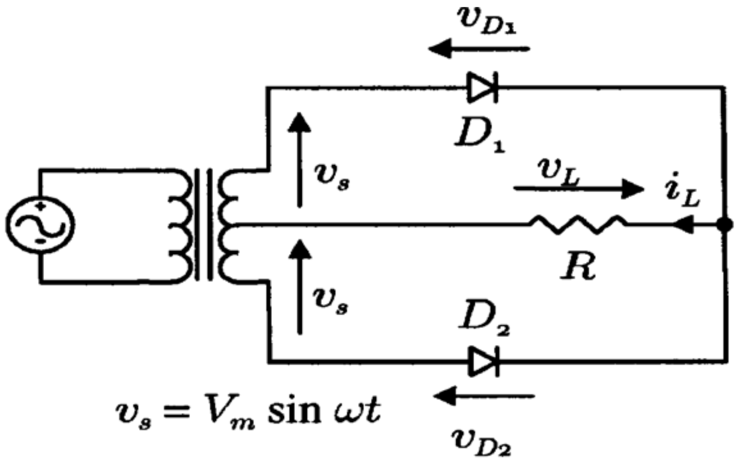
LECTURE NO. 7

Single-Phase Full-Wave Rectifiers

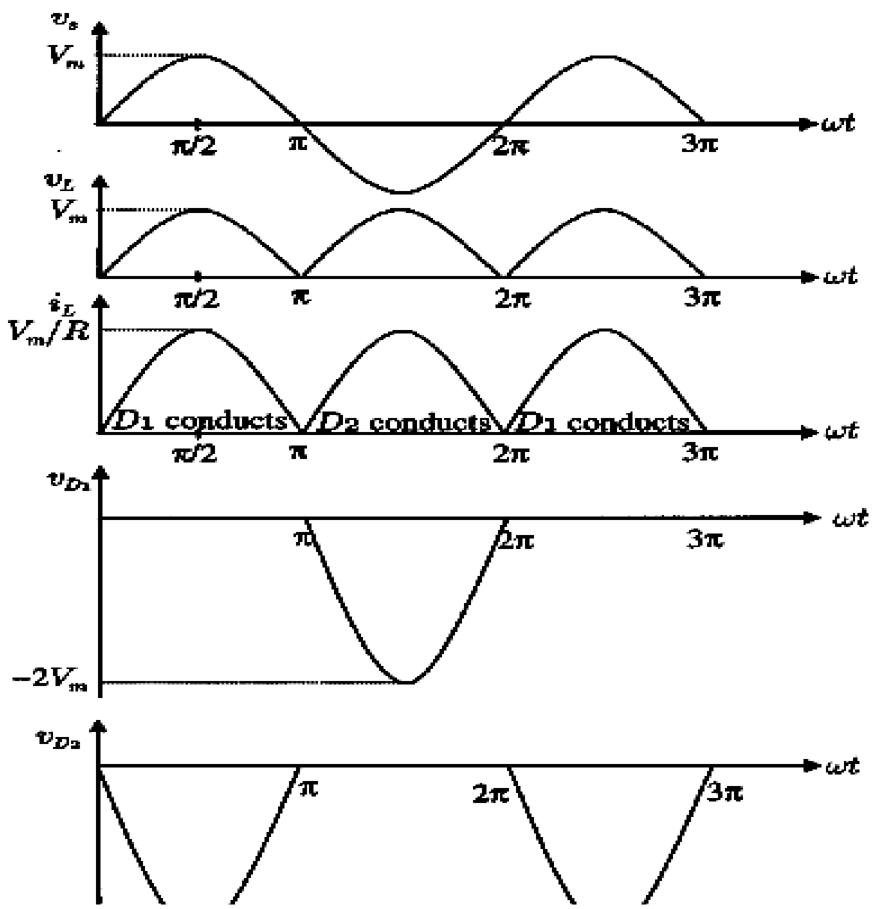
There are two types of single-phase full-wave rectifier, namely, full-wave rectifiers with center-tapped transformer and bridge rectifiers.

I. full-wave rectifier with a center-tapped transformer:

It is clear that each diode, together with the associated half of the transformer, acts as a half-wave rectifier. The outputs of the two half-wave rectifiers are combining to produce full-wave rectification in the load.



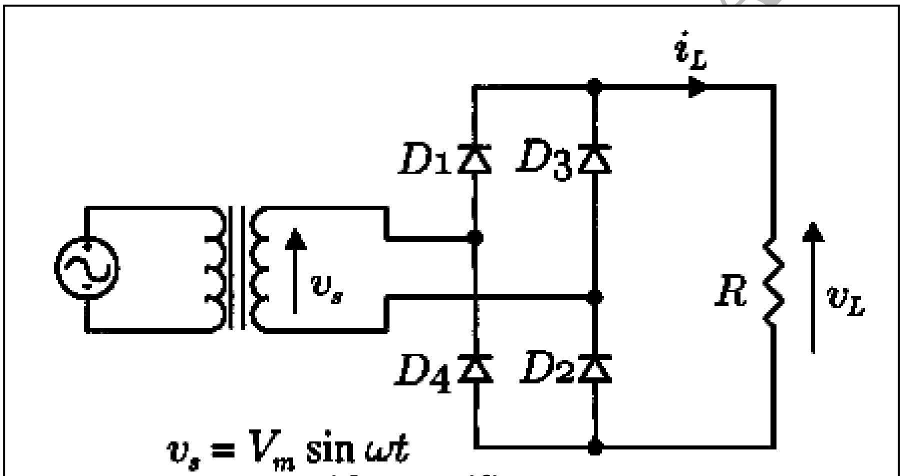
Full-wave rectifier with center-tapped transformer.



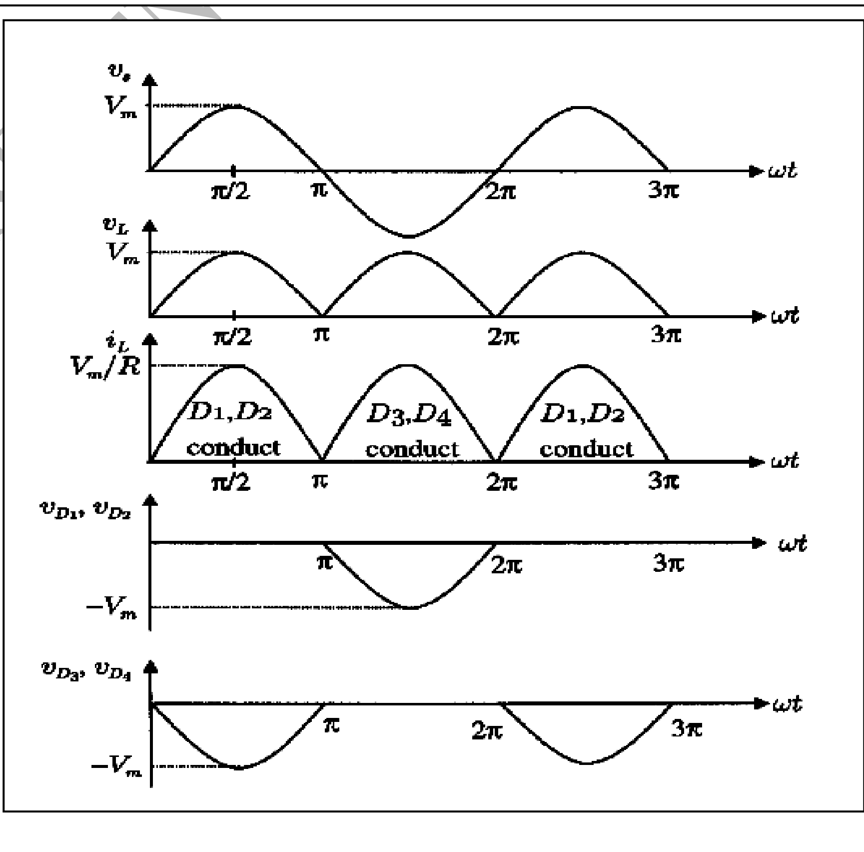
→It is clear that the peak inverse voltage (PIV) of the diodes is equal to $2V_m$ during their blocking state. Hence, the Peak Repetitive Reverse Voltage (V_{RRM}) rating of the diodes must be chose to be higher than $2V_m$ to avoid reverse breakdown.

→During its conducting state, each diode has a forward current that is equal to the load current and, therefore, the Peak Repetitive Forward Current (I_{FRM}) rating of these diodes must be chosen to be higher than the peak load current V_m=R in practice.

Bridge rectifier: It can provide full-wave rectification without using a center-tapped transformer. During the positive half cycle of the transformer secondary voltage, the current flows to the load through diodes D_1 and D_2. During the negative half cycle, D_3 and D_4 conduct.



Bridge rectifier



→As with the full-wave rectifier with center-tapped transformer, the Peak Repetitive Forward Current (I_{FRM}) rating of the employed diodes must be chosen to be higher than the peak load current $V_m = I_m \times R$

→ However, the peak inverse voltage (PIV) of the diodes is reduced from $2V_m$ to V_m during their blocking state.

In the case of a full-wave rectifier, $v_L(t)=V_m |\sin\omega t|$ for both the positive and negative half-cycles. Hence;

$$V_{dc} = \frac{1}{\pi}\int_0^{\pi} V_m \sin\omega t \, d(\omega t)$$

Therefore;

$$\textbf{Full-wave } V_{dc} = \frac{2V_m}{\pi} = 0.636\, V_m$$

The root-mean-square (rms) value of load voltage v_L is V_L, which is defined as:

$$V_L = \left[\frac{1}{T}\int_0^{T} v_L^2(t)dt\right]^{1/2}$$

Hence, the equation can be rewritten as:

$$V_L = \sqrt{\frac{1}{\pi}\int_0^{\pi}(V_m \sin\omega t)^2 d(\omega t)}$$

OR

$$\textbf{Full-wave } V_L = \frac{V_m}{\sqrt{2}} = 0.707\, V_m$$

Therefore; the average and the rms value load current is:

$$I_{dc} = \frac{0.636\, V_m}{R}$$

$$I_L = \frac{0.707\, V_m}{R}$$

The rectification ratio is:

$$\frac{P_{dc}}{P_L} = \frac{V_{dc} I_{dc}}{V_L I_L}$$

$$= \frac{(0.636\ V_m)^2}{(0.707\ V_m)^2} = 81\%$$

The FF can be found by:

$$\mathbf{FF} = \frac{V_L}{V_{dc}} \quad \text{or} \quad \frac{I_L}{I_{dc}}$$

$$\mathbf{FF} = \frac{0.707\ V_m}{0.636\ V_m} = 1.11$$

The ripple factor (RF), which is a measure of the ripple content, is defined as:

$$\mathbf{RF} = \frac{V_{ac}}{V_{dc}}$$

$$V_{ac} = \sqrt{V_L^2 - V_{dc}^2}$$

$$\mathbf{RF} = \sqrt{\left(\frac{V_L}{V_{dc}}\right)^2 - 1} = \sqrt{\mathbf{FF}^2 - 1}$$

$$\mathbf{RF} = \sqrt{1.11^2 - 1} = 0.482$$

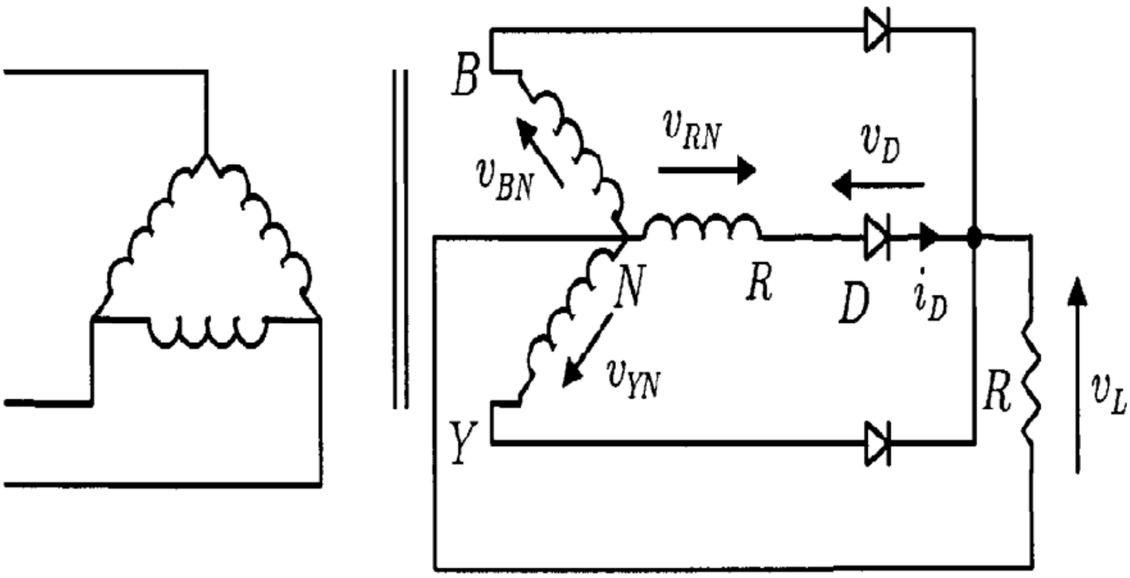
LECTURE NO. 8

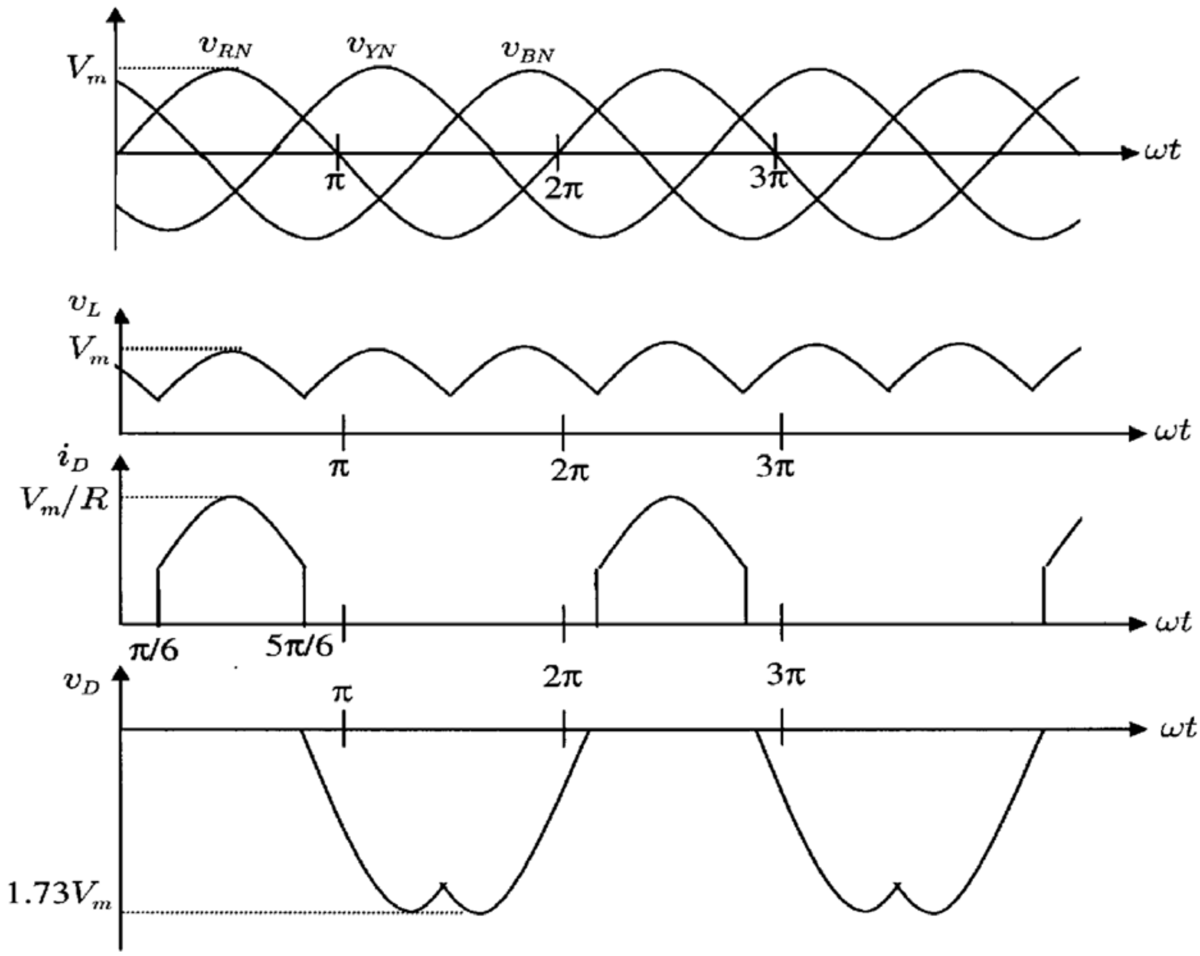
<u>Three-Phase Diode Rectifiers</u>

There are two types of three-phase diode rectifier, star rectifiers and bridge rectifiers.

<u>Three-Phase Star Rectifiers</u>

A basic three-phase star rectifier circuit is shown in Figure below. This circuit can be considered as three single-phase half-wave rectifiers combined together. Therefore, it sometimes referred to as a three-phase half-wave rectifier. The diode in a particular phase conducts during the period when the voltage on that phase is higher than that on the other two phases.





→ It is clear that, unlike the single-phase rectifier circuit, the conduction angle of each diode is **2π=3**, instead of **π**.

→Taking phase R as an example, diode D conducts from **π=6 to 5π=6.** Therefore, the average value of the output can be found as:

$$V_{dc} = \frac{3}{2\pi}\int_{\pi/6}^{5\pi/6} V_m \sin\theta \, d\theta$$

Or,

$$V_{dc} = V_m \frac{3}{\pi}\frac{\sqrt{3}}{2} = 0.827\ V_m$$

Similarly, the rms value of the output voltage can be found as:

$$V_L = \sqrt{\frac{3}{2\pi}\int_{\pi/6}^{5\pi/6} (V_m \sin\theta)^2 \, d\theta}$$

Or,

$$V_L = V_m\sqrt{\frac{3}{2\pi}\left(\frac{\pi}{3} + \frac{\sqrt{3}}{4}\right)} = 0.84 \ V_m$$

The rms current in each transformer secondary winding can also be found as:

$$I_s = I_m\sqrt{\frac{1}{2\pi}\left(\frac{\pi}{3} + \frac{\sqrt{3}}{4}\right)} = 0.485 \ I_m$$

→It is clear that the peak inverse voltage (PIV) of the diodes is equal to $\mathbf{1.73V_m}$ during their blocking state. Hence, the Peak Repetitive Reverse Voltage (V_{RRM}) rating of the diodes must be chose to be higher than $\mathbf{1.73V_m}$ to avoid reverse breakdown.

→During its conducting state, each diode has a forward current that is equal to the load current and, therefore, the Peak Repetitive Forward Current ($\mathbf{I_{FRM}}$) rating of these diodes must be chosen to be higher than the peak load current $\mathbf{I_m = V_m \times R}$ in practice.

→ Form factor of diode current $\mathbf{I_s / I_{dc} = 1.76}$

→ The rectification ratio is:

$$\frac{P_{dc}}{P_L} = \frac{V_{dc} I_{dc}}{V_L I_L}$$

Rectification ratio = 0.968

→ Form factor of three-phase half-wave rectifier

$$\text{FF} = \frac{V_L}{V_{dc}} \quad \text{or} \quad \frac{I_L}{I_{dc}}$$

$$\mathbf{FF = \frac{0.84V_m}{0.827V_m} = 1.0165}$$

→ Ripple factor of three-phase half-wave rectifier

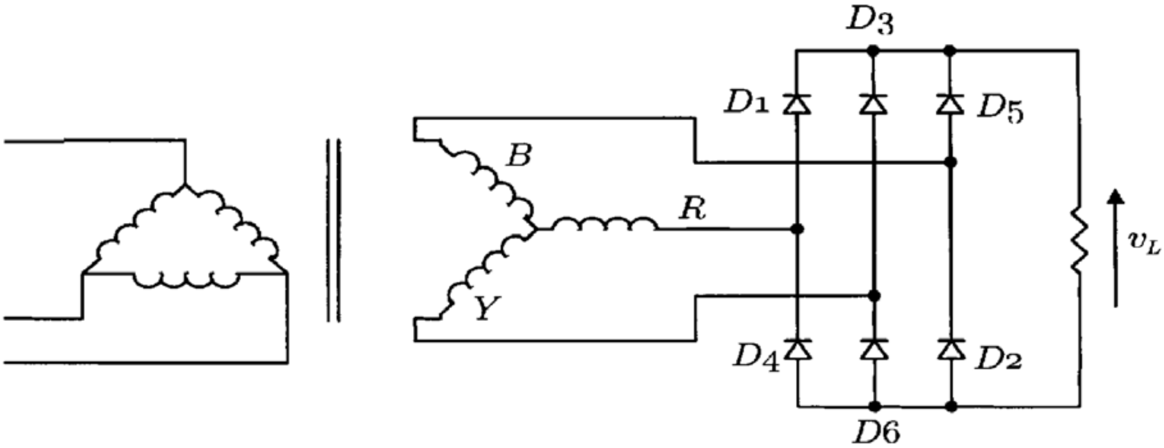
$$\mathbf{RF} = \sqrt{\left(\frac{V_L}{V_{\mathrm{dc}}}\right)^2 - 1} = \sqrt{\mathbf{FF}^2 - \mathbf{1}}$$

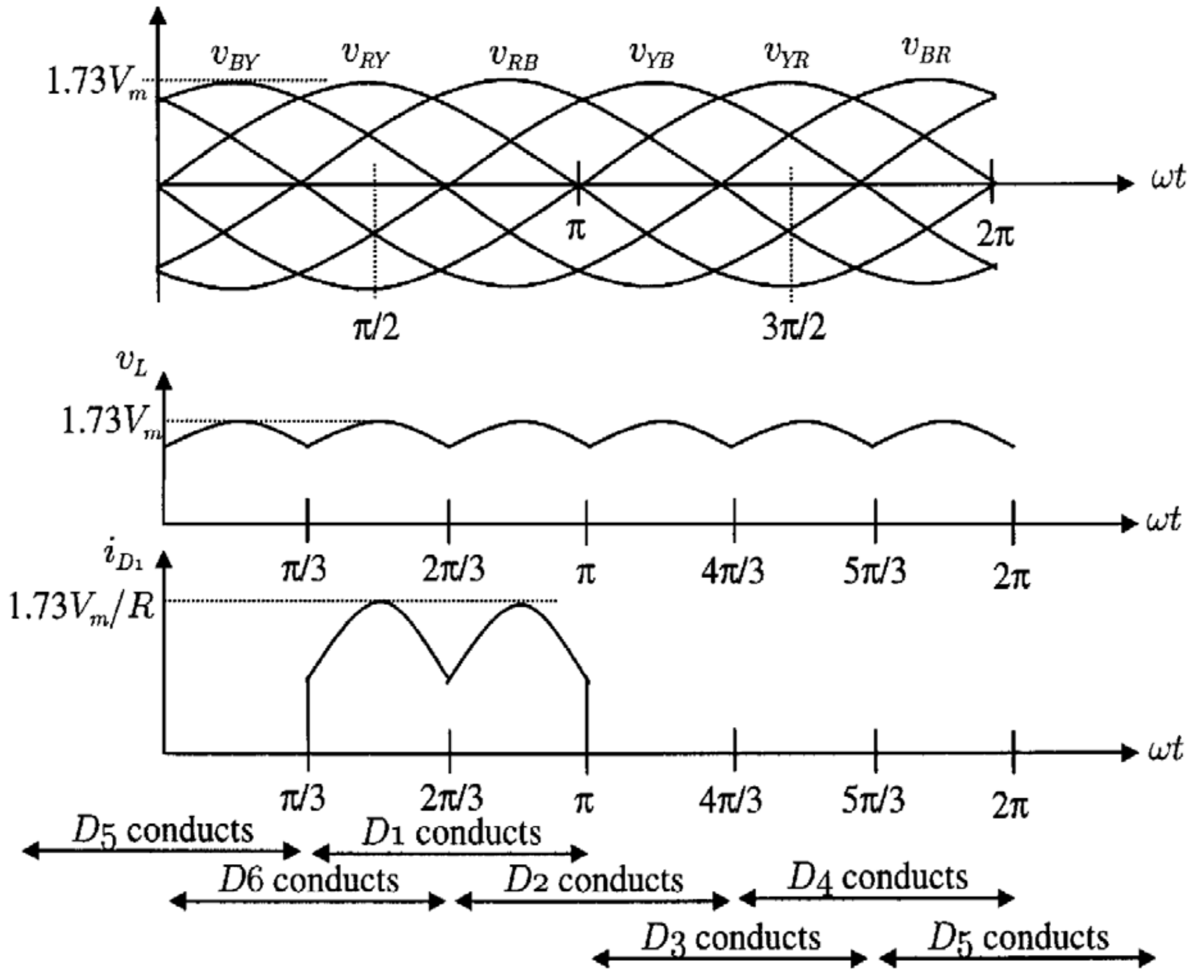
$$= \mathbf{0.182}$$

LECTURE NO. 9

Three-Phase Bridge Rectifiers

Three-phase bridge rectifiers are commonly used for high power applications because they have the highest possible transformer utilization factor for a three-phase system.





The diodes are numbered in the order of conduction sequences and the conduction angle of each diode is **2π=3**. The conduction sequence for diodes is **12, 23, 34, 45, 56, and 61**. The line voltage is **1.73** times the phase voltage of a three-phase star-connected source.

The average values of the output can be found as:

$$V_{dc} = \frac{6}{2\pi}\int_{\pi/3}^{2\pi/3} \sqrt{3}\ V_m \sin\theta\, d\theta$$

Or,

$$V_{dc} = V_m \frac{3\sqrt{3}}{\pi} = 1.654\ V_m$$

Similarly, the rms value of the output voltage can be found as:

$$V_L = \sqrt{\frac{9}{\pi}\int_{\pi/3}^{2\pi/3} (V_m \sin\theta)^2 d\theta}$$

Or,

$$V_L = V_m\sqrt{\frac{3}{2} + \frac{9\sqrt{3}}{4\pi}} = 1.655\ V_m$$

The rms current in each transformer secondary winding can also be found as:

$$I_s = I_m\sqrt{\frac{2}{\pi}\left(\frac{\pi}{6} + \frac{\sqrt{3}}{4}\right)} = 0.78\ I_m$$

The rms current through a diode is:

$$I_D = I_m\sqrt{\frac{1}{\pi}\left(\frac{\pi}{6} + \frac{\sqrt{3}}{4}\right)} = 0.552\ I_m$$

Where, $\mathbf{I_m = 1.73\ V_m/R}$.

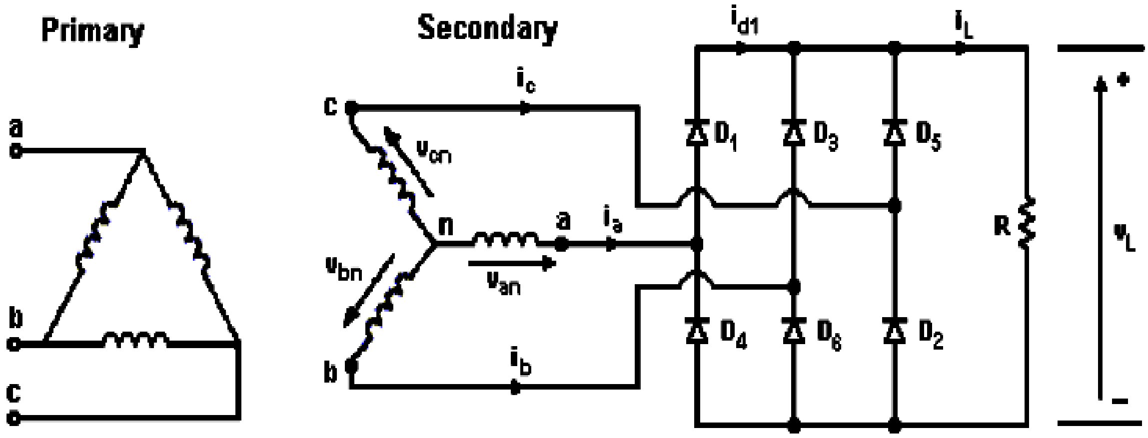
→ The dc output voltage is slightly lower than the peak line voltage or 2.34 times the rms phase voltage.
→ The Peak Repetitive Reverse Voltage (V_{RRM}) rating of the employed diodes is 1.05 times the dc output voltage.
→ The Peak Repetitive Forward Current (I_{FRM}) rating of the employed diodes is 0.579 times the dc output current.

Example 3.4

A three-phase rectifier has a purely resistive load of R. Determine

a. The efficiency
b. The form factor
c. The ripple factor
e. The peak inverse voltage of each diode and
f. The peak current through a diode.

The rectifier delivers I = 60 A at an output voltage of V_{dc} = 280.7V and the source frequency is 60 Hz.



Solution

a. Efficiency, $\eta = \frac{P_{dc}}{P_L}$

Now: $P_{dc} = V_{dc} \times I_{dc}$

$P_L = V_L \times I_L$

Since:

$$V_{dc} = V_m \frac{3\sqrt{3}}{\pi} = 1.654\ V_m$$

$$I_{dc} = \frac{V_{dc}}{R} = \frac{1.654 V_m}{R}$$

$$V_L = V_m\sqrt{\frac{3}{2}+\frac{9\sqrt{3}}{4\pi}} = 1.655\ V_m$$

$$I_L = \frac{V_L}{R} = \frac{1.655V_m}{R}$$

$$\eta = \frac{(1.65V_m)^2 R}{(1.655V_m)^2 R} = 99.85\%$$

b. Form factor:

$$FF = \frac{1.655V_m}{1.654V_m} = 1.0008$$

c. Ripple factor:

$$RF = \sqrt{\left(\frac{V_L}{V_{dc}}\right)^2 - 1} = \sqrt{FF^2 - 1}$$

= 4%

e. $\mathbf{V}_m$ = peak line to neutral voltage
But $\mathbf{V}_{dc} = 1.654\mathbf{V}_m = 280.7$ V

$$\Rightarrow V_m = \frac{280.7}{1.654} = 169.7V$$

PIV = peak inverse value of secondary line to line voltage
= 169.7×3 = 293.9 Volt

e. The average diode current $\mathbf{I}_{dc}$ is given by:

$$I_{dc} = \frac{2\times 2}{2\pi}\int_0^{\pi/6} I_m \cos\omega t \quad d(\omega t)$$

$$I_{dc} = \frac{2I_m}{\pi}\sin\left(\frac{\pi}{3}\right) = 0.318I_m$$

If the average load current is $\mathbf{I}_{dc}$ and each diode is on for 120° of a cycle of 360° then average diode current = 1/3 × average load current

$$I_d = \frac{I_{dc}}{3} = \frac{60}{3} = 20A$$

$$\therefore I_m = \frac{20}{0.318} = 62.83A$$

H.W1 The single-phase full wave rectifier has a purely resistive load of R, determine:

a) The efficiency,
b) The ripple factor RF,
c) The peak inverse voltage PIV of diode

NOTE: Drive any formula that used in solution

H.W2 The single-phase half wave rectifier has R-L load with R= 5Ω and L= 6.5mH. The input voltage V_s=220V at 50Hz, determine:

a) The average diode current
b) The rms diode current
c) The rms output current
d) The average output current

NOTE: Drive any formula that used in solution

H.W3 The single-phase full wave rectifier has a purely resistive load of R, and I_L =10A and average power = 100Watt, determine:

-The efficiency,
-The form factor and ripple factor,
-The peak inverse voltage PIV of diode,

NOTE: Drive any formula that used in solution

H.W4 The diode in the single-phase half wave rectifier has a reverse recovery time of t_{rr} = 150μsec and the source voltage V_s = 200V at frequency = 5 kHz. Calculate the average output voltage.

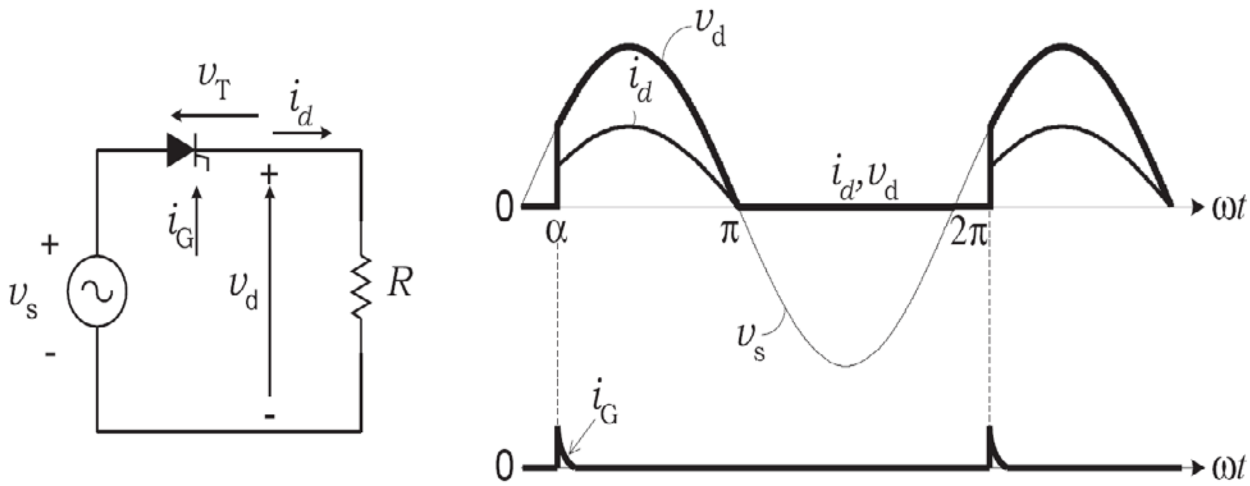
H.W5: Design the single phase half wave rectifier supply the HeNe laser tube. The voltage across tube is 1.8kV and the current pass through tube is 10mA. The designer has two diodes with PIV=1.5kV and saturation current are I_{s1}=100μA and I_{s2}=120μA respectively.

LECTURE NO. 10

Controlled Rectifier

Single-Phase Half-Wave Controlled Rectifier

As shown in Figure below, the single-phase half-wave controlled rectifier uses a single thyristor to control the load voltage. The thyristor will conduct, **ON** state, when the voltage v_T is positive and a firing current pulse i_G is applied to the gate terminal. Delaying the firing pulse by an angle α does the control of the load voltage. The firing angle α is measured from the position where a diode would naturally conduct. The angle α is measured from the zero crossing point of the supply voltage v_s. The load is resistive and therefore current i_d has the same waveform as the load voltage. The thyristor goes to the non-conducting condition, **OFF** state, when the load voltage and, consequently, the current try to reach a negative value.



The load average voltage is given by:

$$\mathbf{V_{dc}} = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\pi} V_m \sin(\omega t)\,d(\omega t)} = \frac{Vm}{2\pi}(1+\cos\alpha)$$

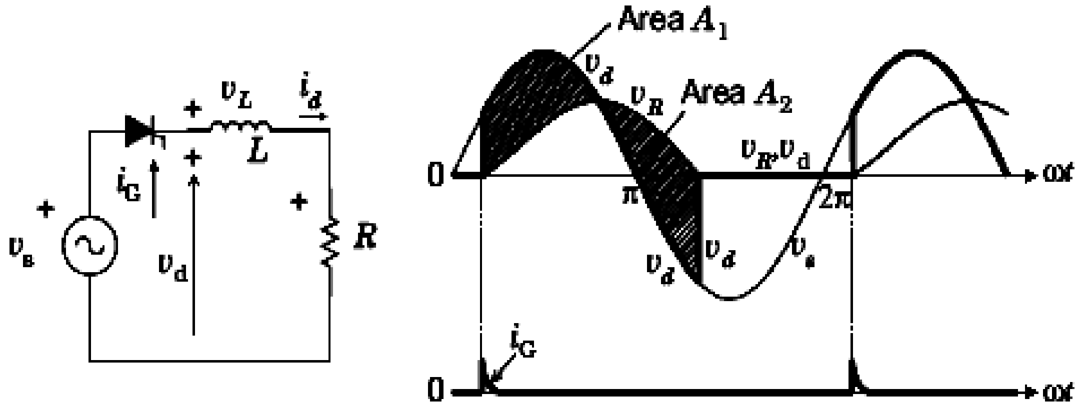
$$\mathbf{V_L} = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\pi} V_m{}^2 \sin^2(\omega t)\,d(\omega t)}$$

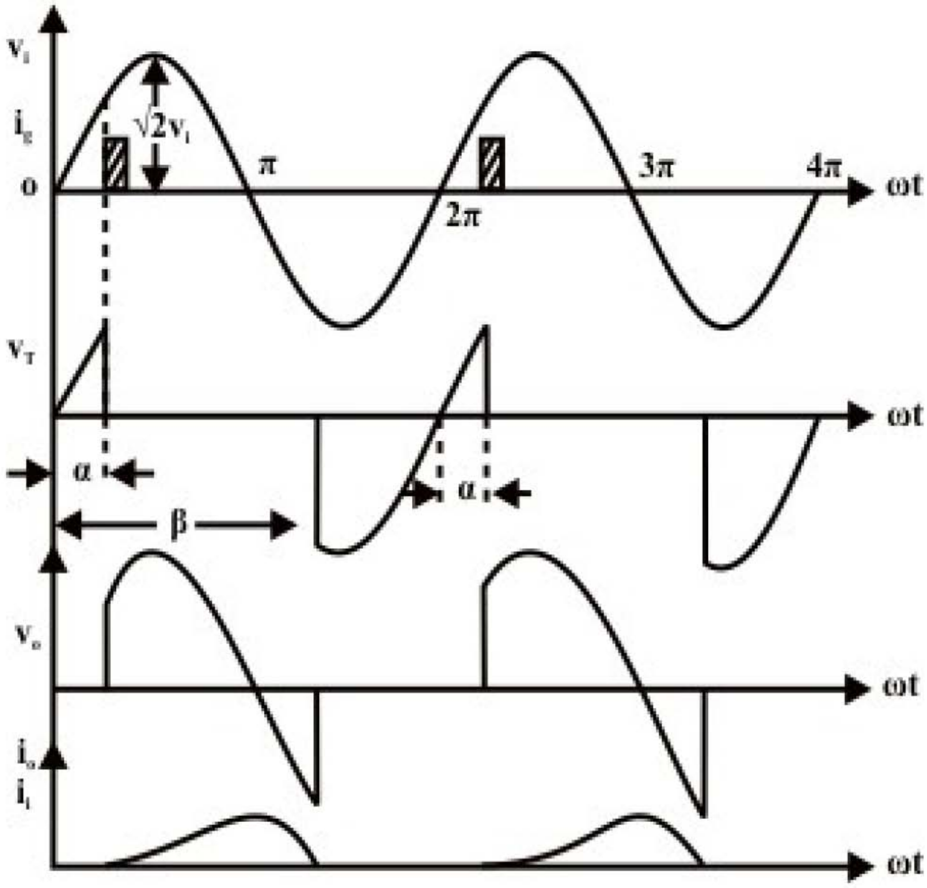
$$= \frac{Vm}{\sqrt{2\pi}}\sqrt{\frac{\pi-\alpha}{2}+\frac{\sin 2(\pi-\alpha)}{4}}$$

Home Work: Drive the form factor and ripple factor and efficiency of single phase half wave controlled rectifier.

Single-Phase Full-Wave Controlled Rectifier with R-L load

Figure below shows the rectifier waveforms for an **R-L** load.





From the preceding discussion

-For $0 \le \omega t \le \alpha$

$$v_o = 0$$

-For $\alpha \le \omega t \le \beta$

$$v_0 = v_i = \sqrt{2}\, V_i \sin\omega t$$

-For $\beta \le \omega t \le 2\pi$

$$v_o = 0$$

The average output voltage is given by:

$$V_{dc} = \frac{1}{2\pi}\int_{\alpha}^{\beta} \sqrt{2}\, V_i \sin\omega t \, d\omega t$$

$$= \frac{V_i}{\sqrt{2}\pi}(\cos\alpha - \cos\beta)$$

Where, $V_m = \sqrt{2} V_i$

The rms output voltage is given by:

$$V_L = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\beta} 2v_i^2 \sin^2\omega t \, d\omega t}$$

$$= \frac{V_i}{\sqrt{2}}\left(\frac{\beta - \alpha}{\pi} + \frac{\sin 2\alpha - \sin 2\beta}{2\pi}\right)^{\frac{1}{2}}$$

$$I_{dc} = \frac{V_i}{\sqrt{2}\pi R}(\cos\alpha - \cos\beta)$$

All these quantities are functions of β which can be found as follows.

-For $0 \le \omega t \le \beta$

$$v_i = \sqrt{2} V_i \sin\omega t = L\frac{dio}{dt} + Ri_0$$

$$i_0\,(\omega t = 0) = i_0\,(\omega t = \beta) = 0$$

The solution is given by:

$$i_0 = I_0 e^{-\frac{\omega t}{\tan\varphi}} + \frac{\sqrt{2}V_i}{Z}\sin(\omega t - \varphi)$$

Where;

$$\tan\varphi = \frac{\omega L}{R}$$

$$Z = \sqrt{R^2 + \omega^2 L^2}$$

Example: Explain what will happen if a free-wheeling diode is connected across the load in single phase half wave controlled rectifier.

Answer:

The free wheeling diode will remain off till $\omega t = \pi$ since the positive load voltage across the load will reverse bias the diode. However, beyond this point as the load voltage tends to become negative the free wheeling diode comes into conduction. The load voltage is clamped to zero there after. As a result

i) Average load voltage increases
ii) RMS load voltage reduces and hence the load voltage form factor reduces.
iii) Conduction angle of load current increases as does its average value. The load current ripple factor reduces.

Example:

The single-phase half wave rectifier has a purely resistive load of R and the delay angle is $\alpha=\pi/2$, determine:

a) The efficiency,
b) The form factor FF,
c) The ripple factor RF,
d) The peak inverse voltage PIV of thyristor.

Solution:

a)

$$V_{d\alpha} = \frac{1}{2\pi}\int_{\alpha}^{\pi} V_{\max}\sin\omega t d(\omega t) = \frac{V_{\max}}{2\pi}(1+\cos\alpha)$$

$$= 0.1592V_m$$

$$I_{dc} = 0.1592V_m/R$$

$$V_L = \left[\frac{1}{2\pi}\int_{\alpha}^{\pi} V_m^2 \sin^2(\omega t) \quad d(\omega t)\right]^{1/2}$$

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

$V_L = 0.3536\ V_m$ and $I_L = 0.3536\ V_m/R$

$$\eta = \frac{V_{dc}\times I_{dc}}{V_L \times I_L} = \frac{(0.1592V_m)^2/R}{(0.3536V_m)^2/R} = 20.27\%$$

b) $FF = \frac{V_L}{V_{dc}} = \frac{0.3536\ Vm}{0.1592V_m} = 2.221$

c) $RF = (FF-1)^{1/2}$

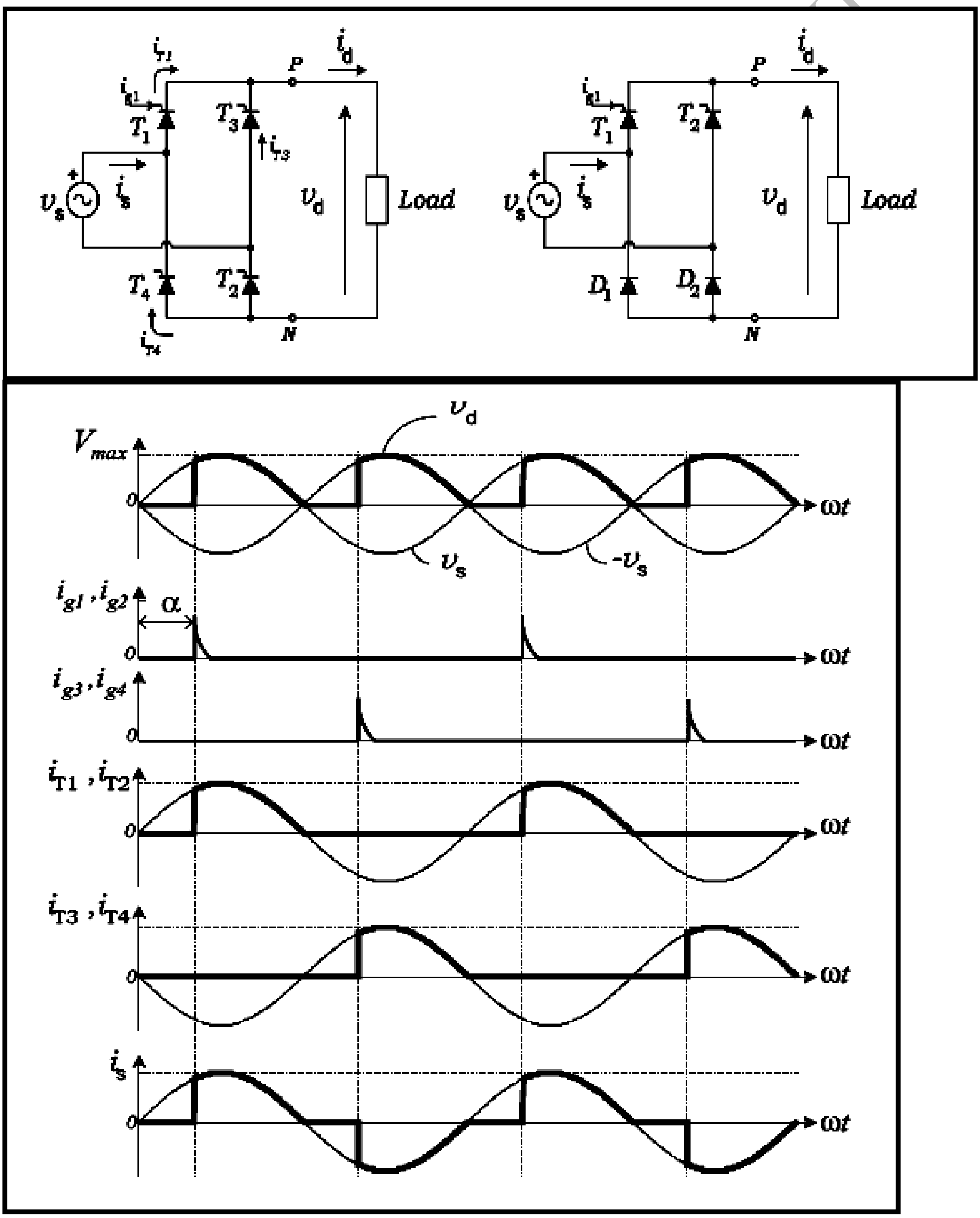
$= (2.221-1)^{1/2} = 1.983$

d) From the waveforms of the single-phase half wave rectifier the peak inverse voltage PIV = V_m.

LECTURE NO. 11

Single-Phase Full-Wave Controlled Rectifier

Figure below shows a fully controlled bridge rectifier, which uses four thyristors to control the average load voltage and the half-controlled bridge rectifier "semi converter rectifier"; which uses two thyristors and two diodes.



Thyristors T_1 and T_2 must be fired simultaneously during the positive half wave of the source voltage v_s to allow conduction of current. Alternatively, thyristors T_3 and T_4 must be fired simultaneously during the negative half wave of the source voltage. To ensure simultaneous firing, thyristors T_1 and T_2 use the same firing signal.

$$\mathbf{V_{dc}} = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} v_0 \, d\omega t = \frac{2\sqrt{2}}{\pi} V_i \cos\alpha$$

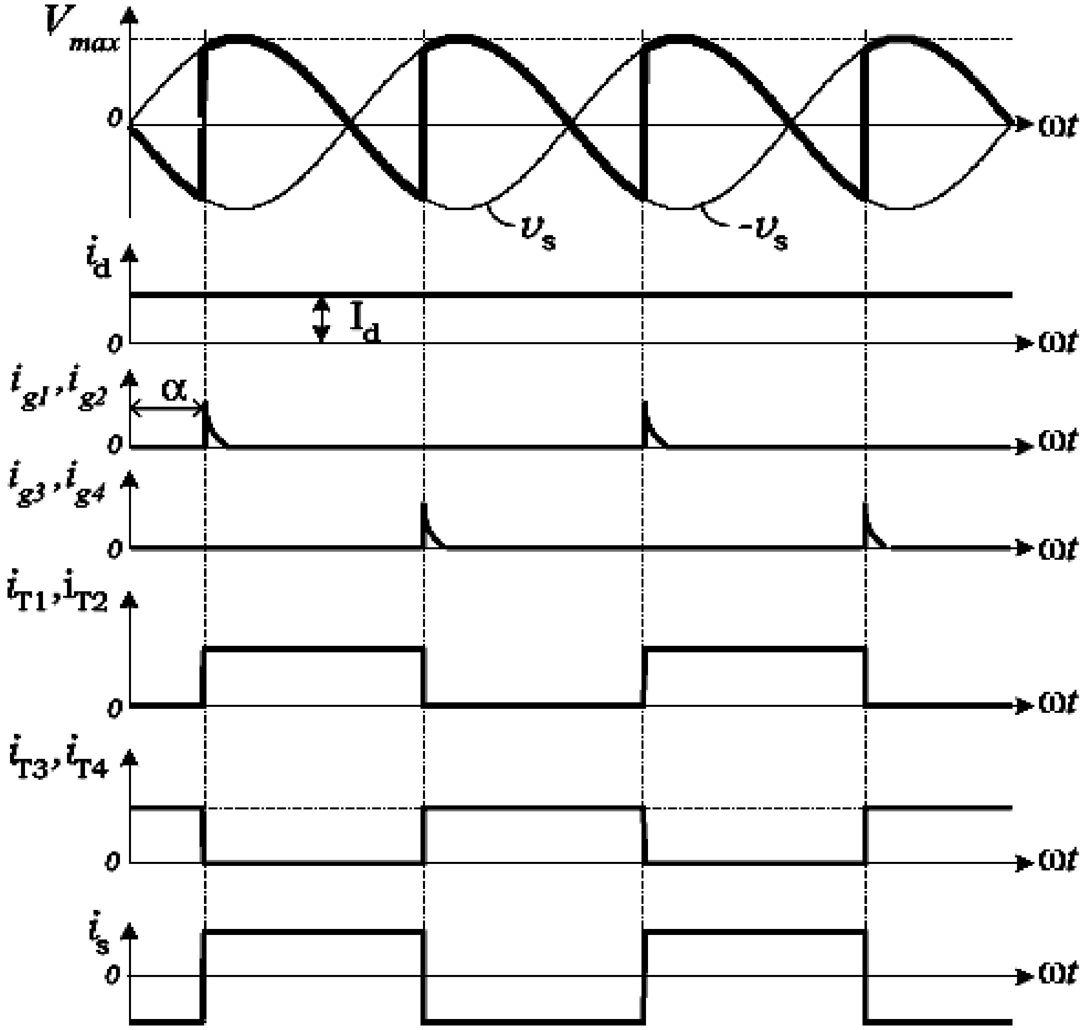
RMS value of v_0 can of course be completed directly from.

$$\mathbf{V_L} = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} v_0^2 d\omega t} = V_i$$

The behavior of the fully controlled rectifier with resistive-inductive load (with **L**→∞) is shown in figure below. The high-load inductance generates a perfectly filtered current and the rectifier behaves like a current source. With continuous load current, thyristors T_1 and T_2 remain in the on-state beyond the positive half-wave of the source voltage v_s. For this reason, the load voltage v_d can have a negative instantaneous value. The firing of thyristors T_3 and T_4 has two effects:

i) They turn off thyristors **T1** and **T2**; and

ii) After the commutation they conduct the load current.



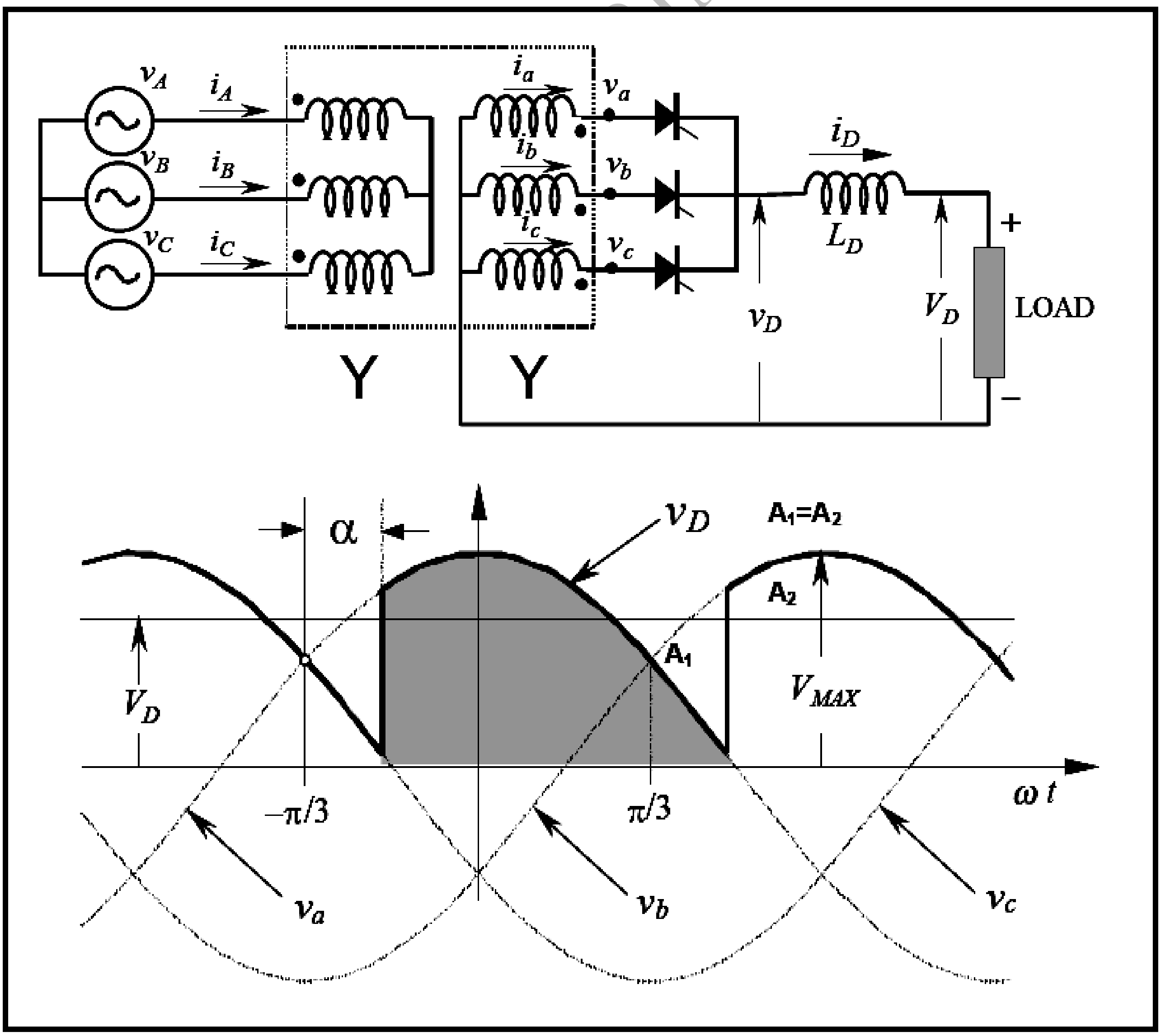
V max
0
ωt
v s
-v s
i d
I d
i g1 , i g2
α
i g3 , i g4
i T1 , i T2
i T3 , i T4
i s

LECTURE NO. 12

Three-Phase Half-Wave Controlled Rectifier

Figure shows the three-phase half-wave controlled rectifier topology. To control the load voltage, the half-wave rectifier uses three common-cathode thyristor arrangements. In this figure, the power supply and the transformer are assumed ideal. The thyristor will conduct (**ON state**), when the anode-to-cathode voltage v_{AK} is positive, and a firing current pulse i_G is applied to the gate terminal. Delaying the firing pulse by an angle α controls the load voltage. The firing angle α is measured from the crossing point between the phase supply voltages. At that point, the anode-to-cathode thyristor voltage v_{AK} begins to be positive.

When the load is resistive, current i_d has the same waveform as the load voltage. As the load becomes more and more inductive, the current flattens and finally becomes constant. The thyristor goes to the non-conducting condition (**OFF state**) when the following thyristor is switched **ON**, or the current tries to reach a negative value.



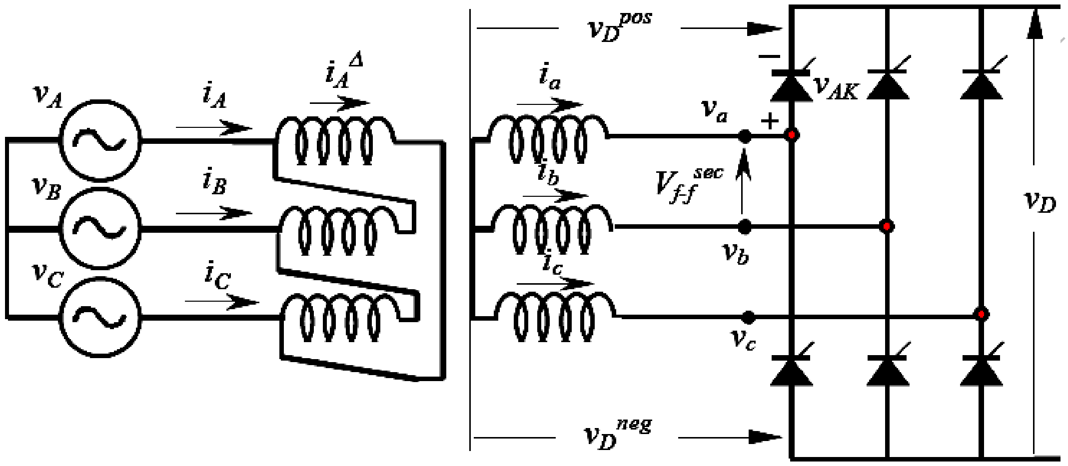
$$\mathbf{V_{dc}} = \frac{V_{max}}{2/3\pi}\int_{-\pi/3+\alpha}^{\pi/3+\alpha} \cos\omega t \cdot d(\omega t)$$

$$= V_{max}\frac{\sin \pi/3}{\pi/3} \cdot \cos\alpha$$

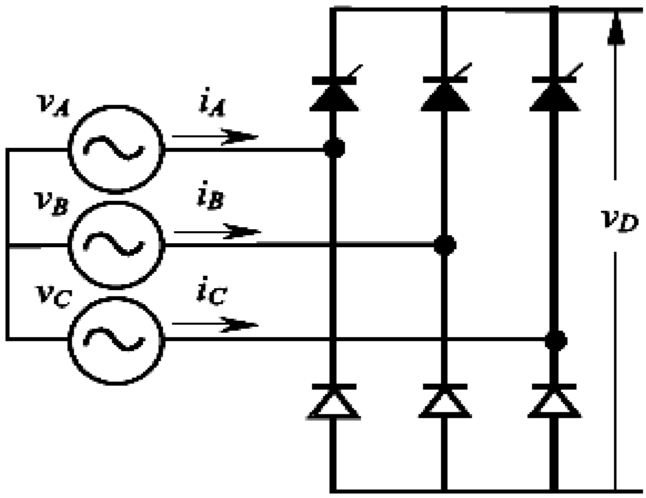
LECTURE NO. 13

Three-Phase Bridge Controlled Rectifiers

Figure below shows the three-phase bridge controlled rectifier. The configuration does not need any special transformer, and works as a 6-pulse rectifier. The series characteristic of this rectifier produces a dc voltage twice the value of the half-wave rectifier.



Three-phase full-wave rectifier



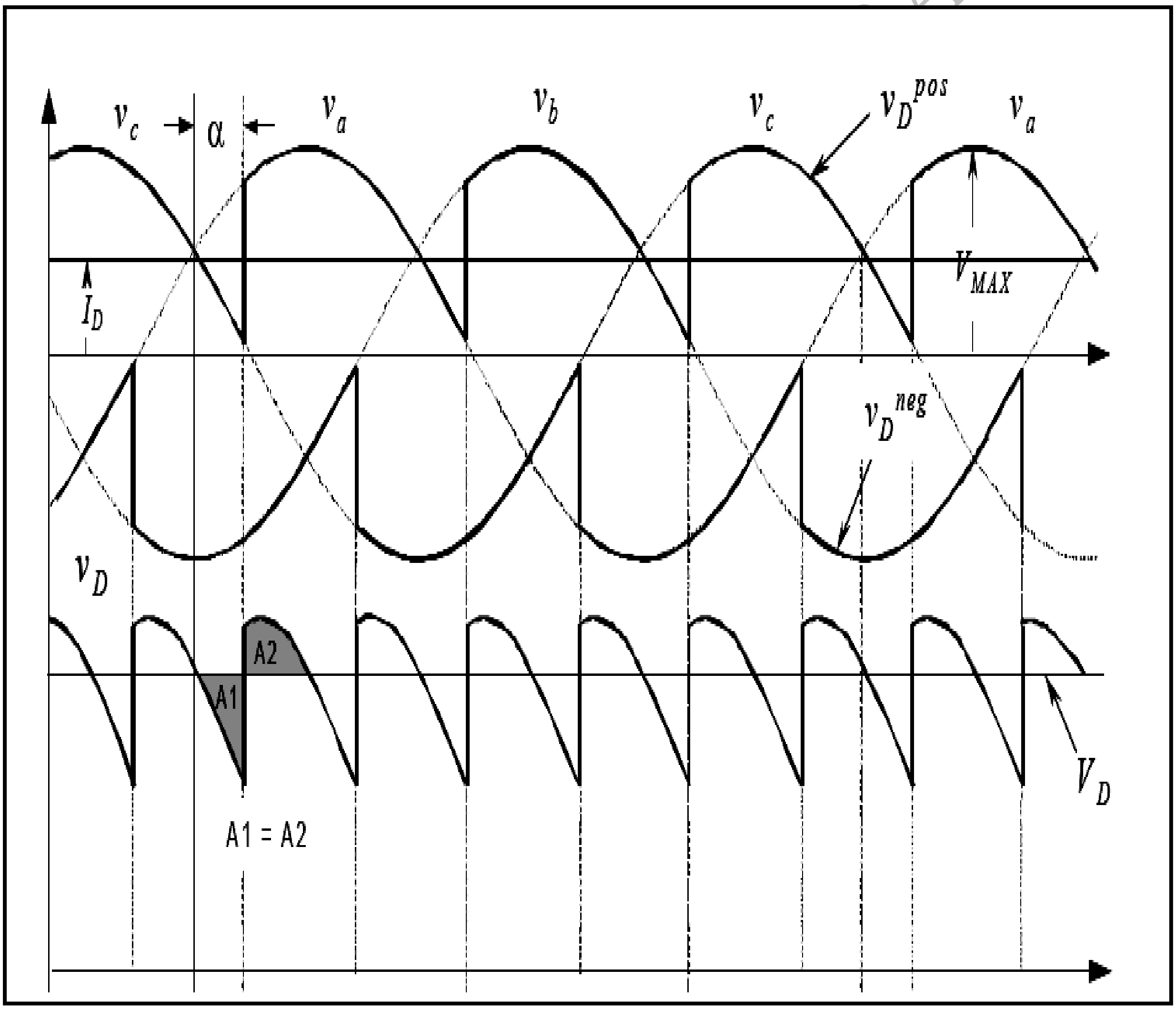
The half-controlled bridge, or ''semi-converter,''

The load average voltage is given by:

$$\mathbf{V_{dc}} = \frac{V_{\max}}{\pi/3}\int_{-\pi/6+\alpha}^{\pi/6+\alpha} \cos\omega t \cdot d(\omega t)$$

$$= V_{\max} \frac{\sin \pi/6}{\pi/6} \cdot \cos \alpha$$

Figure below shows the voltages of each half-wave bridge of this topology $\mathbf{v_D^{pos}}$ and $\mathbf{v_D^{neg}}$, the total instantaneous dc voltage v_D, and the anode-to-cathode voltage v_{AK} in one of the bridge thyristors. The maximum value of v_{AK} is $\sqrt{3}\ V_{max}$, which is the same as that of the half-wave converter.



LECTURE NO. 14

Solving various questions

H.W1 **The single-phase full wave controlled rectifier has a purely resistive load of R and the delay angle is $\alpha=\pi/2$, determine:**

d) **The efficiency,**
e) **The ripple factor RF,**
f) **The peak inverse voltage PIV of thyristor**

***NOTE*: Drive any formula that used in solution**

H.W2 **The single-phase full wave controlled rectifier has a R-L load with R= 0.5Ω and L= 6.5mH. The input voltage V_s=220V at 50Hz. The delay angle is α=60, determine:**

e) **The average thyristor current**
f) **The rms thyristor current**
g) **The output rms current**
h) **The average output current**

***NOTE*: Drive any formula that used in solution**

H.W3 **The single-phase full wave controlled rectifier has a R-L load with R= 0.5Ω and L= 6.5mH. The input voltage V_s=220V at 50Hz. The delay angle is α=30, plot the input and output waveforms. Then determine:**

-The average thyristor current
-The rms thyristor current
-The output rms current
-The average output current
- The efficiency

***NOTE*: Drive any formula that used in solution**

H.W4 **The single-phase full wave controlled rectifier has a purely resistive load of R and the delay angle is $\alpha=2\pi/3$, and I_L =10A and P_L=100Watt determine:**

-The efficiency,
-The ripple factor RF,
-The peak inverse voltage PIV of thyristor

***NOTE*: Drive any formula that used in solution**

H.W5

Design the single-phase half wave controlled rectifier has a purely resistive load of R=10Ω and the average output voltage varied from 30V to 120V.

LECTURE NO. 15

Power Bipolar Transistor

1. Introduction

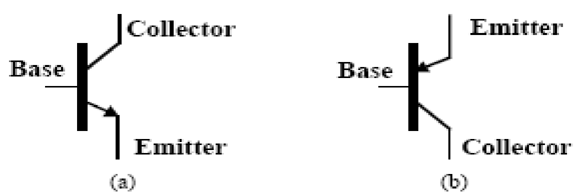
The first transistor was created in 1948 by a team of physicists at the Bell Telephone Laboratories and soon became a semiconductor device of major importance. Power semiconductor switches constitute the heart of modern power electronics. Such devices should have:

a) Larger voltage and current ratings,
b) Instant turn on and turn-off characteristics,
c) Very low voltage drop when fully on,
d) Zero leakage current in blocking condition,
e) Enough ruggedness to switch highly inductive loads.

2. Basic Structure and Operation

The bipolar junction transistor (BJT) consists of a three-region structure of n-type and p-type semiconductor materials; it can be constructed as npn as well as pnp. The operation is closely related to that of a junction diode where in normal conditions the pn junction between the base and collector is forward-biased ($V_{BE} > 0$), causing electrons to be injected from the emitter into the base. As the base region is thin, the electrons travel across it and arrive at the reverse biased base-collector junction ($V_{BC} < 0$), where there is an electric field (depletion region). Upon arrival at this junction, the electrons are pulled across the depletion region and drawn into the collector. These electrons flow through the collector region and out the collector contact. Because electrons are negative carriers, their motion constitutes positive current flowing into the external collector terminal. Even though the forward-biased base-emitter junction injects holes from base to emitter, the holes do not contribute to the collector current but result in a net current flow component into the base from the external base terminal.

The circuit symbols are shown in Figure below. Most of power electronics applications use NPN transistors because electrons move faster than holes, and therefore, NPN transistors have considerable faster commutation times.



Circuit symbols (a) NPN transistor; and (b) PNP transistor.

The emitter current is exponentially related to the base-emitter voltage by the equation:

$$i_E = i_{E0}\left(e\frac{v_{BE}}{\eta \cdot v_T} - 1\right)$$

And

$$i_C = \alpha i_E$$

The collector and base currents are thus related by the ratio:

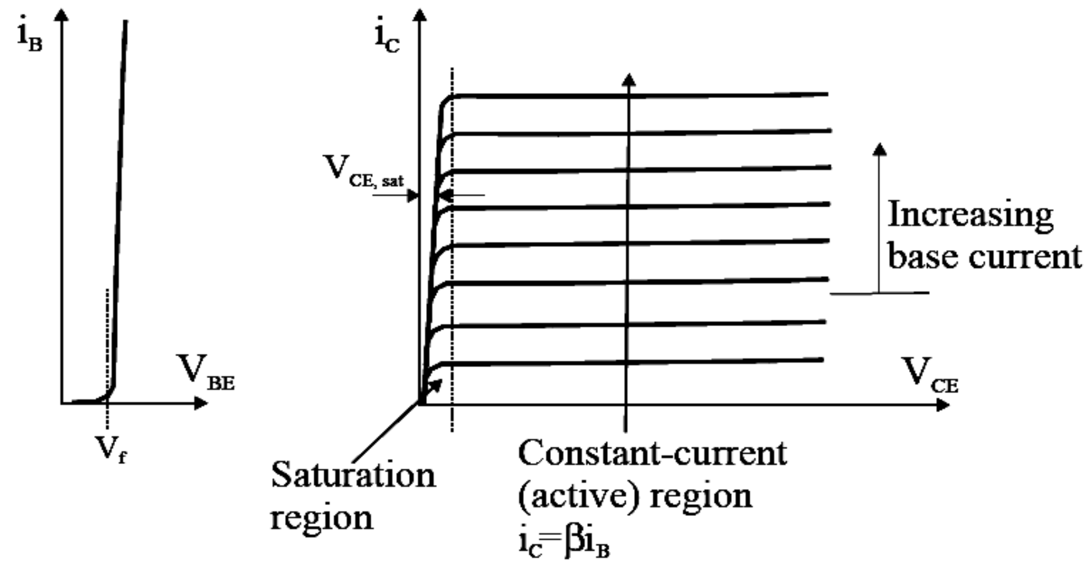
$$\frac{i_c}{i_B} = \frac{\alpha}{1-\alpha} = \beta$$

Static Characteristics

A family of voltage-current characteristic curves is shown in figure below. The base current i_B plotted as a function of the base-emitter voltage V_{BE} and the collector current i_C as a function of the collector emitter voltage V_{CE}, with i_B as the controlling variable.

The figure shows several curves distinguished from each other by the value of the base current. The active region is defined where flat, horizontal portions of voltage-current curves show ‘‘constant’’ i_C current, because the collector current does not change significantly with V_{CE} for a given i_B. Those portions are used only for small signal transistors operating as linear amplifiers.

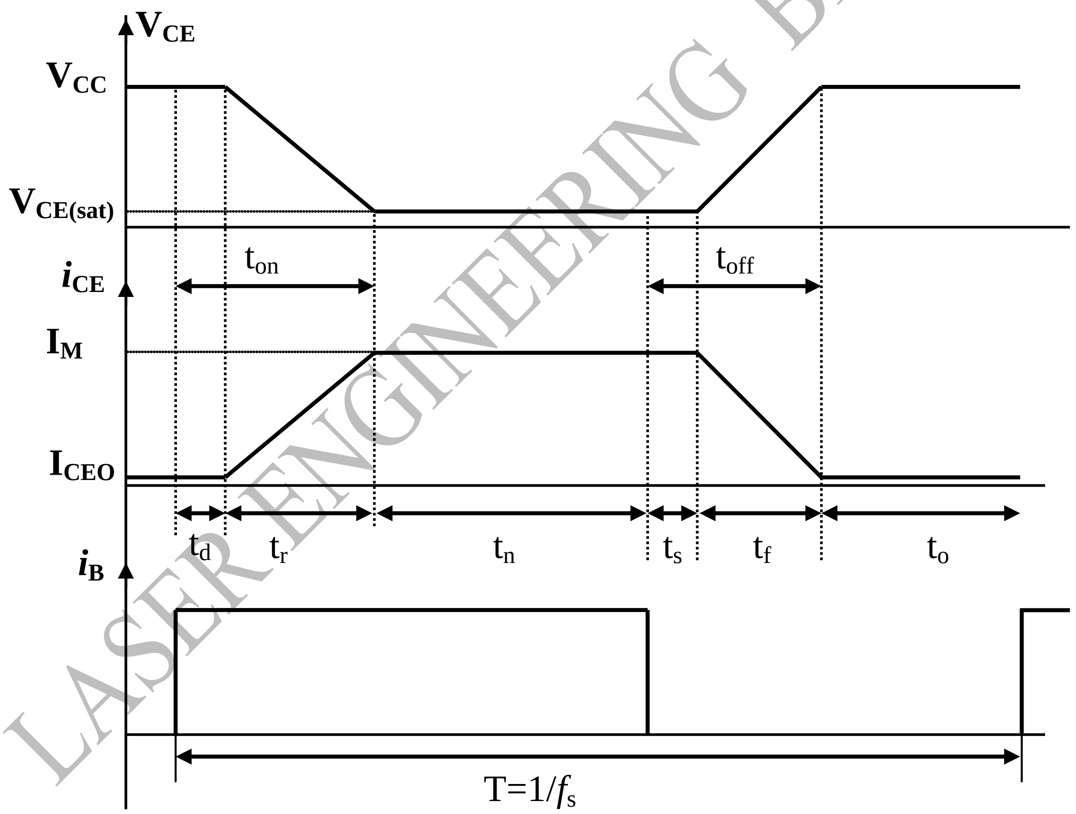
On the other hand, switching power electronics systems require transistors to operate either in the saturation region where V_{CE} is small or in the cutoff region where the current is zero and the voltage is upheld by the device. A small base current drives the flow of a much larger current between collector and emitter.



Dynamic Switching Characteristics

Switching characteristics are important in defining device velocity during change from conduction (on) to blocking (off) states. Such transition velocity is of paramount importance because most of the losses are due to high frequency switching. Figure shows typical waveforms for a resistive load.

a) The rising time" $\mathbf{t_r}$" (from 10 to 90% of maximum value) collector current or voltage.
b) The falling time **"$\mathbf{t_f}$"** is the falling time, that is, when the transistor is blocking such time corresponds to crossing from the saturation to the cutoff state.
c) The delay time is denoted by **td**, corresponding to the time to discharge the capacitance of junction base-emitter,
d) Storage time (ts) is a very important parameter for BJT transistors, it is the time required to neutralize the carriers stored in the collector and the base.



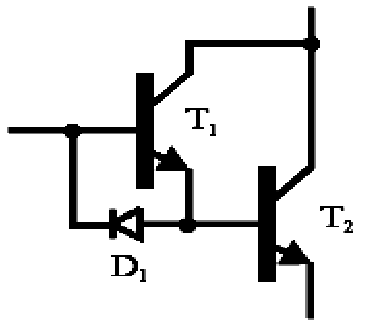
Current and voltage are interchanged at turn-on and an approximation based upon straight line switching intervals (resistive load) gives the average switching losses calculated using:

$$P_S = \frac{V_S I_M}{2} \tau f_s$$

Where **τ** represent either ***tr*** or ***tf***

LECTURE NO. 16

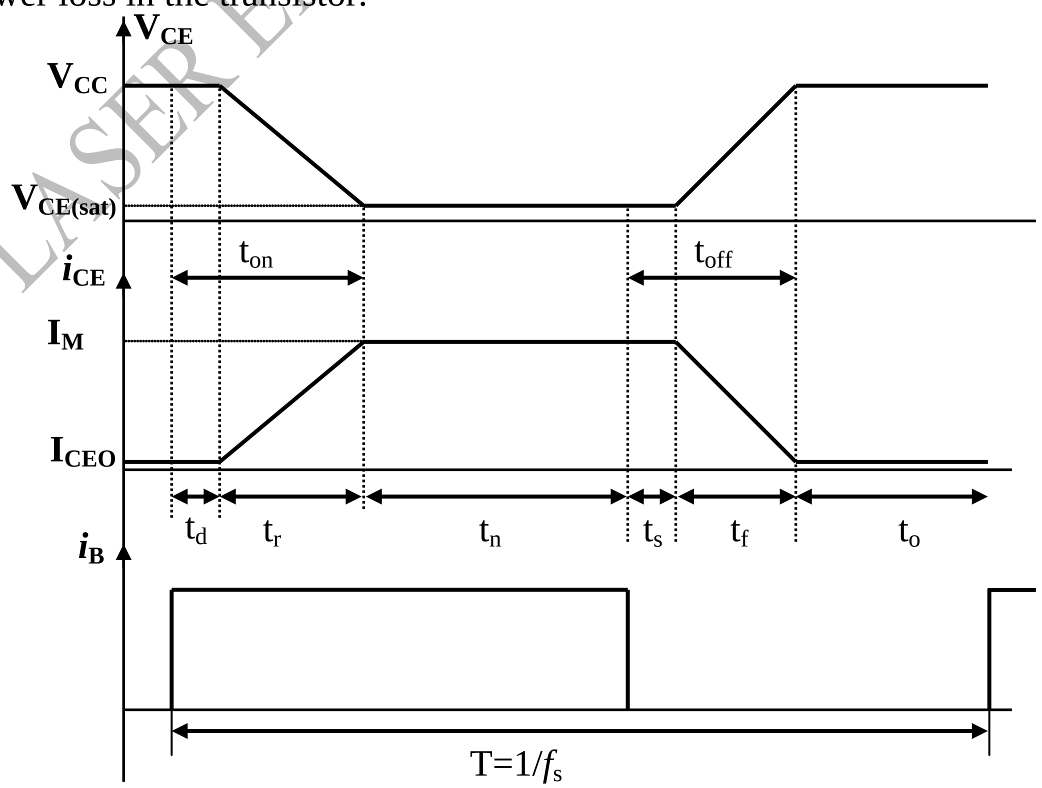
High voltage BJTs typically has low current gain, and hence Darlington-connected devices, as indicated in Figure below are commonly used. Considering gains β_1 and β_2 for each one of these transistors, the ***Darlington*** connection will have an increased gain of $\beta_1+\beta_2+\beta_1\beta_2$ and diode D1 speeds up the turn-off process by allowing the base driver to remove the stored charge on the transistor bases.



Darlington-connected BJTs

<u>Example:</u>

The waveforms of the transistor switch in Figure below. The parameters are V_{CC}=250V, $V_{CE(sat)}$=2V, I_M=100A, I_{CEO}=3mA , t_d=0.5μS, t_r=1μS, t_s=5μS t_f=3μS and frequency f_s=10kHz. Determine the total power loss in the transistor.



Solution

a) During delay time, $0 \le t \le t_d$

$i_C(t) = I_{CEO} = 3mA$

$V_{CE}(t) = V_{CC} = 250V$

$Pd(t) = i_C(t)\, V_{CE}(t) = 0.75W$

The average power loss during the delay time is:

$$P_d = \frac{1}{T}\int_0^{t_d} Pd(t)dt = I_{CEO}V_{CC}t_d f_s$$

$$= 3.75mW$$

b) During rise time $0 \le t \le t_r$

$$i_C(t) = \frac{I_M}{t_r}t$$

$$V_{CE}(t) = V_{CC} + \left(V_{CE(sat)} - V_{CC}\right)\frac{t}{t_r}$$

$P_r(t) = i_C(t)\, V_{CE}(t)$

$$= I_M \frac{t}{t_r}\left[V_{CC} + \left(V_{CE(sat)} - V_{CC}\right)\frac{t}{t_r}\right]$$

$$P_r = \frac{1}{T}\int_0^{t_r} I_M \frac{t}{t_r}\left[V_{CC} + \left(V_{CE(sat)} - V_{CC}\right)\frac{t}{t_r}\right]$$

$$= f_s I_M t_r\left[\frac{V_{CC}}{2} + \frac{\left(V_{CE(sat)} - V_{CC}\right)}{3}\right] = 42.33W$$

c) During Conduction period, $0 \le t \le t_n$

$i_C(t) = I_M = 100A$

$V_{CE}(t) = V_{CE(sat)} = 2V$

$P_n(t) = i_C(t)\, V_{CE}(t) = 200W$

The average power loss during the delay time is:

$$P_n = \frac{1}{T}\int_0^{t_n} P_n(t)dt = I_M V_{CE(sat)} t_n f_s$$

= 97W

d) During storage period, $0 \le t \le t_s$

$i_C(t) = I_M = 100A$

$V_{CE}(t) = V_{CE(sat)} = 2V$

$P_s(t) = i_C(t)\, V_{CE}(t) = 200W$

The average power loss during the delay time is:

$$P_s = \frac{1}{T}\int_0^{t_s} P_s(t)dt = I_M V_{CE(sat)} t_s f_s = 10W$$

e) During fall period, $0 \le t \le t_f$

$$i_C(t) = I_M\left(1 - \frac{t}{t_f}\right)$$

$$V_{CE}(t) = V_{CC}\frac{t}{t_f}$$

$$P_f(t) = i_C(t)\, V_{CE}(t) = V_{CC} I_M\left[\left(1 - \frac{t}{t_f}\right)\frac{t}{t_f}\right]$$

$$P_f = \frac{1}{T}\int_0^{t_f} P_f(t)dt = \frac{V_{CC} I_M t_f f_s}{6} = 125W$$

f) During off-period, $0 \le t \le t_o$

$i_C(t) = I_{CEO} = 3mA$

$V_{CE}(t) = V_{CC} = 250V$

$P_o(t) = i_C(t)\, V_{CE}(t) = 0.75W$

The average power loss during the off-period is:

$$P_o = \frac{1}{T}\int_0^{t_o} P_o(t)dt = I_{CEO} V_{CC} t_o f_s$$

$= 0.315W$

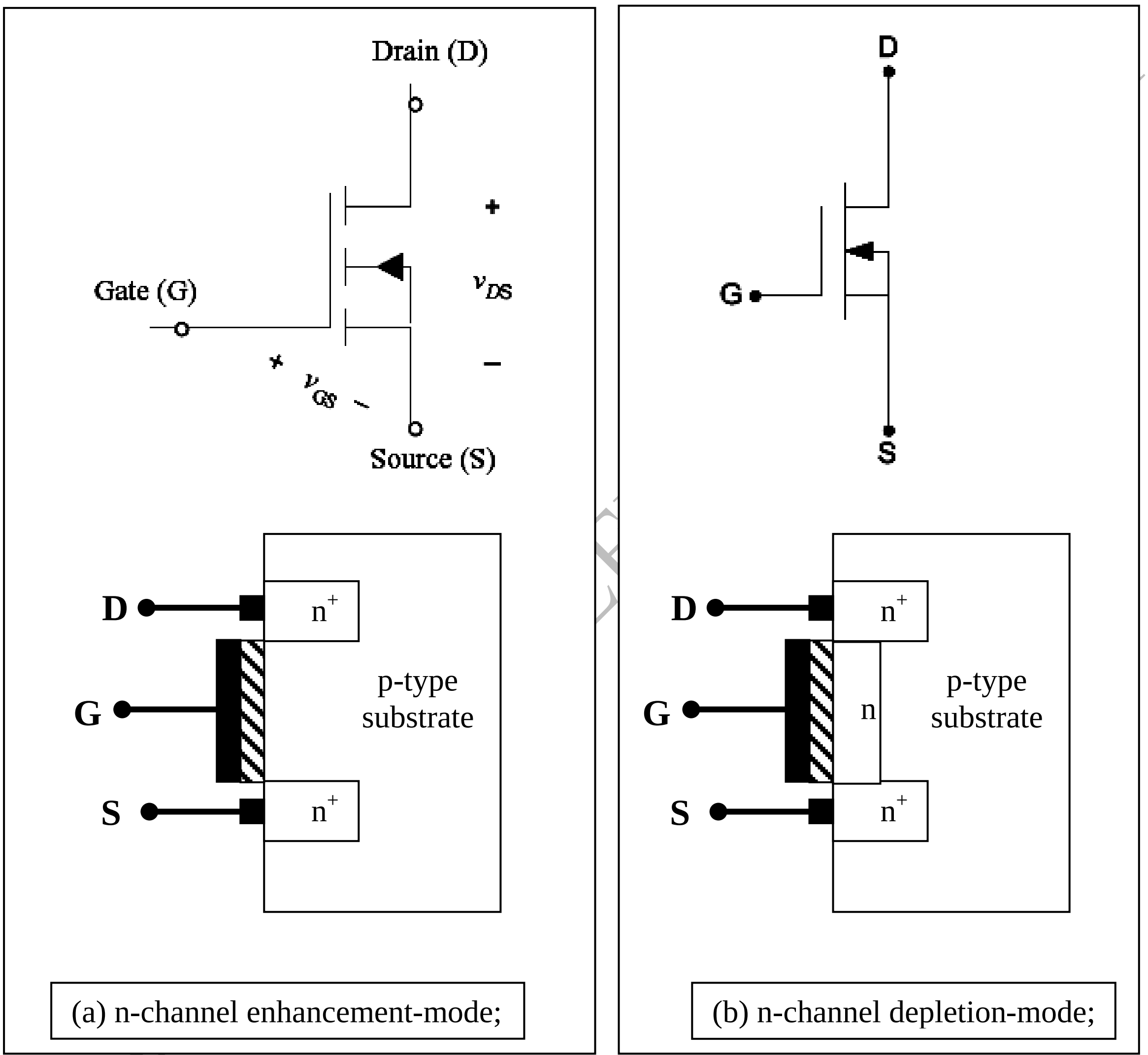
$\therefore$ The total power loss in the transistor due to collector current is:

$$P_T = P_d + P_r + P_n + P_s + P_f + P_o$$
$$= 0.00375 + 42.33 + 97 + 10 + 125 + 0.315 = 274.65\ W$$

LECTURE NO. 17

The Power MOSFET

The device symbol for a p- and n-channel enhancement and depletion types are shown in Figure below.



(a) n-channel enhancement-mode;

(b) n-channel depletion-mode;

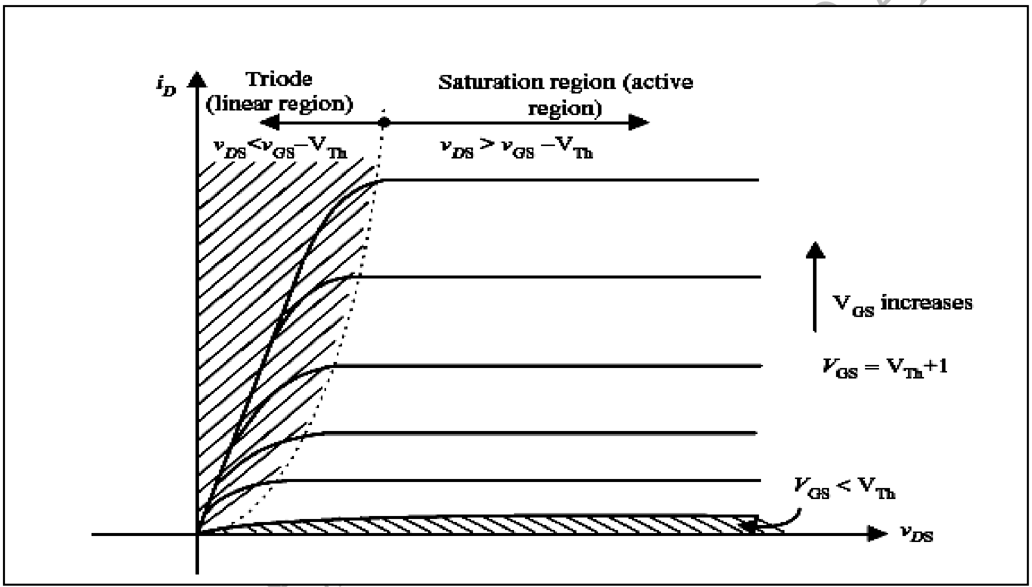
Most MOSFET devices used in power electronics applications are of the **n-channel, enhancement type**. For the MOSFET to carry drain current, a channel between the drain and the source must be created. This occurs when the gate-to-source voltage exceeds the device threshold voltage $\mathbf{V_{Th}}$.

1. For given v_{GS}, with small v_{DS} ($v_{DS} < v_{GS} - V_{Th}$), the device operates in the triode region (saturation region in the BJT), and

2. For larger v_{DS} (v_{DS} > v_{GS} $-V_{Th}$), the device enters the saturation region (active region in the BJT).
3. For v_{GS} < V_{Th}, the device turns off, with drain current almost equal to zero.

Under both regions of operation, the gate current is almost zero. This is why the MOSFET is known as a voltage-driven device and, therefore, requires simple gate control circuit.

The characteristic curves in Figure blow show that there are three distinct regions of operation labeled as triode region, saturation region, and cut-off region. When used as a switching device, only triode and cut-off regions are used, whereas, when it is used as an amplifier, the MOSFET must operate in the saturation region, which corresponds to the active region in the BJT.



On-State Resistance

When the MOSFET is in the on state (triode region), the channel of the device behaves like a constant resistance $\mathbf{R_{DS.on}}$. that is linearly proportional to the change between $\mathbf{v_{DS}}$ and $\mathbf{i_D}$ as given by the following relation:

$$R_{DS(on)} = \frac{\partial v_{DS}}{\partial i_D}\Big|_{v_{GS=Constant}}$$

The total conduction (on-state) power loss for a given MOSFET with forward current I_D and on-resistance $\mathbf{R_{DS.on}}$ is given by:

$$P_{on,diss} = I_D^2 R_{DS(on)}$$

Comparison between the BJT and the MOSFET,

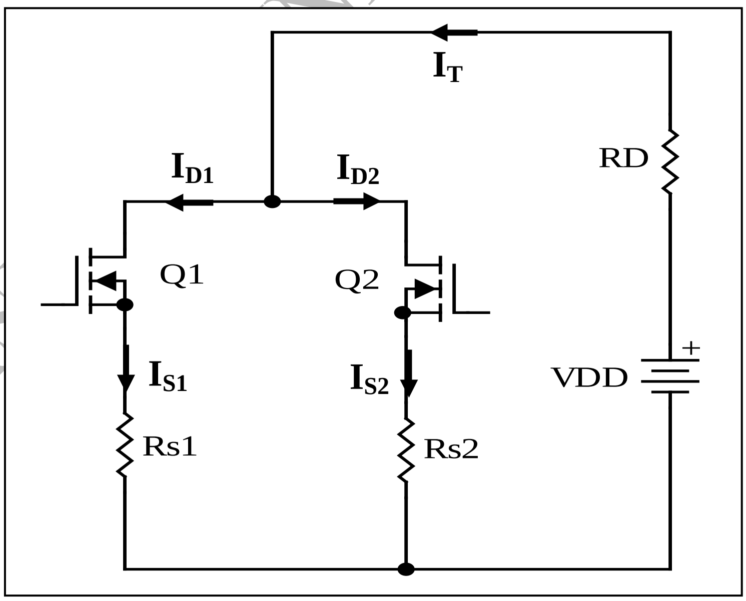
- The BJT has greater power handling capabilities and smaller switching speed,
- The MOSFET device has less power handling capabilities and relatively fast switching speed.
- The MOSFET device has a higher on-state resistor than the bipolar transistor.
- Another difference is that the BJT parameters are more sensitive to junction temperature when compared to the MOSFET,
- Unlike the BJT, MOSFET devices do not suffer from second breakdown voltages
- Sharing current in parallel devices is possible.

Parallel Operation

Transistors are connected in parallel if one device cannot handle the load current demand. For equal current sharing the transistors should be matched for:

- gain
- Trans-conductance
- Saturation voltage
- Turn-on and turn-off time.

The resistors in figure will help current sharing under steady state condition.



Example

Two MOSFETs connected in parallel similar to figure above. The total current I_T=20A. The drain to source voltage of Q_1 is V_{DS1}=2.5V and the drain to source voltage of Q2 is V_{DS2} =3V. Determine the drain current of each transistor and difference current sharing if current sharing series resistances are: a) $R_{s1}=0.3\Omega$ and $R_{s2}=0.2\Omega$, b) $R_{s1}=R_{s2}=0.5\Omega$

Solution

a) $I_T = I_{D1} + I_{D2}$ and $V_{DS1} + I_{D1}R_{s1} = V_{DS2} + I_{D2}R_{s2}$

$V_{DS1} + I_{D1}R_{s1} = V_{DS2} + (I_T - I_{D1})R_{s2}$

$$I_{D1} = \frac{V_{DS2} - V_{DS1} + I_T R_{s2}}{R_{s1} + R_{s2}} = \frac{3 - 2.5 + 20 \times 0.2}{0.3 + 0.2} = 9A$$

$I_{D2} = I_T - I_{D1} = 20 - 9 = 11A \Rightarrow \Delta I = I_{D2} - I_{D1} = 11 - 9 = 2A = 10\%$

b) $$I_{D1} = \frac{V_{DS2} - V_{DS1} + I_T R_{s2}}{R_{s1} + R_{s2}} = \frac{3 - 2.5 + 20 \times 0.5}{0.5 + 0.5} = 10.5A$$

$I_{D2} = 20 - 10.5 = 9.5A \Rightarrow \Delta I = I_{D1} - I_{D2} = 10.5 - 9.5 = 1A = 5\%$

LECTURE NO. 18

Pulse Width Modulation

In many industrial applications, it is often required to control the output voltage of converters. The most efficient method of controlling the output voltage is to incorporate pulse-width modulation (PWM) control within the inverters. The commonly used techniques are:

1. **Single pulse-width modulation**
2. **Multiple pulse width modulation**

Single pulse width modulation

In single pulse-width modulation control, there is only one pulse per half-cycle and the width of the pulse is varying to control the output voltage. Fig.(1) shows the generation of gating signals of single pulse width modulation. The gating signals are generated by:

i. Convert the reference signal to the square wave signal. This process is obtained by inter the reference signal to the zero-crossing circuit witch consider the positive part of the input signal is positive part of the output signal(square wave) and the negative part of the input signal is negative part of the output signal as shown in Fig(1). That is :

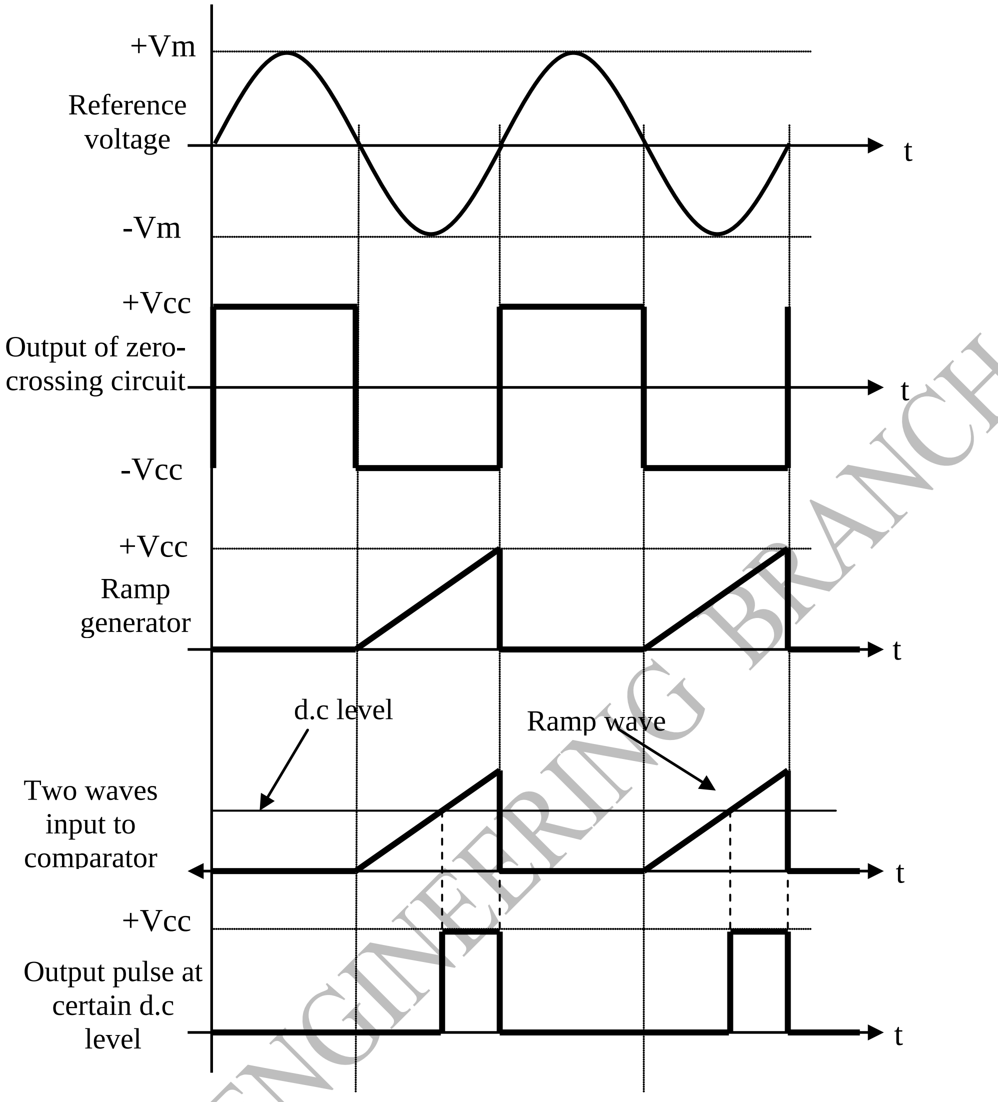
$$F(t) = \begin{cases} -V_{CC} & F(t) < 0 \\ +V_{CC} & F(t) > 0 \end{cases}$$

ii. Then, the output signal of zero-crossing circuit is become control signal of the ramp generator. Ramp generator integrate the input signal to the saw-toothed signal as shown in Fig.(1).

iii. Then, the output of the ramp generator inter to the comparator circuit which compare between the variable d.c level and the ramp wave. The certain d.c level gives the certain pulse width and any change in the d.c level will produce change in the pulse width as shown in Fig.(1).

The rms value of output voltage can be found from

$$Vo = \left[\frac{1}{\pi}\int_{(\pi-\delta)/2}^{(\pi+\delta)/2} V_s^2 d(\omega t)\right]^{1/2} = V_s\sqrt{\frac{p\delta}{\pi}}$$



Fig(1): shows the generation of gating signals of single pulse width modulation

Multiple Pulse width modulation

The harmonic content can be reduced by using several pulses in each half-cycle of output voltage. The generation of gating signals for turning on and off transistors is shown in Figure (3). The gating signals are produced by comparing reference signal with triangular carrier wave. The frequency of the reference signal sets the output frequency (f_o) and carrier frequency (f_c) determine the number of pulses per half cycle, p:

$$\mathbf{p = \frac{f_c}{2f_o}}$$

$$\textbf{Modulation index (M)} = \frac{V_m}{V_C}$$

The variation of modulation index (**M**) from **0** to **1** varies the pulse width from **0** to **π/p** , and the output voltage from **0** to **Vm**.

Uniform pulse width modulation (UPWM)

Figure (3) shows the uniform pulse width modulation (UPWM). It can be note the reference voltage is square wave changed from the **Vm** to **–Vm** in frequency = **fo**. The carrier frequency is triangle wave with amplitude equal to **Vc** in frequency = **fc**. If the **δ** is the width of each pulse, the rms output voltage can be found from:

$$V_o = \left[\frac{2p}{2\pi}\int_{(\pi/p-\delta)/2}^{(\pi/p+\delta)/2} V_s^{2}\,d(\omega t)\right]^{1/2} = V_s\sqrt{\frac{p\delta}{\pi}}$$

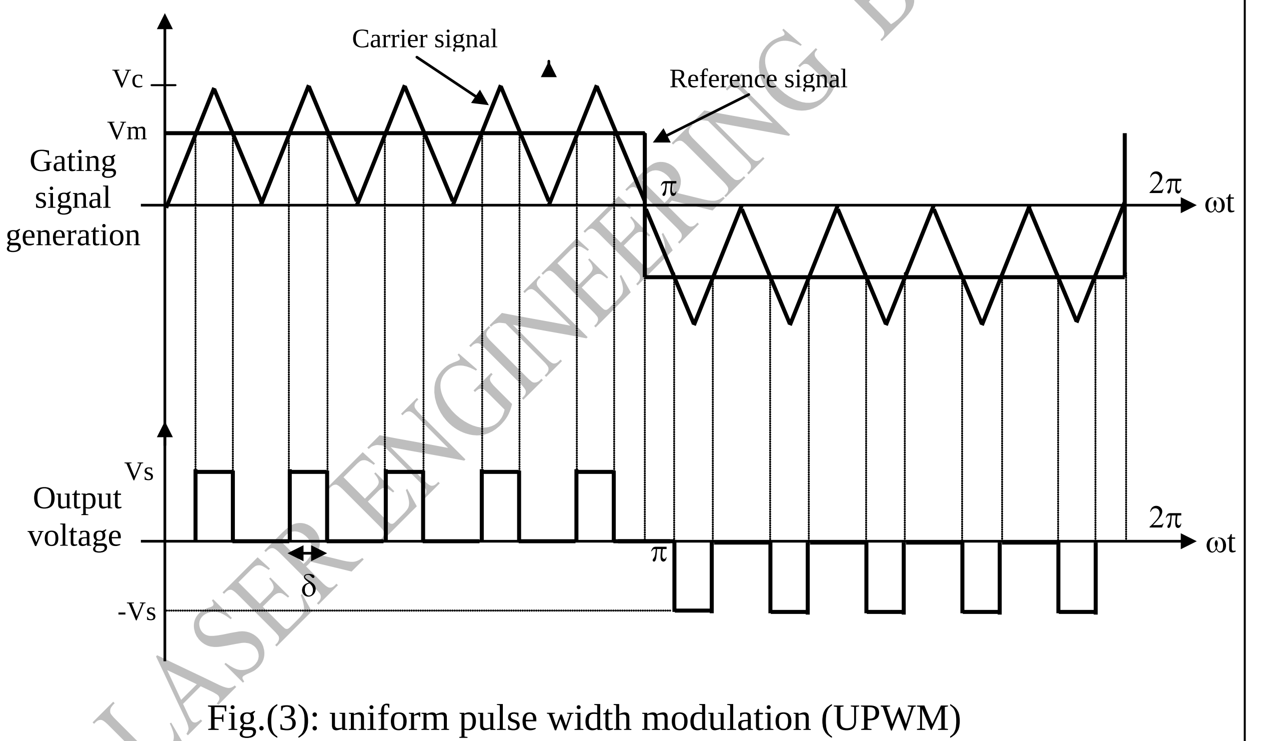


Fig.(3): uniform pulse width modulation (UPWM)

Sinusoidal Pulse Width modulation

Instead of maintaining the width of all pulses the same as in the case of uniform pulse width modulation, the width of each pulse is vary in proportion to the amplitude of a sine wave evaluated at the center of the same pulse. The distortion factor and lower-order harmonics are reduced scientifically. The gating signals as shown in Fig.(4) are generated by comparing a sinusoidal reference signal with a triangular carrier signal of frequency $\mathbf{f_c}$.

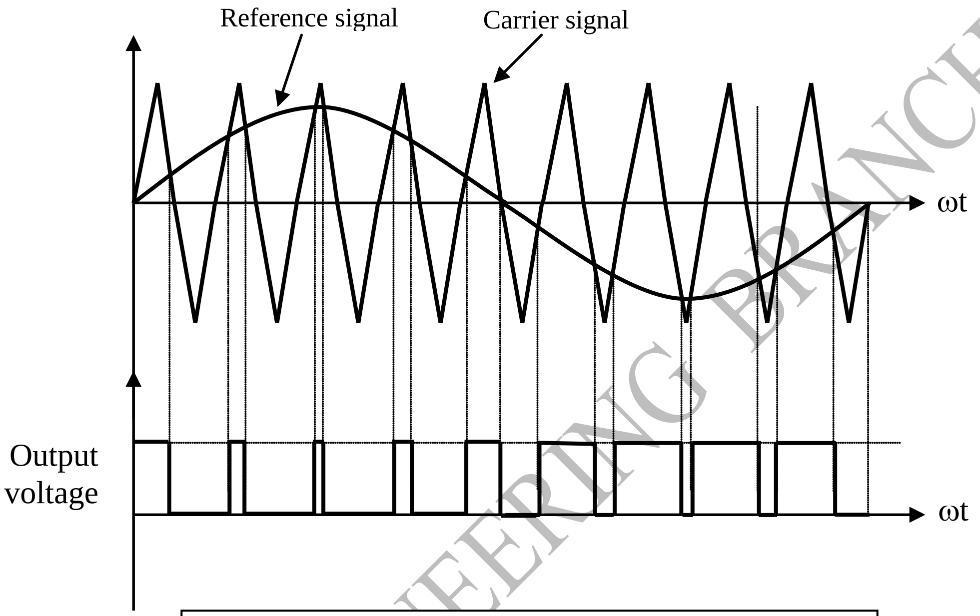


Fig.(4): Sinusoidal Pulse width modulation

The rms value of output voltage is:

$$\mathbf{V_o = V_s\left(\sum_{m=1}^{p}\frac{\delta_m}{\pi}\right)^{1/2}}$$

Where $\mathbf{\delta_m}$ is the width of *mth* pulse

LECTURE NO. 19

DC-DC Converters

Modern electronic systems require high-quality, small, lightweight, reliable, and efficient power supplies. Linear power regulators, whose principle of operation is based on a voltage or current divider, are inefficient. This is because they are limited to output voltages smaller than the input voltage, and also their power density is low because they require low frequency (50 or 60 Hz) line transformers and filters.

The higher the operating frequency, the smaller and lighter the transformers, filter inductors, and capacitors. In addition, the dynamic characteristics of converters improve with increasing operating frequencies.

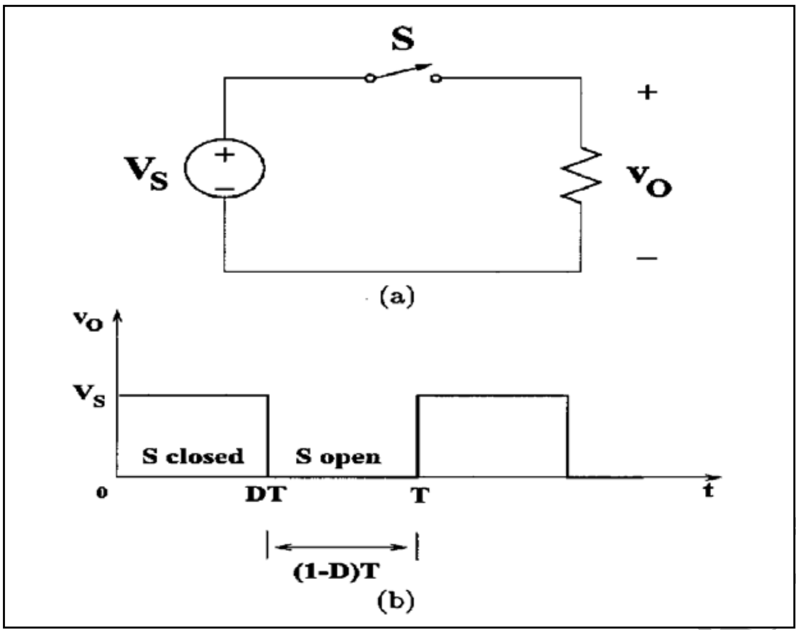
High-frequency electronic power processors are used in dc-dc power conversion. The functions of dc-dc converters are:

- to convert a dc input voltage $\mathbf{V_S}$ into a dc output voltage $\mathbf{V_O}$;
- to regulate the dc output voltage against load and line variations;
- to reduce the ac voltage ripple on the dc output voltage below the required level;
- to provide isolation between the input source and the load (isolation is not always required);
- to protect the supplied system and the input source from electromagnetic interference (**EMI**);

The dc-dc converters can be divided into two main types: hard-switching pulse width modulated (PWM) converters, and resonant and soft-switching converters

DC Choppers

A step-down dc chopper with a resistive load is shown in Figure below. It is a series connection of a dc input voltage source $\mathbf{V_S}$, controllable switch **S**, and load resistance **R**. In most cases, switch **S** has unidirectional voltage-blocking capabilities and unidirectional current-conduction capabilities. Power electronic switches are usually implemented with power MOSFETs, power BJTs, or MCTs.



The switch is being operated with a duty ratio **D** defined as a ratio of the switch on time to the sum of the on and off times. For a constant frequency operation

$$D \equiv \frac{t_{on}}{t_{on} + t_{off}} = \frac{t_{on}}{T}$$

The average value of the output voltage is: $\boldsymbol{V_o = DV_s}$

- From above equation, the output voltage can be regulated by adjusting the duty ratio **D**.
- The average output voltage is always smaller than the input voltage.

The rms value of output voltage is:

$$\mathbf{V_L = \left(\frac{1}{T}\int_0^{DT} Vs^2 dt\right)^{1/2} = \sqrt{D}Vs}$$

The output power is:

$$\mathbf{P_o = \frac{1}{T}\int_0^{DT} Vs\frac{Vs}{R}dt = D\frac{Vs^2}{R}}$$

Example

The DC chopper has a resistive load of R=10 and input voltage is Vs=220V. When the chopper switch remains on its voltage drop =2V, duty cycle =50% and the chopping frequency is f=1kHz.determine a) The average output voltage, b) the rms output voltage ,c) chopper efficiency.

Solution

a) $V_o = DVs$

$= 0.5 \times (220 - 2) = 109V$

b) $V_L = \left(\frac{1}{T}\int_0^{DT} Vs^2 dt\right)^{1/2} = \sqrt{D}Vs$

$= 0.5^{1/2} \times (220 - 2) = 154.15V$

c) The output power is:

$$P_o = \frac{1}{T}\int_0^{DT}(Vs - Vd)\frac{Vs - Vd}{R}dt = D\frac{(Vs - Vd)^2}{R} = 0.5 \times \frac{(220-2)^2}{10} = 2376.2$$

The input power is:

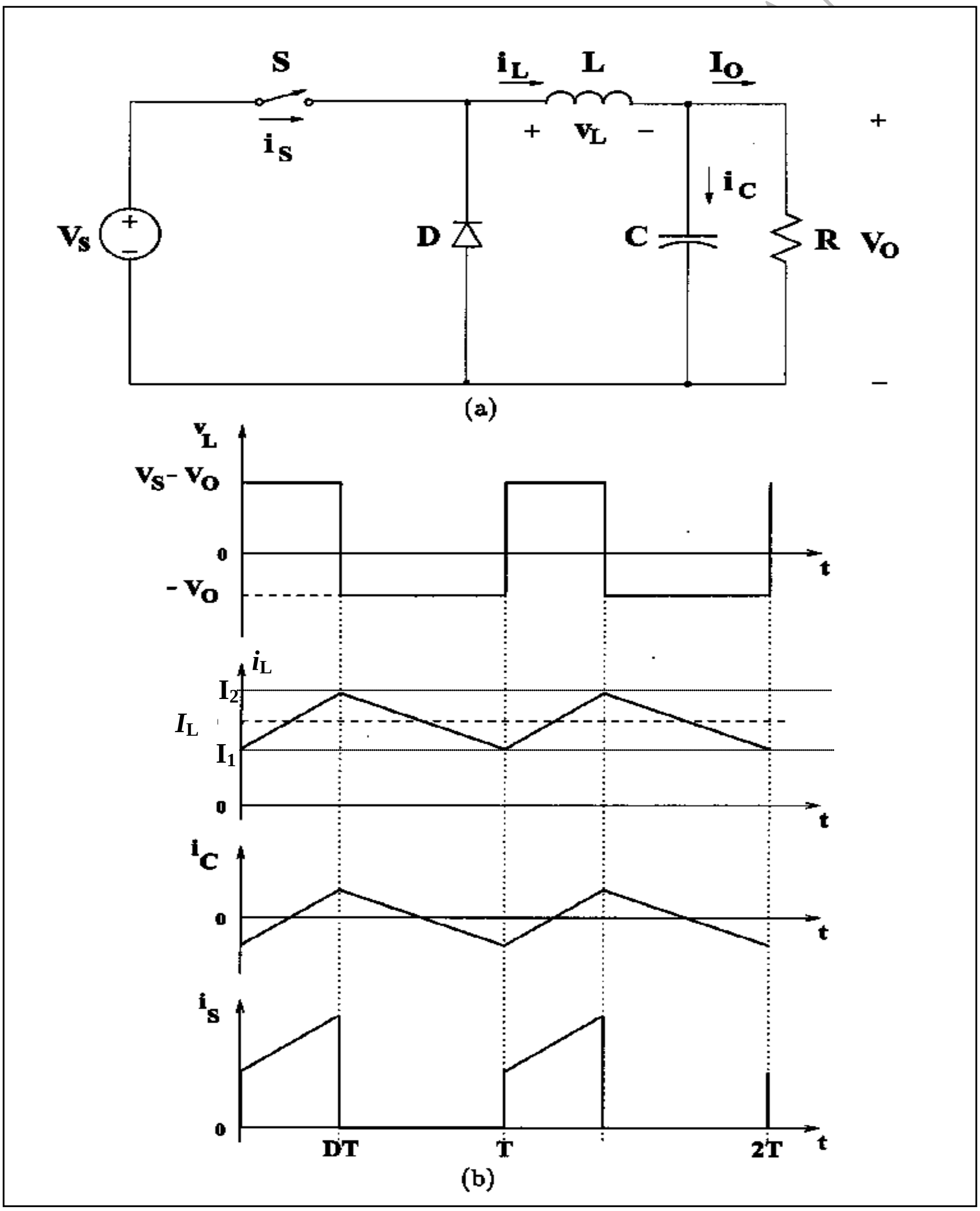
$$P_i = \frac{1}{T}\int_0^{DT} Vs\frac{Vs}{R}dt = D\frac{Vs^2}{R} = 0.5 \times \frac{220^2}{10} = 2398\,W$$

$$\text{The efficiency} = \frac{P_o}{P_i} = \frac{2376.2}{2398} = 99.09\%$$

LECTURE NO. 20

Step-Down dc-dc Converter

The step-down dc-dc converter, commonly known as a buck converter, is shown in Figure below. It consists of dc input voltage source **VS**, controlled switch **S**, diode **D**, filter inductor **L**, filter capacitor **C**, and load resistance **R**. The state of the converter in which the inductor current is never zero for any period of time is called the ***continuous conduction mode*** **(CCM)**. It can be seen from the circuit that when the switch **S** is commanded to the on state, the diode **D** is reverse-biased. When the switch **S** is off, the diode conducts to support an uninterrupted current in the inductor.



$$V_s - V_o = L\frac{I_2 - I_1}{t_1} = L\frac{\Delta I}{t_1}$$

Or

$$t_1 = L\frac{\Delta I}{V_s - V_o}$$

The current falling linearly from I_2 to I_1 in time t_2, then

$$-V_o = L\frac{I_1 - I_2}{t_2} = -L\frac{\Delta I}{t_2}$$

Or

$$t_2 = L\frac{\Delta I}{V_o}$$

But, $t_1 = DT$ and $t_2 = (1-D)T$

$$(V_s - V_o)\,DT = V_o(1 - D)T$$

$$V_o = D\,V_s \quad \text{and} \quad I_s = DI_o$$

$$T = t_1 + t_2 = L\frac{\Delta I}{V_s - V_o} + L\frac{\Delta I}{V_o} = \frac{\Delta I L V_s}{V_o(V_s - V_o)}$$

$$\Delta I = \frac{V_o(V_s - V_o)}{LV_s f}$$

Or

$$\Delta I = \frac{DV_s(1 - D)}{fL}$$

$$i_L = i_c + i_o$$

The average capacitor current I_c which flow into $t_1/2 + t_2/2 = T/2$:

$$Ic = \frac{\Delta I}{4}$$

$$V_c = \frac{1}{C}\int i_c dt + V_c(0)$$

$$\Delta V_c = V_c - V_c(0) = \frac{1}{C}\int_0^{T/2}\frac{\Delta I}{4}dt = \frac{\Delta I T}{8C} = \frac{\Delta I}{8Cf}$$

$$\Delta V_c = \frac{DV_s(1-D)}{8CLf^2}$$

Example

The dc-dc converter has input voltage =12 V. The required output voltage is V_o=5V and ripple output Voltage = 20mV. The switching frequency = 25kHz and ripple inductor current is 0.8A. Determine:

a) The duty cycle D,

b) The inductance L,

c) The filter capacitor.

Solution

a) $V_o = DV_s \quad \Rightarrow \quad D = V_o/V_s = 5/12 = 41.67\%$

b)

$$\Delta I = \frac{V_o(V_s - V_o)}{LV_s f}$$

$$\Rightarrow \quad L = \frac{V_o(V_s - V_o)}{\Delta I V_s f} = \frac{5(12-5)}{0.8 \times 12 \times 25 \times 10^3} = 145.83\mu H$$

c)

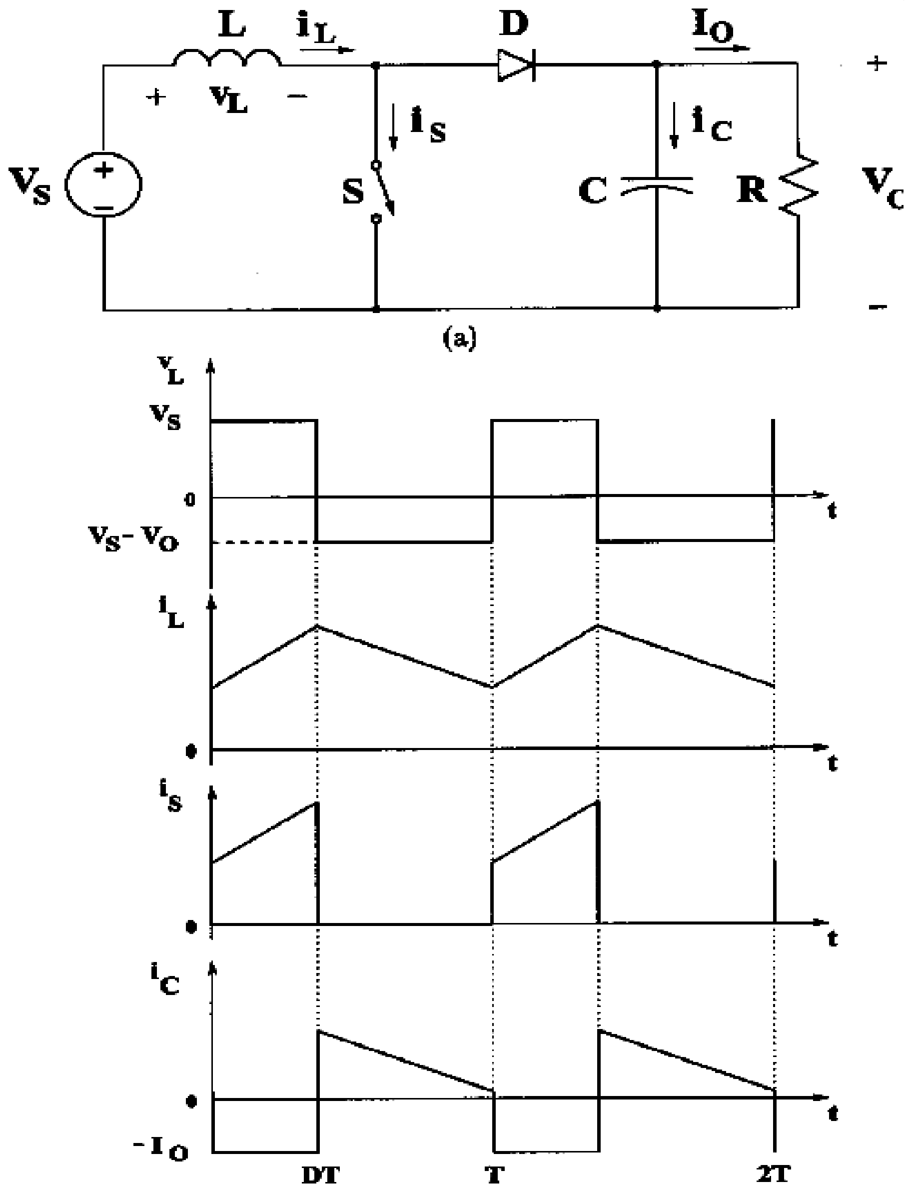
$$\Delta V_c = \frac{\Delta I}{8Cf} \quad \Rightarrow \quad C = \frac{\Delta I}{8\Delta V_c f} = \frac{0.8}{8 \times 20 \times 10^{-3} \times 25 \times 10^3} = 200\mu F$$

LECTURE NO. 21

Step-Up (Boost) Converter

It consists of dc input voltage source V_S, boost inductor **L**, controlled switch **S**, diode **D**, filter capacitor **C**, and load resistance **R**. The converter waveforms in the **CCM** are shown in figure below.

When the switch **S** is in the on state, the current in the boost inductor increases linearly and the diode **D** is off at that time. When the switch **S** is turned off, the energy stored in the inductor is released through the diode to the output **RC** circuit.



$$V_s = L\frac{I_2 - I_1}{t_1} = L\frac{\Delta I}{t_1}$$

Or

$$t_1 = L\frac{\Delta I}{V_s}$$

The current falling linearly from $\mathbf{I_2}$ to $\mathbf{I_1}$ in time $\mathbf{t_2}$**,** then

$$V_s - V_o = L\frac{I_1 - I_2}{t_2} = -L\frac{\Delta I}{t_2}$$

Or

$$t_2 = L\frac{\Delta I}{V_o}$$

But, $\mathbf{t_1 = DT}$ and $\mathbf{t_2 = (1\text{-}D)T}$

$$V_s\ DT = (V_o - V_s)\,(1 - D)T$$

$$Vo = \frac{Vs}{1 - D} \quad \text{and} \quad I_s = \frac{I_o}{1 - D}$$

$$T = t_1 + t_2 = L\frac{\Delta I}{V_s} + L\frac{\Delta I}{V_o - V_s} = \frac{\Delta I L V_o}{V_s(V_o - V_s)}$$

$$\Delta I = \frac{V_s(V_o - V_s)}{L V_o f}$$

Or

$$\Delta I = \frac{D V_s}{f L}$$

$$i_L = i_c + i_o$$

When the transistor is turn on the capacitor supplies the load current for $\mathbf{t = t_1}$. The average capacitor current $\mathbf{I_c = I_o}$**,** and

$$V_c = \frac{1}{C}\int i_c dt + V_c(0)$$

$$\Delta V_c = V_c - V_c(0) = \frac{1}{C}\int_0^{t_1} I_o dt = \frac{I_o t_1}{C}$$

$$\Delta V_c = \frac{I_o(V_o - V_s)}{V_o f C} = \frac{I_o D}{fC}$$

Example

The dc-dc converter has input voltage =5 V. The required output voltage is V_o=15V and the average load current =0.5A. If the switching frequency = 25kHz, L=150μH and C=220μF . Determine:

a) The duty cycle D,

b) The ripple current of inductor ΔI ,

c) The peak current of inductor I_2,

d) The ripple voltage of filter capacitor ΔV.

Solution

a) **Vo=Vs/(1-D)** ⇒ **1-D =5/15=1/3** ⇒ **D=2/3**

b)

$$\Delta I = \frac{V_s(V_o - V_s)}{L V_o f} = \frac{5(15-5)}{150\times10^{-6}\times25\times10^{3}\times15} = 0.89A$$

c)

$$I_s = \frac{I_o}{1-D} \Rightarrow I_s = 0.5/(1-0.667) = 1.5A$$

$$I_2 = I_s + \frac{\Delta I}{2} = 1.5 + \frac{0.89}{2} = 1.945A$$

d)

$$\Delta V_c = \frac{I_o D}{fC} = \frac{0.5\times0.667}{25\times10^{2}\times220\times10^{-6}} = 60.61mV$$

LECTURE NO. 22

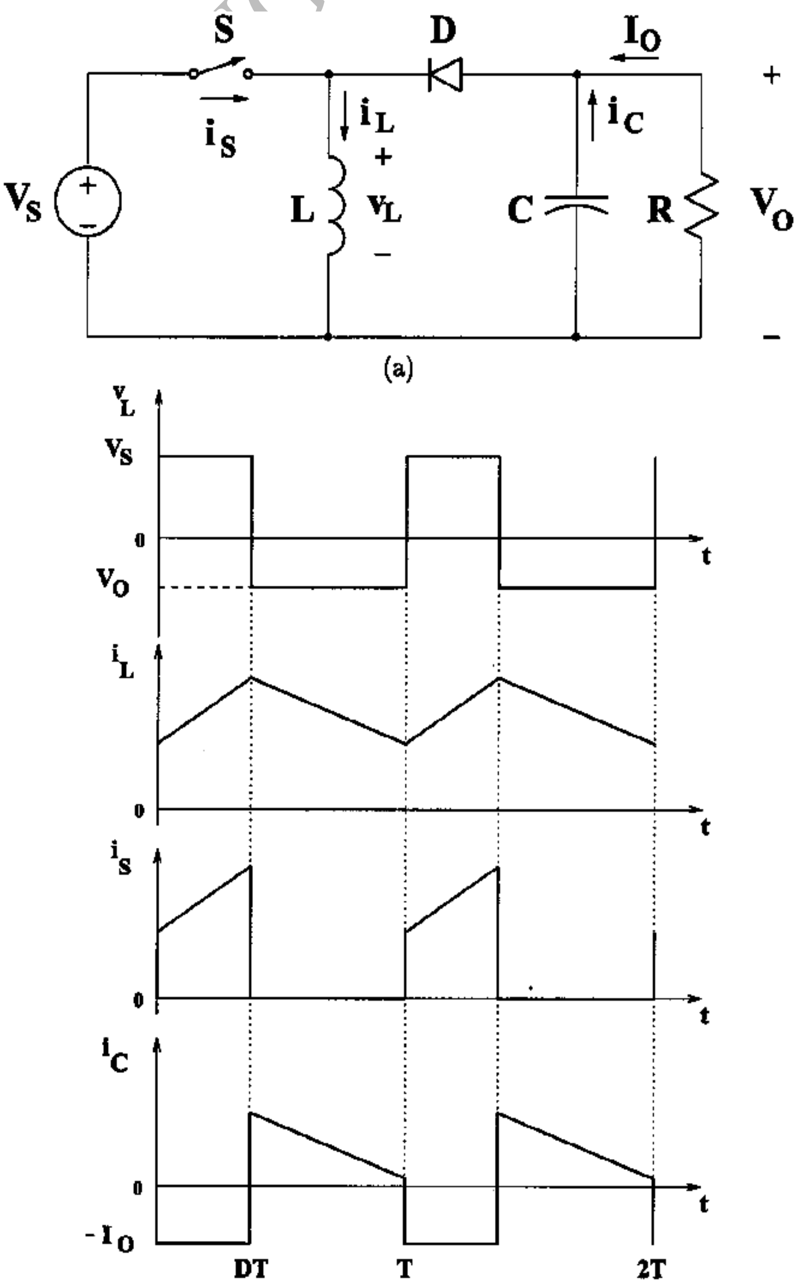
Other Types of DC-DC Converter

1. Buck-Boost Converter

The converter consists of dc input voltage source VS, controlled switch S, inductor L, diode D, filter capacitor C, and load resistance R as shown in figure below. With the switch on, the inductor, current increases while the diode is maintained off. When the switch is turned off, the diode provides a path for the inductor current. Note the polarity of the diode that results in its current being drawn from the output.

$$V_S DT = -V_O(1-D)T$$

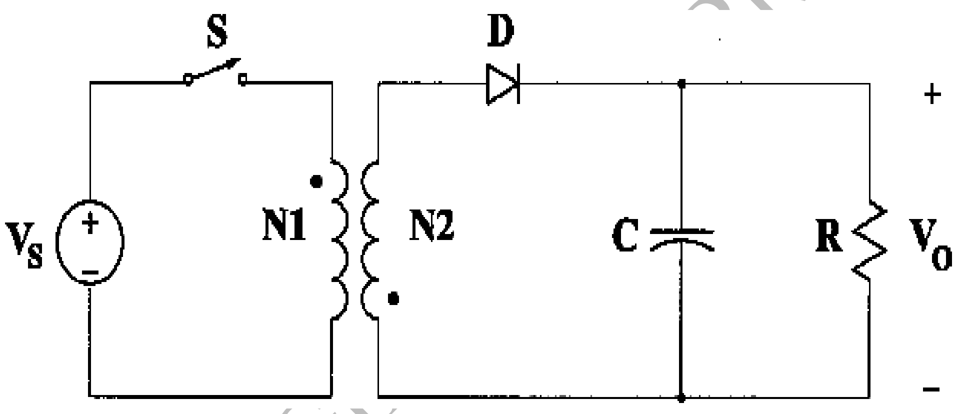
$$\frac{V_O}{V_S} = -\frac{D}{1-D}$$



The output voltage VO is negative with respect to the ground. Its magnitude can be either greater or smaller than the input voltage as the name of the converter implies.

Flyback Converter

A PWM flyback converter is a very practical isolated version of the buck-boost converter. The circuit of the flyback converter is presented in figure below. The inductor of the buck-boost converter has been replaced by a flyback transformer. The input dc source $\mathbf{V_S}$ and switch **S** are connected in series with the transformer primary. The diode **D** and the **RC** output circuit are connected in series with the secondary of the flyback transformer.



When the switch **S** is on, the current in the magnetizing inductance increases linearly, the diode **D** is off and there is no current in the ideal transformer windings. When the switch is turned off, the magnetizing inductance current is diverted into the ideal transformer, the diode turns on, and the transformed magnetizing inductance current is supplied to the **RC** load.
The dc voltage transfer function of the flyback converter is:

$$\frac{V_O}{V_S} = \frac{D}{n(1 - D)}$$

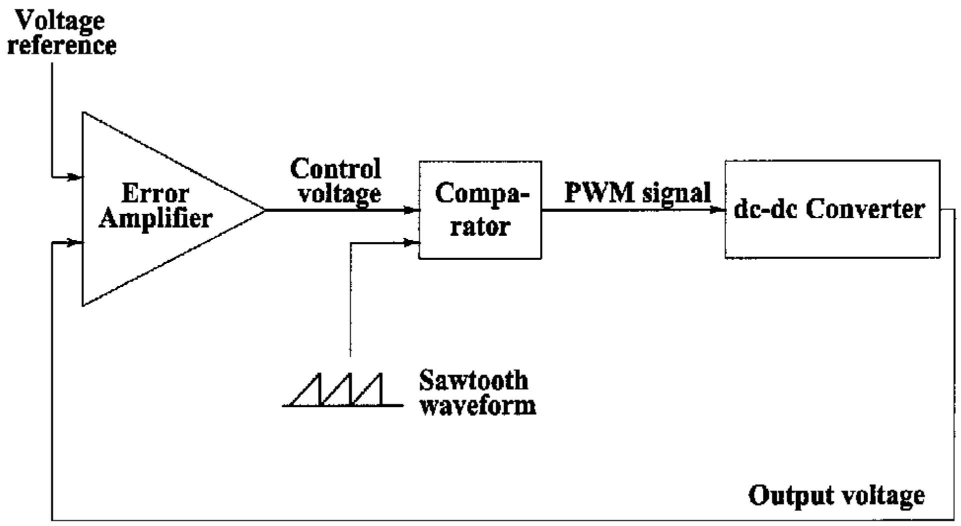
Where **n** is the transformer turns ratio and **n = N1/N2**.

Control Principles

A dc-dc converter must provide a regulated dc output voltage under varying load and input voltage conditions. Hence, the control of the output voltage should be performed in a closed-loop manner using principles of negative feedback. The two most common closed-loop control methods for PWM dc-dc converters are namely, the voltage-mode control and the current-mode control.

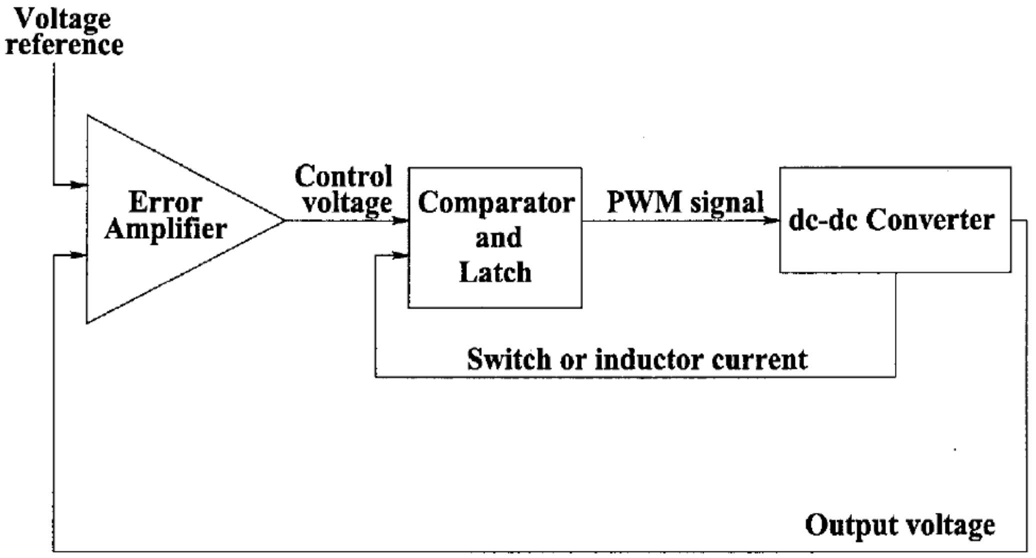
1- The voltage-mode control

The converter output voltage is sensed and subtracted from an external reference voltage in an error amplifier. The error amplifier produces a control voltage that is compared to a constant-amplitude sawtooth waveform. The comparator produces a PWM signal that is fed to drivers of controllable switches in the dc-dc converter. The duty ratio of the PWM signal depends on the value of the control voltage. The frequency of the PWM signal is the same as the frequency of the sawtooth waveform. An important advantage of the voltage-mode control is its simple hardware implementation and flexibility.



2- The current-mode control

An additional inner control loop feeds back an inductor current signal, and this current signal, converted into its voltage analog, is compared to the control voltage. This modification of replacing the sawtooth waveform of the voltage-mode control scheme by a converter current signal significantly alters the dynamic behavior of the converter, which then takes on some characteristics of a current source.


Voltage reference
Error Amplifier
Control voltage
Comparator and Latch
PWM signal
dc-dc Converter
Switch or inductor current
Output voltage

LECTURE NO. 23

DC-AC Converter "Inverters"

The function of an inverter is to change a dc input voltage to a symmetrical ac outputs voltage of desired magnitude and frequency.

Inverters can be broadly classified into two types:

- Single-phase inverters
- Single-phase inverters

These inverters generally use PWM controlled signals for producing an ac output voltage. The inverters are classified into three types according to the input source as follows:

i. ***Voltage source inverter*** if the input voltage remains constant

ii. ***Current source inverter*** if the input currents are maintained constant.

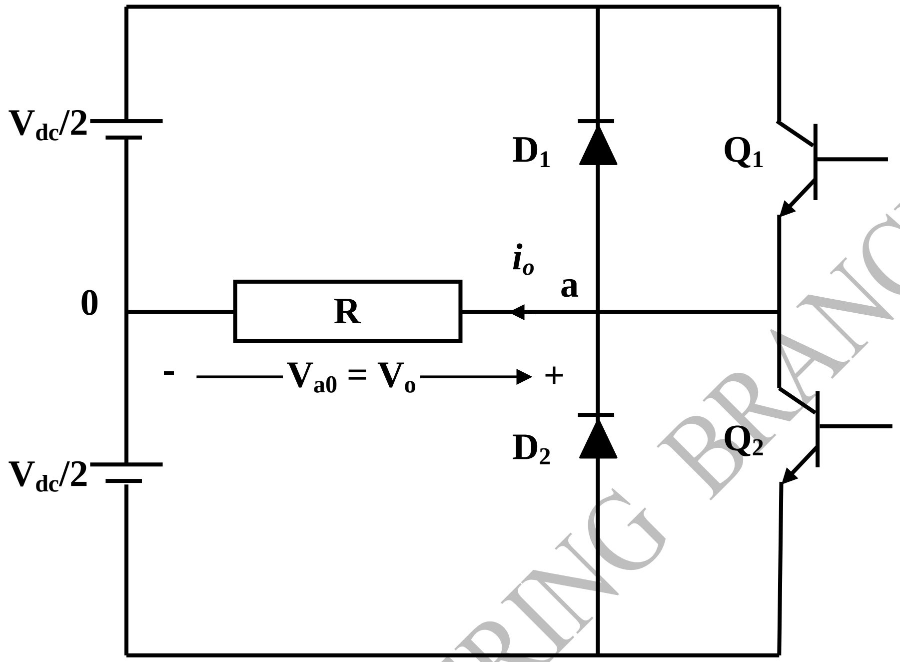
iii. ***Variable dc linked inverter*** if the input voltage is controllable.

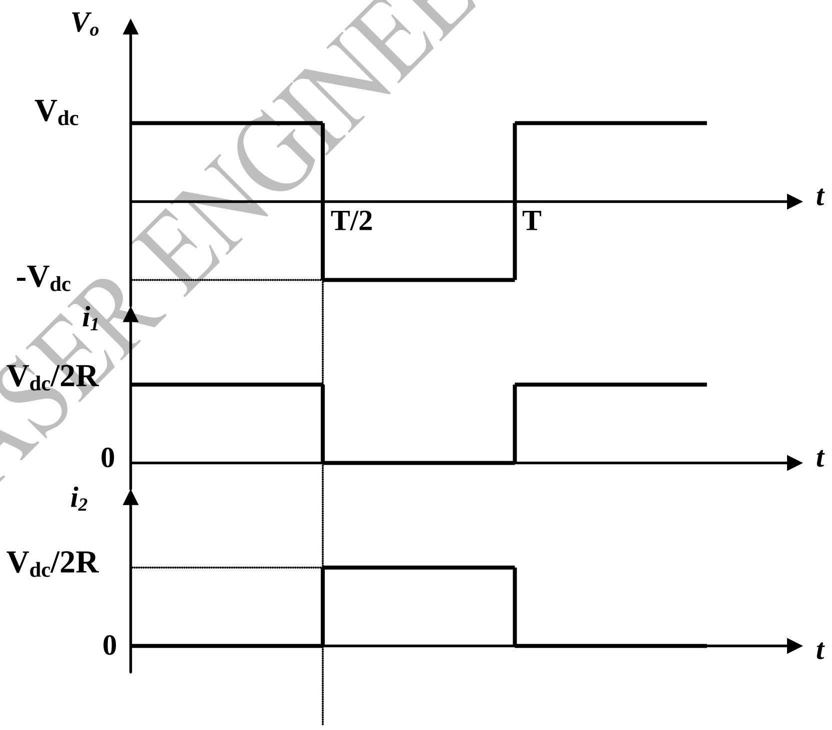
1. Single-Phase Voltage Source Inverters (VSIs)

Single-phase voltage source inverters (VSIs) can be found as half-bridge and full-bridge topologies. Although the power range they cover is the low one, they are widely used in power supplies, single-phase UPSs.

Single-Phase Half-Bridge Inverter

The principle of single-phase half bridge inverter can be explained with figure below. The inverter circuit consists of two choppers. When only Q_1 is turned on for a time T/2, the instantaneous voltage across the load v_o is V_{dc}. If Q_2 only is turned on for a time T/2 – T, $-V_{dc}$ appears across the load. The control circuit should be designed such that Q_1 and Q_2 are not turned on at the same time.





The rms output voltage can be found by:

$$V_o = \left(\frac{2}{T} \int_0^{T/2} \frac{V_{dc}^2}{4} dt \right)^{1/2} = \frac{V_{dc}}{2}$$

•Study of harmonics requires understanding of wave shapes. Fourier Series is a tool to analyze wave shapes.

$$a_o = \frac{1}{\pi} \int_0^{2\pi} f(v) d\theta$$

$$a_n = \frac{1}{\pi} \int_0^{2\pi} f(v) \cos(n\theta) d\theta$$

$$b_n = \frac{1}{\pi} \int_0^{2\pi} f(v) \sin(n\theta) d\theta$$

$$f(v) = \frac{1}{2} a_o + \sum_{n=1}^{\infty} \left(a_n \cos n\theta + b_n \sin n\theta \right)$$

$$a_o = \frac{1}{\pi} \left[\int_0^{\pi} V_{dc} d\theta + \int_{\pi}^{2\pi} -V_{dc} d\theta \right] = 0$$

$$a_n = \frac{V_{dc}}{\pi} \left[\int_0^{\pi} \cos(n\theta) d\theta - \int_{\pi}^{2\pi} \cos(n\theta) d\theta \right] = 0$$

$$b_n = \frac{V_{dc}}{\pi} \left[\int_0^{\pi} \sin(n\theta) d\theta - \int_{\pi}^{2\pi} \sin(n\theta) d\theta \right]$$

$$b_n = \frac{V_{dc}}{n\pi} \left[-\cos(n\theta) \Big|_0^{\pi} + \cos(n\theta) \Big|_{\pi}^{2\pi} \right]$$

$$= \frac{V_{dc}}{n\pi} \left[(\cos 0 - \cos n\pi) + (\cos 2n\pi - \cos n\pi) \right]$$

when n is even, $\cos n\pi = 1$

$b_{n=} 0$

$$= \frac{2V_{dc}}{n\pi}\left[(1-\cos n\pi)\right] \Longrightarrow$$

$$\text{when n is odd}, \cos n\pi = -1$$

$$b_{n=} \frac{4V_{dc}}{n\pi}$$

The instantaneous output voltage can be expressed in Fourier series as:

$$v_o = \sum_{n=1,3,5...}^{\infty} \frac{2 \cdot V_{dc}}{n\pi} \sin n\omega t$$

The rms value of fundamental component is:

$$V_1 = \frac{2 \cdot V_{dc}}{\sqrt{2} \cdot \pi} = 0.45V_{dc}$$

The output of practical inverters contains harmonics and quality of an inverter is normally evaluated in terms of the following performance parameters:

- **Harmonic Factors of *n*th Harmonic "HF$_n$"**

$$HF_n = \frac{V_n}{V_1}$$

- **Total Harmonic Distortion "THD"**

  The total harmonic distortion, which is a measure of closeness in shape between a waveform and its fundamental component, is defined as:

$$THD = \frac{1}{V_1}\left(\sum_{n=2,3}^{\infty} V_n^2\right)^{1/2}$$

- **Distortion factor "DF"**

$$DF_n = \frac{V_n}{n^2 \cdot V_1}$$

LECTURE NO. 24

Example: The single-phase half bridge has a resistive load of R=2.4Ω and the dc input voltage V_{dc}= 24V. Determine the following:

- **a) The rms value of fundamental component,**
- **b) The output power,**
- **c) The average and peak current of each transistor,**
- **d) The total harmonic distortion THD,**
- **e) The distortion factor DF of third harmonic.**

Solution

a) $V_1 = \frac{4 \cdot V_{dc}}{\sqrt{2} \cdot \pi} = 0.9V_{dc} = 0.9 \times 24 = 21.6V$

b) $$V_o = \left(\frac{2}{T} \int_0^{T/2} V_{dc}^2 dt \right)^{1/2} = V_{dc} = 24V$$

The output power $Po = \frac{V_o^2}{R} = \frac{(24)^2}{2.4} = 240W$

c) The peak current $I_p = \frac{V_{dc}}{R} = \frac{24}{2.4} = 10A$

Since the transistor conducts for 50% duty cycle, the average current of each transistor is:

$$I_D = 0.5 \times I_P = 0.5 \times 10 = 5A$$

d)

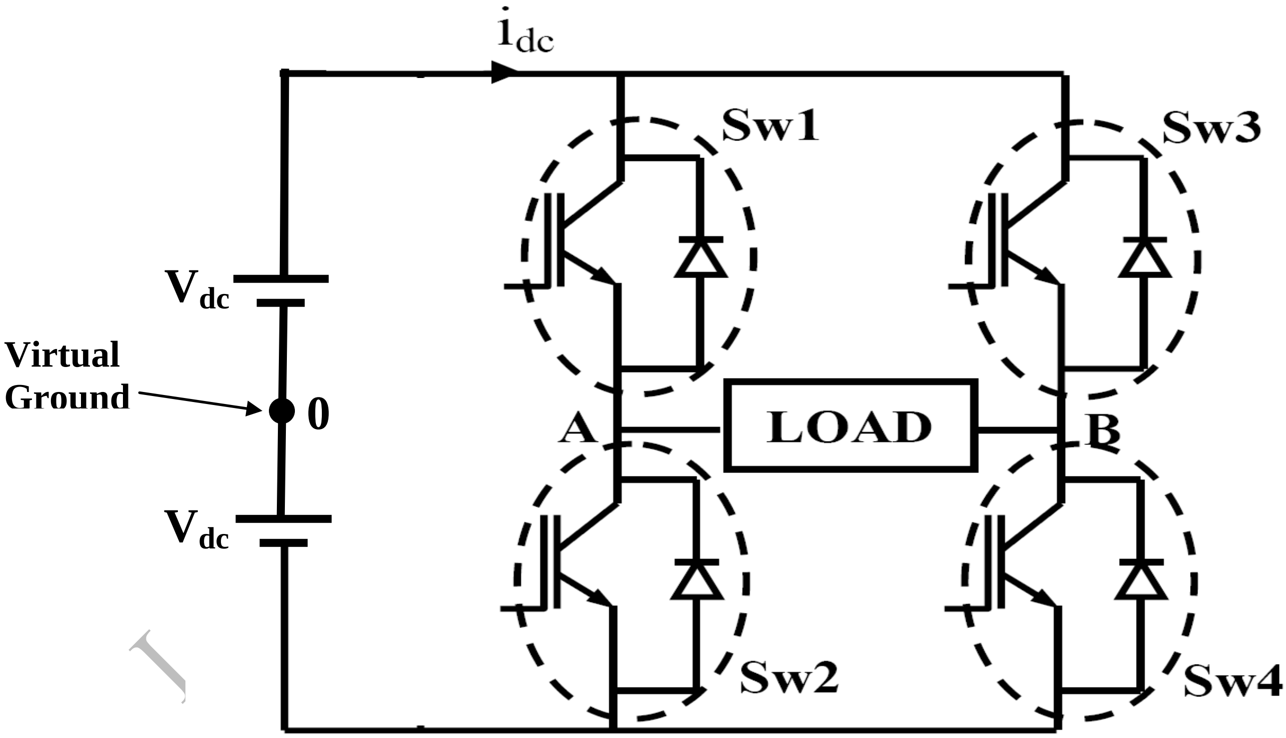
$$THD = \frac{1}{V_1} \left(\sum_{n=2,3}^{\infty} V_n^2 \right)^{1/2} = \frac{\left(V_o^2 - V_1^2\right)^{1/2}}{V_1} = \frac{0.436 \cdot V_{dc}}{0.9 \times V_{dc}} = 48.43\%$$

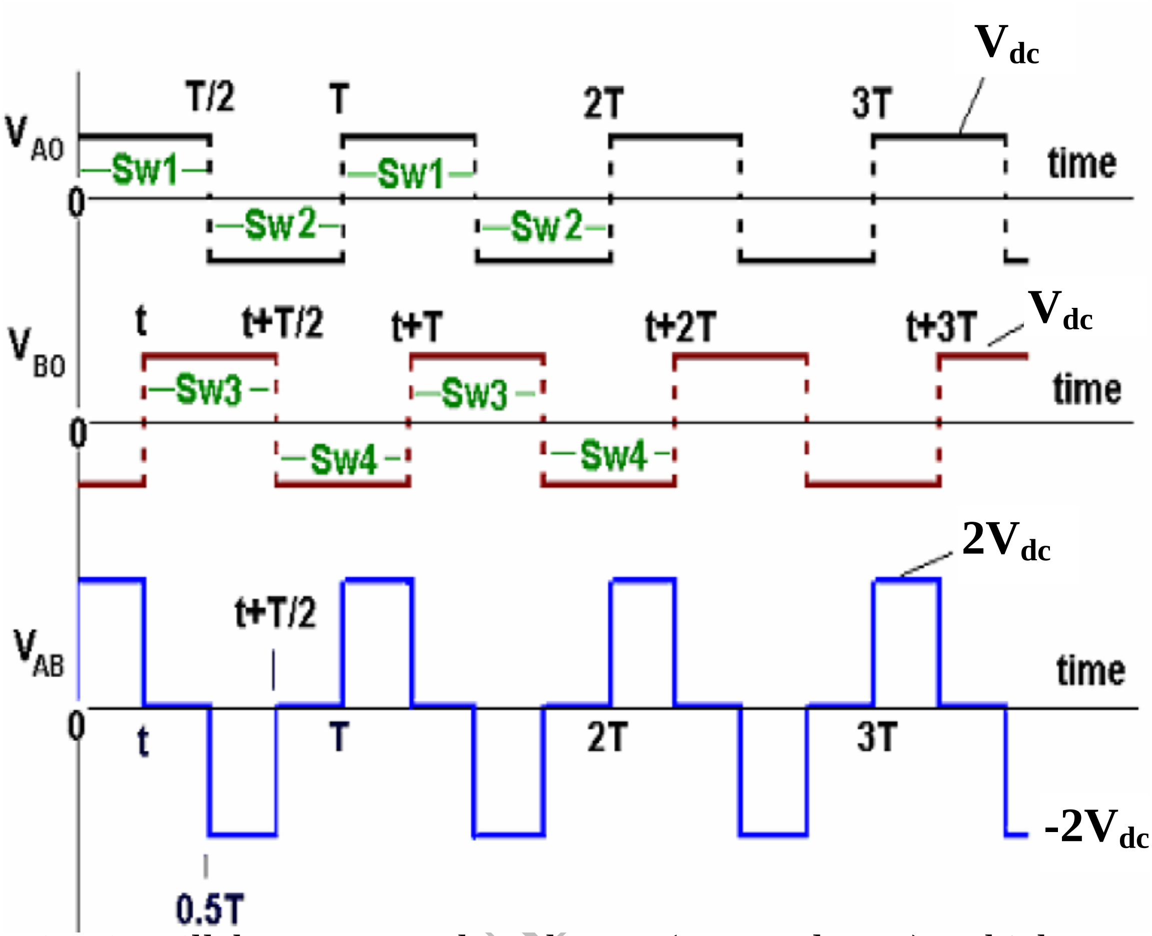
e) $$DF_n = \frac{V_n}{n^2 \cdot V_1}$$

$$V_n = \frac{4 \cdot V_{dc}}{n\pi} \Rightarrow V_3 = \frac{4 \cdot V_{dc}}{3\pi} = \frac{4 \times 24}{3 \times \pi} = 7.2V$$

$$DF_3 = \frac{V_3}{3^2 \times V_1} = \frac{7.2}{9 \times 21.6} = 3.7\%$$

The Single-Phase Full Bridge Inverter





circuit will have two pole-voltages (V_{AO} and V_{BO}), which are similar to the pole voltage V_{AO} of the half bridge circuit. Both V_{AO} and V_{BO} of the full bridge circuit are square waves but they will, in general, have some phase difference. Figure above shows these pole voltages staggered in time by" t " seconds. It may be more convenient to talk in terms of the phase displacement angle 'Φ' defined as below:

$$\Phi = (2\pi)\frac{t}{T} \text{ Radians}$$

$$V_{AO} = \sum_{n=1,3,5,7,\ldots,\infty} \frac{4\mathbf{V_{dc}}}{n\pi} \sin(nwt)$$

$$V_{BO} = \sum_{n=1,3,5,7,\ldots,\infty} \frac{4\mathbf{V_{dc}}}{n\pi} \sin n(wt - \Phi)$$

Difference of V_{AO} and V_{BO} gives the line voltage V_{AB}

$$V_{AB} = \sum_{n=1,3,5,7,\ldots,\infty} \frac{4\mathbf{V_{dc}}}{n\pi}\left[\sin nwt - \sin n(wt - \Phi)\right]$$

The fundamental component of V_{AB} may be written as:

$$V_{AB,1} = \frac{4\mathbf{V_{dc}}}{\pi}\left[\sin wt - \sin(wt - \Phi)\right] = \frac{8\mathbf{V_{dc}}}{\pi}\cos(wt - \frac{\Phi}{2})\sin\frac{\Phi}{2}$$

The n^{th} harmonic component in V_{AB} may similarly be written as:

$$V_{AB,n} = \frac{4\mathbf{V_{dc}}}{n\pi}\left[\sin nwt - \sin n(wt - \Phi)\right] = \frac{8\mathbf{V_{dc}}}{n\pi}\cos n(wt - \frac{\Phi}{2})\sin\frac{n\Phi}{2}$$

The rms value of the fundamental component of load voltage may be written as:

$$V_1 = \frac{8V_{dc}}{\sqrt{2}\cdot\pi}\ \sin\left(\frac{\Phi}{2}\right) = 1.8V_{dc}\ \sin\left(\frac{\Phi}{2}\right)$$

LECTURE NO. 25

Example: The single-phase full bridge has a resistive load of R= 2.4Ω supplied from dc input voltage V_{dc}= 24V with switching frequency of f=50Hz and displacement angle of π/2. Determine the following:

f) The rms value of fundamental component,
g) The output power,
h) The average and peak current of each transistor,
i) The total harmonic distortion THD,
j) The distortion factor DF of third harmonic.

a) $V_1 = 1.8V_{dc} \quad sin\left(\frac{\Phi}{2}\right) = 1.8 \times 24 \quad sin\frac{\pi}{4} = 30.54V$

b) $V_o = \left(\frac{2}{T}\int_0^t \left(2 \cdot V_{dc}\right)^2 dt\right)^{1/2} = 2V_{dc}\sqrt{\frac{2 \cdot t}{T}}$

$$V_o = 2V_{dc} \quad \sqrt{\frac{\Phi}{\pi}} = 33.94V$$

The output power $Po = \frac{V_o^2}{R} = \frac{(33.94)^2}{2.4} = 480W$

c) The peak current $I_p = \frac{2 \cdot V_{dc}}{R} = \frac{2 \times 24}{2.4} = 20A$

Since the transistor conducts for 50% duty cycle, the average current of each transistor is:

$$I_D = D \times I_P = \frac{t}{T} \times 20 = \frac{\Phi}{2\pi} \times 20A = \frac{20}{4} = 5A$$

d)

$$THD = \frac{1}{V_1}\left(\sum_{n=2,3}^{\infty} V_n^2\right)^{1/2} = \frac{\left(V_o^2 - V_1^2\right)^{1/2}}{V_1}$$

$$THD == \frac{\left(V_o^2 - V_1^2\right)^{1/2}}{V_1} = \frac{\left[(33.94)^2 - (30.54)^2\right]^{1/2}}{30.54} = 48.43\%$$

e)

$$DF_n = \frac{V_n}{n^2 \cdot V_1}$$

$$V_n = \frac{8 \cdot V_{dc}}{n\pi\sqrt{2}} \sin\frac{n\Phi}{2} \Rightarrow \quad V_3 = \frac{8 \cdot V_{dc}}{3\sqrt{2}\pi} \sin\frac{3\pi}{4}$$

$$V_n = \frac{8 \times 24}{3\pi\sqrt{2}} = 14.4V$$

$$DF_3 = \frac{V_3}{3^2 \times V_1} = \frac{14.4}{9 \times 30.54} = 5.24\%$$

H.W: Repeat the solution of example with displacement angles:

i) $\Phi = 0$,
ii) $\Phi = \pi/3$,
iii) $\Phi = \pi$,
iii) $\Phi = 2\pi/3$.

LECTURE NO. 26

AC voltage controller

If a thyristor switch is connected between ac supply and load, the power flow can be controlled by varying the rms of ac voltage applied to the load.

The application of voltage controller

1. Heating
2. light controls
3. speed control of induction motor

There are two types:

1. On-off control
2. Phase-angle control.

1. On-off Control Principle

The principle of on-off control can be explained with a single-phase full-wave controller