VSM COLLEGE OF ENGINEERING

ECE DEPARTMENT

LECTURE NOTES

ON

POWERELECTRONICS(R19)

JAWAHARLAL NEHRU TECHNOLOGICAL UNIVERSITY: KAKINADA
KAKINADA – 533 003, Andhra Pradesh, India
DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

III Year - II Semester		L	T	P	C
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POWER ELECTRONICS
Open Elective (OE1)

Course objectives:
The main objectives of this course are:
- To study the characteristics of various power semiconductor devices and gate drivecircuits.
- To understand the operation of single phase full–wave converters and analyze harmonics in the inputcurrent.
- To study the operation of three phase full–waveconverters.
- To understand the operation of different types of DC-DCconverters.
- To understand the operation of inverters and application of PWM techniques forvoltage control and harmonicmitigation.

UNIT–I:
Power Semiconductor Devices: Operation of SCR, power MOSFET and power IGBT and their characteristics–Gate drive circuits for SCR, IGBT and MOSFET-protection circuits for power IGBT and power MOSFETs.

UNIT–II:
AC-DC Single-Phase Converters: 1-phase fully-controlled bridge rectifiers feeding R load, RL, RLE loads (continuous and discontinuous current conduction mode of operation)– 1-phase semi-controlled bridge rectifiers feeding R, RL and RLE loads (continuous and discontinuous current conduction mode of operation)– HarmonicAnalysis.

UNIT–III:
AC-DC Three-Phase Converters: 3-phase Full converter feeding R, RL and RLE loads (continuous current conduction mode only)– 3-phase semi-converter feeding R, RL and RLE loads (continuous current conduction mode only)–Harmonic analysis -Dual converter.

UNIT–IV:
DC–DC Converters: Analysis of Buck, boost, buck-boost converters in Continuous Conduction Mode (CCM) and Discontinuous Conduction Modes (DCM) – Output voltage equations using volt-sec balance in CCM & DCM- output voltage ripple & inductor current ripple for CCM only – Principle operation of forward and fly back converters inCCM.

UNIT – V:

DC–AC Converters and AC-AC converters: 1- phase half-bridge and full bridge inverters with R and RL loads – Unipolar and bipolar switching-Quasi-square wave pulse width modulation-3-phase square wave inverters – 120^0 conduction and 180^0 conduction modes of operation – Sinusoidal pulse width modulation –single-phase Current Source Inverter (CSI)-single-phase AC-AC voltage regulator with R and RLload.

TEXT BOOKS:

1. Power Electronics: converters, applications & design -by Nedmohan, Tore M.Undeland, Robbins by Wiley India Pvt.Ltd.
2. Power Electronics- by Daniel W.Hart, Mc Graw Hillpublications
3. Power Electronics: Circuits, Devices and Applications – by M. H. Rashid, Prentice Hallof India

REFERENCE BOOKS:

1. Power Electronics: Essentials & Applications by L.Umanand, Wiley, Pvt. Limited, India,2009

2. Elements of Power Electronics–Philip T.Krein. Oxfordpublishers.

3. Power Electronics – by P.S.Bhimbra, KhannaPublishers.

Course Outcomes:

At the end of this course the student will be able to:

- Explain the characteristics of various power semiconductor devicesand understand the gate drivercircuits.
- Explain the operation of single-phase full wave converters and performharmonic analysis.
- Explain the operation of three phase full–wave converters and performharmonic analysis.
- Analyze the operation of different types of DC-DCconverters.
- Explain the operation of inverters and application of PWM techniques for voltagecontrol and harmonicmitigation.

POWER ELECTRONICS

UNIT - I

POWER SEMICONDUCTOR DEVICES

Introduction to the subject :-

Basically, the field of electrical engineering may be divided in to three areas of specialisation namely, (i) electronics
(ii) power
(iii) control

→ In that Electronics deals with the study of semi conductor devices and circuits at low power level
→ power deals with the generation, transmission and distribution of electrical energy with static and rotating power equipments.
→ control deals with the steady state and dynamic characteristics of closed loop systems.

Def :- power electronics is defined as the use of solid state electronics for the control and conversion of electric power. (control of electric power means, the output voltage can be controlled and conversion of electric power means, ac to dc, dc to ac, dc to dc and ac to ac)

HISTORY OF POWER ELECTRONICS :-

→ The Power electronics history began with the development of mercury arc rectifier in the year 1900. Then the other power devices like metal tank rectifier, grid controlled vacuum tube rectifier, ignitron, phanotron, thyratron and magnetic amplifier, were developed & used gradually for power control applications until 1950.

→ The first SCR (Silicon controlled Rectifier) or Thyristor was invented and developed by Bell lab's in 1956 which was the first PNPN triggering transistor.

→ The second electronic revolution began in the year 1958 with the development of the commercial grade Thyristor by the General Electric Company (GE)

Applications of Power Electronics :-

→ 1. control of ac and dc drives in rolling mills, paper and textile mills, traction vehicles, mine winders, cranes Ventilation fans etc.

→ 2. Uninterruptible power supplies (UPS) for critical loads such as computers and space applications

→ Machine tool control.

→ power control in metallurgical and chemical processes using arc melting, induction heating and melting, resistance heating, arc welding etc.

→ Static power compensators, transformer tap changers and static contactors for industrial power systems.

→ High voltage Direct current (HVDC) system

→ Illumination controls for lighting in trains, homes and theatres

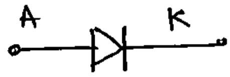
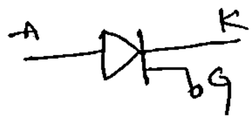
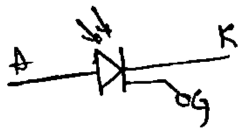
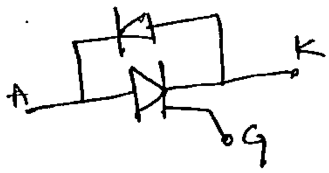
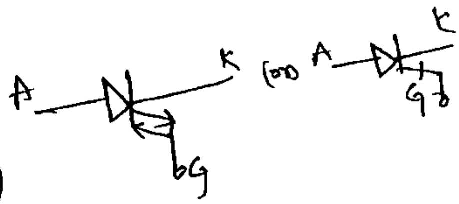
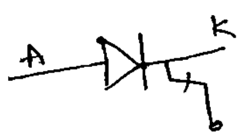
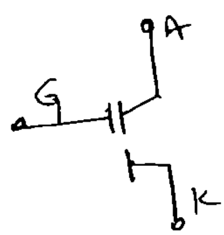
→ Excitation systems for alternator and synchronous condenser.

→ Battery charging

→ Electric Traction

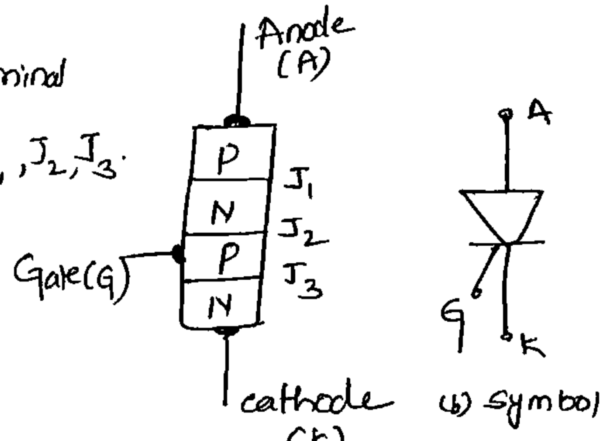
→ Solid State controllers for home appliances

Maximum Ratings of Power semiconductor devices.

S.No.	Device	circuit symbol	Voltage/Current rating	Upper operating frequency (KHz)
1.	Diode		5000 V / 5000A	1.0
2.	Thyristors			
	a) SCR		7000V / 5000 A	1.0
	b) LASCR (Light activated SCR)		6000V / 3000A	1.0
	c) ASCR / RCT (Asymmetrical SCR, Reverse conducting thyristor)		2500V / 400A	2.0
	d) GTO (Gate turn off Thyristor)		5000V / 3000A	2.0
	e) SITH (Static Induction Thyristor)		2500V / 500A	100.0
	f) MCT (CMOS controlled Thyristor)		1200V / 40A	20.0
	g) TRIAC		1200V / 1000A	0.5

PRINCIPLE OF OPERATION OF SCR:-

→ SCR is a four layered, three terminal device with three junctions namely J_1, J_2, J_3. It is a PNPN switching device. The four layers in this device are PNPN layers.

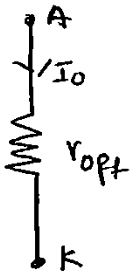


(a) structure. (b) symbol

→ The three terminals of the device are Anode, cathode and gate. Here, the Anode and cathode terminals are connected to the main power circuit. The gate terminal carries a low level gate current in the direction gate to cathode. Normally, the gate terminal is provided at the p layer near the cathode. This is known as cathode gate.

→ When the end P layer near the anode is made more positive when compared to N layer near the cathode, Junctions J_1 and J_3 gets forward biased where as the middle junction J_2 gets reverse biased. Junction J_2 is known as Junction capacitance as it acts as a capacitor in this mode. Due to the depletion layer formed at this junction, no current flows through the device. But due to the drift of mobile charge carriers a small amount of leakage current flows through the circuit. As the leakage current is negligibly small, the device does not conduct. This state is known as forward blocking state or OFF state of the device as it blocks the forward biased voltage.

→ During the 'OFF' state, an SCR acts as a high Impedance device.

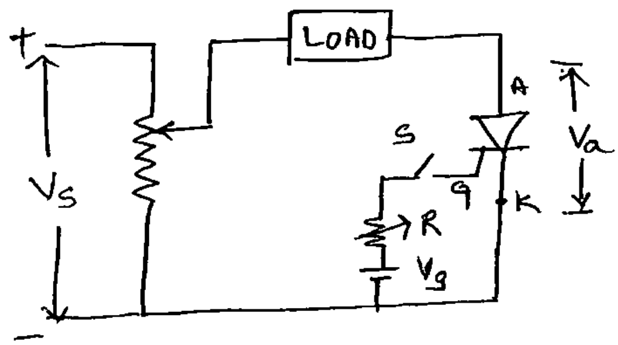


Equivalent ckt during off state.

STATIC V-I CHARACTERISTICS OF AN SCR:-

→ An elementary circuit diagram for obtaining static V-I characteristics of a thyristor is shown in fig.

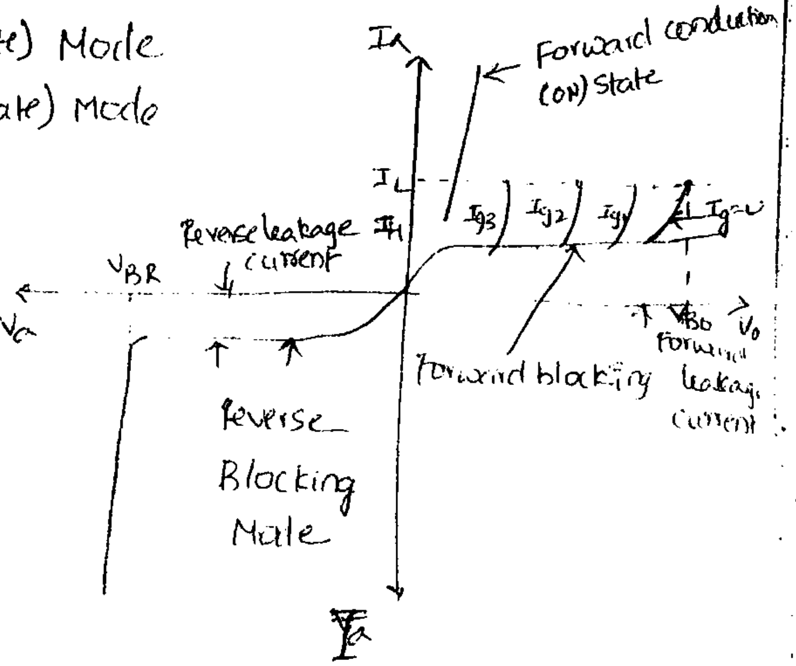
→ The anode and cathode are connected to main source through the load. The gate and cathode are fed from a source V_g which gives positive gate current from gate to cathode



→ V_a is the anode voltage across thyristor terminals A and K and I_a is the anode current. The static V-I characteristic of a thyristor has three basic modes of operation.

a) Reverse blocking Mode
b) Forward blocking (off-state) Mode
c) Forward conduction (ON-state) Mode

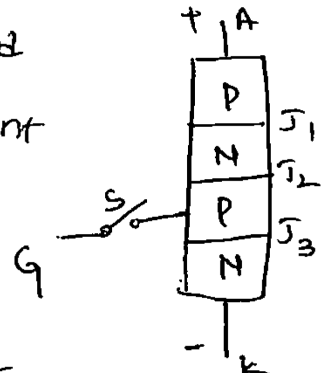
a)



V_{BO} - Forward break over voltage
V_{BR} - Reverse breakover voltage
I_g - gate current
I_L - Latching current
I_H - Holding current

b) Forward Blocking Region :-

In this region, the anode is made positive w.r.t cathode and therefore, Junctions J_1 & J_3 are F.B and J_2 remains R.B. Hence the anode current is a small forward leakage current.



J_2 R.B, J_1 & J_3 F.B

→ Incase the forward voltage is increased, then the reverse biased junction J_2 will have an avalanche breakdown at a voltage called forward breakover voltage V_{BO}.

→ when forward voltage is less then V_{BO}, thyristor offers high Impedance. ∴ SCR can be treated as an open switch even in the forward blocking mode.

c) FORWARD CONDUCTION MODE :-

→ In this mode, SCR conducts currents from Anode to cathode with a very small voltage drop across it. A SCR is brought from forward blocking mode to forward conduction mode by turning it ON by exceeding the forward breakover voltage (or) by applying a gate between gate and cathode.

→ In this high conduction Mode, the anode current is determined essentially by the external load impedance. Therefore when the thyristor conducts forward current, it can be regarded as a closed switch.

→ Anode current < latching current, Holding current

Types of Power Electronics Converters :-

→ A power electronic converter is made up of some power semiconductor devices controlled by Integrated circuits. This converter converts the input power of one form to output power of some other form.

→ The power electronic converter (or circuits) can be classified into six types

1. Diode rectifiers
2. AC - DC converters (controlled Rectifiers)
3. AC - AC converters.
   (i) AC voltage regulators
   (ii) cyclo converters
4. DC - DC converters (DC choppers)
5. DC - AC converters (Inverters)
6. Static Switches.

1. Diode Rectifiers :-

A Diode rectifier circuit converts ac input voltage into fixed dc output voltage. The i/p voltage to the rectifier could be either single phase or three phase.

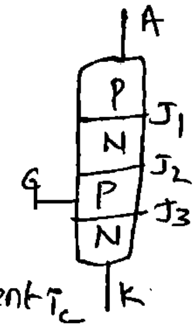
Applications :-

(a) Electric traction
b) Battery charging
c) uninterruptible power supply (UPS)
d) Power supplies
e) electro chemical processing

Need For Snubber Circuit :-

→ When the Forward voltage is applied across the anode and cathode of the thyristor, the outer two junctions (J_1 & J_3) are Forward biased and the inner junction (J_2) is reverse biased. In the reverse biased condition, junction J_2 exhibits the characteristics of a capacitor. Holes from P layer of J_1 accumulate at the junction

→ J_2 and electrons from N layer of J_3 accumulates at the other side of junction J_2. There exists space charge carriers across the junction J_2.

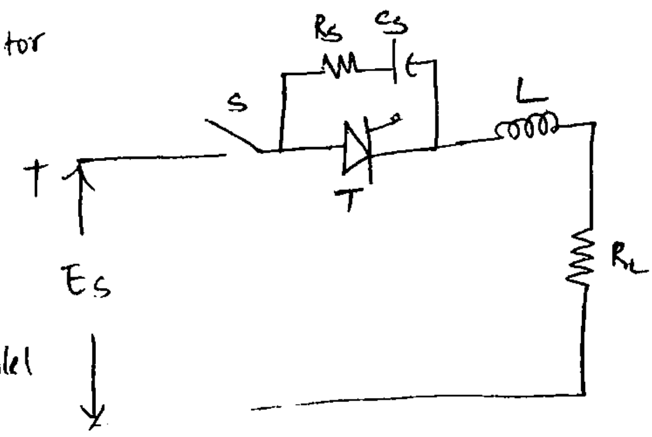


→ If a large amount of voltage is applied with in a short interval of time, charging current i_c flows through SCR. without the application of the gate signal the SCR gets turned ON. It leads to the malfunctioning of the device.

→ So, the rate of rise of voltage across the anode to cathode should be limited. So, an RC network should be connected across the SCR inorder to limit $\frac{dv}{dt}$ rating.

Design Aspects of Snubber circuit :-

→ When the switch 'S' is closed, a sudden voltage appears across the circuit capacitor C_s. The capacitor behaves as a short circuit.



→ The voltage across the capacitor and thyristor is zero at that instant because they are connected in parallel

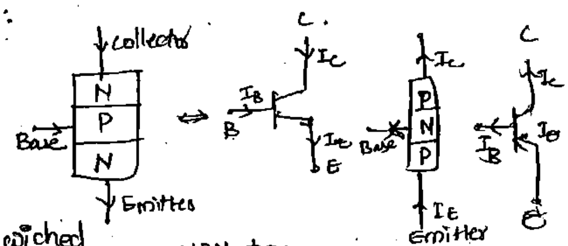
→ As the time goes on, the voltage across the capacitor C_s builds up slowly with less $\frac{dv}{dt}$ rating

CLASSIFICATION OF POWER TRANSISTORS:-

Power transistors may be classified into three types. they are

1. Bipolar junction Transistors (BJTs)
2. Metal oxide semiconductor field Effect Transistors (MOSFETs)
3. Insulated gate bipolar transistors (IGBTs)

Bipolar Junction Transistors :-



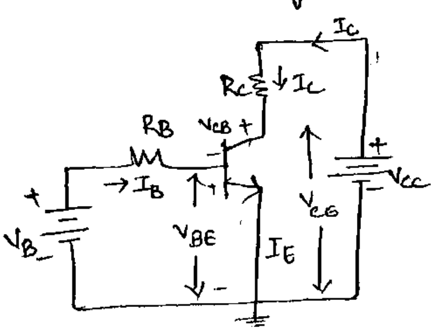
NPN type

→ It is a three layered device having two junctions npn or pnp semiconductor device.

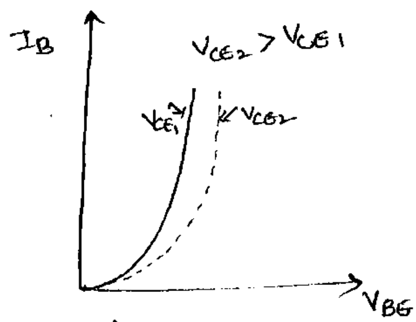
→ whenever the p region is sandwiched by two n regions an npn transistor is formed.

→ whenever the n region is sandwiched by two p regions a pnp transistor is formed.

⇒ BJT is a device where the current flow in the device is due to the mobility of both the charge carriers i.e electrons and holes.



NPN transistor Circuit

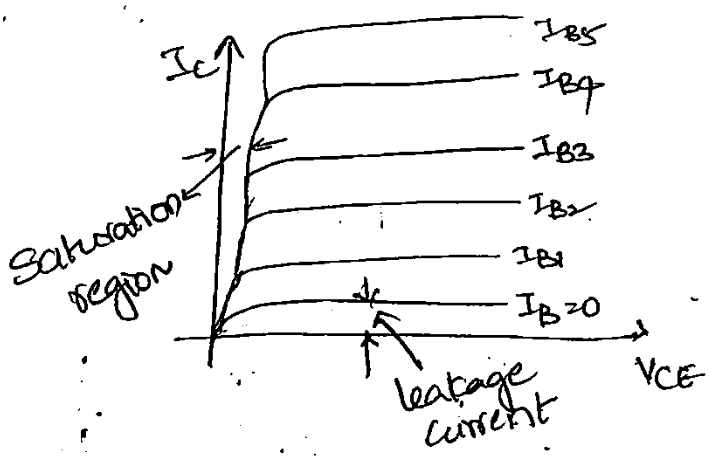


I/P characteristics

→ common emitter configuration of transistor is most commonly used for switching application.

→ I/P characteristics is obtained by plotting the graph b/w the base current I_B and the base emitter voltage. V_{BE}

→ From the i/p characteristics curve, we observe that whenever V_{CE} is increased, the base current gets decreased.



o/p characteristics

→ o/p characteristics of BJTS are obtained by plotting a graph b/w collector current I_C and collector emitter voltage V_{CE}. whenever $I_B=0$, there exists a small leakage current as the Voltage V_{CE} value is increased

POWER MOSFETS :-

→ MOSFET stands for Metal oxide semiconductor, field effect transistor. It has 3 terminals i.e. gate, source and drain.

→ It is a voltage controlled device and is available for high voltage and current ratings.

→ MOSFETs are becoming popular in low to medium power applications and high frequency power electronic circuits, since the turn on time is very less.

→ In the case of transistor secondary breakdown take place. But in the case of MOSFETs, it doesnot have the problem of secondary breakdown, as it operates in the safe operating area.

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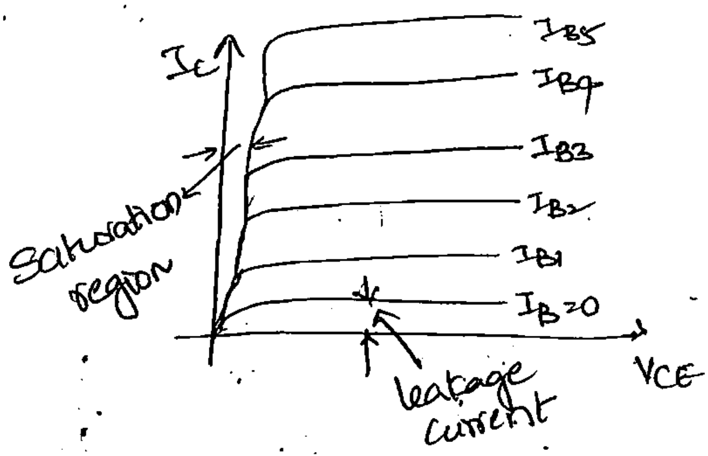

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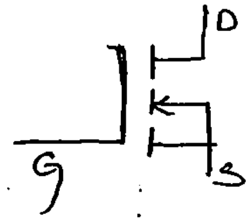
→ In the case of transistor secondary breakdown take place. But in the case of MOSFETS, it doesnot have the problem of secondary breakdown, as it operates in the safe operating area.

→ The switching times are very short, being in the range of few tens of nano secs to a few hundred nano sec. depending upon the type of device

→ It is used in high current applications



symbol of Power MOSFET.

Types of power MOSFET:-

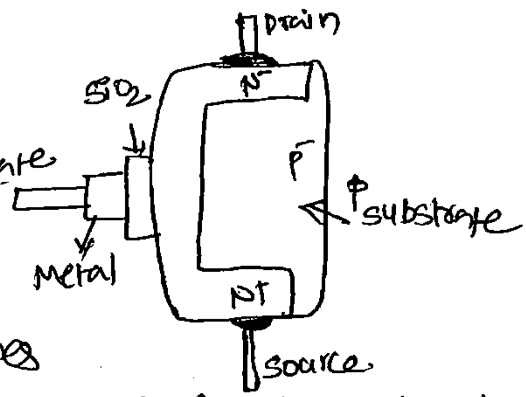
The two main types of Power MOSFETs are

1. Depletion MOSFET
2. Enhancement MOSFET

Each type are further classified as

(i) n channel MOSFET
(ii) p channel MOSFET

→ n channel enhancement MOSFET is more common because of higher mobility of electrons.



Basic structure of N channel power Mosfet

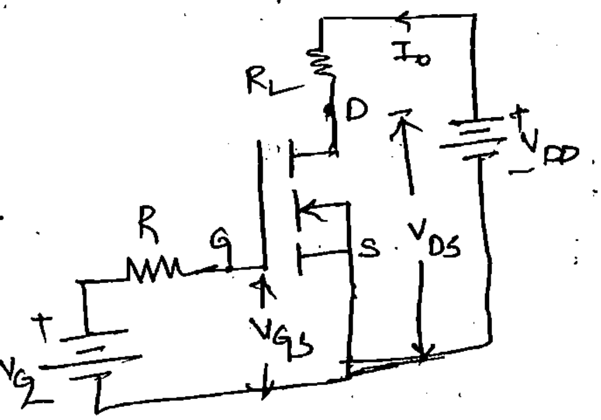
→ The bottom layer is n^+ substrate. Gate and treated as a source.

the n^- layer is called the drain drift region. This drift region determines the break down voltage of the device, a metal layer is deposited to form the drain terminal.

→ p^- regions are diffused in the epitaxially grown n^- layer SiO_2 (silicon dioxide) layer is added which is then etched so as to fit metallic source and gate terminals.

Operation :-

When the Gate source Voltage V_{GS} is zero, and drain source Voltage V_{DD} is present, then $n^- - p^-$ junctions are reverse biased and no current flows from drain to source. So, the device acts as a open switch.



N channel Power MOSFET Circuit diagram

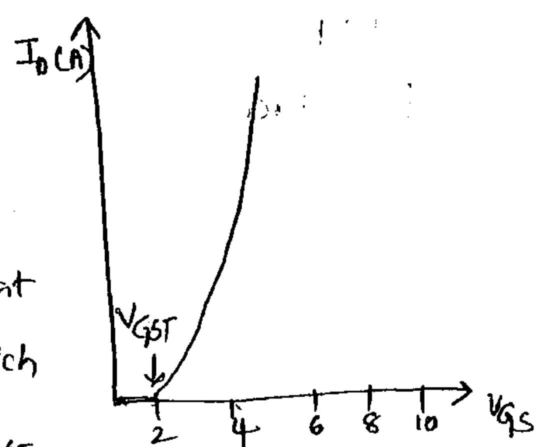
→ when Gate terminal is made +ve w.r.t source, an electric field is created and electrons form n-channel in the p^- region. Now, the current flows from Drain to source. When gate voltage V_{GS} is increased drain current I_D also increases. i.e., o/p current can be controlled by gate voltage.

so Power MOSFET is also called as Voltage controlled device. Here the controlling parameter is gate source voltage V_{GS}.

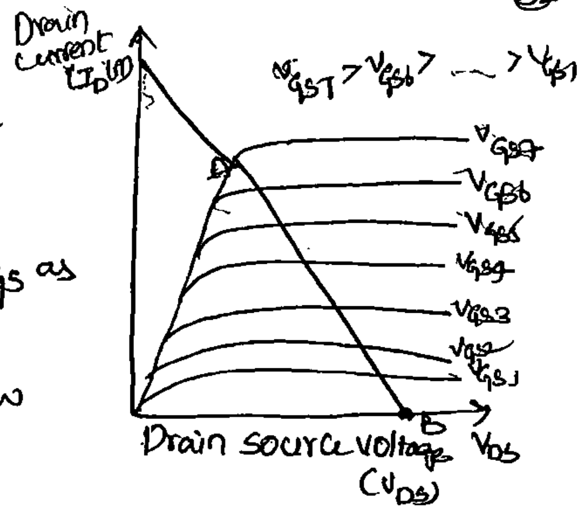
Static characteristics :-

(a) Transfer characteristics :-

This characteristic shows the variation of drain current I_D as a function of gate source Voltage V_{GS}. It is seen that there is threshold voltage V_{GST} below which the device is OFF. The magnitude of V_{GST} is of the order of 2 to 3V.



Transfer characteristics for n-channel Power MOSFET output characteristics :-



→ Power MOSFET o/p characteristics indicate the variation of drain current I_D as a function of drain-source voltage V_{GS} as a parameter.

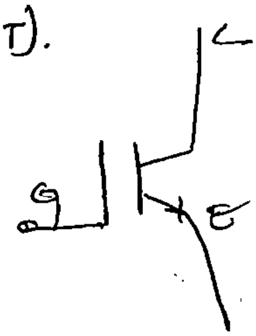
→ For low values of V_{DS}, the graph b/w $I_D - V_{DS}$ is almost linear. $R_{DS} = \frac{V_{DS}}{I_D}$.

→ For given V_{GS}, if V_{DS} is increased, o/p characteristics is relatively flat indicating that drain current is nearly constant.

MOSFET	BJT
1. power MOSFET has lower switching losses.	1. BJT has higher switching losses
2. It has more conduction losses	2. It has low conduction losses
3. It is a voltage controlled device.	3. It is a current controlled device.
4. It is a unipolar device	4. It is a bipolar device
5. power MOSFET operate at switching frequencies in the MHz range.	5. BJT operate at switching frequencies in kHz range.
6. MOSFET has positive temp. coefficient	6. BJT has negative temp coefficient
7. secondary breakdown doesnot occur in MOSFET	7. BJT has secondary breakdown.
8. MOSFETs are available with ratings upto 500V, 140A	8. BJTs are available with ratings upto 1200V and 800A.

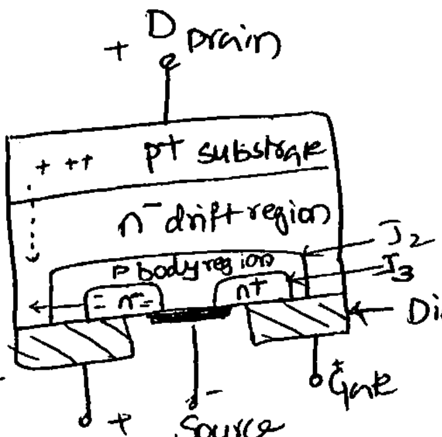
IGBT (Insulated Gate Bipolar Transistor):

→ IGBT has high i/p Impedance like a MOSFET and low ON state power loss as in a BJT. IGBT is also known as Metal oxide insulated Gate Transistor (MOSIGT), conductively-Modulated Field effect transistor (COMFET) or Grain Modulated FET (GEMFET). It is also called insulated Gate transistor (IGT).



symbol

Structure of IGBT:-



Structure of IGBT

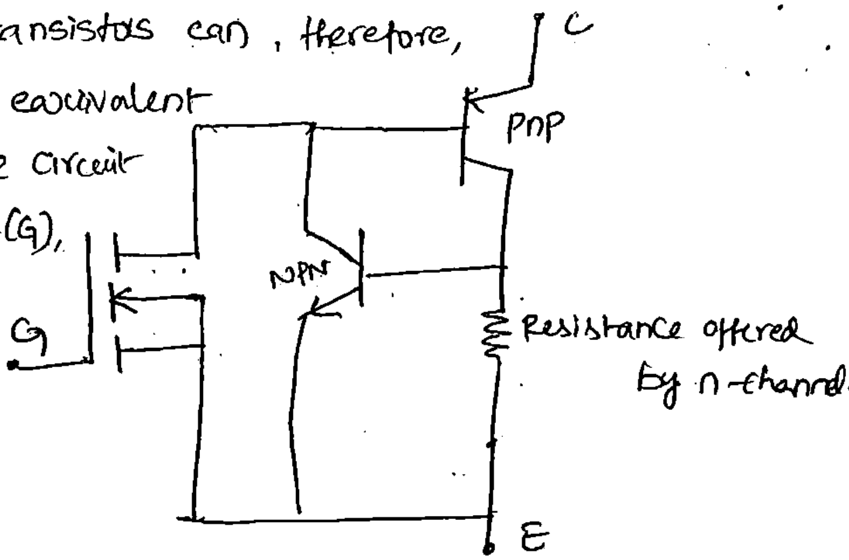
→ The IGBT structure is very close to the n-channel MOSFET. The major difference b/w the structure of the n-channel MOSFET and IGBT is that a highly doped Gate p^+ type substrate is provided with IGBT.

→ From the basic structure, n^+ p body region, n^- forms the power MOSFET. The n^- drift region forms the drain. The next part will constitute the three layers $p^+ n^- p$, that forms a BJT b/w the drain and source terminals $p\,n^-p^+$ regions will behave as collector, base and emitter (E) of pnp transistor resp.

Drift current: The transport of the charges in a device under the influence of the electric field is known as drift current.

Diffusion current: The transport of charges in a device, under the influence of the non uniform concentration gradient is termed as diffusion current.

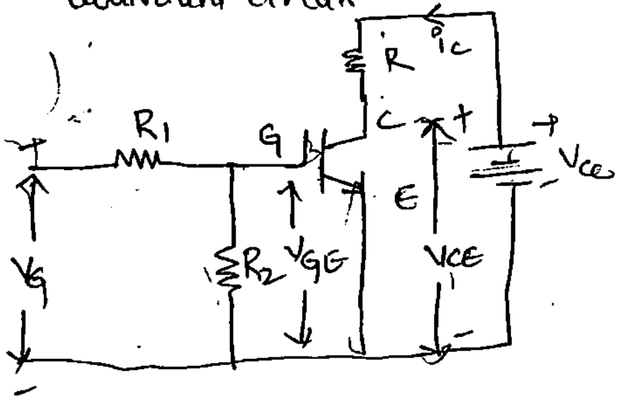
→ The two PNP and NPN transistors can, therefore, be connected to give the equivalent circuit of an IGBT. The circuit symbol for IGBT with gate (G), emitter (E) and collector (C) as its three terminals



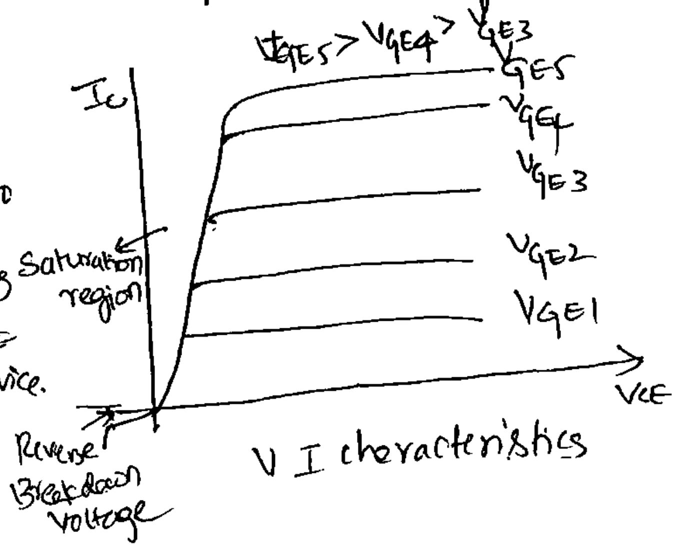
Equivalent circuit.

IGBT Static characteristics:-

→ Static V-I characteristics of an IGBT (n-channel type) shows the plot of collector current I_C Vs collector emitter voltage V_{CE} for various values of Gate emitter voltages. In the forward direction, the shape of the o/p characteristics is similar to that of BJT. But here the controlling parameter is gate emitter voltage V_{GE} because IGBT is a voltage controlled device.

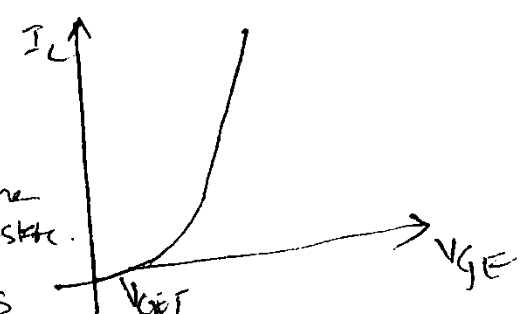


IGBT circuit diagram



V I characteristics

→ The transfer characteristic of an IGBT is a plot of collector current I_C Vs. gate emitter voltage V_{GE}. This characteristics is same as power MOSFET. when V_{GE} is less than V_{GET}, IGBT is in the OFF state.



Transfer Characteristics

→ when the device is OFF, junction J_2 blocks forward voltage and in case reverse voltage appears across collector and emitter junction J_1 blocks it.

IGBT Applications:

→ IGBTs are widely used in medium power applications such as dc and ac motor drives, UPS systems, power supplies and drives for solenoids, relays and contactors.

MOSFETs	IGBTs
→ In the power MOSFET, the decrease in the electron mobility with increasing temp. results in a rapid increase in the ON state resistance of the channel and hence the ON state drop.	→ In IGBTs, the increase in voltage drop is very small.
2. The ON state voltage drop increases by a factor of 3 between room temp. and 200°C	2. Here with the identical conditions, the increment in the ON state voltage drop is very small.
3. All highest temp., max. current rating goes down to 1/3 value	3. At high ambient temp., IGBT is extraordinarily well suited
4. Current sharing in multiple Paralleled MOSFETs is comparatively poor than IGBTs	4. Current sharing in multiple Paralleled IGBTs is far better than Power MOSFET.
5. The turn ON transients are identical to IGBTs	5. Turn ON transients are identical to MOSFETs
6. Power MOSFET is suited for applications that require low blocking voltages and high operating frequencies	6. IGBT is the preferred device for applications that require high blocking voltages and lower operating frequencies

UNIT – II

Phase control technique – Single phase Line commutated converters

Unlike diode rectifiers, PCRs or phase controlled rectifiers has an advantage of regulating the output voltage. The diode rectifiers are termed as uncontrolled rectifiers. When these diodes are switched with Thyristors, then it becomes phase control rectifier. The o/p voltage can be regulated by changing the firing angle of the Thyristors. The main application of these rectifiers is involved in speed control of DC motor.

What is a Phase Controlled Rectifier?

The term PCR or Phase controlled rectifier is a one type of rectifier circuit in which the diodes are switched by Thyristors or SCRs (Silicon Controlled Rectifiers). Whereas the diodes offer no control over the o/p voltage, the Thyristors can be used to differ the output voltage by adjusting the firing angle or delay. A phase control Thyristor is activated by applying a short pulse to its gate terminal and it is deactivated due to line communication or natural. In case of heavy inductive load, it is deactivated by firing another Thyristor of the rectifier during the negative half cycle of i/p voltage.

Types of Phase Controlled Rectifier

The phase controlled rectifier is classified into two types based on the type of i/p power supply. And each kind includes a semi, full and dual converter.

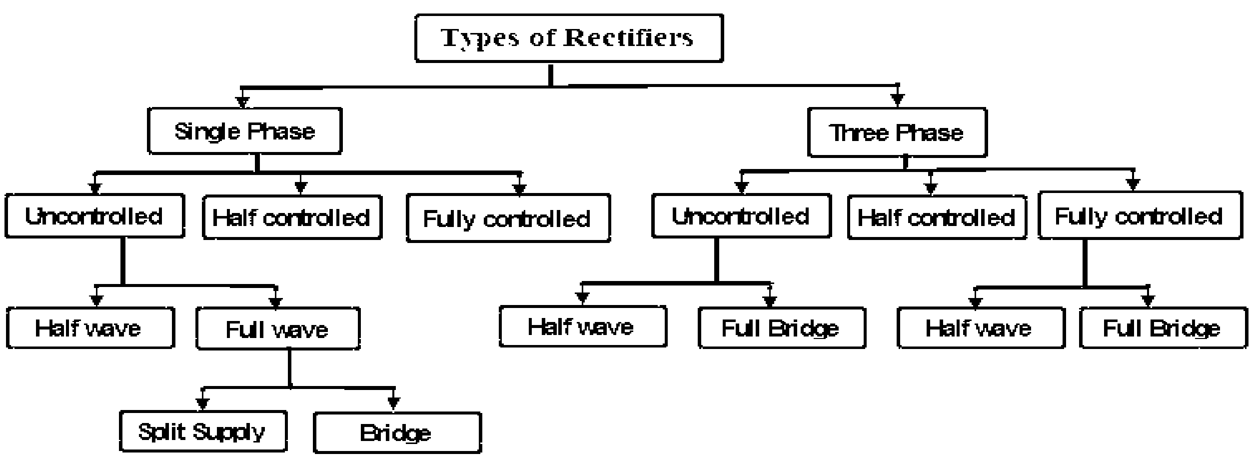


Figure: 2.1. Classification of rectifiers

Single-phase Controlled Rectifier

This type of rectifier which works from single phase AC i/p power supply

Single Phase Controlled Rectifiers are classified into different types

Half wave Controlled Rectifier: This type of rectifier uses a single Thyristor device to provide o/p control only in one half cycle of input AC supply, and it offers low DC output.

Full wave Controlled Rectifier: This type of rectifier provides higher DC output

- Full wave controlled rectifier with a center tapped transformer requires two Thyristors.
- Full wave bridge controlled rectifiers do not need a center tapped transformer

Three-phase Controlled Rectifier

This type of rectifier which works from three phase AC i/p power supply

- A semi converter is a one quadrant converter that has one polarity of o/p voltage and current.
- A full converter is a a two quadrants converter that has polarity of o/p voltage can be either +ve or –ve but, the current can have only one polarity that is either +ve or -ve.
- Dual converter works in four quadrants – both o/p voltage and o/p current can have both the polarities.

Operation of Phase Controlled Rectifier

The basic working principle of a PCR circuit is explained using a single phase half wave PCR circuit with a RL load resistive shown in the following circuit.

A single phase half wave Thyristor converter circuit is used to convert AC to DC power conversion. The i/p AC supply is attained from a transformer to offer the required AC supply voltage to the Thyristor converter based on the o/p DC voltage required. In the above circuit, the primary and secondary AC supply voltages are denoted with VP and VS.

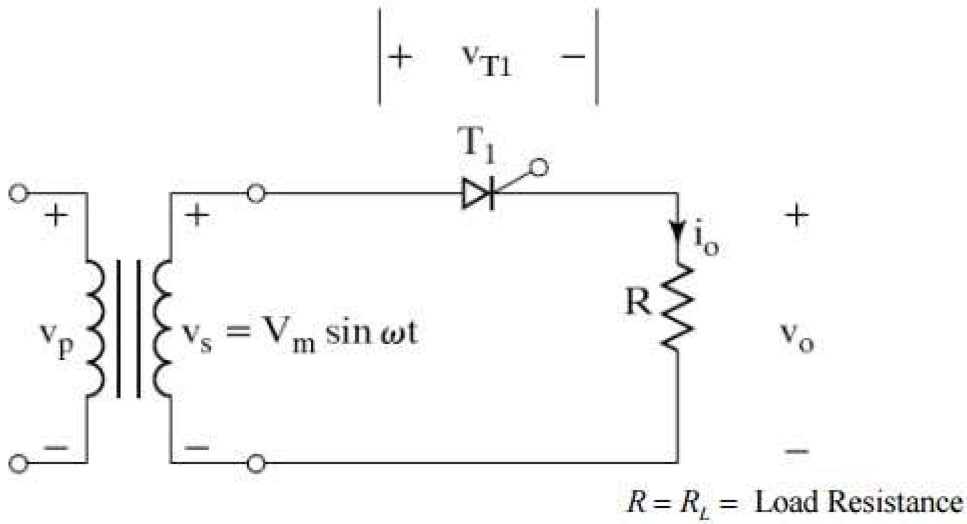


Figure: 2.2. Single phase half wave rectifier circuit

During the +ve half cycle of i/p supply when the upper end of the transformer secondary winding is at a + ve potential with respect to the lower end, the Thyristor is in a forward biased state.

The thyristor is activated at a delay angle of $\omega t = \alpha$, by applying an appropriate gate trigger pulse to the gate terminal of thyristor. When the thyristor is activated at a delay angle of $\omega t = \alpha$, the thyristor behaviors and assuming a perfect thyristor. The thyristor acts as a closed switch and the i/p supply voltage acts across the load when it conducts from $\omega t = \alpha$ to π radians For a purely resistive load, the load current io that flows when the thyristor T1 is on, is given by the expression.

$$\mathbf{Io = vo/ RL, \text{ for } \alpha \leq \omega t \leq \pi}$$

Applications of Phase Controlled Rectifier

Phase controlled rectifier applications include paper mills, textile mills using DC motor drives and DC motor control in steel mills.

- AC fed traction system using a DC traction motor.
- Electro-metallurgical and Electrochemical processes.
- Reactor controls.
- Magnet power supplies.
- Portable hand instrument drives.

- Flexible speed industrial drives.
- Battery charges.
- High voltage DC transmission.
- UPS (Uninterruptible power supply systems).

Operation of half converter with R and RL loads

Single Phase Half Wave Controlled Rectifier with 'R' load:

As shown in figure below primary of transformer is connected to ac mains supply with which SCR becomes forward bias in positive half cycle. T1 is triggered at an angle α, T1 conducts and voltage is applied across R.

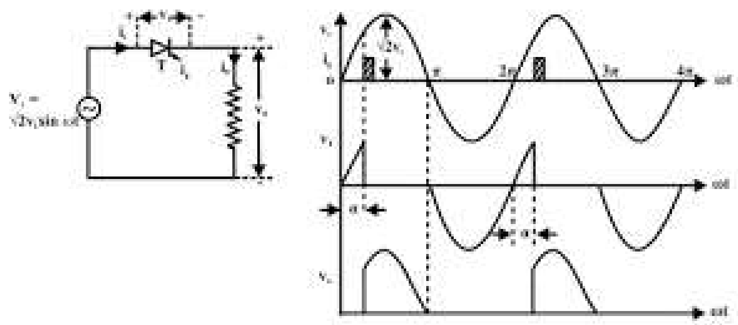


Figure: 2.3 Single phase half wave rectifier with R load with waveforms

The load current i_0 flows through 'R'
the waveforms for voltage & current are as shown above.
As load is resistive,
Output current is given as,

$$I_O = \frac{V_O}{R}$$

Hence shape of output current is same as output voltage
As T1 conducts only in positive half cycle as it is reversed bias in negative cycle, the ripple frequency of output voltage is-
fripple= 50 Hz (supply frequency)

Average output voltage is given as,

$$V_0(Avg) = \frac{1}{T} \int_o^T V_0(wt)\, dwt$$

i.e Area under one cycle.

Therefore T=2π&Vo(ωt) = Vm sinωt from α to π& for rest of the period Vo(ωt)=0

$$\therefore V_0(Avg) = \frac{1}{2\pi} \int_0^{2\pi} V_m sin(wt)\, dwt$$

$$= \frac{V_m}{2\pi} [-coswt]_\alpha^\pi$$

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

Power transferred to load,

$$P_0(Avg) = \frac{V_0^2(Avg)}{R}$$

Thus, power & voltage can be controlled by firing angle.

Single Phase Half Wave Controlled Rectifier with 'RL' load:

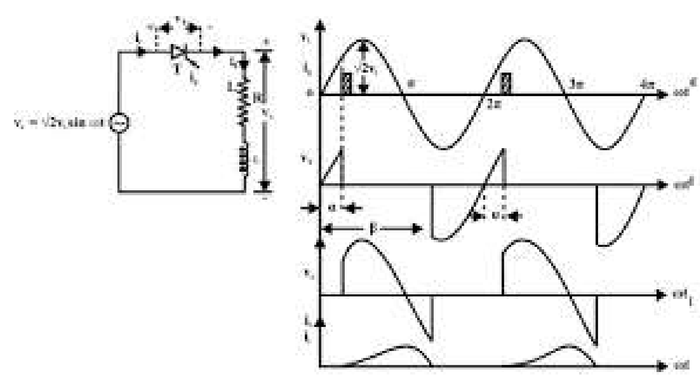


Figure: 2.4 Single phase half wave rectifier with RL load with waveforms

Figure above shows the single phase half wave rectifier with RL Load.

- Normally motors are inductive loads

L= armature of field coil inductance

R= Resistance of coil.

- In positive half cycle, SCR starts conduction at firing angle “α”.
- Drop across SCR is small & neglected so output voltage is equal to supply voltage.
- Due to ‘R_L’ load, current through SCR increases slowly.
- At ‘π’, supply voltage is at zero where load current is at its max value.
- In positive half cycle, inductor stores energy & that generates the voltage.
- In negative half cycle, the voltage developed across inductor, forward biases SCR & maintains its conduction.
- Basically with the property of inductance it opposes change in current.
- Output current & supply current flows in same loop, so all the time $i_o=i_s$.
- After π the energy of inductor is given to mains & there is flow of ‘io’. The energy reduces as if gets consumed by circuit so current also reduces.
- At ‘β’ energy stored in inductance is finished, hence ‘i_o’ becomes zero & ‘T1’ turns off.
- ‘i_o’ becomes zero from ‘β’ to ‘2π+α’ hence it is discontinuous conduction.

The average output voltage $V_0 = \frac{1}{2\pi}\int_{\alpha}^{\beta} Vmsinwt\ d(wt) = \frac{\text{Vm}}{2\pi}(\cos\alpha - \cos\beta)$

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

RMS load voltage $V_{0r} = \left\{\frac{1}{2\pi}\int_{\alpha}^{\beta} Vm^2 sin^2 wt\ d(wt)\right\}^{1/2}$

$$= \frac{Vm}{2\sqrt{\pi}}\left[(\beta - \alpha) - \frac{1}{2}\{sin2\beta - sin2\alpha\}\right]^{1/2}$$

Single phase half controlled converter with RLE load

The diode D2 and D4 conducts for the positive and negative half cycle of the input voltage waveform respectively. On the other hand T1 starts conduction when it is fired in the positive half cycle of the input voltage waveform and continuous conduction till T3 is fired in the negative half cycle. Fig. shows the circuit diagram and the waveforms of a single phase half controlled converter supplying an R – L – E load.

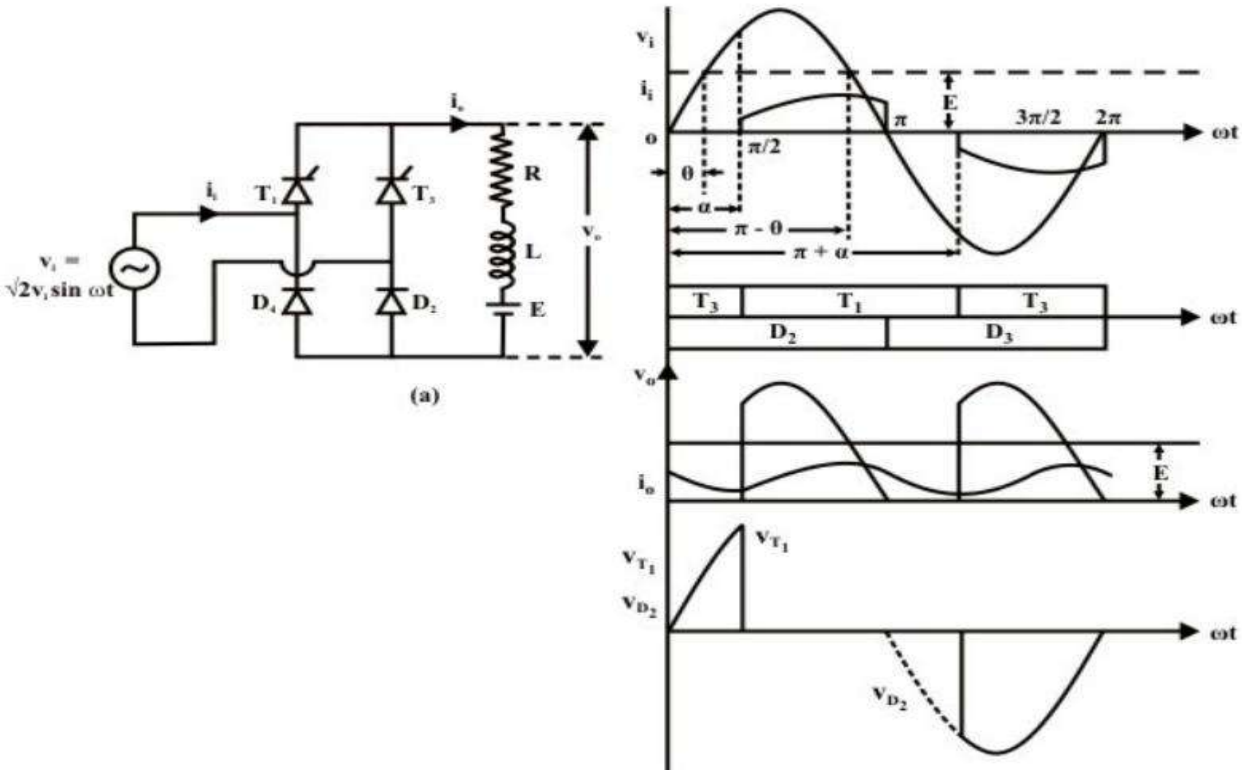


Figure: 2.5 single phase half controlled converter with RLE load

Referring to Fig T1 D2 starts conduction at ωt = α. Output voltage during this period becomes equal to vi. At ωt = π as vi tends to go negative D4 is forward biased and the load current commutates from D2 to D4 and freewheels through D4 and T1. The output voltage remains clamped to zero till T3 is fired at ωt = π + α. The T3 D4 conduction mode continues upto ωt = 2π. Where upon load current again free wheels through T3 and D2 while the load voltage is clamped to zero. From the discussion in the previous paragraph it can be concluded that the output voltage (hence the output current) is periodic over half the input cycle. Hence

$$V_{oav} = \frac{1}{\pi}\int_{o}^{\pi} v_o d\omega t = \frac{1}{\pi}\int_{\alpha}^{\pi} \sqrt{2}V_i \sin\omega t \, d\omega t = \frac{\sqrt{2}V_i}{\pi}(1+\cos\alpha)$$

$$I_{ov} = \frac{V_{oav} - E}{R} = \frac{\sqrt{2}V_i}{\pi R}(1+\cos\alpha - \pi\sin\theta)$$

Single phase half controlled converter with RLE load and freewheeling diode

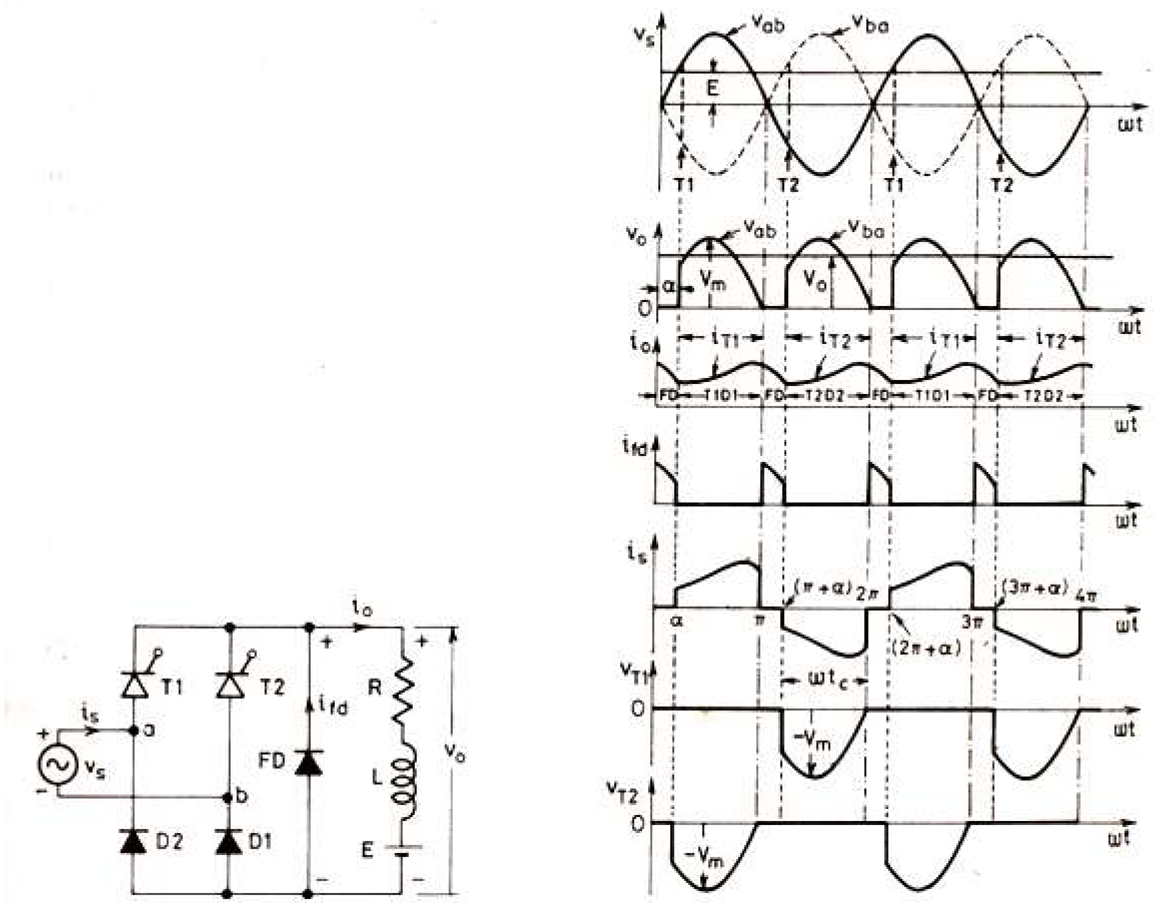


Figure: 2.6 single phase half controlled converter with RLE load and freewheeling diode

Numerical problems

1. A single phase 230V, 1 Kwheater is connected across 1 phase 230V, 50Hz supply through an SCR. For firing angle delay of 45^0 and 90^0, calculate the power absorbed in the heater element.

   Solution: Heater resistance $R = 230^2/1000\ \Omega$

The rms value of voltage is $V_{or} = \frac{Vm}{2\sqrt{\pi}}\left[(\pi - \alpha) + \frac{1}{2}sin2\alpha\right]^{1/2}$

$$= \frac{\sqrt{2}\times 230}{2\sqrt{\pi}}\left[\left(\pi - \frac{\pi}{4}\right) + \frac{1}{2}sin90\right]^{1/2} = 155.071V$$

Power absorbed by the heater element for $\alpha = 45^0$ is

$$\frac{Vor^2}{R} = \left[\frac{155.071}{230}\right]^2 \times 1000 = 454.57W$$

for $\alpha = 90^0$ the rms voltage is

$$V_{or} = \frac{\sqrt{2}\times 230}{2\sqrt{\pi}}\left[\left(\pi - \frac{\pi}{2}\right) + \frac{1}{2}sin180\right]^{1/2} = 115V$$

Power absorbed by the heater element for $\alpha = 90^0$ is

$$\frac{Vor^2}{R} = \left[\frac{115}{230}\right]^2 \times 1000 = 250W$$

2. A resistive load of 10Ω is connected through a half-wave controlled rectifier circuit to 220V, 50 Hz, single phase source. Calculate the power delivered to the load for a firing angle of 60°. Find also the value of input power factor
3. A single phase semi converter delivers to RLE load with R=5Ω, L = 10mH and E = 80V. The source voltage is 230V, 50Hz. For continuous conduction, Find the average value of output current for firing angle = 50^o.

Single phase full wave controlled rectifier

Single Phase Full Wave Controlled Rectifier with 'R' load:

Figure below shows the Single phase Full Wave Controlled Rectifiers with R load

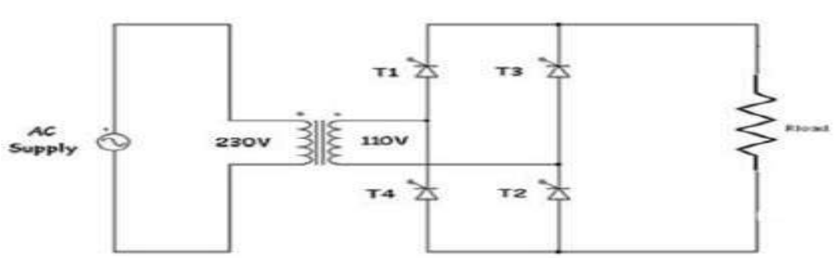


Figure: 2.7 single phase full converter circuit with R load

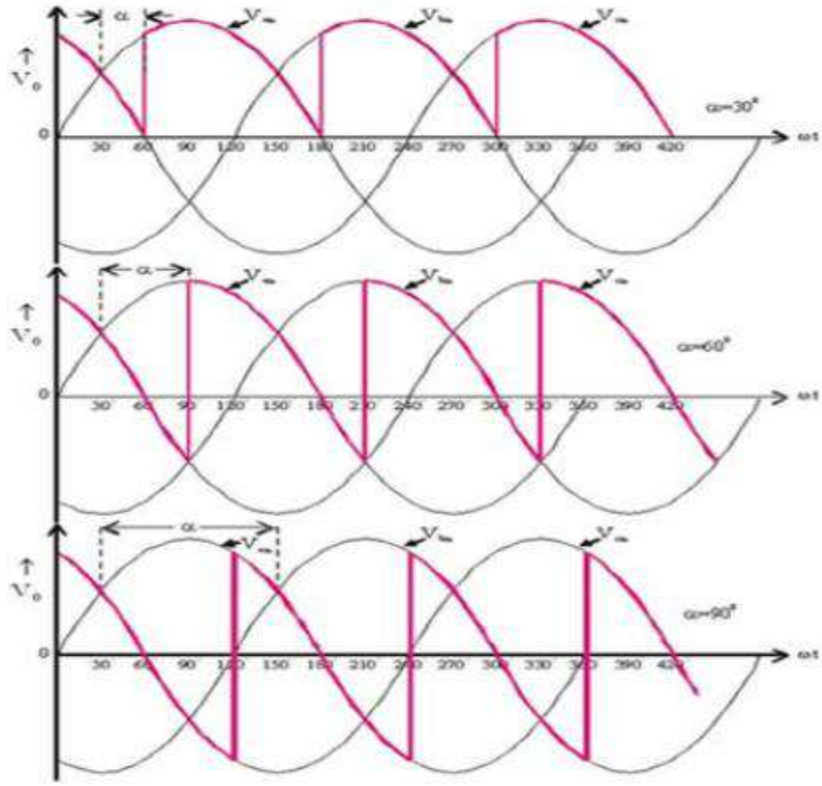


Figure: 2.8 single phase full converter circuit with R load input and output waveforms

• The single phase fully controlled rectifier allows conversion of single phase AC into DC. Normally this is used in various applications such as battery charging, speed control of DC motors and front end of UPS (Uninterruptible Power Supply) and SMPS (Switched Mode Power Supply).

• All four devices used are Thyristors. The turn-on instants of these devices are dependent on the firing signals that are given. Turn-off happens when the current through the device reaches zero and it is reverse biased at least for duration equal to the turn-off time of the device specified in the data sheet.

• In positive half cycle Thyristors T1 & T2 are fired at an angle α .

• When T1 & T2 conducts

Vo=Vs

IO=is=Vo/R=Vs/R

• In negative half cycle of input voltage, SCR's T3 &T4 are triggered at an angle of (π+α)

• Here output current & supply current are in opposite direction

∴ is=-io

T3 & T4 becomes off at 2π.

$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} Vmsinwt\ d(wt) = \frac{2Vm}{\pi}\ cos\alpha$

Single Phase Full Wave Controlled Rectifier with 'RL' load:

Figure below shows Single phase Full Wave Controlled Rectifiers with RL load.

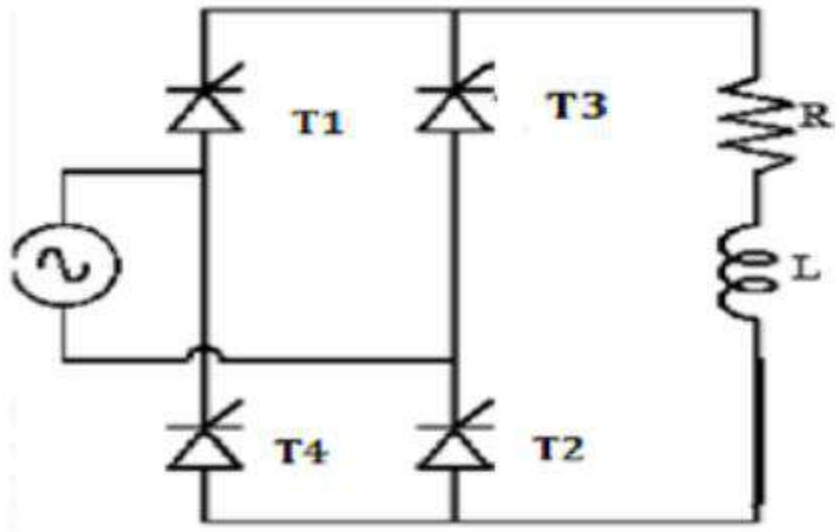


Figure: 2.9 single phase full converter circuit with RL load

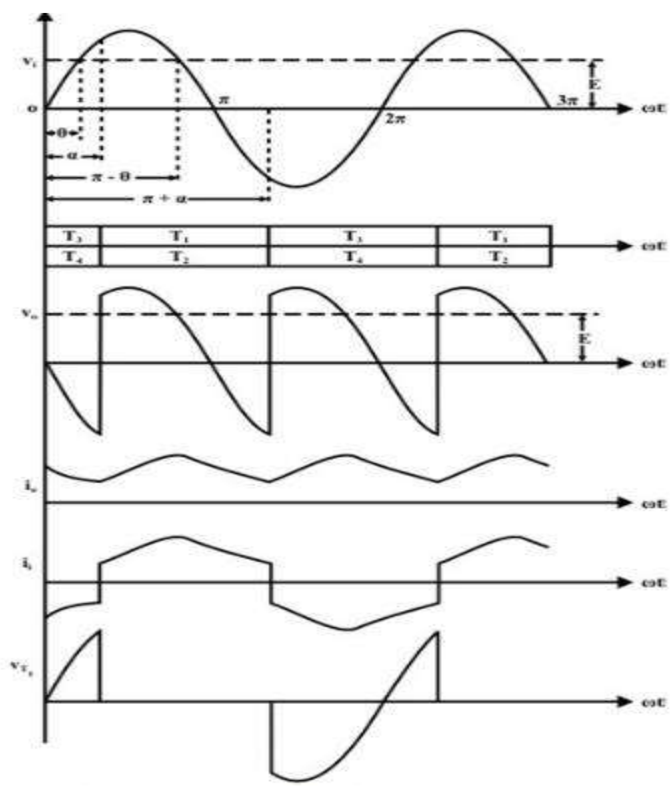


Figure: 2.10 single phase full converter circuit with RL load input and output waveforms

Operation of this mode can be divided between four modes

Mode 1 (α toπ)

• In positive half cycle of applied ac signal, SCR's T1 & T2 are forward bias & can be turned on at an angle α.
• Load voltage is equal to positive instantaneous ac supply voltage. The load current is positive, ripple free, constant and equal to Io.
• Due to positive polarity of load voltage & load current, load inductance will store energy.

Mode 2 (π toπ+α)

• At wt=π, input supply is equal to zero & after π it becomes negative. But inductance opposes any change through it.
• In order to maintain a constant load current & also in same direction. A self inducedemf appears across 'L' as shown.
• Due to this induced voltage, SCR's T1 & T2 are forward bais in spite the negative supply voltage.
• The load voltage is negative & equal to instantaneous ac supply voltage whereas load current is positive.
• Thus, load acts as source & stored energy in inductance is returned back to the ac supply.

Mode 3 (π+α to 2π)

• At wt=π+α SCR's T3 & T4 are turned on & T1, T2 are reversed bias.
• Thus , process of conduction is transferred from T1,T2 to T3,T4.
• Load voltage again becomes positive & energy is stored in inductor
• T3, T4 conduct in negative half cycle from (π+α) to 2π
• With positive load voltage & load current energy gets stored

Mode 4 (2π to 2π+α)

• At wt=2π, input voltage passes through zero.
• Inductive load will try to oppose any change in current if in order to maintain load current constant & in the same direction.
• Induced emf is positive & maintains conducting SCR's T3 & T4 with reverse polarity also.

• Thus VL is negative & equal to instantaneous ac supply voltage. Whereas load current continues to be positive.

• Thus load acts as source & stored energy in inductance is returned back to ac supply

• At wt=α or 2π+α, T3 & T4 are commutated and T1,T2 are turned on.

$$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} Vmsinwt\ d(wt) = \frac{2Vm}{\pi}\ cos\alpha$$

Single phase fully controlled converters with RLE load

The circuit diagram of a full wave bridge rectifier using thyristors in shown in figure below. It consists of four SCRs which are connected between single phase AC supply and a load.

This rectifier produces controllable DC by varying conduction of all SCRs.

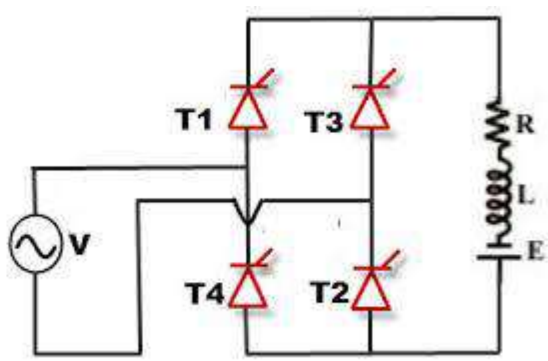


Figure: 2.11 single phase full converter circuit with RLE load

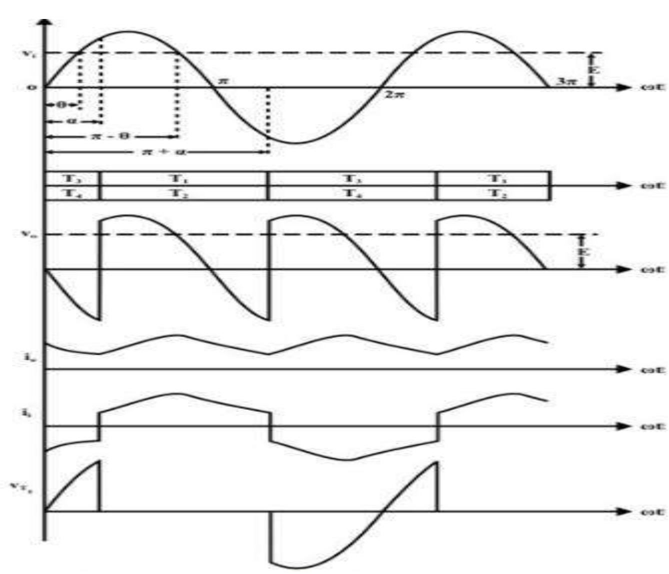


Figure: 2.12 single phase full converter circuit with RLE load input and output waveforms

In positive half-cycle of the input, Thyristors T1 and T2 are forward biased while T3 and T4 are reverse biased. Thyristors T1 and T2 are triggered simultaneously at some firing angle in the positive half cycle, and T3 and T4 are triggered in the negative half cycle.

The load current starts flowing through them when they are in conduction state. The load for this converter can be RL or RLE depending on the application.

By varying the conduction of each thyristor in the bridge, the average output of this converter gets controlled. The average value of the output voltage is twice that of half-wave rectifier.

The average output voltage is

$V_0 = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} Vmsinwt\ d(wt) = \frac{2Vm}{\pi}\ cos\alpha$

Line commutated converters

For single phase half wave converter

1. Average DC load voltage: (V_{oavg})

$$V_{oavg} = V_0 = \frac{1}{T}\int_0^T Vmsinwt\ d(wt) \quad \text{where T is time period}$$

$$V_{oavg} = \frac{1}{2\pi}\left[\int_{\alpha}^{\pi} Vmsinwt\ d(wt) + \int_{\pi}^{2\pi+\alpha} 0\ d(wt)\right]$$

$$= \frac{1}{2\pi}\left[\int_{\alpha}^{\pi} Vmsinwt\ d(wt)\right]$$

$$= \frac{Vm}{2\pi}[-coswt]_{\alpha}^{\pi}$$

$$= \frac{Vm}{2\pi} - [cos\pi - cos\alpha]$$

$$= \frac{Vm}{2\pi}[1 + cos\alpha]$$

If $\alpha = 0$ $V_{oavg\ max} = \frac{Vm}{\pi}$

If $\alpha = 180$ $V_{oavg} = 0$

2. Average DC load current is given as

$$I_{oavg} = \frac{V0avg}{R}$$

$I_{oavg} = \frac{Vm}{2\pi R}[1 + cos\alpha]$

3. RMS load voltage

$$V_{rms} = \left\{\frac{1}{T}\int_0^T Vm^2 sin^2 wt\ d(wt)\right\}^{1/2}$$

$$V_{rms} = \left\{\frac{1}{2\pi}\int_\alpha^\Pi Vm^2 sin^2 wt\ d(wt)\right\}^{1/2}$$

$$V_{rms} = \frac{Vm}{2\sqrt{\pi}}\left[(\pi - \alpha) + \frac{1}{2}sin2\alpha\right]^{1/2}$$

If $\alpha = 0$ $V_{rms} = \frac{Vm}{2}$

If $\alpha = 180$ $V_{rms} = 0$

The RMS voltage may be varied from 0 to $\frac{Vm}{2}$ by varying α from 180 to 0

4. Power delivered to the resistive load is given

P_L = (RMS load voltage)(RMS load current)

= $V_{rms} X\ I_{rms}$

$= \frac{Vrms^2}{R} = Irms^2 XR$

5. Input volt amperes = (RMS source voltage)(RMS line current)

= $V_s\ I_{rms}$

$= V_s \frac{\sqrt{2}Vs}{R2\sqrt{\pi}}\left[(\pi - \alpha) + \frac{1}{2}sin2\alpha\right]^{1/2}$

$= \frac{Vs^2}{\sqrt{2\pi}XR}\left[(\pi - \alpha) + \frac{1}{2}sin2\alpha\right]^{1/2}$

6. Input power factor: It is defined as the ratio of total mean input power to the total rms input volt amperes

$$\text{Input power factor} = \frac{\frac{\sqrt{2}Vs}{2\sqrt{\pi}}\left[(\pi-\alpha)+\frac{1}{2}sin2\alpha\right]^{1/2}}{Vs}$$

$$= \frac{1}{\sqrt{2\pi}}\left[(\pi-\alpha)+\frac{1}{2}sin2\alpha\right]^{1/2}$$

7. Form factor: Form factor is defined as the ratio of RMS voltage to the average DC voltage

$$\text{Form Factor} = \frac{\text{Vrms}}{\text{Vavg}}$$

8. Effective value of the AC component of the output voltage

$$V_{ac} = [\text{Vrms}^2 - \text{Vavg}^2\,]^{1/2}$$

9. Ripple factor (R_f)

   It is defined as the ratio of AC component to the DC. Where ripple is the amount of AC component present in DC component

$$R_f = \frac{\text{Vac}}{\text{Vavg}} = \frac{[\text{Vrms}^2 - \text{Vavg}^2\,]^{1/2}}{\text{Vavg}} = \left[\left(\frac{\text{Vrms}}{\text{Vavg}}\right)^2 - 1\right]^{1/2} = \sqrt{FF^2 - 1}$$

10. Transformer Utilization Factor (TUF):

    It is defined as the ratio of output DC power to the volt ampere rating of the transformer

$$\text{TUF} = \frac{\text{Pdc}}{\text{VA rating of secondary winding of the transformer}}$$

11. Rectifier efficiency:

    It is defined as the ratio of output DC power to the input ac power

$$\eta = \frac{\text{VavgIavg}}{\text{VrmsIrms}}$$

12. Peak inverse voltage (PIV):

    It is defined as the maximum voltage that an SCR can be subjected to in the reverse biased condition

    In the case of Half wave rectifier it is V_m

Operation of three phase fully controlled rectifier with R and RL loads

Three phase full converter is a fully controlled bridge controlled rectifier using six thyristors connected in the form of a full wave bridge configuration. All the six thyristors are controlled switches which are turned on at a appropriate times by applying suitable gate trigger signals.

The **three phase full converter** is extensively used in industrial power applications upto about 120kW output power level, where two quadrant operations is required. The figure shows a **three phase full converter** with highly inductive load. This circuit is also known as three phase full wave bridge or as a six pulse converter.

The thyristors are triggered at an interval of (∏/3) radians (i.e. at an interval of 30°). The frequency of output ripple voltage is $6f_s$ and the filtering requirement is less than that of **three phase semi and half wave converters**.

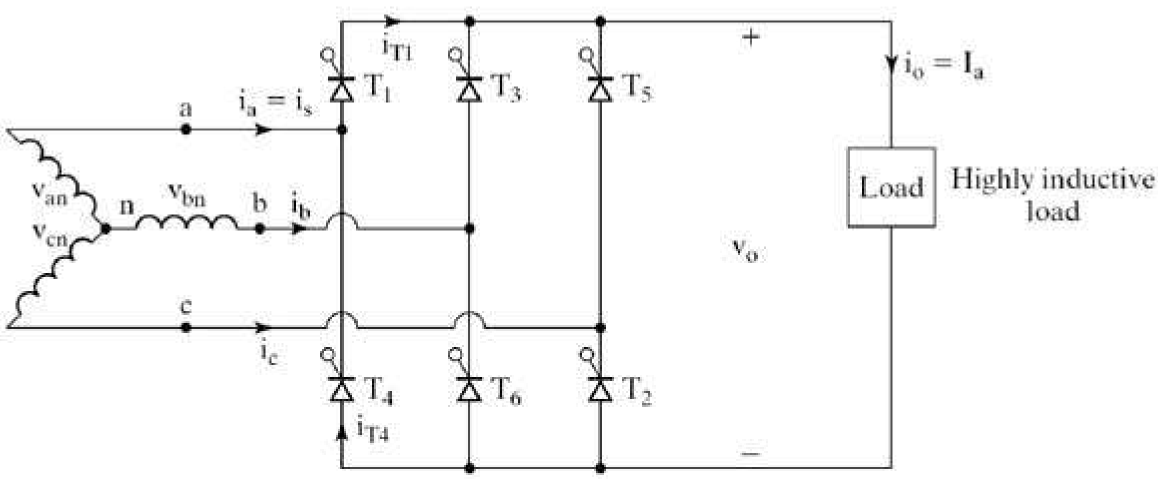


Figure: 2.20 circuit diagram three phase fully controlled rectifier with R and RL load

At $\omega t=(\prod/6 +\alpha)$, thyristor is already conducting when the thyristor is turned on by applying the gating signal to the gate of . During the time period $\omega t=(\prod/6 +\alpha)$ to (∏/2 +α), thyristors and conduct together and the line to line supply voltage appears across the load.

At $\omega t=(\prod/2 +\alpha)$, the thyristor T_2 is triggered and T_6 is reverse biased immediately and T_6 turns off due to natural commutation. During the time period $\omega t=(\prod/ +\alpha)$ *to* $(5\prod/6 +\alpha)$, thyristor T_1 and T_2 conduct together and the line to line supply voltage appears across the load.

The thyristors are numbered in the circuit diagram corresponding to the order in which they are triggered. The trigger sequence (firing sequence) of the thyristors is 12, 23, 34, 45, 56, 61, 12, 23, and so on. The figure shows the waveforms of three phase input supply voltages, output voltage, the thyristor current through T_1 and T_4, the supply current through the line ‘a’.

We define three line neutral voltages (3 phase voltages) as follows

$V_{RN} = V_{an} = V_m$ sinwt where V_m is the maximum voltage

$V_{YN} = V_{bn} = V_m \sin(wt - \frac{2\pi}{3})$

$V_{BN} = V_{cn} = V_m \sin(wt - \frac{4\pi}{3})$

The corresponding line to line voltages are

$V_{RY} = V_{ab} = V_{an} - V_{bn} = \sqrt{3}\,\text{Vm}\sin\left(\text{wt} + \frac{\pi}{6}\right)$

$V_{YB} = V_{bc} = V_{bn} - V_{cn} = \sqrt{3}\,\text{Vm}\sin\left(\text{wt} - \frac{\pi}{2}\right)$

$V_{BR} = V_{ca} = V_{cn} - V_{an} = \sqrt{3}\,\text{Vm}\sin\left(\text{wt} + \frac{\pi}{2}\right)$

To derive an expression for the average output voltage of **three phase full converter** with highly inductive load assuming continuous and constant load current

The output load voltage consists of 6 voltage pulses over a period of 2∏ radians, hence the average output voltage is calculated as

$$V_{avg} = \frac{6}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} \text{Vod(wt)}$$

$$V_o = V_{ab} = \sqrt{3}\,\text{Vm}\sin\left(\text{wt} + \frac{\pi}{6}\right)$$

$$V_{avg} = \frac{3}{\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} \sqrt{3}\,\text{Vm}\sin\left(\text{wt} + \frac{\pi}{6}\right)\text{d(wt)}$$

$$= \frac{3\sqrt{3}Vm}{\pi}\ cos\alpha$$

$$= \frac{3Vml}{\pi}\ cos\alpha$$

The RMS value of the output voltage is found from

$$V_{orms} = \left[\frac{6}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} Vo^2 d(wt)\right]^{1/2}$$

$$= \left[\frac{6}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} Vab^2 d(wt)\right]^{1/2}$$

$$= \left[\frac{3}{\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} 3\ Vm^2 \sin^2\left(wt+\frac{\pi}{6}\right) d(wt)\right]^{1/2}$$

$$= \sqrt{3}Vm\left(\frac{1}{2}+\frac{3\sqrt{3}}{4\pi}cos2\alpha\right)^{1/2}$$

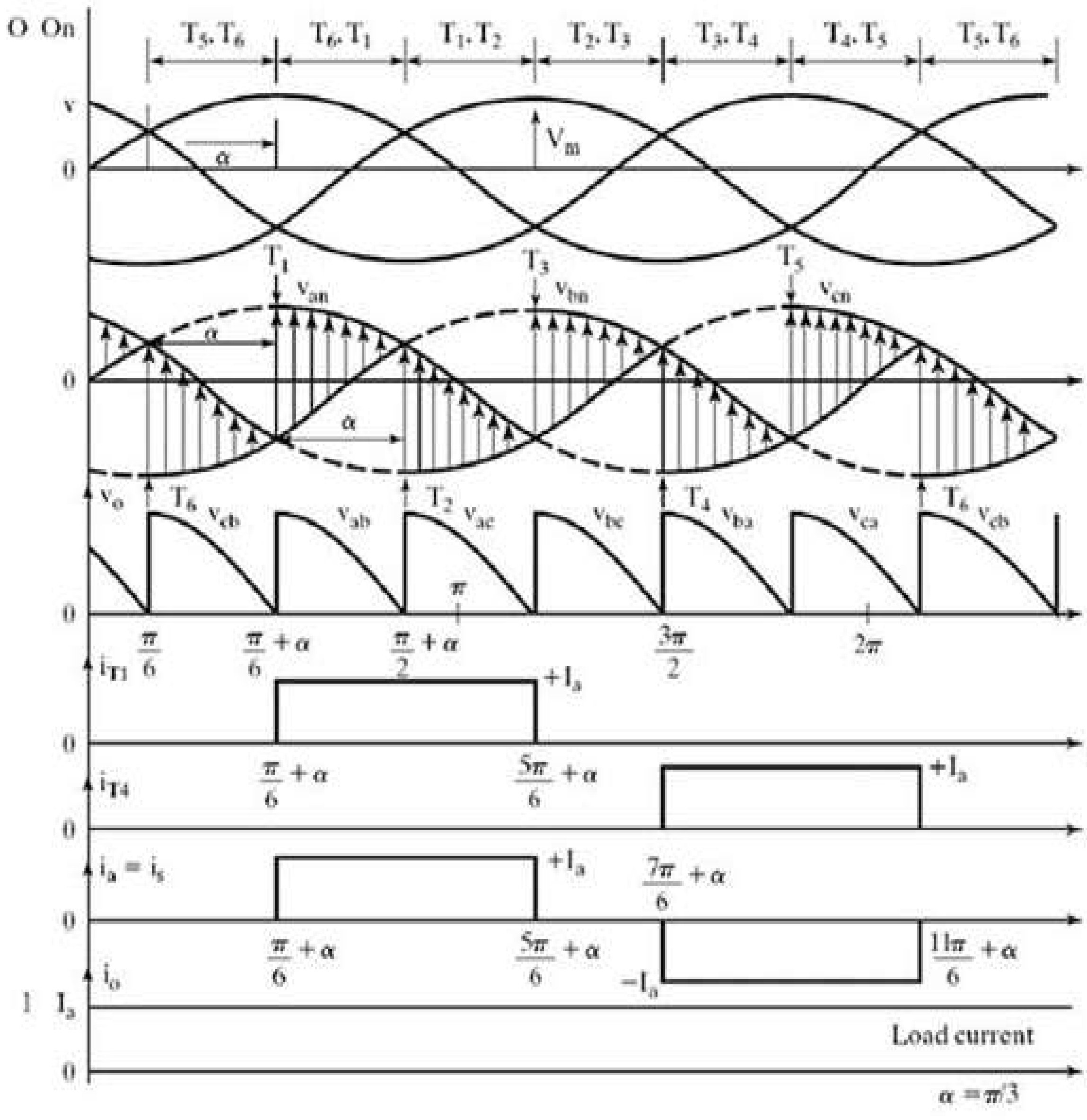


Figure: 2.21 Input and output waveforms of three phase fully controlled rectifier

Operation of three phase half wave rectifier with RLE loads

A three phase fully controlled converter is obtained by replacing all the six diodes of an uncontrolled converter by six thyristors as shown in Figure

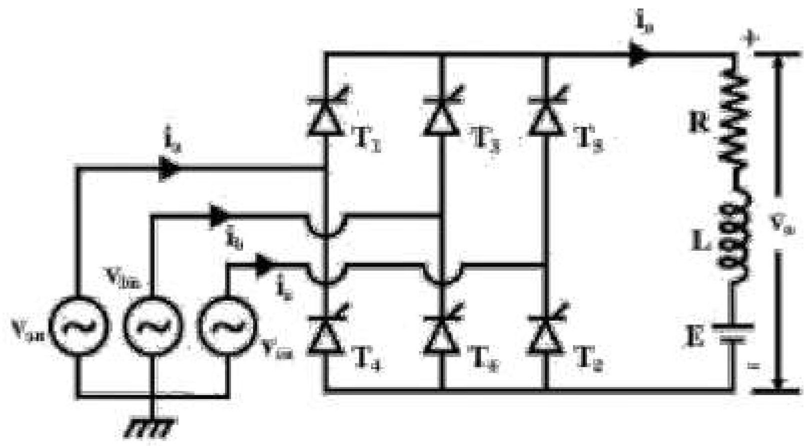


Figure: 2.22 circuit diagram of three phase fully controlled rectifier with RLE load

For any current to flow in the load at least one device from the top group (T1, T3, T5) and one from the bottom group (T2, T4, T6) must conduct. It can be argued as in the case of an uncontrolled converter only one device from these two groups will conduct.

Then from symmetry consideration it can be argued that each thyristor conducts for 120° of the input cycle. Now the thyristors are fired in the sequence T1 → T2 → T3 → T4 → T5 → T6 → T1 with 60° interval between each firing. Therefore thyristors on the same phase leg are fired at an interval of 180° and hence can not conduct simultaneously. This leaves only six possible conduction mode for the converter in the continuous conduction mode of operation. These are T1T2, T2T3, T3T4, T4T5, T5T6, T6T1. Each conduction mode is of 60° duration and appears in the sequence mentioned. Each of these line voltages can be associated with the firing of a thyristor with the help of the conduction table-1. For example the thyristor T1 is fired at the end

of T5 T6 conduction interval. During this period the voltage across T1 was vac. Therefore T1 is fired α angle after the positive going zero crossing of vac. similar observation can be made about other thyristors.

Fig. 2.23 shows the waveforms of different variables. To arrive at the waveforms it is necessary to draw the conduction diagram which shows the interval of conduction for each thyristor and can be drawn with the help of the phasor diagram of fig. 2.22. If the converter firing angle is α each thyristor is fired "α" for $\mu \le 60°$. It can be shown that for this condition to be satisfied

$$I_0 \le \frac{V_L}{\sqrt{2}\omega L}\cos\left(\alpha - \frac{\pi}{3}\right)$$

To calculate the dc voltage

For $\alpha \le \omega t \le \alpha + \mu$

$$v_0 = v_a - v_b + L\frac{di_b}{d_t} = \frac{3}{2}v_a$$

for $\alpha + \mu \le \omega t \le \alpha + \frac{\pi}{3}$ $\quad v_0 = v_{ac}$

$$\therefore \quad V_0 = \frac{3}{\pi}\left[\int_{\alpha}^{\alpha+\mu}\frac{3}{2}v_a\, d\omega t + \int_{\alpha+\mu}^{\alpha+\frac{\pi}{3}}v_{ac}\, d\omega t\right]$$

$$= \frac{3}{\pi}\left[\int_{\alpha}^{\alpha+\mu}\left(v_{ac} + \frac{3}{2}v_a - v_{ac}\right) + \int_{\alpha+\mu}^{\alpha+\frac{\pi}{3}}v_{ac}\, d\omega t\right]$$

$$= \frac{3}{\pi}\left[\int_{\alpha}^{\alpha+\frac{\pi}{3}}v_{ac}\, d\omega t + \int_{\alpha}^{\alpha+\mu}\left(\frac{v_a}{2} + v_c\right)d\omega t\right]$$

$$= \frac{3\sqrt{2}}{\pi}V_L\cos\alpha - \frac{3}{2\pi}\int_{\alpha}^{\alpha+\mu}v_{bc}\, d\omega t$$

or $$V_0 = \frac{3\sqrt{2}}{\pi}V_L\cos\alpha - \frac{3\sqrt{2}V_L}{2\pi}\int_{\alpha}^{\alpha+\mu}\sin\omega t\, d\omega t$$

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

$$V_0 = \frac{3\sqrt{2}}{\pi}V_L\cos\alpha - \frac{3}{\pi}\omega L I_0$$

Introduction to dual converters

Dual converter, the name itself says two converters. It is really an electronic converter or circuit which comprises of two converters. One will perform as rectifier and the other will perform as inverter. Therefore, we can say that double processes will occur at a moment. Here, two full converters are arranged in anti-parallel pattern and linked to the same dc load. These converters can provide four quadrant operations. The basic block diagram is shown below

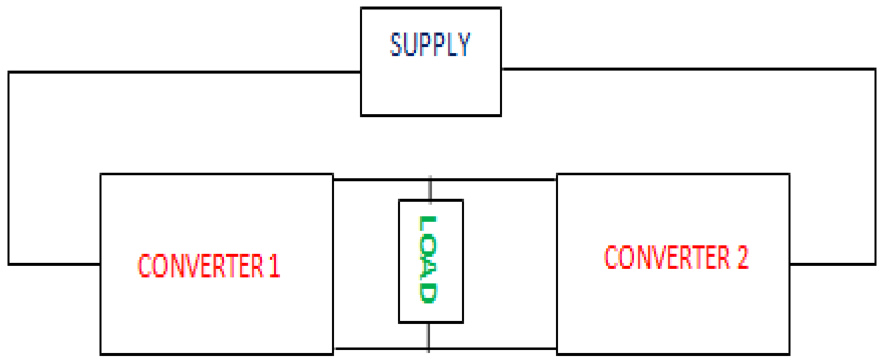


Figure: 2.28 Block diagram of dual converter

Modes of Operation of Dual Converter

There are two functional modes: Non-circulating current mode and circulating mode.

Non Circulating Current Mode

- One converter will perform at a time. So there is no circulating current between the converters.
- During the converter 1 operation, firing angle (α_1) will be $0<\alpha_1< 90^o$; V_{dc} and I_{dc} are positive.
- During the converter 2 operation, firing angle (α_2) will be $0<\alpha_2< 90^o$; V_{dc} and I_{dc} are negative.

Circulating Current Mode

- Two converters will be in the ON condition at the same time. So circulating current is present.
- The firing angles are adjusted such that firing angle of converter 1 (α_1) + firing angle of converter 2 (α_2) = 180^o.
- Converter 1 performs as a controlled rectifier when firing angle be $0<\alpha_1< 90^o$ and Converter 2 performs as an inverter when the firing angle be $90^o<\alpha_2< 180^o$. In this condition, V_{dc} and I_{dc} are positive.
  - Converter 1 performs as an inverter when firing angle be $90^o<\alpha_1< 180^o$ and Converter 2 performs as a controlled rectifier when the firing angle be $0<\alpha_2< 90^o$ In this condition, V_{dc} and I_{dc} are negative.
  - The four quadrant operation is shown below

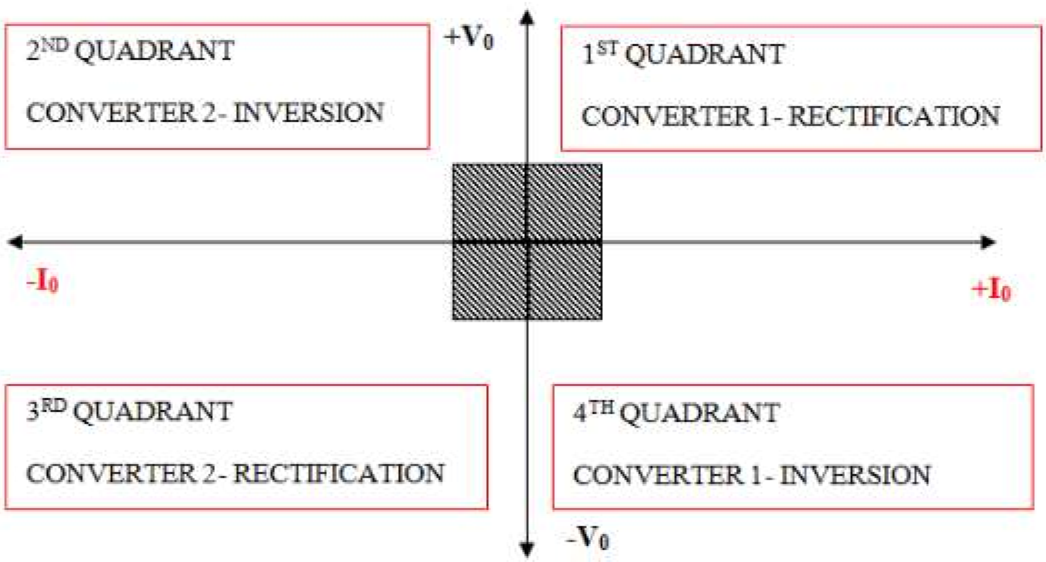


Figure: 2.29 Four quadrant operations of dual converter

Ideal Dual Converter

The term 'ideal' refers to the ripple free output voltage. For the purpose of unidirectional flow of DC current, two diodes (D_1 and D_2) are incorporated between the converters. However, the direction of current can be in any way. The average output voltage of the converter 1 is V_{01} and converter 2 is V_{02}. To make the output voltage of the two converters in same polarity and magnitude, the firing angles of the Thyristors have to be controlled.

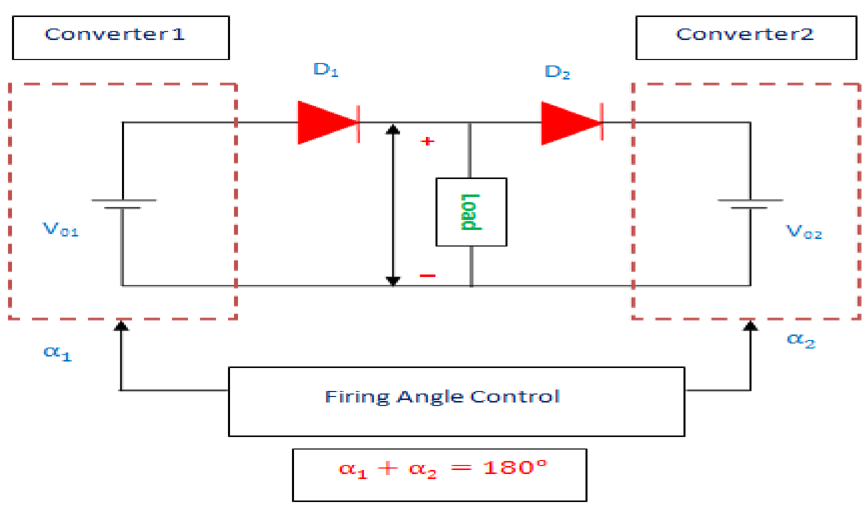


Figure: 2.30 Ideal dual converter

Single Phase Dual Converter

The source of this type of converter will be single-phase supply. Consider, the converter is in non-circulating mode of operation. The input is given to the converter 1 which converts the AC to DC by the method of rectification. It is then given to the load after filtering. Then, this DC is provided to the converter 2 as input. This converter performs as inverter and converts this DC to AC. Thus, we get AC as output. The circuit diagram is shown below.

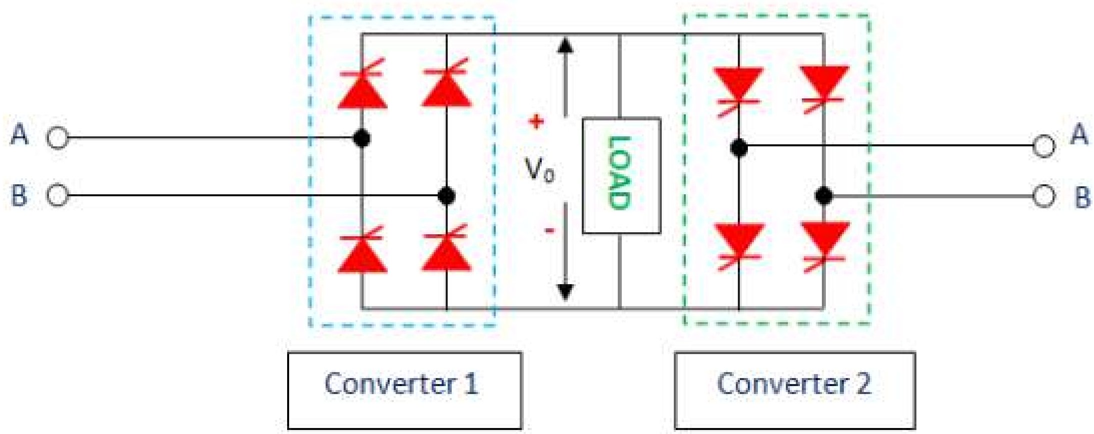


Figure: 2.31 Single phase Dual converter

Average output voltage of Single-phase converter= $\frac{2V_m Cos\ \alpha}{\pi}$

Average output voltage of Three-phase converter = $\frac{3V_{ml} Cos\ \alpha}{\pi}$

For converter 1, the average output voltage, $V_{01} = V_{max} Cos\alpha_1$

For converter 2, the average output voltage, $V_{02} = V_{max} Cos\alpha_2$

Output voltage,
$$\begin{aligned} V_0 &= V_{01} = -V_{02} \\ V_{max}Cos\alpha_1 &= -V_{max}Cos\alpha_2 \\ Cos\alpha_1 &= Cos(180^o - \alpha_2)\ or\ Cos\alpha_2 = Cos(180^o + \alpha_2) \\ \alpha_1 + \alpha_2 &= 180^o\ And\ \alpha_1 - \alpha_2 = 180^o \end{aligned}$$

The firing angle can never be greater than 180°. So, $\alpha_1 + \alpha_2 = 180^o$

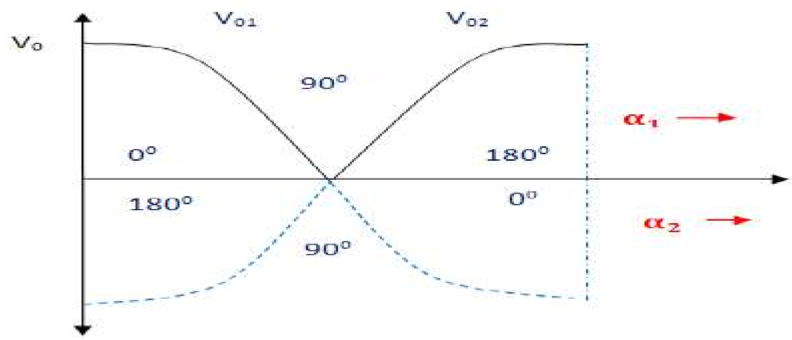


Figure: 2.32 output voltage variation with firing angle

Three Phase Dual Converter

Here, three-phase rectifier and three-phase inverter are used. The processes are similar to single-phase dual converter. The three-phase rectifier will do the conversion of the three-phase AC supply to the DC. This DC is filtered and given to the input of the second converter. It will do the DC to AC conversion and the output that we get is the three-phase AC. Applications where the output is up to 2 megawatts. The circuit is shown below.

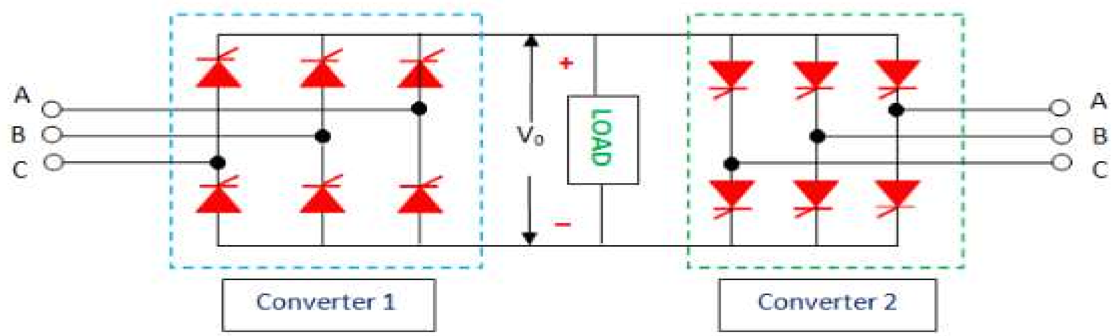
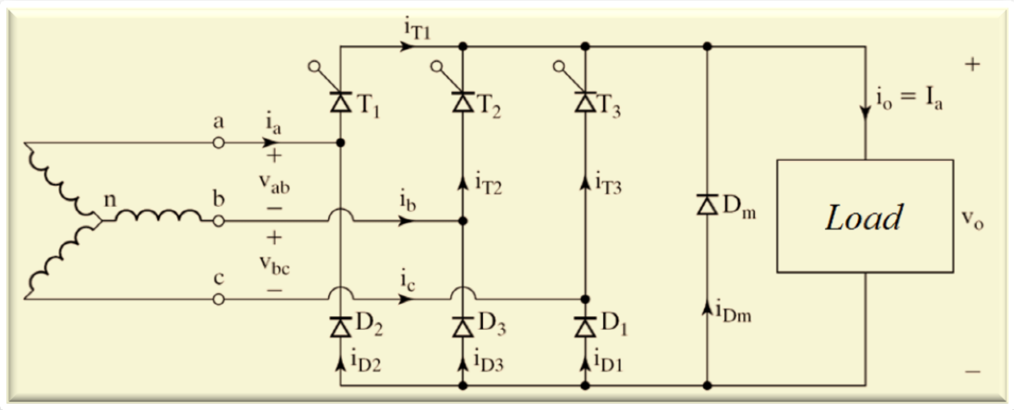


Figure: 2.33 Three phase dual converter

Application of Dual Converter

- Direction and Speed control of DC motors.
- Applicable wherever the reversible DC is required.
- Industrial variable speed DC drives.

Three Phase Full Wave Half Controlled Rectifiers



- **3-phase semi-converters are three phase half controlled bridge controlled rectifiers which employ three thyristors and three diodes connected in the form of a bridge configuration. Three thyristors are controlled switches which are turned on at appropriate times by applying appropriate gating signals. The three diodes conduct when they are forward biased by the corresponding phase supply voltages.**
- **The power factor of 3-phase semi-converter decreases as the trigger angle α increases. The power factor of a 3-phase semi-converter is better than three phase half wave converter.**

Three Phase Full Wave Half Controlled Rectifiers

- **Thyristor T_1 is forward biased when the phase supply voltage v_{an} is positive and greater than the other phase voltages v_{bn} and v_{cn}. The diode D1 is forward biased when the phase supply voltage v_{cn} is more negative than the other phase supply voltages.**

- **Thyristor T_2 is forward biased when the phase supply voltage v_{bn} is positive and greater than the other phase voltages. Diode D_2 is forward biased when the phase supply voltage van is more negative than the other phase supply voltages.**

- **Thyristor T_3 is forward biased when the phase supply voltage v_{cn} is positive and greater than the other phase voltages. Diode D_3 is forward biased when the phase supply voltage v_{bn} is more negative than the other phase supply voltages.**

- **The frequency of the output supply waveform is $3f_S$, where f_S is the input ac supply frequency. The trigger angle α can be varied from 0 to 180^o.**

Three Phase Full Wave Half Controlled Rectifiers

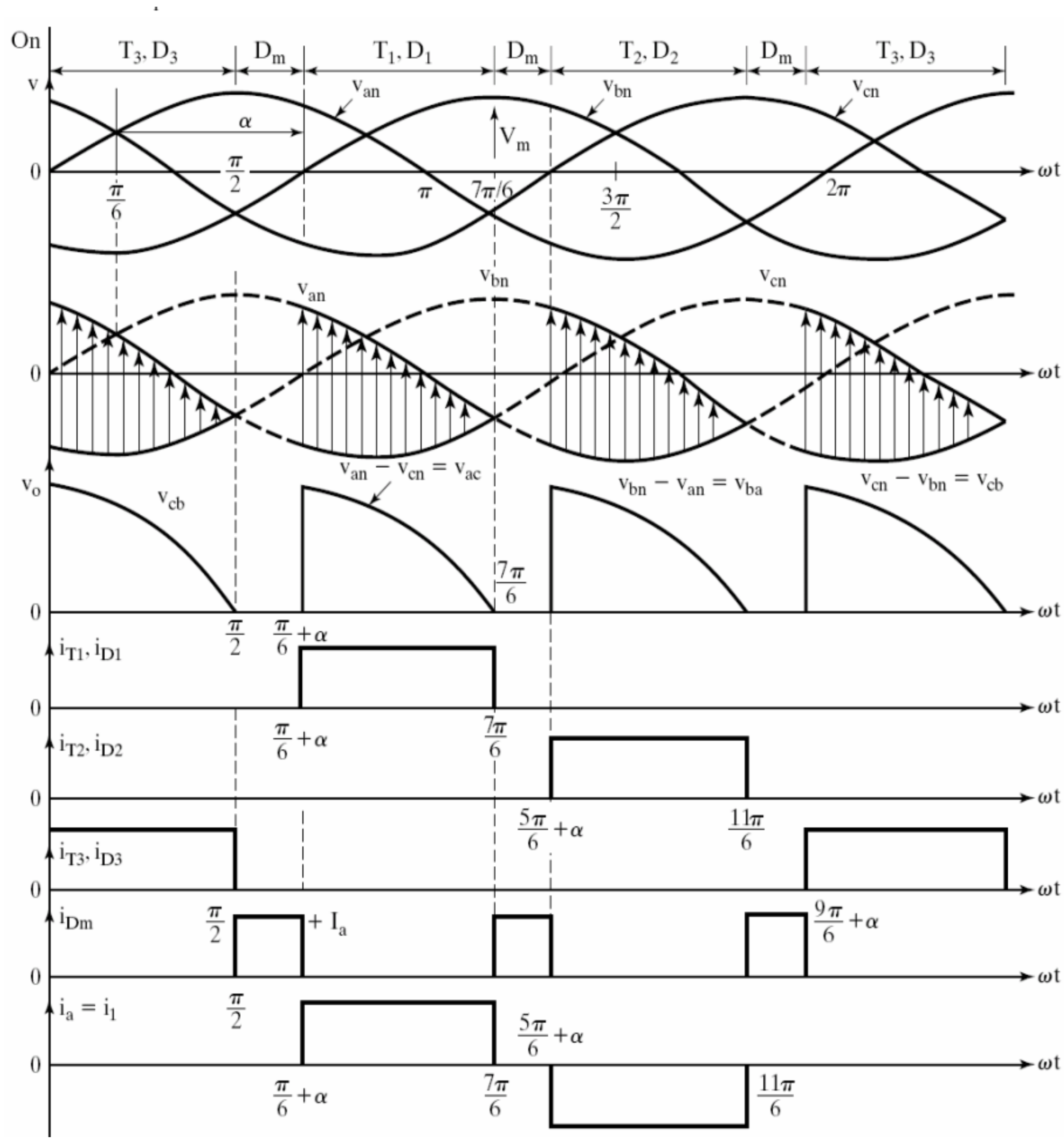
For $\alpha > 60^o$

- **During the time period $\pi/6 \leq \omega t \leq 7\pi/6$ (i.e. $30^o \leq \omega t \leq 210^o$) thyristor T_1 is forward biased. If T_1 is triggered at $\omega t = \pi/6 + \alpha$, T_1 and D_1 conduct together and the line to line supply voltage v_{ac} appears across the load. At $\omega t = 7\pi/6$, v_{ac} starts to become negative and the free wheeling diode D_m turns on and conducts. The load current continues to flow through the free wheeling diode D_m and thyristor T_1 and diode D_1 are turned off.**

- **If the free wheeling diode D_m is not connected across the load, then T_1 would continue to conduct until the thyristor T_2 is triggered at $\omega t = 5\pi/6 + \alpha$ and the free wheeling action is accomplished through T_1 and D_2, when D_2 turns on as soon as v_{an} becomes more negative at $\omega t = 7\pi/6$.**

Three Phase Full Wave Half Controlled Rectifiers

Waveforms for α=90º

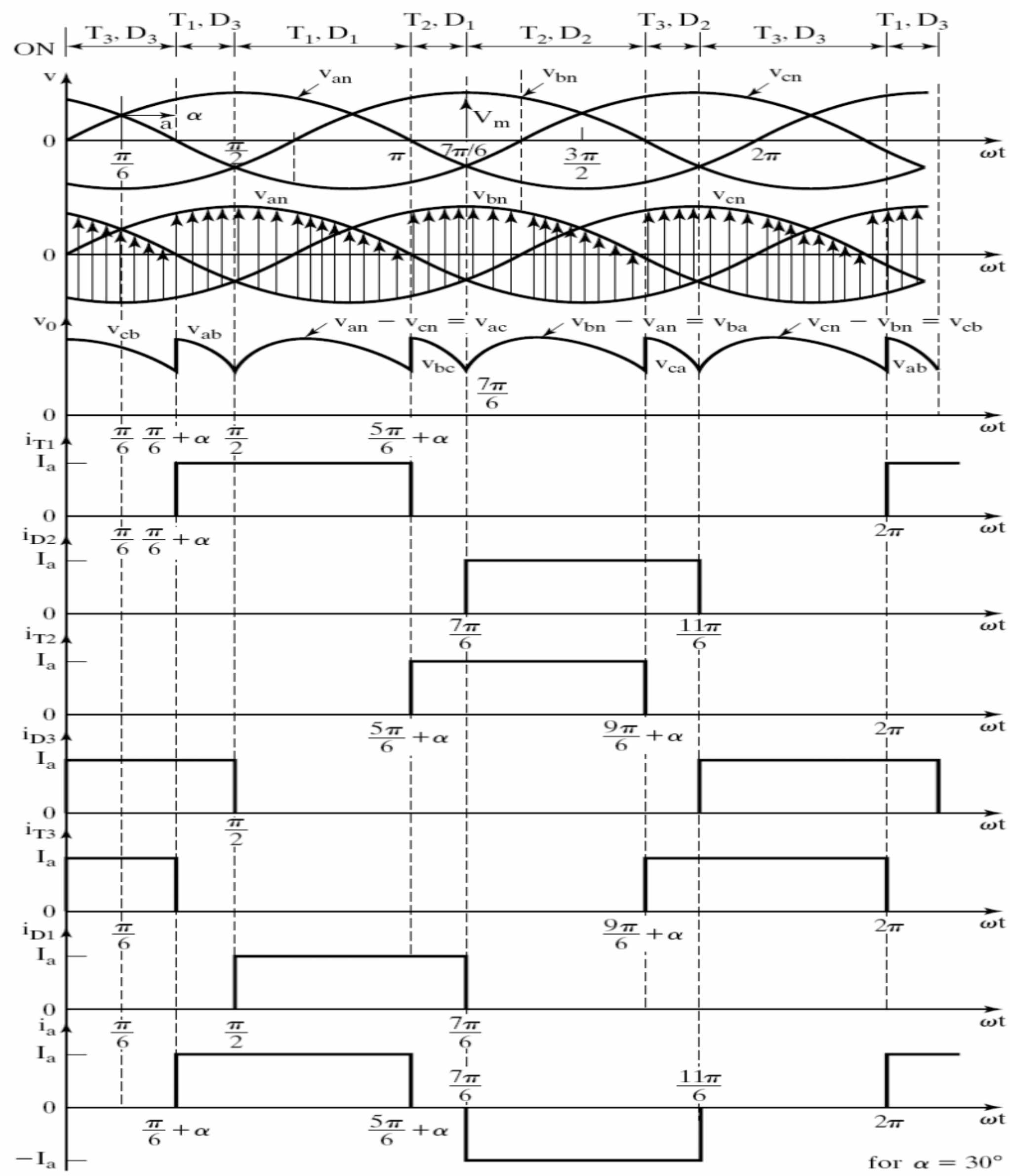


Three Phase Full Wave Half Controlled Rectifiers

For α<60º

If the trigger angle α≤π/3 each thyristor conducts for 2π/3 and the free wheeling diode D_m does not conduct.

Waveforms for α=30º

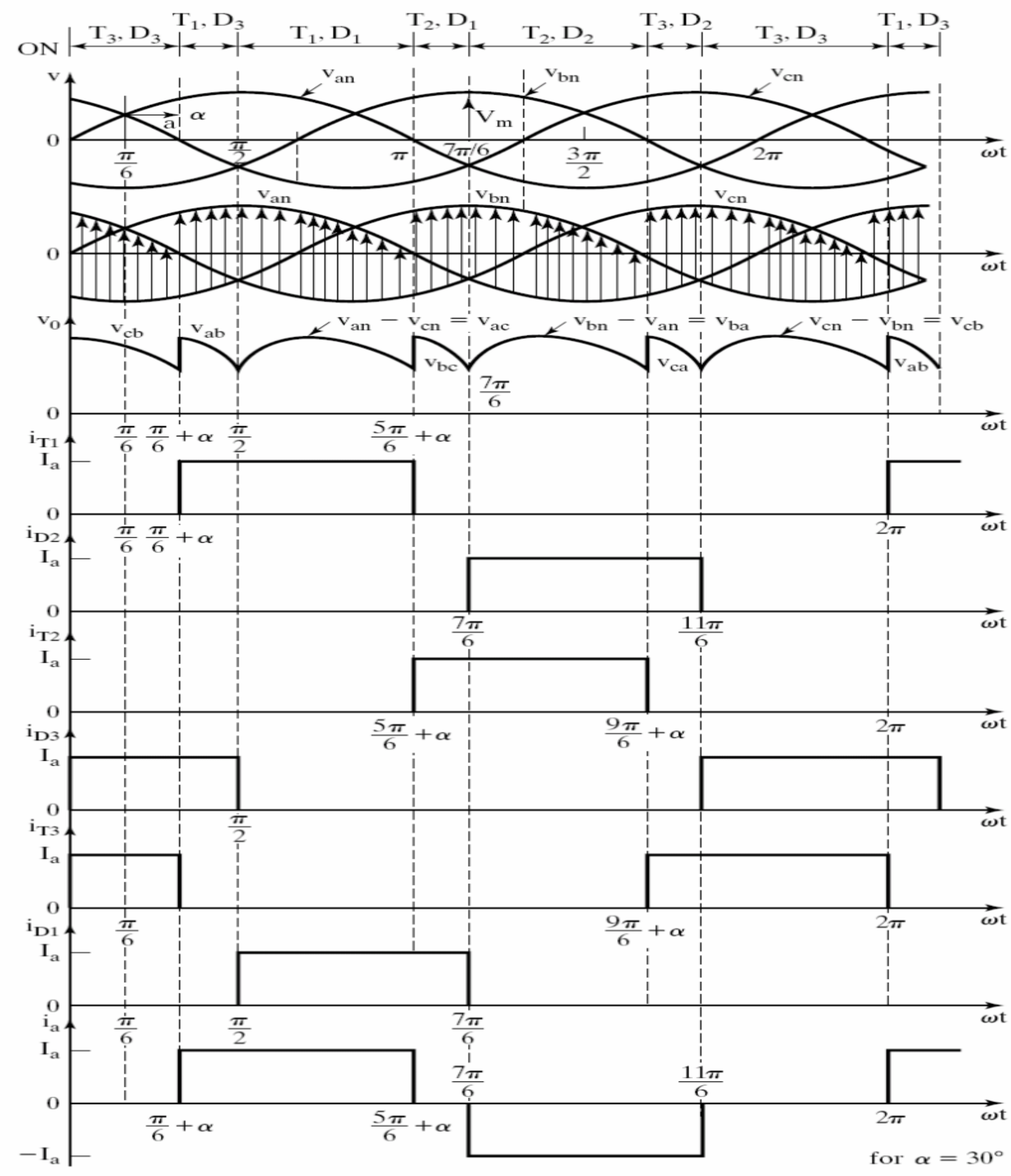


Three Phase Full Wave Half Controlled Rectifiers

For α<60º

If the trigger angle $\alpha \leq \pi/3$ each thyristor conducts for $2\pi/3$ and the free wheeling diode D_m does not conduct.

Waveforms for α=30º



Three Phase Full Wave Half Controlled Rectifiers

Let $V_{an} = V_m \sin\omega t$ $\quad V_{bn} = V_m \sin(\omega t\text{-}2\pi/3)$ $\quad V_{bn} = V_m \sin(\omega t\text{-}4\pi/3)$

For α>60º and Discontinuous Output Voltage

$$V_o = V_{ac} = \sqrt{3}V_m \sin(\omega t - \frac{\pi}{6})$$

The <u>dc component</u> of the output voltage and current can be found as

$$V_{dc} = \frac{3}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{7\pi}{6}} \sqrt{3}V_m \sin(\omega t - \frac{\pi}{6}) d\omega t = \frac{3\sqrt{3}V_m}{2\pi}(1+\cos\alpha)$$

$$I_{dc} = \frac{V_{dc}}{R} = \frac{3\sqrt{3}V_m}{2\pi R}(1+\cos\alpha)$$

The *rms* component of the output voltage and current waveforms are determined from

$$V_{rms} = \sqrt{\frac{3}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{7\pi}{6}} \left(\sqrt{3}V_m \sin(\omega t - \frac{\pi}{6})\right)^2 d\omega t} = \frac{3V_m}{2}\sqrt{1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi}}$$

$$I_{rms} = \frac{V_{rms}}{\sqrt{R^2 + (\omega L)^2}} = \frac{3V_m}{2\sqrt{R^2 + (\omega L)^2}}\sqrt{1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi}}$$

Three Phase Full Wave Half Controlled Rectifiers

For α≤60º and Continuous Output Voltage

$$V_o = V_{ab} = \sqrt{3}V_m \sin(\omega t + \frac{\pi}{6})$$

The <u>dc component</u> of the output voltage and current can be found as

$$V_{dc} = \frac{3}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}} \sqrt{3}V_m \sin(\omega t + \frac{\pi}{6})d\omega t = \frac{3\sqrt{3}V_m}{2\pi}(1 + cos\ \alpha)$$

$$I_{dc} = \frac{V_{dc}}{R} = \frac{3\sqrt{3}V_m}{2\pi R}(1 + cos\ \alpha)$$

The *rms* component of the output voltage and current waveforms are determined from

$$V_{rms} = \sqrt{\frac{3}{2\pi}\left[\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}} (V_{ab})^2 d\omega t + \int_{\frac{\pi}{62}}^{\frac{5\pi}{6}} (V_{ac})^2 d\omega t\right]} = \frac{3V_m}{2}\sqrt{\frac{2}{3} + \frac{\sqrt{3}(cos\alpha)^{\ 2}}{\pi}}$$

$$I_{rms} = \frac{V_{rms}}{\sqrt{R^2 + (\omega L)^2}} = \frac{3V_m}{2\sqrt{R^2 + (\omega L)^2}}\sqrt{\frac{2}{3} + \frac{\sqrt{3}(cos\alpha)^{\ 2}}{\pi}}$$

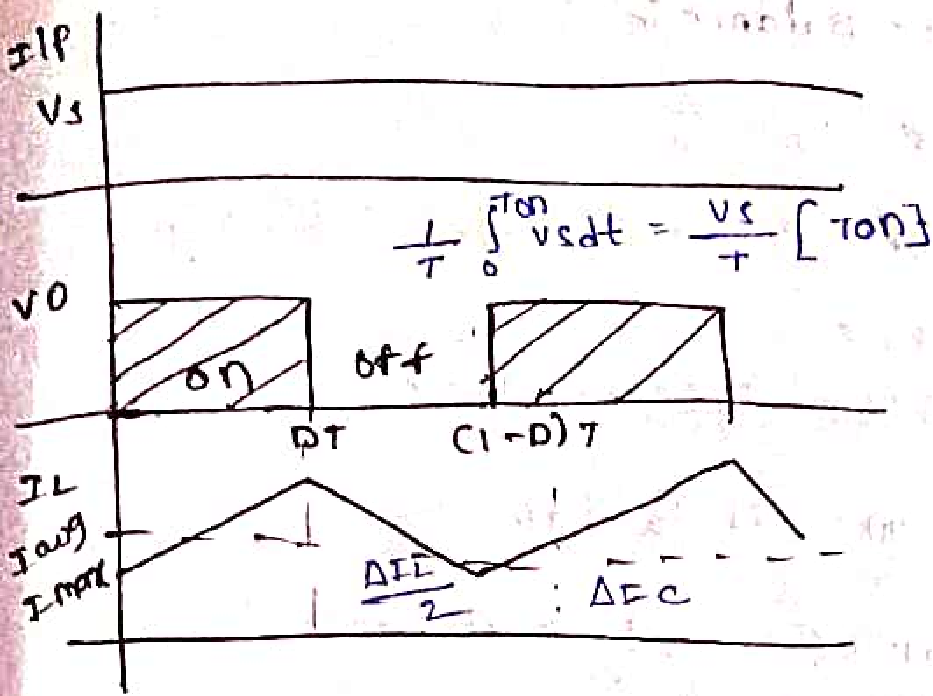
Unit-IV

switched mode regulators (DC-DC converters)
classified into 2 types.

1. NON isolated
2. Isolated → 1) Half bridge
   2) full-bridge
   3) fly Back
   4) Push pull
   5) forward.

NON-isolated:
1. Buck converter. $(V_o < V_s)$ | step down
2. Boost converter $(V_o > V_s)$ | step up
3. Buck-Boost converter step up & down.
4. CUK
5. SEPIC

Assumptions:
1. Inductor current is continous.
2. the inductance is large enough to minir
current ripple.
3. the capacitor is very Large so that t
voltage is held constant.



Switch off condition :-

$L^{(-)}$ - load - Diode - $L^{(+)}$

$T_{off} = T - T_{on}$.

$V_L(off) = -V_O$

$I_C(off) = I_L - I_O$

** Volt sec Balance :-

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

$(V_S - V_O)DT + (-V_O)(1-D)T = 0$

$V_S DT - V_O DT - V_O T + V_O DT = 0$

$V_S DT - V_O T = 0$

$V_S D\cancel{T} = V_O\cancel{T}$

$\boxed{V_S D = V_O}$

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

Max value of inductor current :-

$$= I_L + \frac{\Delta I_L}{2}$$

$$= I_o + \frac{\Delta I_L}{2}$$

$$I_{L\,max} = I_o + \frac{D(1-D)V_s}{2fL}$$

$$I_{L\,min} = I_L - \frac{\Delta I_L}{2}$$

$$= I_o - \frac{D(1-D)V_s}{2fL}.$$

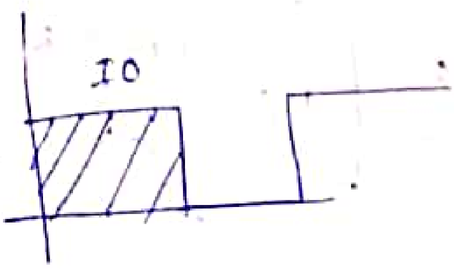
Source current :-

$$P_{in} = P_{out}$$

$$V_s I_s = V_o I_o$$

$$I_s = \frac{V_o I_o}{V_s}$$

Switch current :-

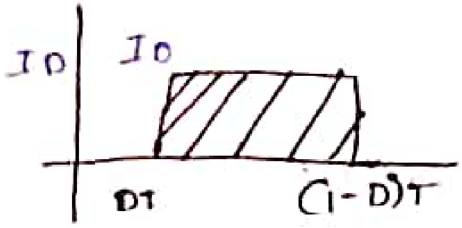


$$I_{sw}(avg) = I_o \frac{DT}{T} = I_o D$$

$$I_{sw}(rms) = I_o \sqrt{\frac{DT}{T}}$$

$$= I_o \sqrt{D}$$

Diode current:



$$I_D = I_0 \frac{(1-D)T}{T}$$

$$I_{D(avg)} = I_0(1-D)$$

$$I_{D\,rms} = I_0 \sqrt{\frac{(1-D)T}{T}}$$

* $$I_{D\,rms} = I_0 \sqrt{(1-D)}$$

itical value of inductance:

$$I_L(min) = 0$$

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

$$I_0 - \frac{\Delta I_L}{2} = 0$$

$$I_0 = \frac{\Delta I_L}{2}$$

$$\frac{V_0}{R} = \frac{\Delta I_L}{2}$$

$$\frac{D V_s}{R} = \frac{D(1-D)V_s}{2FL}$$

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

$$\frac{1}{R} = \frac{(1-D)}{2FLC}$$

$$R = \frac{2FLC}{(1-D)}$$

** ΔV_C or ΔV_0 :

$Q = CV$

$\Delta Q = C\Delta V$

$\Delta V = \frac{\Delta Q}{C}$

$$\boxed{\Delta V = \frac{\Delta I_L}{8fC}}$$

$$\Delta V = \frac{\frac{D(1-D)V_s}{fL}}{8fC}$$

critical value of capacitance

$V_C\, min = 0$

$V_C - \frac{\Delta V_C}{2} = 0$

$V_C = \frac{1}{2}[\Delta V_C]$

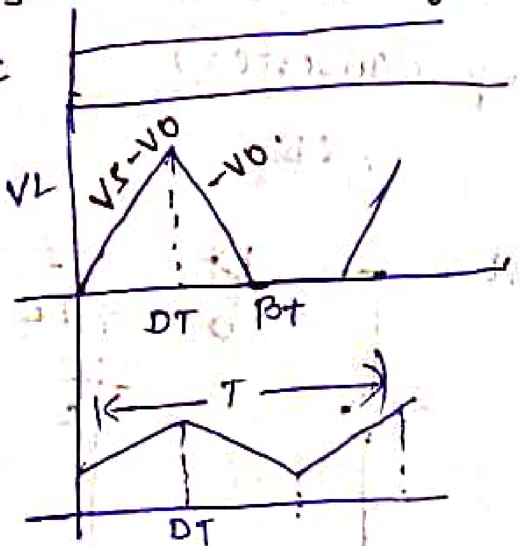
$V_C = \frac{1}{2}\left[\frac{\Delta I_L}{8fC}\right]$

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

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

$C = \frac{(1-D)}{16f^2L}$

Discontinous current mode :



$\boxed{L < L_{cr} \rightarrow \text{DisCM}}$

$\boxed{V_o(avg)\, DCM > V_o(avg)\, CCM}$

Switch on :

$V_{L(on)} = V_s - V_o$, $T_{on} = DT$

Switch off

$V_{L\,off} = -V_o$

volt - sec balance =

$T_{off} + T_{on} = 0$

$T_{off} = (\beta - D)T$

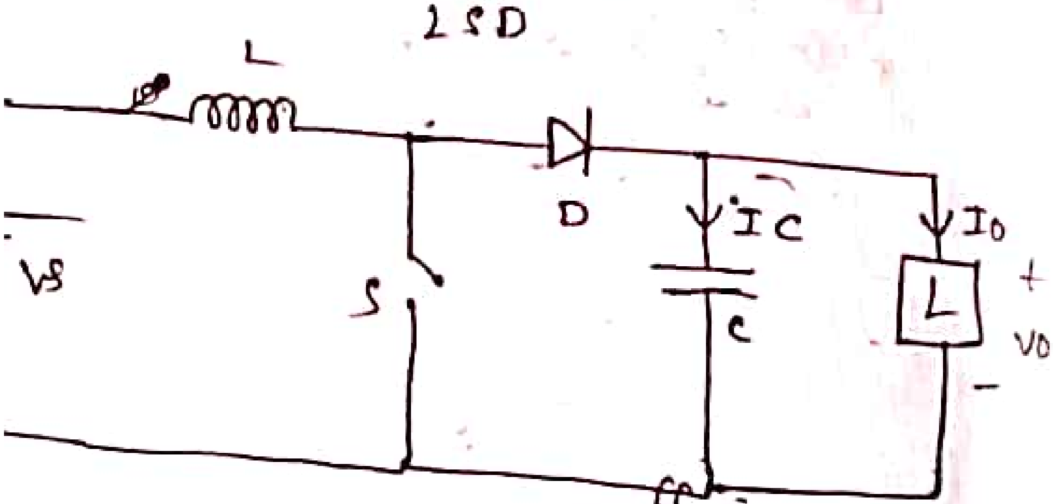
$(V_s - V_o) DT + (-V_o)(\beta - D)T = 0$

$V_s DT - V_o \beta T = 0$

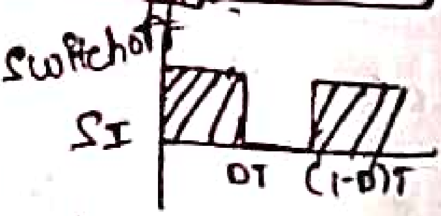
$V_s D = V_o \beta$

$$V_{o\,(avg)} = \frac{V_s D}{\beta}$$

ost converter:
(step up converter)

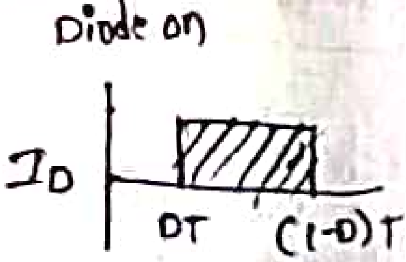


peration:

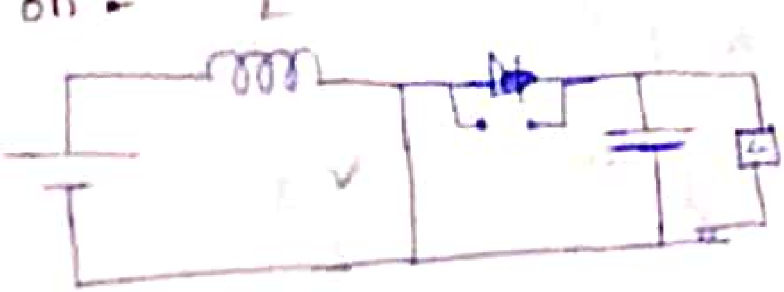


Continous current mode:

states ← on switch.
↖ off

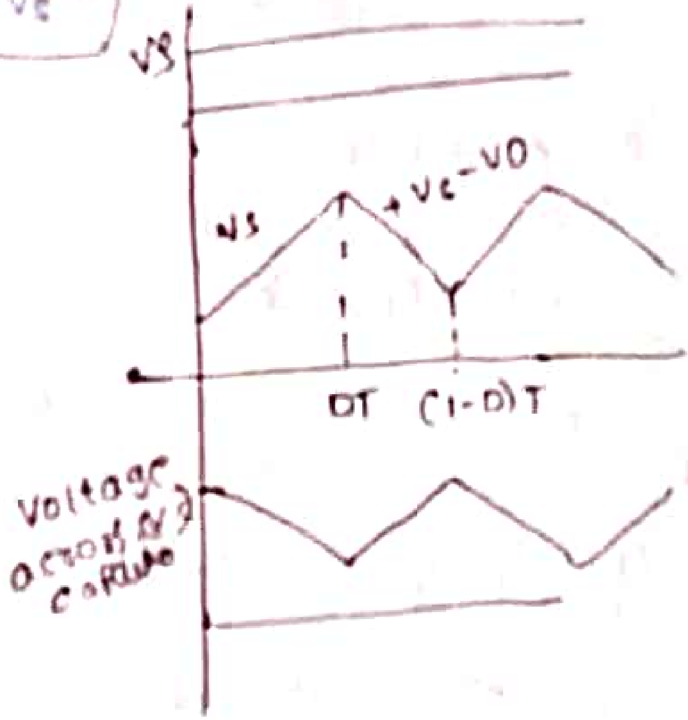


switch on :-



S is on, Diode is off

$V_S^+ - L - SW - V_S^-$



$V_L(on) = V_S$

1) $T_{on} = DT$

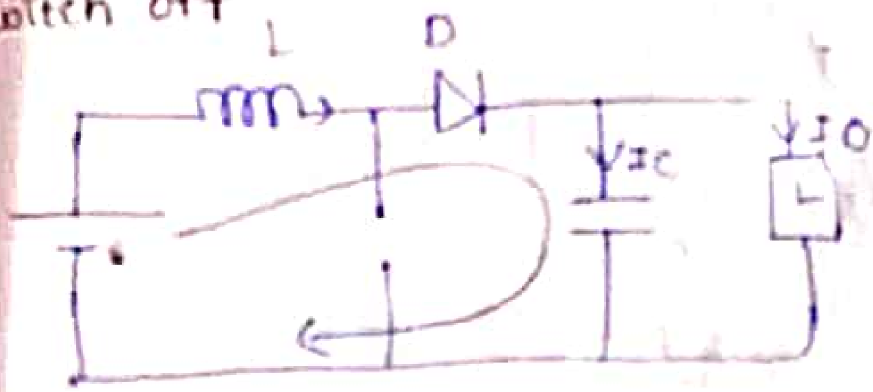
2) $I_C = -I_O$

$I_D = I_C + I_O$

$0 = I_C + I_O$

$I_C = -I_O$

switch off



$-V_S + V_L(off) + V_0 = 0$

$V_L(off) = V_S - V_0$

$$-I_0DT + I_L(1-D)T - I_0(1-D)T = 0$$

$$-I_0DT + I_LT - I_LDT - I_0T + I_0DT = 0$$

$$I_LT - I_LDT - I_0T = 0$$

$$I_LT[1-D] - I_0T = 0$$

$$I_0T = I_LT(1-D)$$

$$\boxed{I_0 = I_L(1-D)}$$

$$\boxed{I_L = \frac{I_0}{(1-D)}}$$

**

Current ripple (ΔI_L):

$$V_L(on) = V_S$$

$$L\frac{di(on)}{dt} = V_S$$

$$L\frac{\Delta I_L}{DT} = V_S$$

$$\boxed{\Delta I_L = \frac{V_S D}{fL}}$$

Buck:

$$V_L = L\frac{di}{dt}$$

$$V_L(on) = V_S - V_O$$

$$L\frac{di}{dt} = V_S - V_O$$

$$t_{on} = DT$$

$$L\frac{\Delta I_L}{DT} = V_S - V_O$$

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

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

Switch current:

$$I_{sw}(avg) = I_L\frac{DT}{T}$$

$$= I_LD$$

Switch RMS :

$$I_{SR} = I_L \sqrt{\frac{DT}{T}}$$

$$\Rightarrow I_L \sqrt{D}$$

$$\Rightarrow \frac{I_O}{(1-D)} \sqrt{D}.$$

iode current :

$$I_{D(avg)} = I_L \frac{(1-D)T}{T}$$

$$= \frac{I_O}{(1-D)} (1-D)$$

$$= I_O.$$

Buck current

$$I_D = I_O \frac{(1-D)T}{T}$$

$$= I_O (1-D)$$

I_D

$$I_{D rms} = I_L \sqrt{\frac{(1-D)T}{T}}$$

$$= I_L \sqrt{(1-D)}$$

$$= \frac{I_O}{(1-D)} \left(\sqrt{1-D}\right)$$

$$I_{D rms} = I_O \sqrt{\frac{1-D}{T}}$$

$$= I_O \sqrt{(1-D)}$$

e in output voltage :

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

$$I_C = -I_O$$

$$C \frac{dv}{dt} = \ldots$$

$$V_C = \frac{1}{2}\left[\frac{I_0 D}{FC}\right]$$

$$V_C = \frac{1}{2}\left[\frac{V_0 D}{RFC}\right]$$

$$\cancel{V_C = \frac{1}{2}\left[\frac{\frac{V_S}{(1-D)} D}{RFC}\right]}$$

$V_C = V_0$

$$V_0 = \frac{1}{2}\left[\frac{V_0 D}{RFC}\right]$$

$$\boxed{C = \frac{D}{2fR}}$$

Discontinous current mode :-

Boost converter.

$V_{on} = V_S$

$T_{on} = DT$

$V_{off} = V_S - V_0$

$T_{off} = (B-D)T$

Volt sec Balance :-

$V_{on} \cdot T_{on} + V_{off} \cdot T_{off} = 0$

$V_S DT + (V_S - V_0)(B-D)T = 0$

$V_S DT + V_S BT - V_S DT - V_0 BT + V_0 DT = 0$

$V_s \beta T - V_o \beta T + V_o D T = 0$

$V_s \beta T - V_o T(\beta - D) = 0$

$V_s \beta \cancel{T} = V_o \cancel{T}(\beta - D)$

$$V_o = \frac{V_s \beta}{\beta - D}$$

Problems :-

A Buck regulator has a supply voltage of 24 volts and a duty ratio of 0.375, the chopping frequency is 25 KHZ. The fiter consist of an inductance of 100 μH and a capacitance of 200 μF the average load current is 2 Ampe. Determine the peak to peak ripple current, upper and lower limits currents and pecak to peak ripple voltage.

Sol :-

Given data

$V_s = 24$ volts.

duty ratio (D) = 0.375

frequency = 25 KHZ

Assignent-4.

1. $V_s = 220V$

$F = 1KHZ$

$I_0 = 50A$

$R = 3\Omega$

$L = ?$

$\Delta I_L = ?$

$$\Delta I_L = \frac{V_0(1-D)}{FL}$$

$$L = \frac{R(1-D)}{2f} \Rightarrow 3(1-$$

1. Design a boost converter (or) Dc boost regulator with an output voltage of 15 V from a 6 V source. The load is pure resistance of 25 ohms. The peak to peak ripple is to be < 0.6%. The inductor current is to be continous. also find maximum and minimum value of the inductor current.

Sol:

$V_s = 6\,V$

$V_0 = 15V$

$R = 25\Omega$

$I_L + \frac{\Delta I_L}{2}$

Peak to peak capacitance.

$$C = \frac{I_0 D}{(\Delta V_0 F)} \Rightarrow \frac{0.6 \times 0.6}{150 \times \frac{0.6}{100} \times 30 \times 10^3}$$

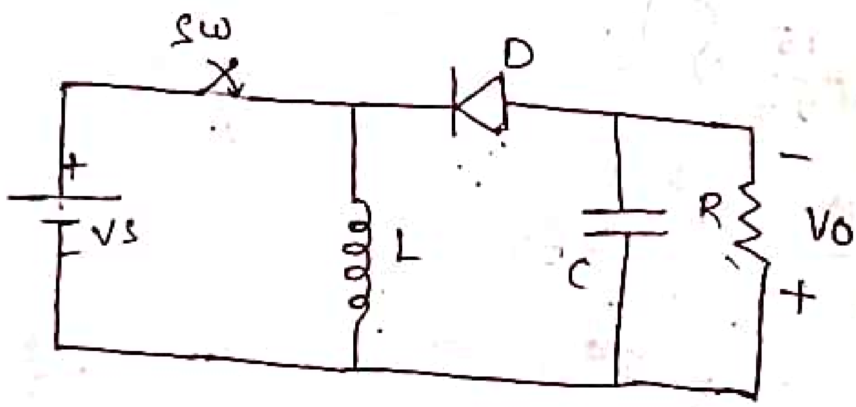
$$\Rightarrow \frac{0.36}{~~9000~~ 180 \times 15}$$

$$\Rightarrow ~~4 \times 10^{-5}~~ \Rightarrow 1.33 \times 10^{-4}$$

$$\Rightarrow 133.3$$

Buck-Boost Converter:

Stepdown and stepup / Indirect Regulator:



It operates 2 modes.

1. Switch on. $(0 < D < DT)$
2. Switch off $(DT < D < T)$

1. Switch on:

Voltage V_L

$V_L = V_S$

ΔI_L (current ripple):

$V_L on = V_s$

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

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

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

$I_{L_{max}} = I_L + \frac{\Delta I_L}{2}$

$I_{L min} = I_L - \frac{\Delta I_L}{2}$

switch current:

$I_{sw(avg)} = I_L$

$$\boxed{V_C = V_0}$$

$\frac{0D}{FC} = 0$

$\frac{D}{C} = 0$

$\frac{D}{\quad}$

Critical value of inductance:

$$I_L \min = 0$$

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

$$-\left(\frac{I_O}{(1-D)}\right) - \frac{V_S D}{2fL} = 0$$

$$-\left(\frac{\frac{V_O}{R}}{(1-D)}\right) - \frac{V_S D}{2fL} = 0$$

$$-\left(\frac{V_O}{R(1-D)}\right) - \frac{V_S D}{2fL} = 0$$

$$-\left(\frac{-V_S D}{2(1-D)^2}\right) = \frac{1}{2fL}$$

$$2fL = R(1-D)^2$$

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

Critical value of ~~inductan~~ capacitance:

$$V_C \min = 0 \qquad \boxed{V_C = V_O}$$

$$V_C - \frac{\Delta V_C}{2} = 0$$

~~$\frac{I_O}{C}(DT)$~~ $$V_O - \frac{I_O D}{2FC} = 0$$

$$V_O - \frac{V_O D}{2RFC} = 0$$

$$V_O = \frac{V_O D}{2RFC}$$

220 μF and the load resistance is 10-ohms.
Determine avg o/p voltage, average max and min value of Inductor current & peak to peak voltage Ripple?

Sol: Given that

$V_s = 24$, $D = 0.4$, $f = 40KHz$,

$L = 100\mu H$, $C = 220\mu f$, $R = 10\Omega$

(1) $V_{o_{avg}} = \frac{-V_s D}{(1-D)}$ $\quad 0 < D < 0.5$ BUCK.

$= \frac{-24(0.4)}{1-0.4} \Rightarrow \frac{9.6}{0.6} \Rightarrow -16$ volts.

(2) average max and min.

$V_{max} \Rightarrow \Delta V_C + \frac{V_C}{2}$

$I_{L max} = I_L + \frac{\Delta I_L}{2}$

$I_L = -\left(\frac{I_O}{1-D}\right) \Rightarrow -\left(\frac{V_O}{R(1-D)}\right) \Rightarrow -\left(\frac{-V_s D}{R(1-D)}\right)$

$\Rightarrow \left(\frac{24 \times 0.4}{10(0.6)}\right) \Rightarrow 2.66$

$\Delta I_L \Rightarrow \frac{V_s D}{FL} \Rightarrow \frac{24 \times 0.4}{40 \times 10^3 \times 100 \times 10^{-6}} \Rightarrow \frac{9.6}{4}$

$\Rightarrow 2.4\,A$

$I_{L max} = 2.66 + \frac{2.4}{2} \Rightarrow 3.86$

to peak ripple voltage?

Given that

$V_S = 24V$, $f = 30$, $D = 0.25$,

$L = 300\mu H$, $C = 150\mu F$, $I_0 = 1.5A$

verge o/p voltage

$$V_0 = -\frac{V_S D}{(1-D)} \Rightarrow -\left(\frac{24 \times 0.25}{1-0.25}\right) \Rightarrow -8$$

nductor current

$$\Delta I_L \Rightarrow \frac{D V_S}{f L} \Rightarrow \frac{0.25 \times 24}{30 \times 10^{3} \times 300 \times 10^{-6}}$$

$$\Rightarrow 0.66 \text{ Amps.}$$

eak to peak ripple ~~current~~ voltage.

$$\Delta V_C = \frac{I_0 D}{FC} \Rightarrow \frac{(1.5)(0.25)}{30 \times 10^{3} \times 150 \times 10^{-6}}$$

$$\Rightarrow \frac{0.375}{} \Rightarrow 0.083 \text{ V.}$$

$$L_c = \frac{R(1-D)^2}{2f} \Rightarrow \frac{V_0 (1-D)^2}{2 f I_0}$$

$$\Rightarrow \frac{-8(1-0.25)^2}{2 \times 30 \times 10^{3} \times 1.5} \Rightarrow 5 \times 10^{-5}$$

$$C = \frac{D}{2 f R} \Rightarrow \frac{0.25}{2 \times 30 \times 10^{3} \times \frac{V_0}{I_0}} \Rightarrow \frac{0.25}{60 \times 10^{3} \times 5.3}$$

$I_L min = I_L - \frac{\Delta I}{2}$

$\Rightarrow 2.66\cancel{7} - 1.2$

$\Rightarrow 1.46$ Amp.

(3)

Peak to peak ripple $\Delta V_C \Rightarrow \frac{I_O D}{FC}$

$$\Delta V_C \Rightarrow \frac{(0.4)(-1.6)}{40\times10^{3}\times220\times10^{-6}}$$

$$\Rightarrow \frac{-0.64}{8.8}$$

$$\Rightarrow 0.072$$

Percentage of voltage ripple

$$\Rightarrow \frac{\Delta V_o}{V_o}\times 100.$$

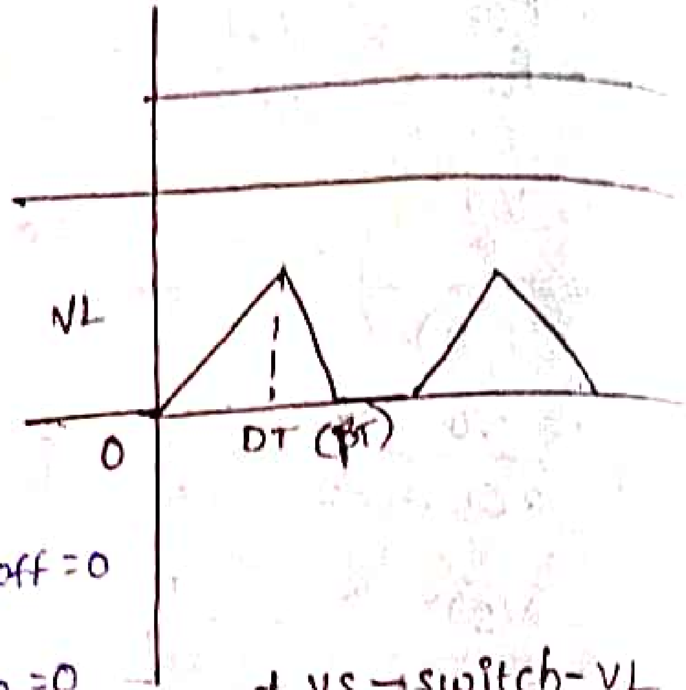
$$\Rightarrow \frac{0.072}{\cancel{0.96}\ 16}\times100 \Rightarrow 4.5$$

Assignment :-

BUCK BOOST converter has input 24 V and operates at 30 KHZ, when the duty cycle is .25, L = 300 μH, C = 150 μF, avg load current 1.5A. Determine the average peak to peak ...

$$C = \frac{D}{2FR}$$

discontinous current:



$V_L on = V_S$

$V_L off = V_o$

$T_{on} = DT$

$T_{off} = (\beta - D)T$

Volt sec Balance:

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

$V_S DT + (\beta - D)T \; V_o = 0$

+ VS - switch - VL

$V_S DT + V_o \beta T - V_o DT = 0$

VL = (... - 0 - VL)

$V_S DT + V_o T(\beta - D) = 0$

$V_S D\cancel{T} = -V_o \cancel{T}(\beta - D)$

$$V_o = -\frac{V_S D}{(\beta - D)}$$

1. Design a Buck Boost regulator with an input voltage of 25 volts and duty ratio of 0.4. the switching freeuency is 40 KHZ. The inductance value is 100 μH and capacitance value is

Ripple in voltage (ΔV_C) :-

ΔV_C :-

During on D→off

$I_C = -I_0$

$$C \frac{dV_C}{dt} = -I_0$$

$$\int dV_C = \int \frac{-I_0}{C} dt$$

$$\int_{Max}^{min} dV_C = \int_0^{DT} -\frac{I_0}{C} dt$$

$$V_{min} - V_{max} = -\frac{I_0}{C}(DT)$$

$$+\Delta V_C = \frac{+I_0}{C}(DT)$$

$$\boxed{\Delta V_C = \frac{I_0}{C}(DT)}$$

$$\Delta V_C = \frac{I_0 D}{FC}$$

$-I_L T(1-D) - I_0$

$-I_L f(1-D) = I$

$-I_L(1-D) =$

$$\boxed{I_0 = -I_L(1-D}$$

$I_L = -\left(\frac{I_0}{\right.}$

$$V_S DT + V_o(1-D)T = 0$$

$$V_S DT + V_o T - V_o DT = 0$$

$$V_S DT + V_o T(1-D) = 0$$

$$V_S D\cancel{T} = -V_o \cancel{T}(1-D)$$

$$V_S D = -V_o(1-D)$$

$$\boxed{V_o = \frac{-V_S D}{(1-D)}}$$

ampere sec balance theory:

$$I_c(on)\,DT + I_c\,off\,(1-D)T = 0$$

$$-I_o DT + -(I_L + I_o)(1-D)T = 0$$

$$-I_o DT - (I_L T - I_L DT + I_o T - I_o DT) = 0$$

$$-\cancel{I_o DT} - I_L T + I_L DT - I_o T + \cancel{I_o DT} = 0$$

$$-I_L T + I_L DT - I_o T = 0$$

$$-I_L T(1-D) - I_o T = 0$$

$$-I_L \cancel{T}(1-D) = I_o \cancel{T}$$

$$-I_L(1-D) = I_o$$

$$\boxed{I_o = -I_L(1-D)}$$

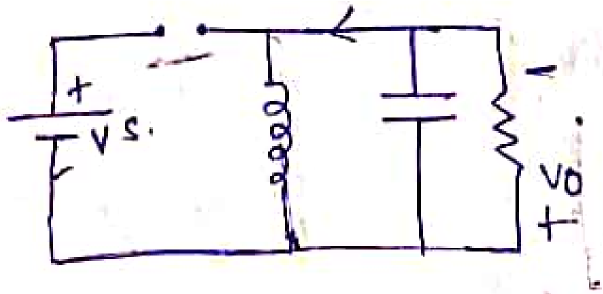
$$I_L = -\left(\frac{I_o}{1-D}\right)$$ → opposite to Boost converter.

$I_D = I_C + I_O$

$0 = I_C + I_O$

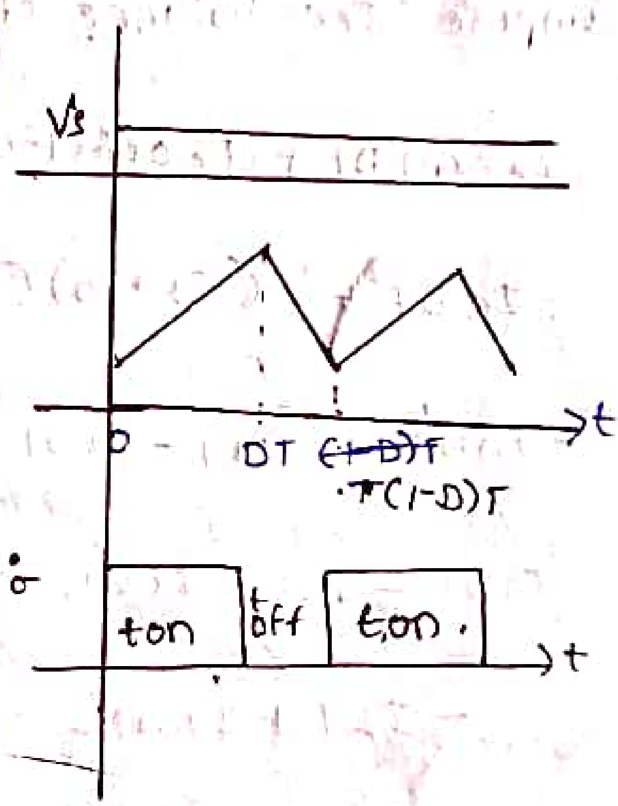
$\boxed{I_{C_{on}} = -I_O}$

Switch off:



$V_L off - V_O = 0$.

$\boxed{V_L(off) = V_O}$



$I_C off = -(I_L + I_O)$

Volt sec balance theory:

$V_{on}T_{on} + V_{off}T_{off} = 0$

~~$V_S DT + V_O(1-D)T = 0$~~

~~$V_S DT + V_O T - V_O DT = 0$~~

~~$V_S DT + V_O T($~~

~~$V_S DT = -V_O T$~~

~~$V_S D = -V_O$~~

~~$\boxed{V_O = -V_S D}$~~

$I_{max} = I_L + \frac{\Delta I_L}{2}$

$I_{min} = I_L - \frac{\Delta I_L}{2}$

$\Delta I_L = \frac{V_s D}{f L} \Rightarrow$

$D \Rightarrow$ ~~V_o~~

$V_o = \frac{V_s}{1-D} \Rightarrow$

$(1-D) = \frac{V_s}{V_o}$

$(1-D) \Rightarrow \frac{6}{15} \Rightarrow 0.4$

$D = 1 - 0.4$

$D = 0.6.$

$L = \frac{D(1-D)^2 R}{2F}$

chopping frequenc $F = 30KHZ$

$L = \frac{0.6 (1-0.6)^2 25}{2(30)}$

$\Rightarrow$ ~~0.16~~.

$\Rightarrow 40 \mu.H$

$I_o = \frac{V_o}{R} \Rightarrow \frac{15}{25} \Rightarrow 0.6.$

$\Delta I_L = \frac{V_s D.}{f L} \Rightarrow \frac{6 \times 0.6}{30 \times 60}$

$\Rightarrow$ ~~3×10^{6}~~ $2A$

$I_L = \frac{I_o}{(1-D)}$

$\Rightarrow \left(\frac{0.6}{1-0.6}\right)$

$\Rightarrow \frac{0.6}{0.4} \Rightarrow 1.5$

~~Imax =~~

select an inductance of $l = 60 \mu.H$

$I_{max} = 1.5 + \frac{2}{2}$

$\Rightarrow 1.5 + 1 \Rightarrow 2.5$

$= 2 + \frac{2.25}{2}$

$= 3.125$

I_L min $\Rightarrow I_L - \frac{\Delta I_L}{2}$

$\Rightarrow 2 - \frac{2.25}{2}$

$= 0.875$

determine the min value of inductance for which the current is continous.

$$L_{min} \text{ (or) } L_C = \frac{R(1-D)}{2fL}$$

$$\Rightarrow \frac{D(1-D)V_s}{2fL}$$

$$\Rightarrow \frac{5.625}{2 \times 25 \times 10^3 \times 100 \times 10^{-6}}$$

$\Rightarrow$

Note :-

the relation b/w ΔI_L and I_C in buck converter $L_C = \frac{\Delta I_L}{2}$

Inductance = 100 µH

capacitance = 200 µf

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

$$\Rightarrow \frac{0.375(1-0.375)24}{10^3 \times 25 \times 100}$$

$\Rightarrow$ 2.25 Amperes.

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

$$= \frac{0.375(1-0.375)24}{8 \times (25)^2 (100)(200)}$$

$$\Rightarrow \frac{5.625}{8 \times (25 \times 10^3)^2 (100)(200)}$$

$$= \frac{5.625}{1000}$$

= 0.05625 volts

$$I_L max = I_L + \frac{\Delta I_L}{2}$$

$$\Rightarrow I_0 + \frac{\Delta I_L}{2}$$

$$\int_{Max}^{Min} dv = \int_0 -\frac{I_O}{C}\, dt$$

$$V_{min} - V_{max} = -\frac{I_O}{C}[DT - 0]$$

$$-\Delta V_C = -\frac{I_O}{C}[DT]$$

$\therefore V_{max} - V_{min} = \Delta V_C$

$$\boxed{\Delta V_C = \frac{I_O D}{fC}}$$

Buck :-

ΔV_C :-

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

Critical value of inductance :-

$I_L\, min = 0$

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

$$\frac{I_O}{(1-D)} - \frac{V_S D}{2fL} = 0$$

$$\Rightarrow \frac{I_O}{(1-D)} - \frac{V_O}{}$$

$$\Rightarrow \frac{\frac{V_O}{R}}{(1-D)} - \frac{V_S D}{2fL} = 0$$

$$\Rightarrow \frac{\frac{V_S}{R(1-D)}}{(1-D)} - \frac{V_S D}{2fL} = 0$$

$$\frac{V_S}{R(1-D)^2} - \frac{V_S D}{2fL} = 0$$

$$\frac{V_S}{R(1-D)^2} = \frac{V_S D}{2fL}$$

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

Critical value of capacitance :-

$$T_{off} = (1-D)T$$

$$I_D = I_C + I_O$$

$$I_C = I_D - I_O$$

$$\boxed{I_D = I_L}$$

$$\boxed{I_{C_{off}} = I_L - I_O}$$

Volt sec Balance :-

$$T_{on} + T_{off} = 0$$

$$V_S DT + (1-D)T(V_S - V_O) = 0$$

$$V_S DT + V_S T - V_O T - V_S DT + V_O DT = 0$$

$$V_S T - V_O T + V_O DT = 0$$

$$V_S T - V_O T(1-D) = 0$$

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

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

$$\boxed{V_{O\,(avg)} = \frac{V_S}{(1-D)}}$$

✓

se sec balance :-

$$I_{C(on)} DT + I_{C\,off} (1-D)T = 0$$

$$-I_O DT + (I_L - I_O)(1-D)T = 0$$

UP I

* ampere sec Balance :

$I_c(on) = I_1 - I_0$

$I_c(off) = I_1 - I_0$

~~$(I_1 - I_0) T_{on} +$~~

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

$(I_L - I_0) T_{on} + (I_1 - I_0) T_{off} = 0$

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

$I_L DT - I_0 DT + I_L T - I_0 DT - I_0 T + I_0 DT = 0$

$I_L T - I_0 T = 0$

$I_L T = I_0 T$

$$\boxed{I_L = I_0}$$

* ripple current ΔI_L :

$$V_L = L \frac{di}{dt}$$

$V_L(on) = V_s - V_0$

$$L \frac{di_{on}}{dt_{on}} = V_s - V_0$$

$t_{on} = DT$

$$L \frac{\Delta I_L}{DT} = V_s - V_0$$

$$\Delta I_L = \frac{(V_s - V_0) D}{fL}$$

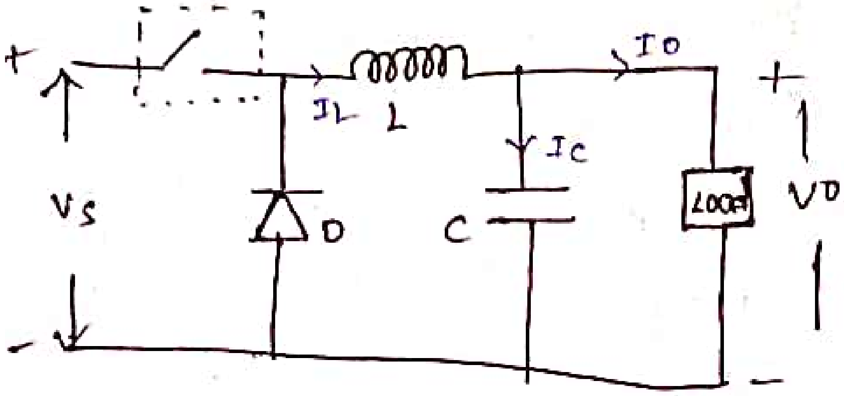
$$= \frac{(V_s - V_s D) D}{fL}$$

4. The circuit is operating at steady state.

$$\text{Duty cycle "D"} = \frac{T_{on}}{T} = \frac{T_{on}}{T_{on} + T_{off}}$$

5. $T_{on} = DT$, and switch $T_{off} = (1-D)T$

Analysis of Buck Converter:



continous current mode:

it operates in 2 modes.

1. switch on 2. switch off condition.

During switch on condition:

$V_s^+ - L - \text{load} - V_s^-$

$T_{on} = DT$

CT = (chopping time period)/switching period

f = chopping frequency.

$V_L(on) = V_s - V_0$

$I_c(on) = I_L - I_0$

Unit - 5

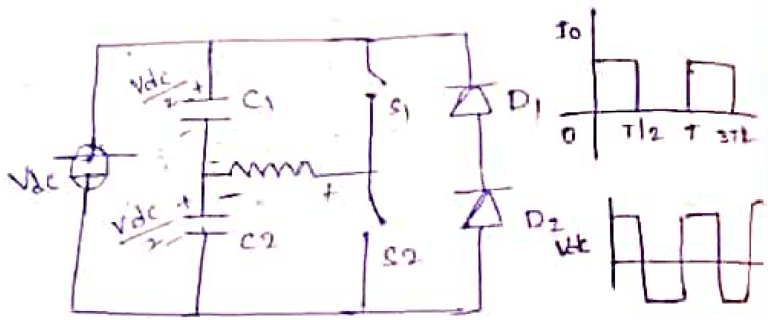
DC - AC Converters

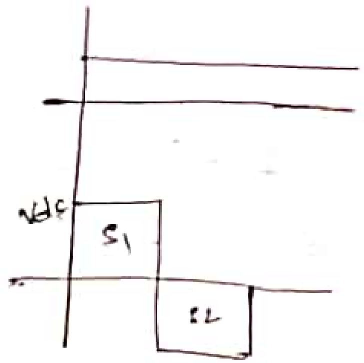
Classification : 1-ϕ → H.B, F.B → R, RL (Home appliances, Electrical vehicles)

3-ϕ → 120°, 180° (variable frequency drives, AC drives)

- Applications : UPS, HVDC, FACTS, induction heating, ...

Single Phase Half bridge inverter with R-load :





Rms o/p voltage :-

$$V_{or} = \sqrt{\frac{1}{T_1}\int_0^{T_1}\left(\frac{V_{dc}}{2}\right)^2 dt}$$

$$V_{or} = \sqrt{\frac{1}{T_1}[T_1]\left(\frac{V_{dc}}{2}\right)^2}$$

$$V_r = \frac{V_{dc}}{2}$$

V_o can be expressed in fourier series as

$$V_o = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos n\omega t + b_n \sin n\omega t$$

Due to quarter wave symmetry along time

axis, the value of a_0 and a_n is zero. the value of b_n is

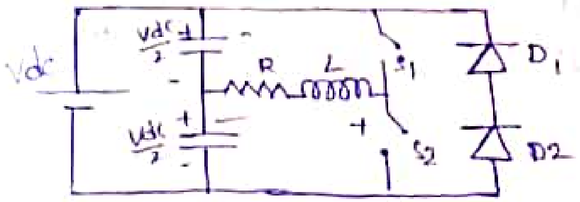
$$b_n = \frac{1}{\pi}\int_{-\pi/2}^{0} \frac{-V_{in}}{2}\, d(\omega t) + \int_{0}^{\pi/2} d(\omega t) = \frac{2V_m}{n\pi} \Rightarrow \frac{2V_{dc}}{n\pi}$$

$$V_0 = \sum_{n=1,3,5}^{\infty} \frac{2V_{dc}}{n\pi} \sin(n\omega t)$$

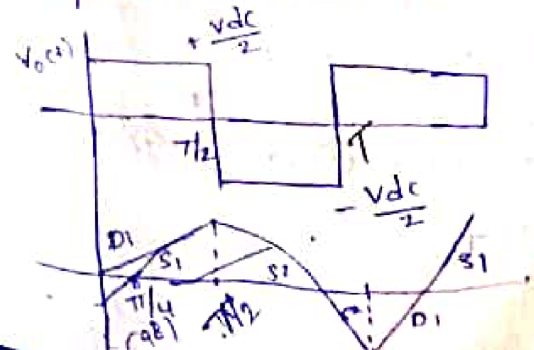
similarly current through the resistor.

$$i_L = \sum_{n=1,2,3\ldots}^{\infty} \frac{1}{R} \frac{2V_{dc}}{2\pi} \sin(n\omega t)$$

Single phase half bridge with R-L load:



It operates in 4 modes (4 intervals)



Voltage control of inverters : (PWR)

Two types of "

1. External control

2. internal control

width of the longest Pulse :

$$\left(1 - \frac{V_r}{V_C}\right) \pi/N$$

Sinusodial pulse width modulation.

① No of pulses $N_P = \frac{f_C}{2f_R}$ for half cycle.

② $N_{P-1} \Rightarrow \frac{f_C}{2f_{P-1}}$ when the peak voltages → call ... the reference wave { Both of

③ The Harmonic number of the highest amplitude is equal to

$$\frac{f_C}{f_R} \pm 1 = 2MP$$

Problem :

A 50 HZ, PWM inverters employ sinusodial pulse width modulation based on sine triangle comparison. If the triangular frequency is 15 KHZ, what will be no. of pulses for half period in the o/p waveform and 80% modulation index. what will be the width of the longest pulse.

Sol : $MI = 80\% \Rightarrow 0.8 \left(\frac{V_R}{V_C}\right)$

$f_C = 15 KHZ$

$f_R = 50\,Hz$

① No of pulses per half cycle

$$\Rightarrow \frac{F_c}{2F_R} \Rightarrow \frac{15 \times 10^3}{2 \times 50} = 150$$

② $\Rightarrow \left(1 - \frac{V_r}{V_c}\right)\frac{\pi}{N}$

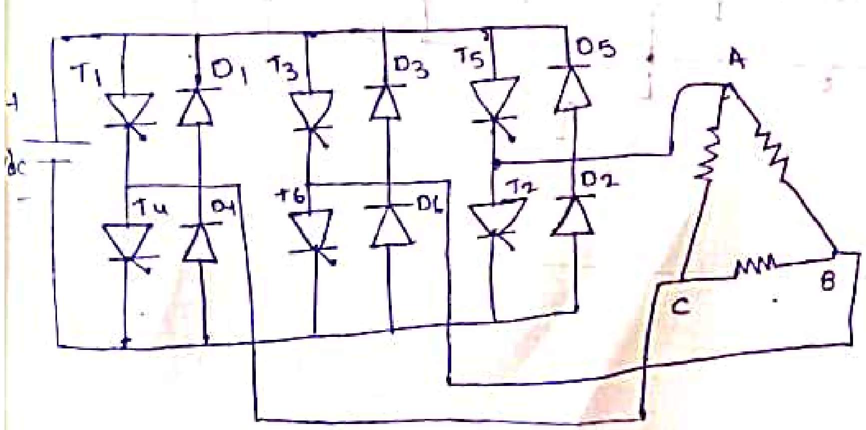
$$\Rightarrow \left(1 - 0.8\right)\frac{\pi}{150} \Rightarrow 4.18\ M.s$$

Note:-

o/p voltage of 1-ϕ PWM inverter

$$V_o(t) = \sum_{n=1,3,5}^{\infty} \frac{V_s}{n\pi} \sin n d \sin n\omega t$$

1. Explain the working of a 3-ϕ inverter with 120° mode of conduction with 3-ϕ delta connected resistive load?



A is connected +ve, B is -ve.

Mode -2.

$T < t < t_2$

firing pulses are given to T_3 & T_4

B is +ve, A is -ve.

Mode - 3

$t_2 < t < 3T/2$

T_3 & T_4 are on.

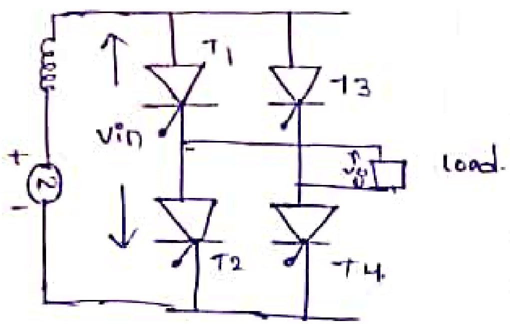
Mode - 4

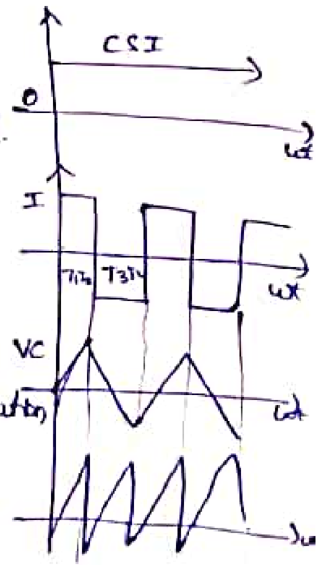
$\frac{3T}{2} < t < 2T$ $(0 < t < t_1)$

T_3 & T_4 off

2. Current Source inverter ?

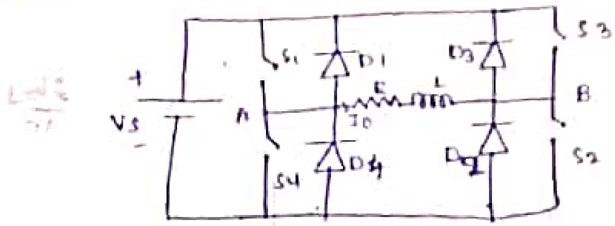
A)

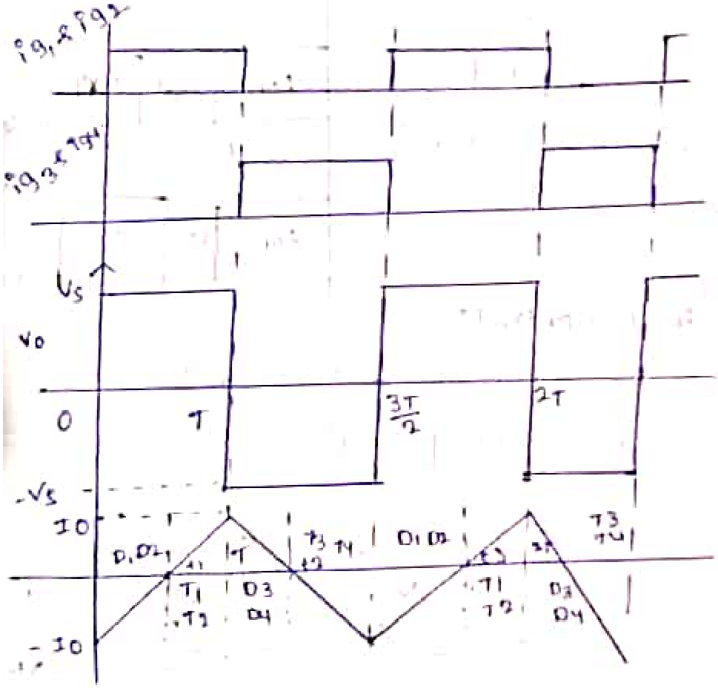




To maintain constant current Inductance will be used load commutation depends upon the load.

1. Draw a neat ckt diagram for 1-ϕ full bridge inverter feeding inductive load. what is the function of feedback diode?





4- Modes.

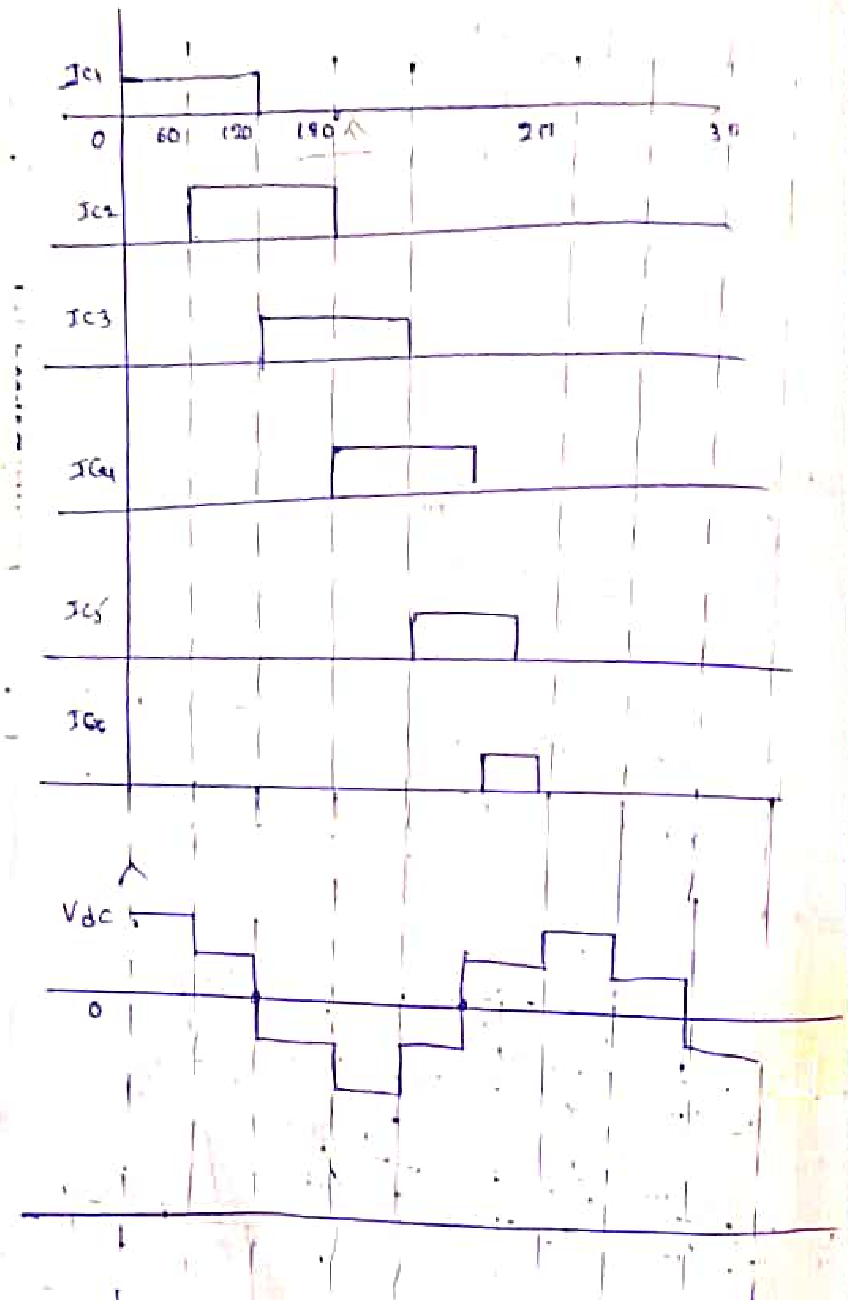
Mode 1 :

$t_1 < t < T$

thyristor T_1 and T_2 are on condition.

current passing through the supply to S_1 to load to S_2

- Ve supply positive current increase wave



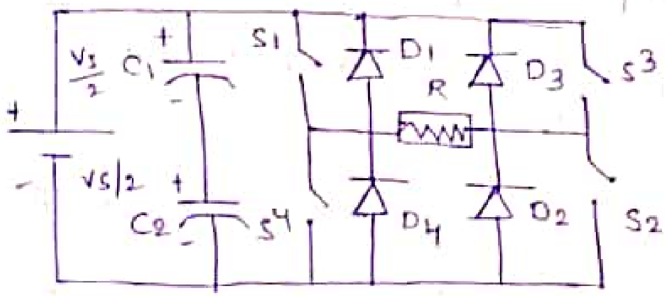
IG1
0
60
120
180
2π
3π
IG2
IG3
IG4
IG5
IG6
Vdc
0

Each thyristor T/4.

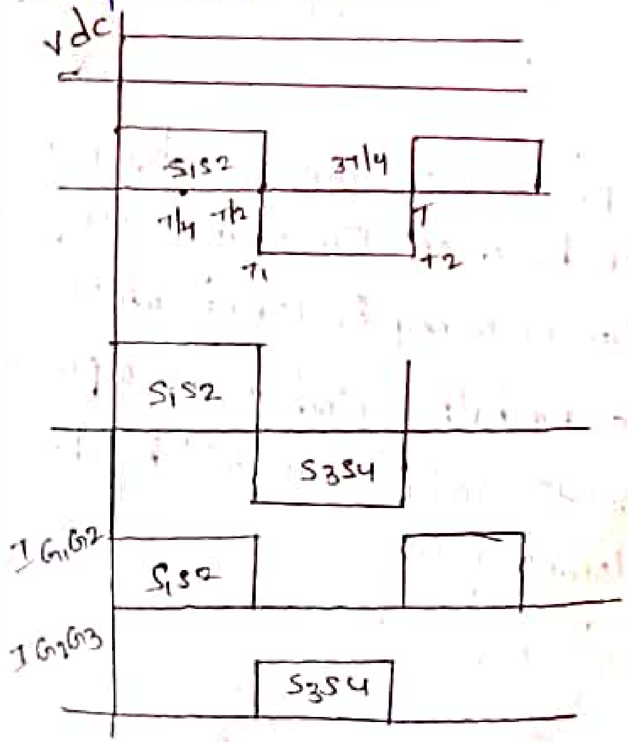
$V_o rms = \frac{Vs}{2}$

$I_o rms = \frac{Vs}{2R}$

single phase full bridge inverter with R load:



It operates in 2 modes



1) S_1 close

$$-\frac{V_{dc}}{2} + V_0 = 0 \quad \Big| \quad V_0 > 0, \; I_0 > 0$$

$$V_0 = \frac{V_{dc}}{2}$$

2) Diode close (D_1)

$$-\frac{V_{dc}}{2} + V_0 = 0 \quad \Big| \quad I_0 < 0, \; V_0 > 0$$

3) S_2 close

$$V_0 = \frac{-V_{dc}}{2} \quad \Big| \quad I_0 < 0, \; V_0 < 0$$

4) D_2 - on

$$-\frac{V_{dc}}{2} - V_0 = 0 \quad \Big| \quad I_0 > 0, \; V_0 < 0$$

Note:- If an inverter is loading a pure inductive load the nature of current is Δ^{lr} wave.

Peak value of current $(I_{peak}) = \frac{V_S}{L}(T/4)$

Peak to peak value of current $= \frac{V_S}{L}(T/2)$

conduction angle of each diode is 90° i.e, conduction time is $T/4$

Lecture 15: Three Phase DC-AC Inverters

Three Phase DC-AC Inverters

Introduction

The topics covered in this chapter are as follows:

- Three phase DC-AC Converters
- 180-Degree Conduction with Star Connected Resistive Load
- 180-Degree Conduction with Star Connected *R-L* Load

Three Phase DC-AC Converters

Three phase inverters are normally used for high power applications. The advantages of a three phase inverter are:

- The frequency of the output voltage waveform depends on the switching rate of the switches and hence can be varied over a wide range.
- The direction of rotation of the motor can be reversed by changing the output phase sequence of the inverter.
- The ac output voltage can be controlled by varying the dc link voltage.

The general configuration of a three phase DC-AC inverter is shown in **Figure 1**. Two types of control signals can be applied to the switches:

- 180^o conduction
- 120^o conduction

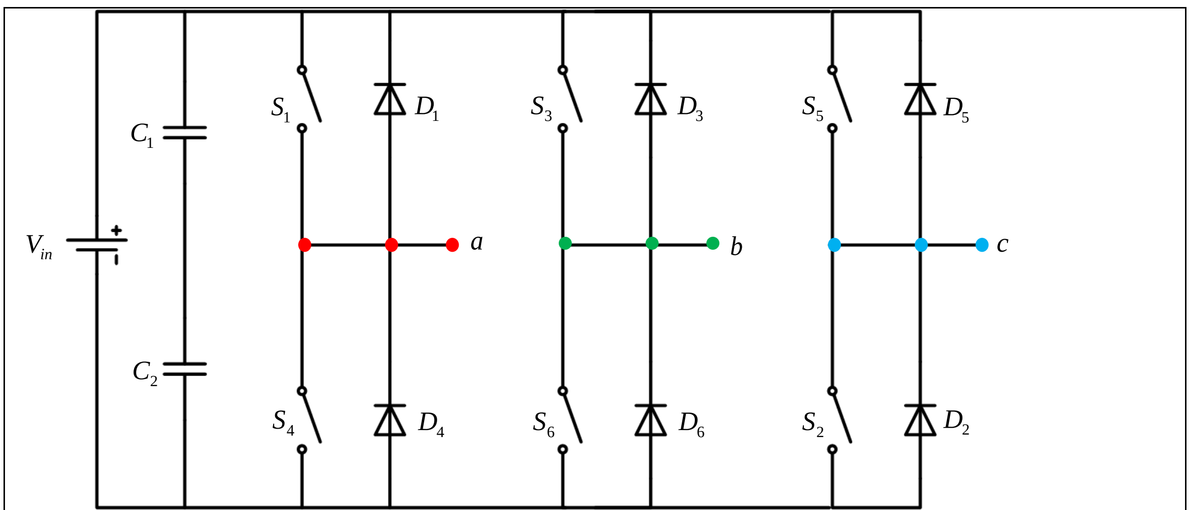


Figure 1: Configuration of a Three-Phase DC-AC Inverter

180-Degree Conduction with Star Connected Resistive Load

The configuration of the three phase inverter with star connected resistive load is shown in **Figure** 2. The following convention is followed:

- A current leaving a node point ***a***, ***b*** or ***c*** and entering the neutral point ***n*** is assumed to be positive.
- All the three resistances are equal, $R_a = R_b = R_c = R$.

In this mode of operation each switch conducts for 180^o. Hence, at any instant of time ***three switches*** remain ***on***. When S_1 is ***on***, the terminal ***a*** gets connected to the positive terminal of input DC source. Similarly, when S_4 is ***on***, terminal ***a*** gets connected to the negative terminal of input DC source. There are six possible modes of operation in a cycle and each mode is of 60^o duration and the explanation of each mode is as follows:

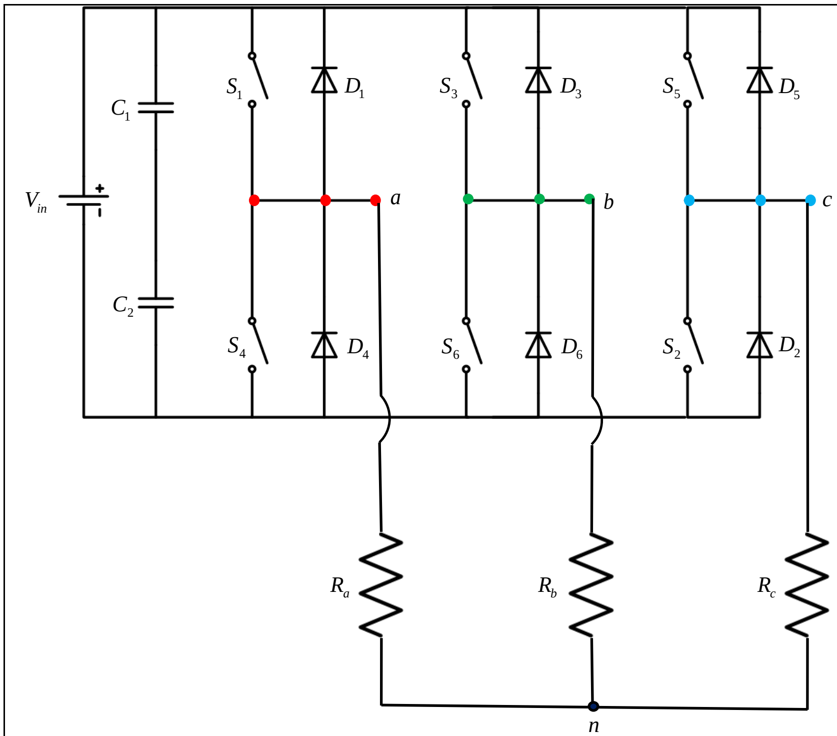


Figure 2: Three-Phase DC-AC Inverter with star connect resistive load

Mode 1*:** In this mode the switches S_5, S_6 and S_1 are turned ***on for time interval $0 \le \omega t \le \frac{\pi}{3}$. As a result of this the terminals ***a*** and ***c*** are connected to the positive terminal of the input DC source and the terminal ***b*** is connected to the negative terminal of the DC source. The current flow through R_a, R_b and R_c is shown in **Figure 3a** and the equivalent circuit is shown in **Figure 3b**. The equivalent resistance of the circuit shown in **Figure 3b** is

$$R_{eq} = R + \frac{R}{2} = \frac{3R}{2} \tag{1}$$

The current i delivered by the DC input source is

$$i = \frac{V_{in}}{R_{eq}} = \frac{2}{3}\frac{V_{in}}{R} \tag{2}$$

The currents i_a and i_b are

$$i_a = i_c = \frac{1}{3}\frac{V_{in}}{R} \tag{3}$$

Keeping the current convention in mind, the current i_b is

$$i_b = -i = -\frac{2}{3}\frac{V_{in}}{R} \tag{4}$$

Having determined the currents through each branch, the voltage across each branch is

$$v_{an} = v_{cn} = i_a R = \frac{V_{in}}{3};\ v_{bn} = i_b R = -\frac{2V_{in}}{3} \tag{5}$$

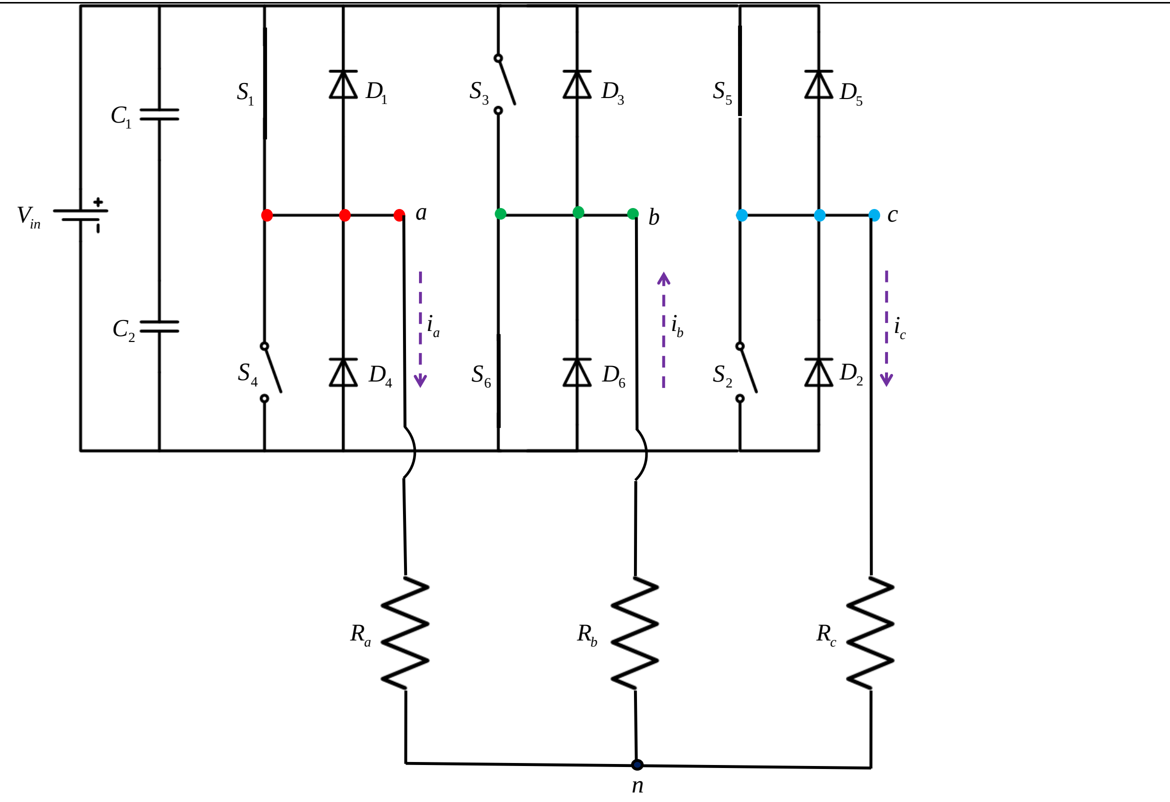


Figure 3a: Current through the load in *Mode 1*

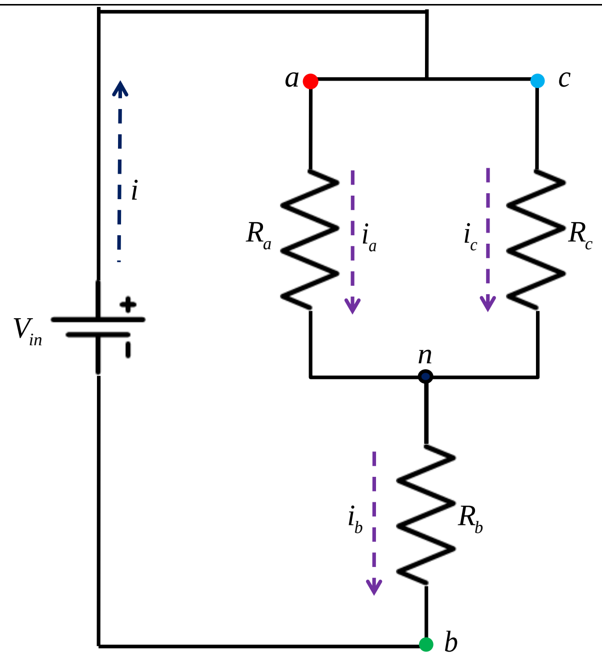


Figure 3b: Equivalent circuit in *Mode 1*

Mode 2*:** In this mode the switches S_6, S_1 and S_2 are turned ***on for time interval $\frac{\pi}{3} \le \omega t \le \frac{2\pi}{3}$.

The current flow and the equivalent circuits are shown in **Figure 4a** and **Figure 4b** respectively. Following the reasoning given for ***mode 1***, the currents through each branch and the voltage drops are given by

$$i_b = i_c = \frac{1}{3}\frac{V_{in}}{R};\ i_a = -\frac{2}{3}\frac{V_{in}}{R} \tag{6}$$

$$v_{bn} = v_{cn} = \frac{V_{in}}{3};\ v_{an} = -\frac{2V_{in}}{3} \tag{7}$$

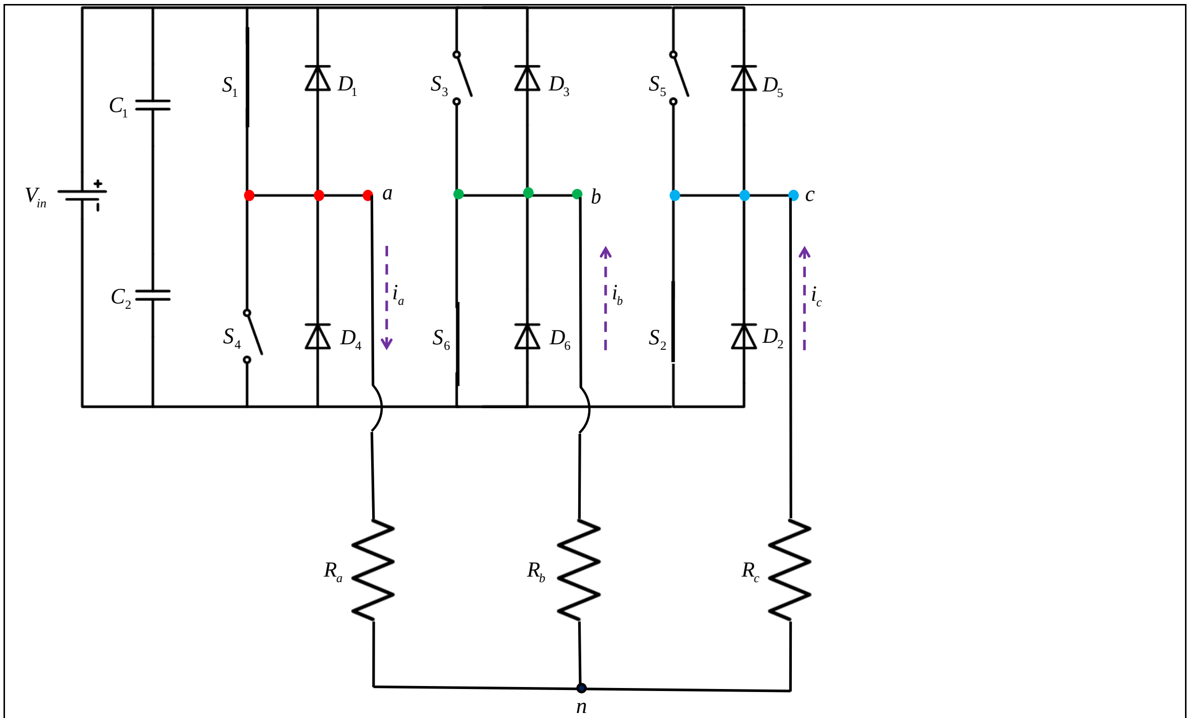


Figure 4a: Current through the load in *Mode 2*

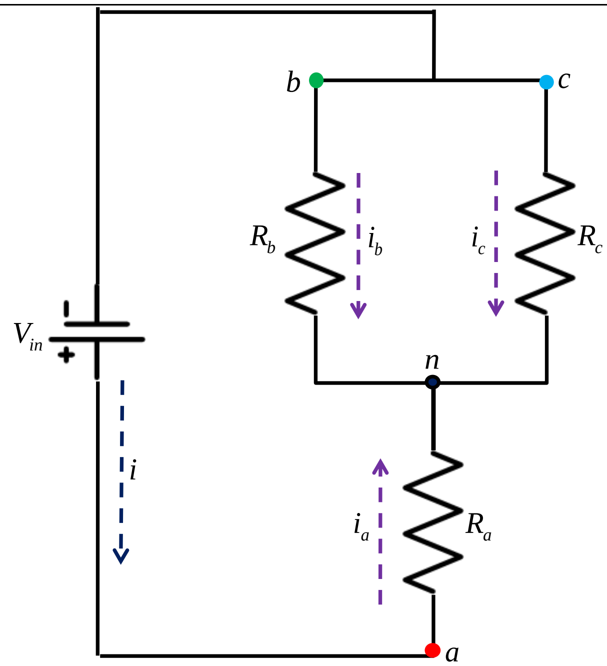


Figure 4b: Equivalent circuit in *Mode 2*

Mode 3*:** In this mode the switches S_1, S_2 and S_3 are ***on for $\frac{2\pi}{3} \le \omega t \le \pi$. The current flow and the equivalent circuits are shown in **Figure 5a** and **figure 5b** respectively. The magnitudes of currents and voltages are:

$$i_a = i_b = \frac{1}{3}\frac{V_{in}}{R};\ i_c = -\frac{2}{3}\frac{V_{in}}{R} \tag{8}$$

$$v_{an} = v_{bn} = \frac{V_{in}}{3};\ v_{cn} = -\frac{2V_{in}}{3} \tag{9}$$

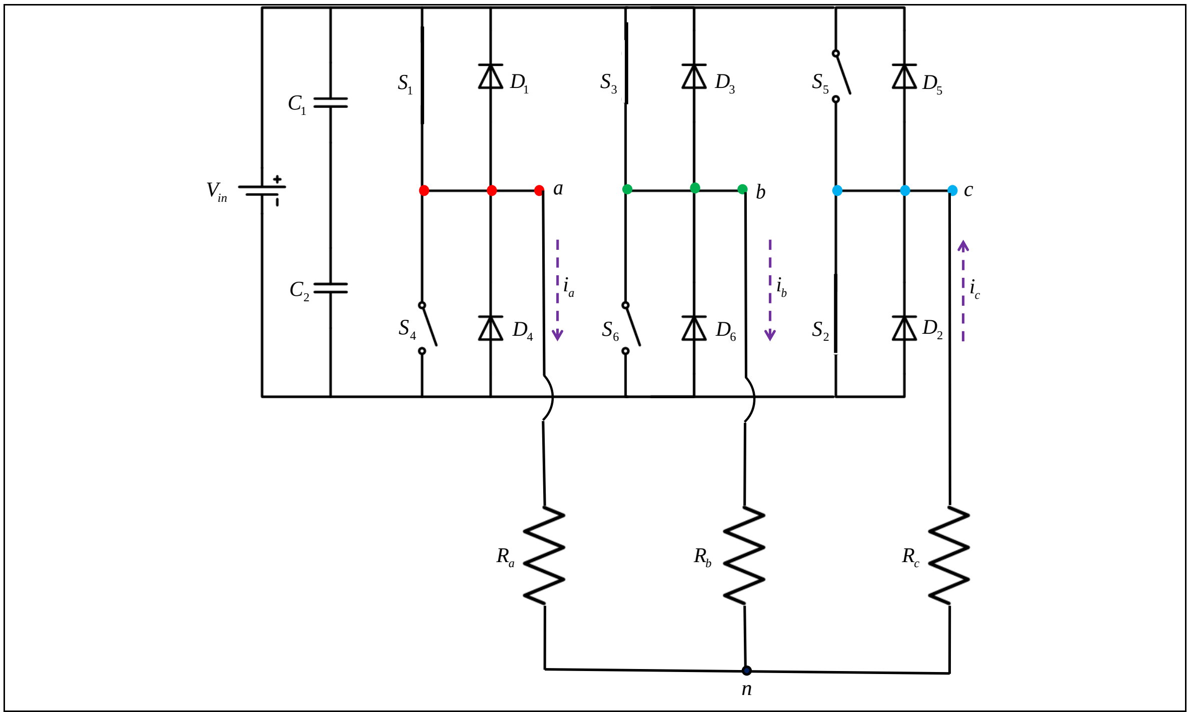


Figure 5a: Current through the load in *Mode 32*

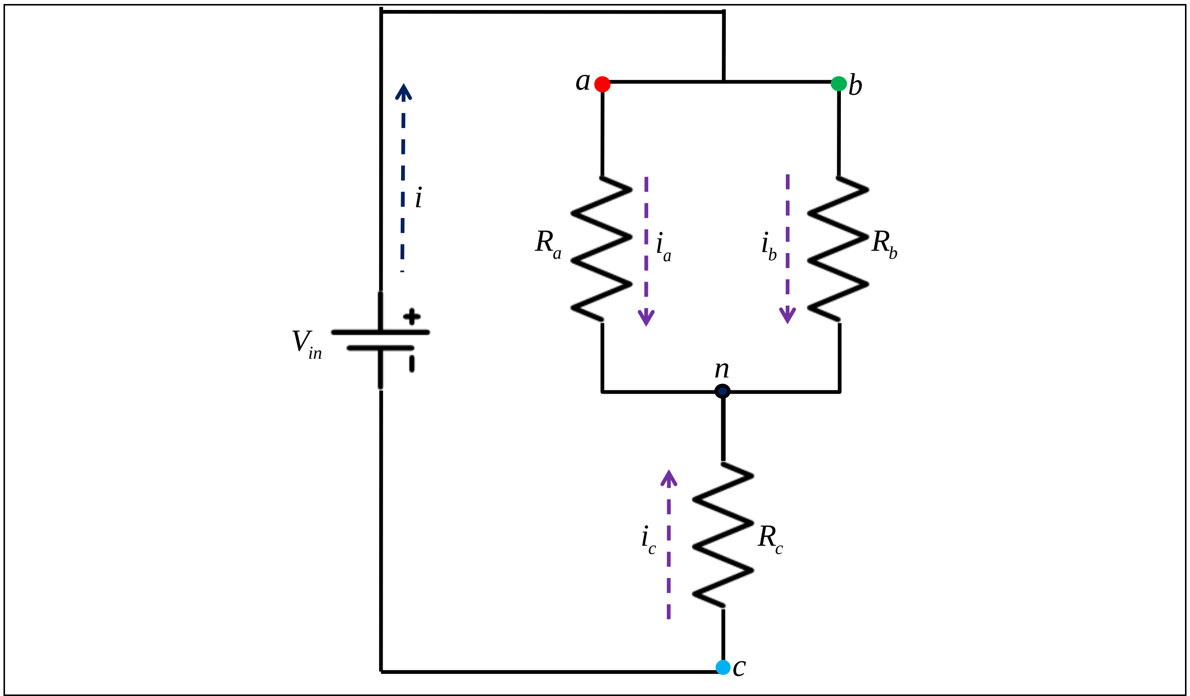


Figure 5b: Equivalent circuit in *Mode 3*

For ***modes 4, 5*** and ***6*** the equivalent circuits will be same as ***modes 1, 2*** and ***3*** respectively. The voltages and currents for each mode are:

$$\left.\begin{aligned} i_a = i_c = -\frac{1}{3}\frac{V_{in}}{R};\ i_b = \frac{2}{3}\frac{V_{in}}{R} \\ v_{an} = v_{cn} = -\frac{V_{in}}{3}; V_{bn} = \frac{2V_{in}}{3} \end{aligned}\right\} \text{ for } \textbf{\textit{mode 4}} \tag{10}$$

$$\left.\begin{aligned} i_b = i_c = -\frac{1}{3}\frac{V_{in}}{R};\ i_a = \frac{2}{3}\frac{V_{in}}{R} \\ v_{bn} = v_{cn} = -\frac{V_{in}}{3}; V_{an} = \frac{2V_{in}}{3} \end{aligned}\right\} \text{ for } \textbf{\textit{mode5}} \tag{11}$$

$$\left.\begin{aligned} i_a = i_b = -\frac{1}{3}\frac{V_{in}}{R};\ i_c = \frac{2}{3}\frac{V_{in}}{R} \\ v_{an} = v_{bn} = -\frac{V_{in}}{3}; V_{cn} = \frac{2V_{in}}{3} \end{aligned}\right\} \text{ for } \textbf{\textit{mode 6}} \tag{12}$$

The plots of the phase voltages (v_{an}, v_{bn} and v_{cn}) and the currents (i_a, i_b and i_c) are shown in **Figure 6**. Having known the phase voltages, the line voltages can also be determined as:

$$\begin{aligned} v_{ab} &= v_{an} - v_{bn} \\ v_{bc} &= v_{bn} - v_{cn} \\ v_{ca} &= v_{cn} - v_{an} \end{aligned} \tag{13}$$

The plots of line voltages are also shown in **Figure 6** and the phase and line voltages can be expressed in terms of Fourier series as:

$$\begin{aligned} v_{an} &= \sum_{n=1,3,5,\dots}^{\infty} \frac{4V_{in}}{3n\pi}\left[1+\sin\frac{n\pi}{2}\sin\frac{n\pi}{6}\right]\sin\left(n\omega t\right) \\ v_{bn} &= \sum_{n=1,3,5,\dots}^{\infty} \frac{4V_{in}}{3n\pi}\left[1+\sin\frac{n\pi}{2}\sin\frac{n\pi}{6}\right]\sin\left(n\omega t - \frac{2n\pi}{3}\right) \\ v_{cn} &= \sum_{n=1,3,5,\dots}^{\infty} \frac{4V_{in}}{3n\pi}\left[1+\sin\frac{n\pi}{2}\sin\frac{n\pi}{6}\right]\sin\left(n\omega t - \frac{4n\pi}{3}\right) \end{aligned} \tag{14}$$

$$\begin{aligned} v_{ab} = v_{an} - v_{bn} &= \sum_{n=1,3,5,\dots}^{\infty} \frac{4V_{in}}{n\pi}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}\sin\left(n\omega t + \frac{n\pi}{6}\right) \\ v_{bc} = v_{bn} - v_{cn} &= \sum_{n=1,3,5,\dots}^{\infty} \frac{4V_{in}}{n\pi}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}\sin\left(n\omega t - \frac{n\pi}{2}\right) \\ v_{ca} = v_{cn} - v_{an} &= \sum_{n=1,3,5,\dots}^{\infty} \frac{4V_{in}}{n\pi}\sin\frac{n\pi}{2}\sin\frac{n\pi}{3}\sin\left(n\omega t - \frac{7n\pi}{6}\right) \end{aligned} \tag{15}$$

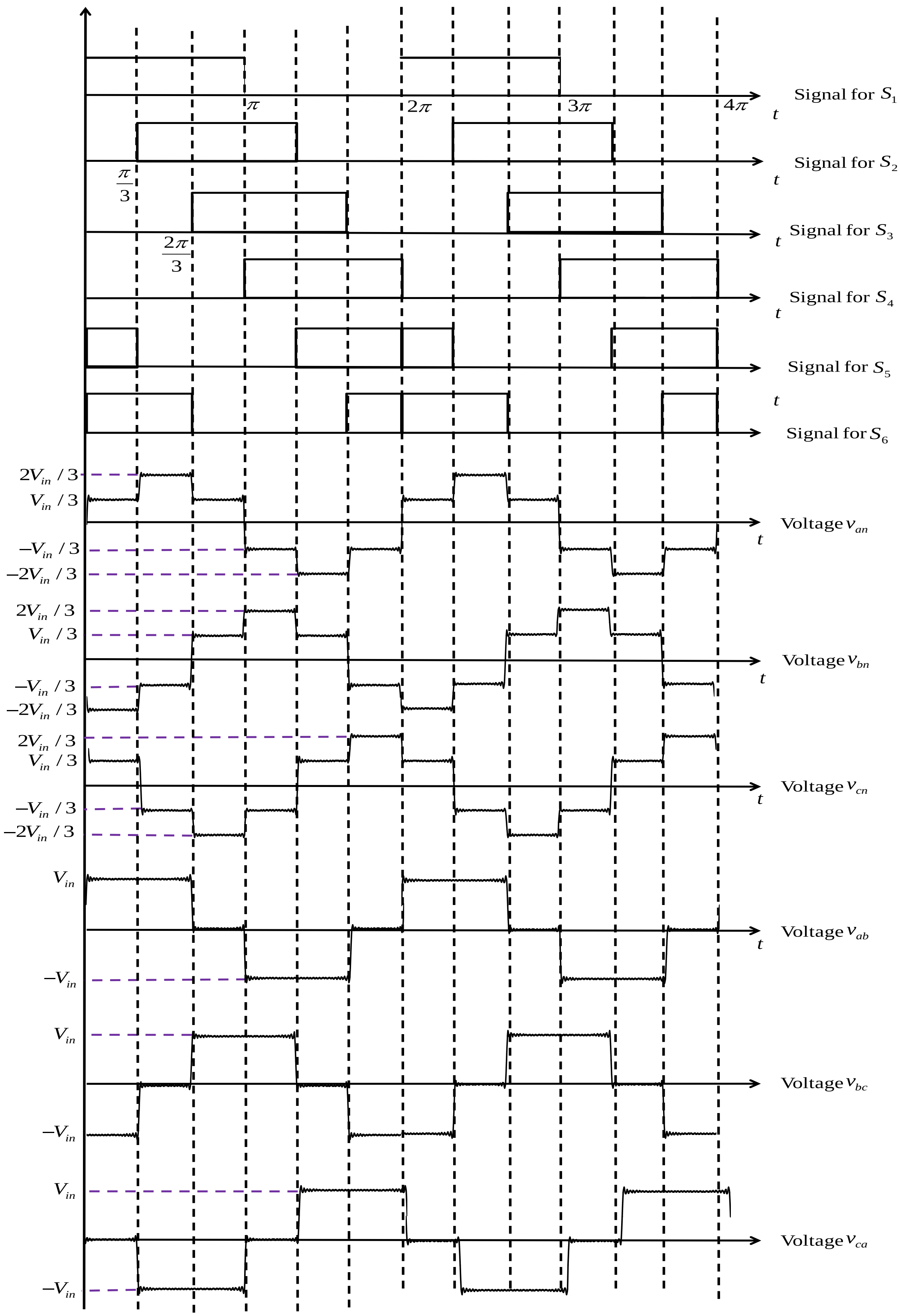


Figure 6: Voltage waveforms for Resistive load for 180°

180-Degree Conduction with Star Connected *R-L* Load

In ***mode 1*** the switches S_5, S_6 and S_1 are turned ***on***. The mode previous to ***mode1*** was ***mode 6*** and the in ***mode 6*** the switches S_4, S_5 and S_6 were ***on***. In the transition from ***mode 6*** to ***mode 1*** the switch S_4 is turned ***off*** and S_1 turned ***on*** and the current i_a changes its direction (***outgoing phase***). When the switch S_4 was ***on***, the direction of current was from point ***n*** to point ***a***, the circuit configuration is shown in **Figure 7a** and the equivalent circuit is shown in **Figure 7b**. When S_1 is turned ***on*** the direction of current should be from point ***a*** to point ***n***. However, due to the presence of inductance, the current cannot change its direction instantaneously and continues to flow in the previous direction through diode D_1 (**Figure 7c**) and the equivalent circuit of the configuration is shown in **Figure 7d**. Once $i_a = 0$, the diode D_1 ceases to conduct and the current starts flowing through S_1 as shown already in **Figure 3a** and **Figure 3b**. When ever one mode gets over and the next mode starts, the current of the outgoing phase cannot change its direction immediately due to presence of the inductance and hence completes its path through the freewheeling diode.

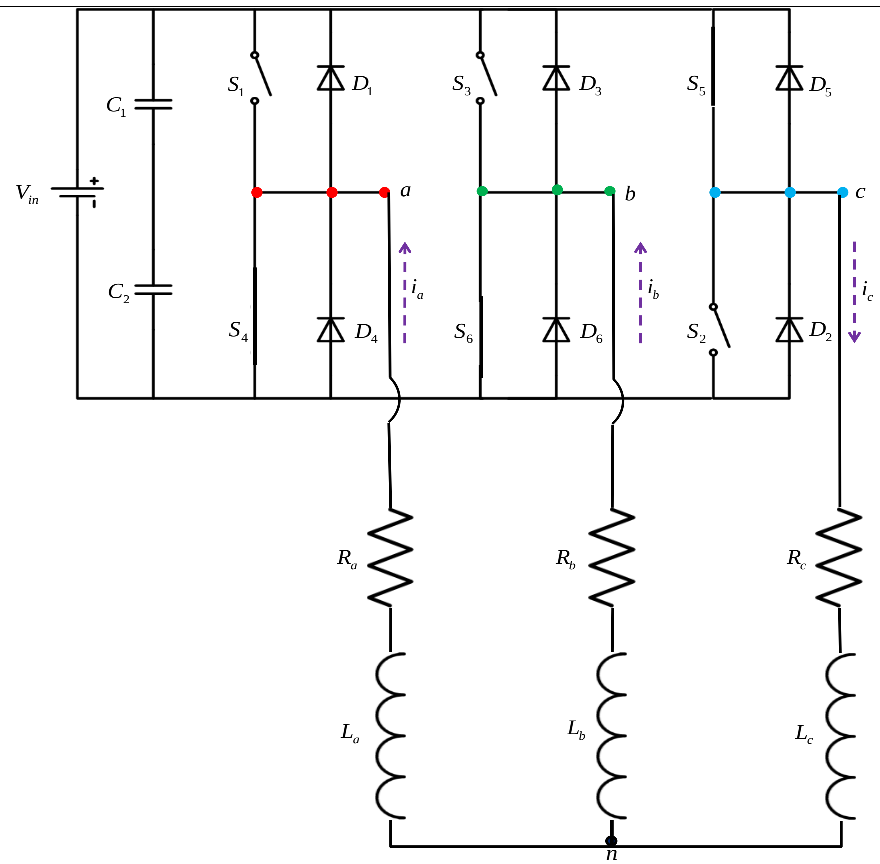


Figure 7a: Current through the load in *Mode 6*

The phase currents are determined as follows:

$$i_a = \sum_{n=1,3,5,...}^{\infty} \frac{1}{\sqrt{R^2 + (n\omega L)^2}} \frac{4V_{in}}{3n\pi}\left[1+\sin\frac{n\pi}{2}\sin\frac{n\pi}{6}\right]\sin\left(n\omega t - \theta_n\right)$$

$$i_b = \sum_{n=1,3,5,...}^{\infty} \frac{1}{\sqrt{R^2 + (n\omega L)^2}} \frac{4V_{in}}{3n\pi}\left[1+\sin\frac{n\pi}{2}\sin\frac{n\pi}{6}\right]\sin\left(n\omega t - \frac{2n\pi}{3} - \theta_n\right)$$

$$i_c = \sum_{n=1,3,5,...}^{\infty} \frac{1}{\sqrt{R^2 + (n\omega L)^2}} \frac{4V_{in}}{3n\pi}\left[1+\sin\frac{n\pi}{2}\sin\frac{n\pi}{6}\right]\sin\left(n\omega t - \frac{4n\pi}{3} - \theta_n\right) \quad (16)$$

where

$$\theta_n = \tan^{-1}\left(\frac{n\omega L}{R}\right)$$

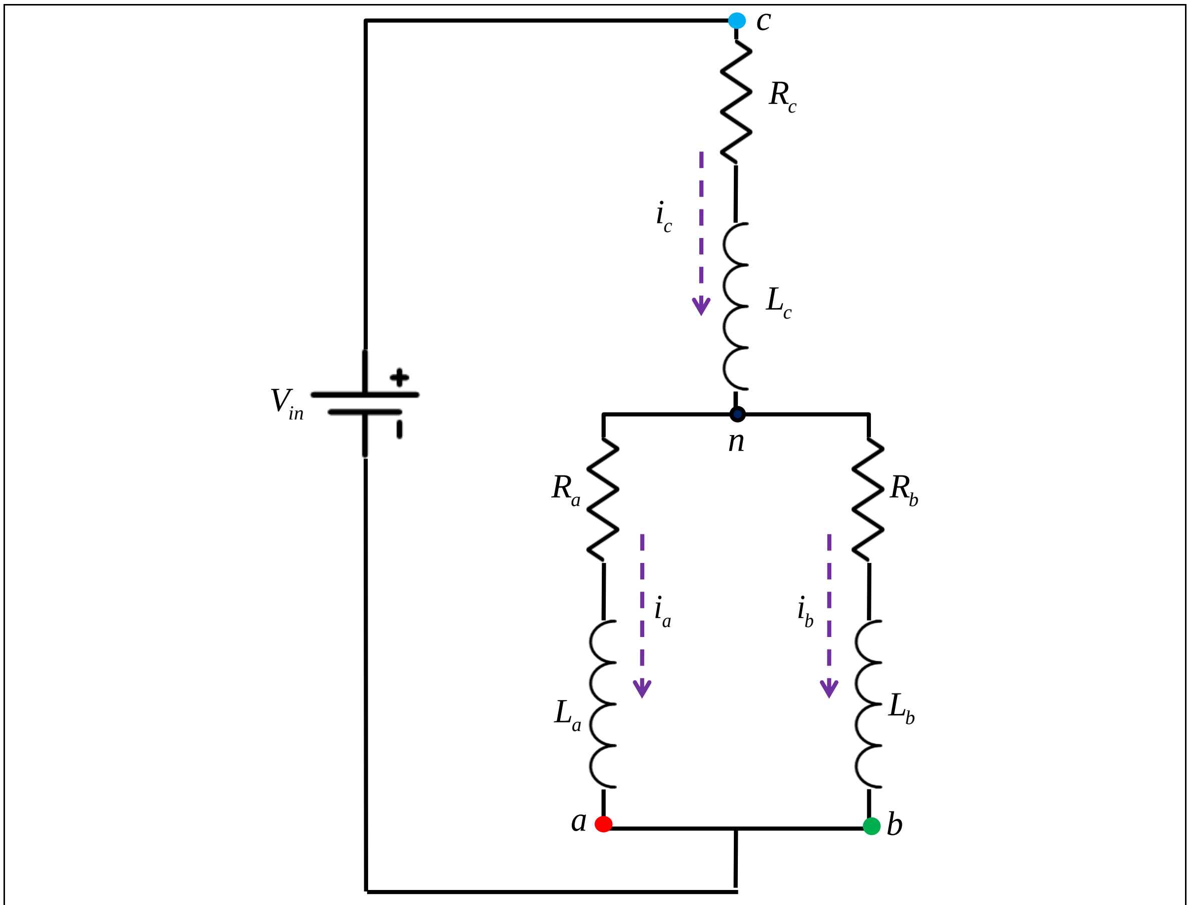


Figure 7b: Equivalent circuit for *Mode 6*

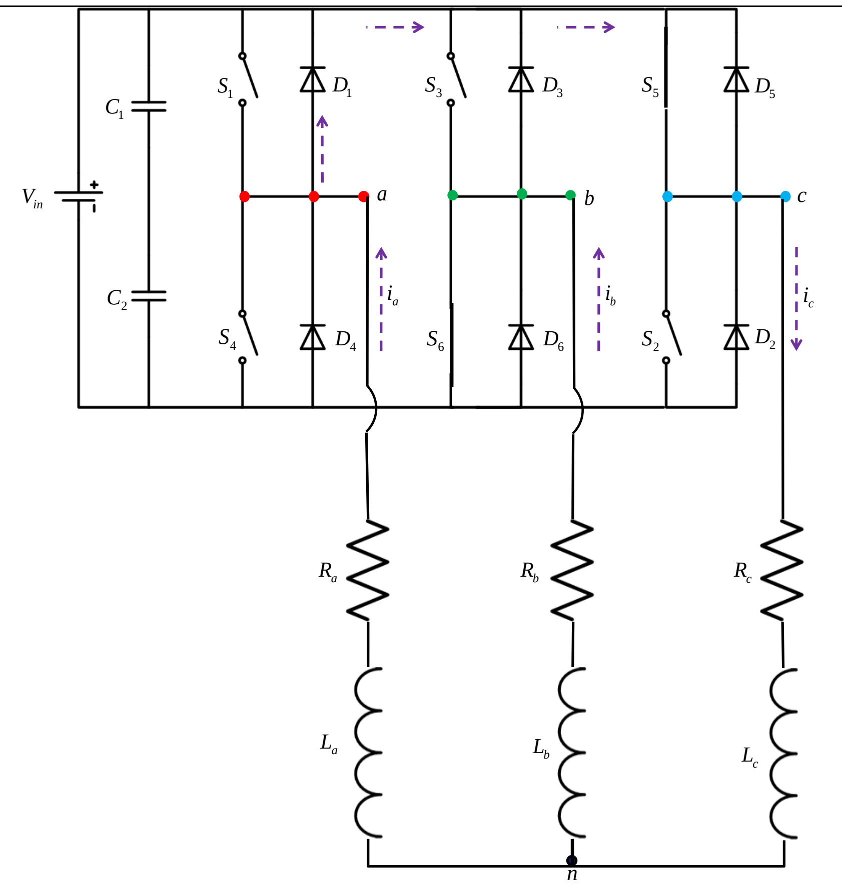


Figure 7d: Current through the load during transition from *Mode 6* to *Mode 1*

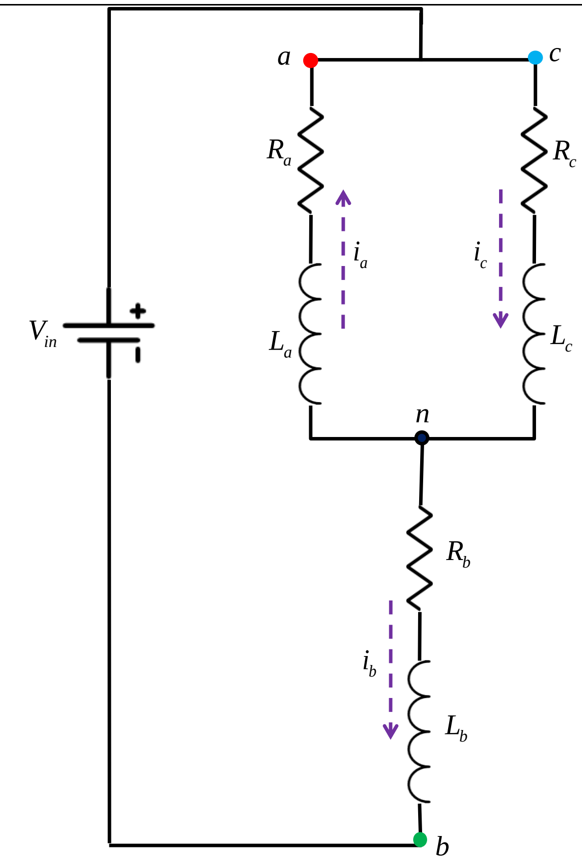


Figure 7e: Equivalent circuit during transition from *Mode 6* to *Mode 1*

Suggested Reading:

[1] M. H. Rashid, *Power Electronics: Circuits, Devices and Applications*, 3rd edition, Pearson, 2004

[2] V. R. Moorthi, *Power Electronics: Devices, Circuits and Industrial Applications*, Oxford University Press, 2007

Lecture 16: Voltage Control of DC-AC Inverters Using PWM

Voltage Control of DC-AC Inverters Using PWM

Introduction

The topics covered in this chapter are as follows:

- Need for PWM
- Single Pulse Width Modulation
- Sinusoidal Pulse Width Modulation
- Three Phase Sinusoidal Pulse Width Modulation

Need for PWM in Voltage Source Inverters

The electric motors used in EV applications are required to have large speed ranges as shown in **Figure 1**. Large speed ranges can be achieved by feeding the motor with voltages of different frequencies and also different voltage magnitudes. One of the most convenient voltage control technique to generate variable frequency and magnitude voltages is **P**ulse **W**idth **M**odulation (PWM).

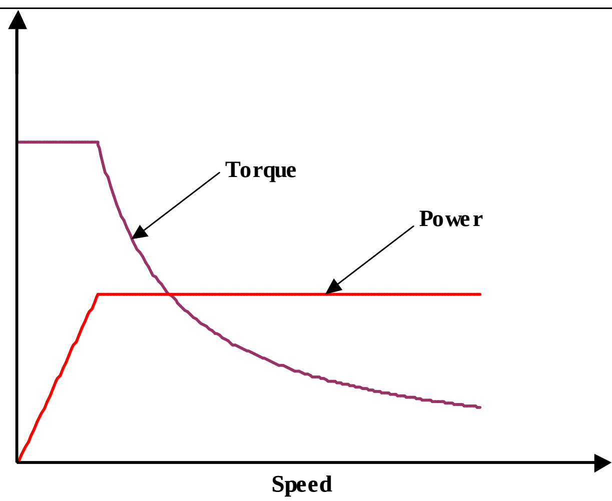


Figure 1: Ideal performance characteristics for a traction motor

The voltage control techniques for single phase inverters are:

- **Single Pulse Width Modulation**
- **Multiple Pulse Width Modulation**
- **Sinusoidal Pulse Width Modulation**
- Modified Sinusoidal Pulse Width Modulation
- Phase Displacement Control

Some of the important voltage control techniques for three phase inverters are:

- **Sinusoidal PWM**
- Space vector modulation

In this lecture, the techniques marked bold are discussed.

Voltage Control of Single Phase Inverter

The single phase DC-AC inverter considered in this section is shown in **Figure 2**.

Single Pulse Width Modulation

In this modulation only one pulse per half cycle exists and the width of the pulse is varied to control the inverter output voltage. The generation of the gating signals and the output voltage of single phase full-bridge inverters are shown in **Figure 3**. The gating signals are generated by comparing a rectangular reference signal of amplitude A_r with a triangular carrier wave of amplitude A_c. ***The frequency of the reference signal determines the fundamental frequency of the output voltage***. The ratio of A_r to A_c is the control variable and defined as the amplitude ***modulation index*** or ***modulation index*** and is given by

$$M = \frac{A_r}{A_c} \tag{1}$$

The output voltage shown in **Figure 3** can be expressed as

$$v_o = \sum_{n=1,3,5,...}^{\infty} \frac{4V_{in}}{n\pi} \sin\frac{n\pi}{2} \sin\frac{n\delta}{2} \sin n\omega t \tag{2}$$

And the rms value of the output voltage is

$$V_{o,rms} = \left[\frac{2}{2\pi} \int_{\frac{\pi-\delta}{2}}^{\frac{\pi+\delta}{2}} V_{in}^2 d(\omega t) \right]^{1/2} = V_{in}\sqrt{\frac{\delta}{\pi}} \tag{3}$$

The relation between δ and modulation index M is:

$$M = \frac{\delta}{\pi} = \frac{A_r}{A_c} \tag{4}$$

Using **equation 4**, the rms voltage can be expressed as

$$V_{o,rms} = V_{in}\sqrt{M} \tag{5}$$

The load current in case of resistive load is

$$i_L = \sum_{n=1,3,5,...}^{\infty} \frac{4V_{in}}{n\pi R} \sin\frac{n\pi}{2} \sin\frac{n\delta}{2} \sin n\omega t \tag{6}$$

For ***R-L*** load, the load current is given by

$$i_L = \sum_{n=1,3,5,...}^{\infty} \frac{4V_{in}}{n\pi\sqrt{R^2 + (n\omega L)^2}} \sin\frac{n\pi}{2} \sin\frac{n\delta}{2} \sin(n\omega t - \theta_n)$$

where (7)

$$\theta_n = \tan^{-1}\left(\frac{\omega L}{R}\right)$$

The currents for both ***R*** and ***R-L*** loads are also shown in **Figure 3**.

By varying A_r from 0 to A_c, the pulse width δ can be modified from 0^o to 180^o and the rms voltage $V_{o,rms}$ from 0 to V_{in}. The harmonic content for different harmonics for different modulation indices is shown in **Figure 4**.

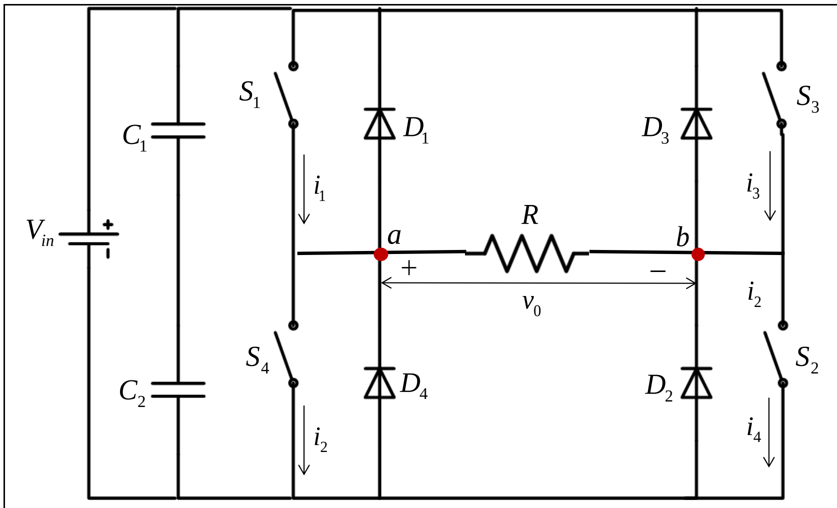


Figure 2: Configuration of the single phase inverter

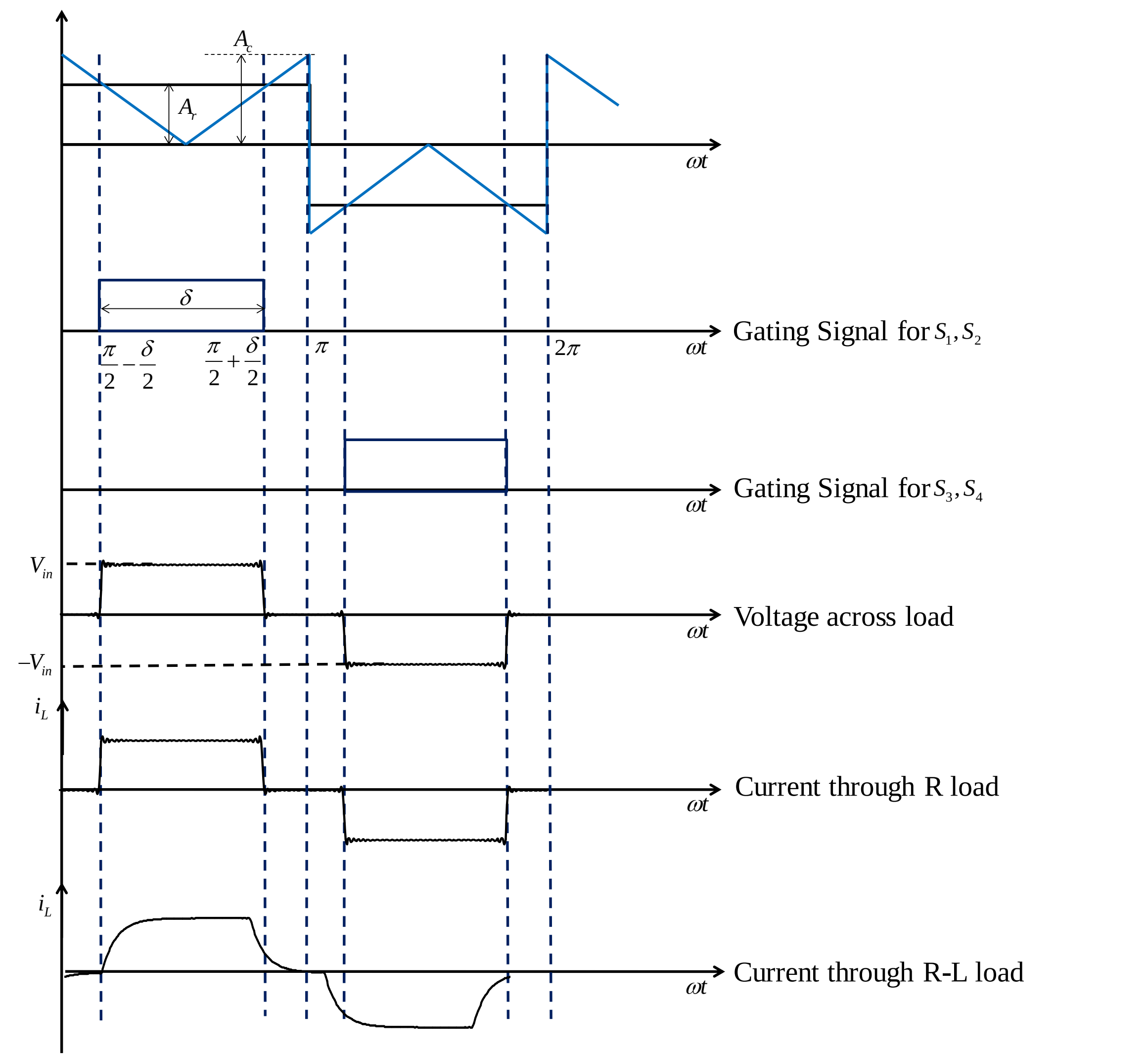


Figure 3: Currents and voltages in single phase DC-AC inverter for single PWM

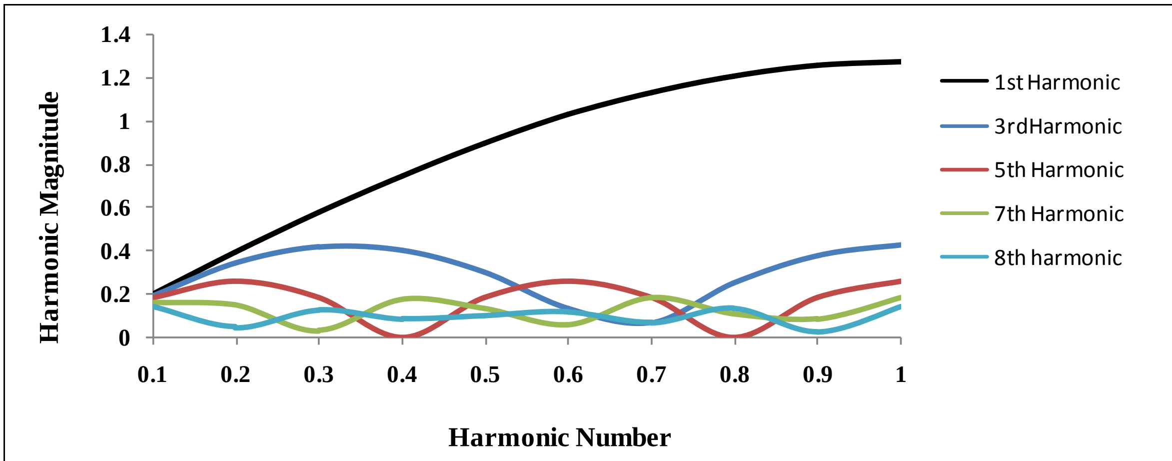


Figure 4: Harmonic content for single pulse width modulation

Single Pulse Width Modulation

The harmonic content in the voltage v_o can be reduced by using several pulses in each half cycle. The generation of the gating signal is done by comparing a reference signal with a triangular carrier waveform (**Figure 5**). The generated gate signals are shown in **Figure 5**. The frequency of the reference signal f_r and the carrier signal f_c determine the number of pulses per half cycle (n_p) as

$$n_p = \frac{f_c}{2f_r} = \frac{m_f}{2} \qquad (8)$$

where

$m_f = \frac{f_c}{f_r}$ is frequency modulation ration

The instantaneous output voltage (v_o) and the current for resistive and inductive loads are shown in **Figure 5**. The output voltage in terms of Fourier series is given by

$$v_o = \sum_{n=1,3,5,\ldots}^{\infty} B_n \sin(n\omega t)$$

where

$$B_n = \sum_{m=1}^{2n_p} \frac{4V_{in}}{n\pi} \sin\frac{n\pi}{2} \sin\frac{n\delta}{2} \sin\left(n\omega t - n\alpha_m + \frac{(2n_p - 1)}{2} n\delta \right)$$

where

n_p is number of pulses in the half cycle

M is modulation index

δ is width of each pulse

α is the angle of left most pulse

$$\delta = \frac{M}{n_p} \times 180$$

$$\alpha = \frac{180(1-M)}{2n_p}$$

$$\alpha_m = (2m-1)\alpha + (m-1)\delta \qquad (9)$$

The magnitude of the currents for ***R-L*** load are given by

$$i_L = \sum_{n=1,3,5,...}^{\infty} A_n \sin(n\omega t)$$

where

$$A_n = \sum_{m=1}^{2n_p} \frac{4V_{in}}{n\pi} \frac{1}{Z_n} \sin\frac{n\pi}{2} \sin\frac{n\delta}{2} \sin\left(n\omega t - n\alpha_m + \frac{(2n_p - 1)}{2} n\delta - \theta_n \right) \quad (10)$$

where

$$Z_n = \sqrt{R^2 + (n\omega L)^2}$$

$$\theta_n = \tan^{-1}\left(\frac{n\omega L}{R}\right)$$

The rms value of the output voltage is

$$V_{o,rms} = \left[\frac{2n_p}{2\pi} \int_{\left(\frac{\pi}{2}-\delta\right)/2}^{\left(\frac{\pi}{2}+\delta\right)/2} V_{in}^2 d(\omega t) \right]^{1/2} = V_{in}\sqrt{\frac{n_p \delta}{\pi}} \quad (11)$$

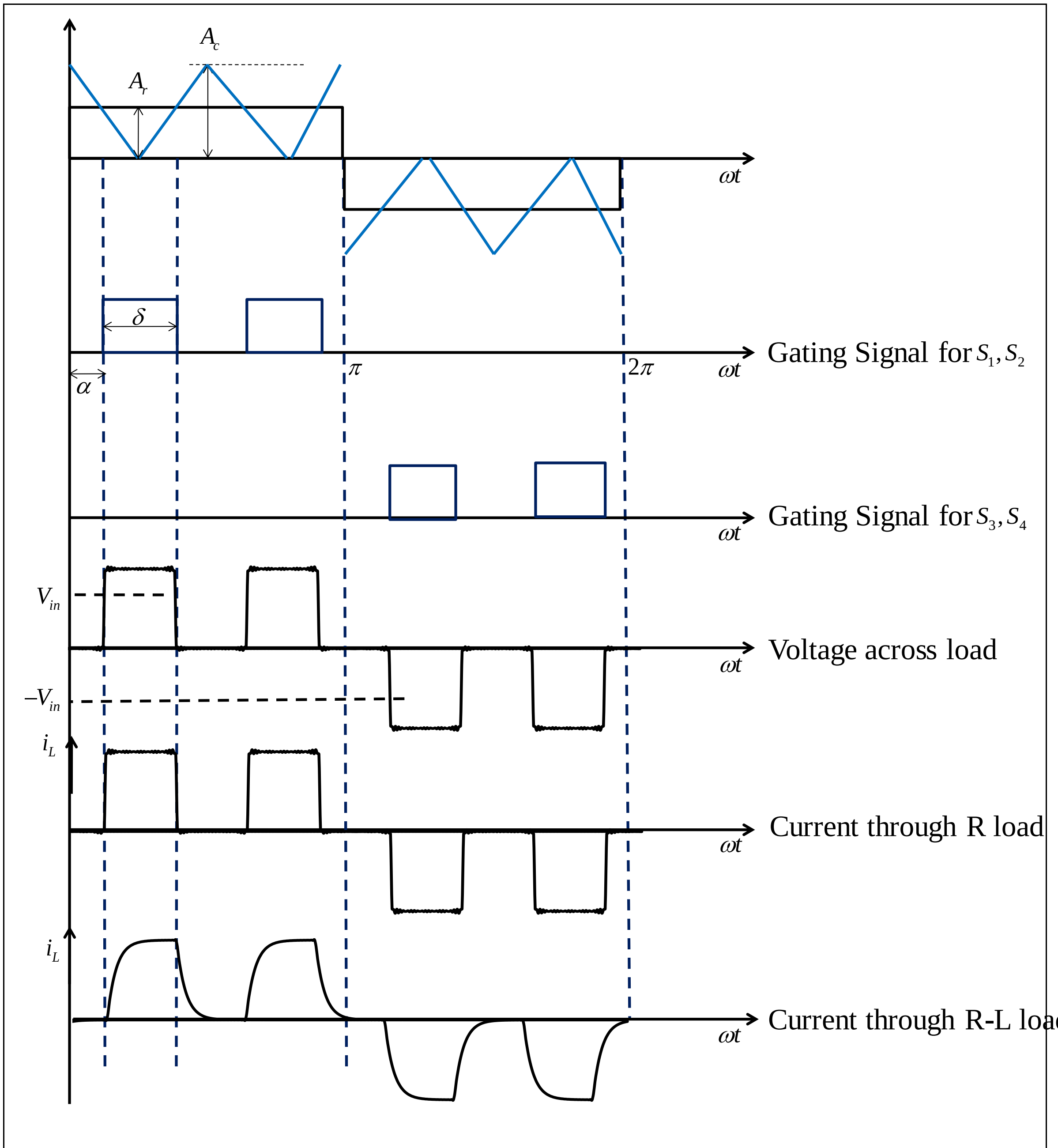


Figure 5: Currents and voltages in single phase DC-AC inverter for Multi-PWM

Sinusoidal Pulse Width Modulation

In sinusoidal PWM, also called ***sine-PWM***, the resulting pulse widths are varied throughout the half cycle in such a way that they are proportional to the instantaneous value of the reference sine wave at the centre of the pulses. The distance between the centres of the pulses is kept constant as in multi-PWM. Voltage control is achieved by varying the widths of all pulses without disturbing the sinusoidal relationship. The generation of the gating signals for sinusoidal PWM and the output voltage and currents is shown in **Figure 6**.

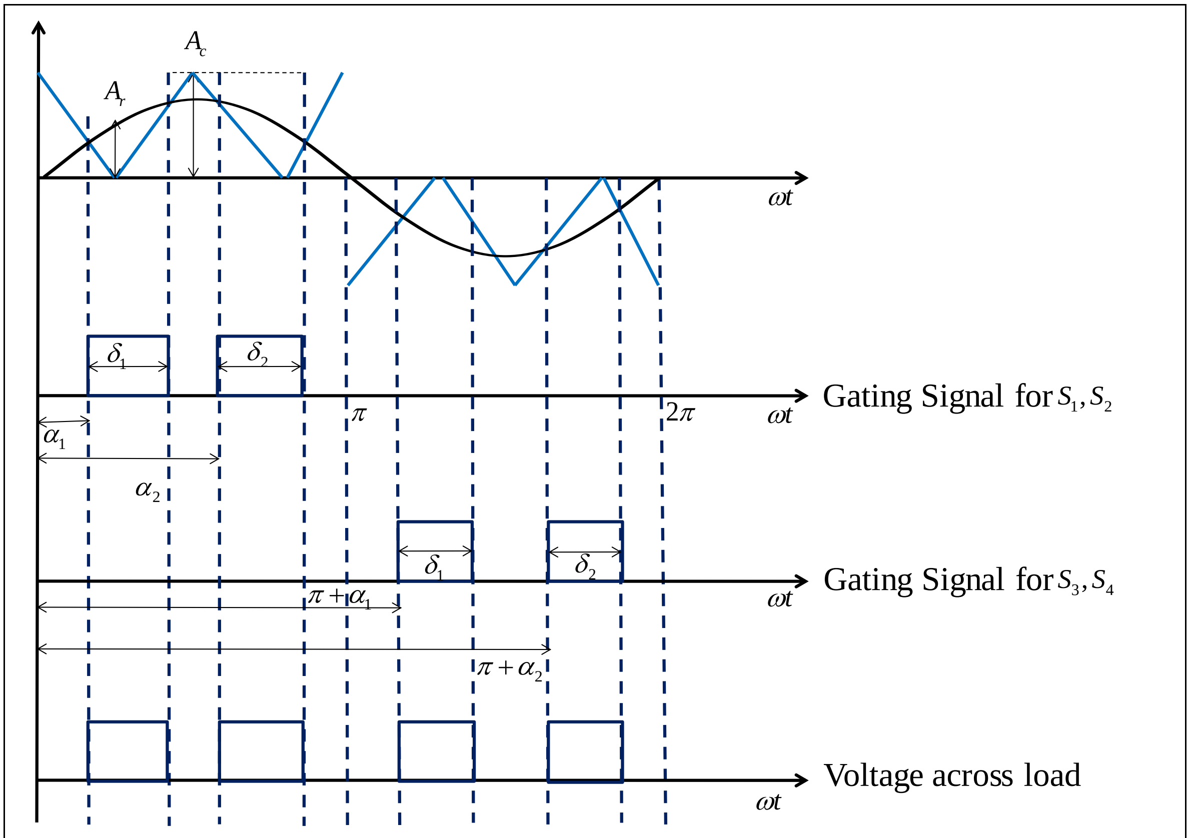


Figure 6: Gating Signal in Sinusoidal PWM

The output voltage in case of sinusoidal PWM can be expressed as

$$v_o = \sum_{n=1,3,5...}^{\infty} \frac{4V_{in}}{n\pi} \sum_{k=1,2,...}^{n_p} \sin\frac{n\delta_k}{2}\left[\cos\left(n\omega t - \frac{n\delta_k}{2} - n\alpha_k\right)\right] \tag{12}$$

where

n_p is the number of pulses in the half cycle

δ_k is the width of the *kth* pulse

α_k is the starting angle of the *kth* pulse

The width of the ***kth pulse*** (δ_k) is approximately given by

$$\delta_k = \left(\frac{\pi}{n_p}\right) m_a \sin(\alpha_k)$$

where (13)

$m_a = \frac{A_r}{A_c}$ is the modulation index

The value of the starting angle of the k^{th} pulse (α_k) is given by numerically solving the following equation

$$m_a \sin(\alpha_k) = -\frac{m_f}{\pi}\alpha_k + (2k-1)$$

where (14)

$m_f = 2n_p$

The angles θ and α for a sine PWM with 6 pulses per half cycle are calculated using **equations 13** and **14** and listed in **Table 1**. The waveforms of the voltage and current are shown in **Figure 7.**

The r.m.s value of the output voltage is

$$v_o = V_{in}\sqrt{\sum_{m=1}^{2n_p}\frac{\delta_m}{\pi}} \qquad (15)$$

The load for an ***R-L*** load is given by

$$i_L = \sum_{n=1,3,5...}^{\infty}\frac{4V_{in}}{n\pi Z_n}\sum_{k=1,2,...}^{n_p}\sin\frac{n\delta_k}{2}\left[\cos\left(n\omega t - \frac{n\delta_k}{2} - n\alpha_k - \theta_n\right)\right]$$

where (16)

$$Z_n = \sqrt{R^2 + (n\omega L)^2}$$

$$\theta_n = \tan^{-1}\left(\frac{\omega L}{R}\right)$$

Table 1: The starting angle and pulse width for Sine PWM with 6 pulses per half cycle

Pulse Number	Starting angle α [^{o}]	Pulse Width δ [^{o}]
1	12.98	4.04
2	39.30	11.40
3	66.73	16.54
4	96.05	17.90
5	127.90	14.20
6	162.26	5.49

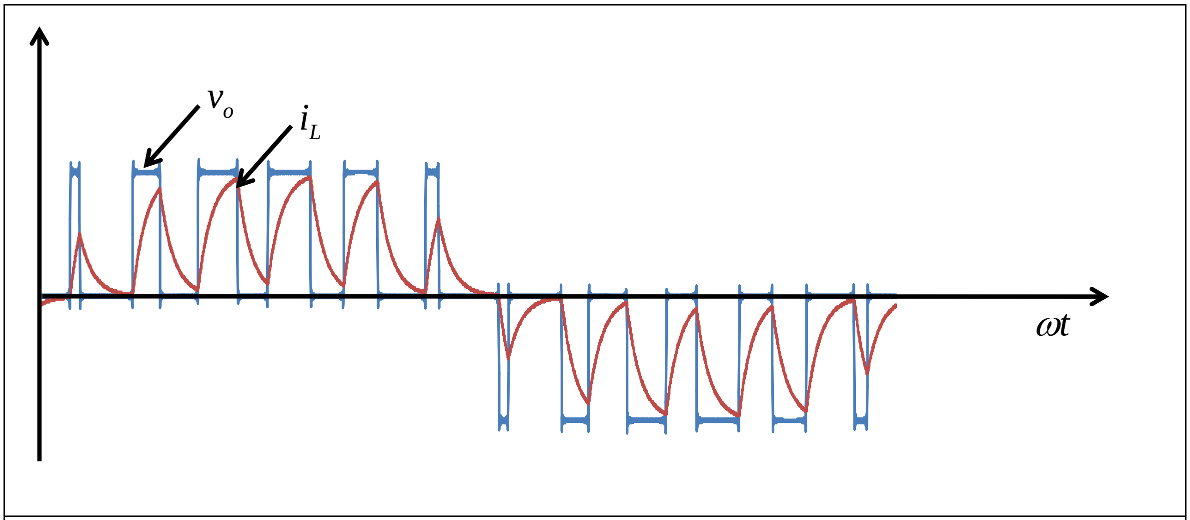


Figure 7: Voltage and Current waveforms for Sinusoidal PWM with 6 pulses per half cycle

Voltage Control of Three Phase DC-AC Inverter using Sinusoidal PWM

The generation of gating signals for a three phase DC-AC inverter with sine PWM are shown in **Figure 8**. There are three sinusoidal reference waves (v_{ra}, v_{rb}, v_{rc}) each shifted by 120^o. A triangular carrier wave is compared with the reference signals to produce the gating signals. Comparing the carrier signal v_{cr} with the reference phases v_{ra}, v_{rb}, v_{rc} produces the signals for gates 1, 2 and 3 (g_1, g_2, g_3). The instantaneous line-to-line output voltage is

$$v_{ab} = V_{in}\left(g_1 - g_3\right) \tag{12}$$

The output voltage is generated by eliminating the condition that two switching devices in the same arm cannot conduct at the same time.

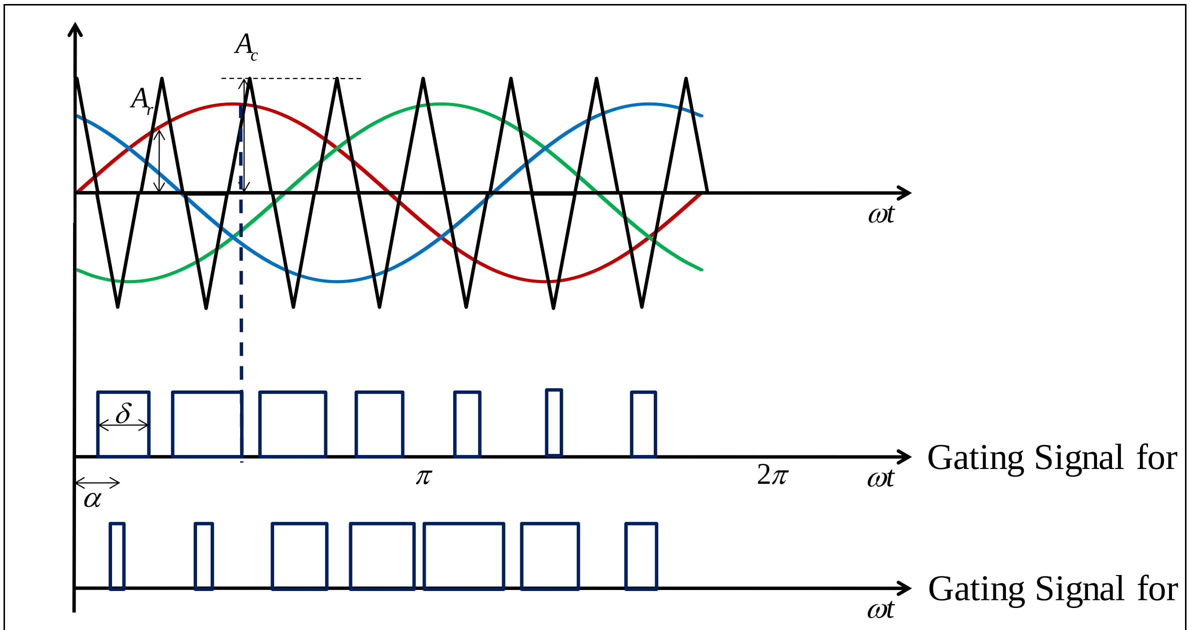


Figure 8: Voltage and Current waveforms for three phase Sinusoidal PWM

Suggested Reading:

[1] M. H. Rashid, *Power Electronics: Circuits, Devices and Applications*, 3rd edition, Pearson, 2004

[2] V. R. Moorthi, *Power Electronics: Devices, Circuits and Industrial Applications*, Oxford University Press, 2007

PREVIOUS YEAR QUESTION PAPERS

III B. Tech I Semester Regular/Supplementary Examinations, October/November - 2019

POWER ELECTRONICS

(Electrical and Electronics Engineering)

Time: 3 hours Max. Marks: 70

Note: 1. Question Paper consists of two parts (**Part-A** and **Part-B)**
2. Answer **ALL** the question in **Part-A**
3. Answer any **FOUR** Questions from **Part-B**

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PART –A (14 Marks)

1. a) What are the necessary conditions for turning ON a SCR? [2M]
   b) What is reactive power input of single phase full converter at $\alpha = 30^0$? [2M]
   c) Give the list of applications of three phase controlled converters. [2M]
   d) What is the principle of operation of fly-back converter in CCM? [3M]
   e) What are the difference between VSI and CSI? [3M]
   f) Draw the waveforms of single phase ac voltage controller with R load with $\alpha = 60^0$. [2M]

PART –B (56 Marks)

2. a) What are the types of switching characteristics of SCR? How do you known turn ON and turn OFF times from the switching characteristics? Explain. [7M]
   b) What are the requirements of good gate driver circuits of IGBT and MOSFET? Explain. [7M]

3. a) Explain the operation of single phase full-wave controlled rectifier using center tapped transformer with R-L load under continuous mode of operation. Draw the waveforms of output voltage, voltage across SCR and average load current for $\alpha = 45^0$. [7M]
   b) A single phase fully controlled bridge converter is connected to R-L load with R = 10 Ω and L = 6 mH. The converter is supplied from 230 V, 50 Hz ac supply. (i) Determine average and rms load current; (ii) if one SCR of the bridge configuration is open circuited due to fault, what will be the average and rms load current at this condition? [7M]

4. a) Draw the output voltage waveforms and derive the average and rms voltage expressions of three phase semi converter on discontinuous conduction mode. [7M]
   b) A three phase full converter is connected to a resistive load of 10 Ω. If the firing angle of SCR is $\alpha = 45^0$ and it feeds 4 kW power to a resistive load determine the amplitude of maximum line input voltage. [7M]

5. a) Explain the operation of boost converter in the CCM mode and obtain the expression for amplitude of ripple current. [7M]
   b) A buck-boost converter has the input voltage of 12 V and it operates at 20 kHz, when the average output voltage is 24 V, the average load current is 1.2 A, it is having L = 300 μH, C= 150 μF. Find duty cycle, ripple current through the inductor, ripple voltage and critical values of L and C. [7M]
~~~~~~

6. a) Discuss various PWM techniques used in inverters. How sinusoidal PWM is useful in the harmonic elimination? [7M]

   b) A 50 Hz single – phase full bridge produces a square wave voltage across load when operating from a 300 V DC supply, the AC load consists of a resistance of 30 Ω in series with inductance 15 mH. Determine the frequencies and r.m.s values of the lowest order harmonics in the AC load current. [7M]

7. Explain the operation of a three – phase bidirectional AC voltage controlled feeding star connected with resistive load. Draw the output voltage waveform with $\alpha = 60^o$ and $\alpha = 120^o$. [14M]

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Code No: R1631025 **R16** SET - 2

III B. Tech I Semester Regular/Supplementary Examinations, October/November - 2019

POWER ELECTRONICS

(Electrical and Electronics Engineering)

Time: 3 hours Max. Marks: 70

Note: 1. Question Paper consists of two parts (**Part-A** and **Part-B)**
2. Answer **ALL** the question in **Part-A**
3. Answer any **FOUR** Questions from **Part-B**

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PART –A **(14 Marks)**

1. a) Define holding current. [2M]
   b) What are the drawbacks of source inductance on the performance of phase controlled rectifiers? [2M]
   c) Compare continuous and discontinuous modes of operation of converters. [2M]
   d) List any two applications of choppers. [3M]
   e) List differences between CSI and VSI. [3M]
   f) Explain the principle of Integral Cycle control. [2M]

PART –B **(56 Marks)**

2. a) Explain the various turn-on methods of SCRs. [7M]
   b) Following are the specifications of a thyristor operating from a peak supply voltage of 500 V. [7M]
   Repetitive peak current, Ip = 250 A;
   $(\frac{di}{dt})_{\max} = 60A/\mu s, (\frac{dv_a}{dt})_{\max} = 200V/\mu s$.
   Take a factor of safety as 2 for the specifications mentioned above. Design a suitable snubber circuit, if the minimum load resistance is 20 Ω. Take ξ=0.65.

3. a) Explain the effect of source inductance on the performance of a single-phase full converter with the help of voltage waveforms. Derive an expression for its output voltage in terms of supply voltage, source inductance and load current. [7M]
   b) A single phase semi converter is supplied from 230 V, 50 Hz source. The load consists of R= 10 Ω and E = 100 V and a large inductor so as to maintain the load current constant. For a firing angle of 45^0, find i) average output voltage ii) average output current iii) average and rms values of thyristor currents iv) input power factor. [7M]

4. a) Explain the working of three phase semi converter with relevant wave forms with highly inductive load for firing angle of 30^0. [7M]
   b) A three-phase, half-wave converter is supplying a load with a continuous constant current of 40A over a firing angle range from 0 to 75 deg. What will be the power dissipated by the load at these limiting values of firing angle? The supply voltage is 415 V (line). [7M]
~~~~~~

5. a) Explain the working of boost converter with relevant waveforms in CCM mode and also derive the expressions for critical values of L and C. [10M]

b) The buck regulator has an input voltage of Vs = 15 V. The required average output voltage is Va = 5 V at R = 400 Ω and the peak-to-peak output ripple voltage is 10 mV. The switching frequency is 20 kHz. If the peak-to-peak ripple current of inductor is limited to 0.6 A, determine: i) the duty cycle ii) the filter inductance L, iii) the filter capacitor C. [4M]

6. a) With necessary waveforms explain the working of single phase full bridge inverter with RL load and also derive the expression for RMS value of output voltage. [7M]

b) Single phase half bridge inverter has a resistive load of R= 3 Ω and DC input voltage of 50 V. Calculate: i) RMS output voltage at fundamental frequency, ii) output power, iii) Average and peak current of each thyristors. [7M]

7. a) Describe the principle of phase control in single phase half wave ac voltage regulator. Derive the expressions for average and rms value of output voltage for this control. [7M]

b) A single phase full wave ac voltage controller has a load of R= 5 Ω and input voltage is 230 V, 50 Hz. If the load power is 5 kW, find firing angle delay of SCR and input power factor. [7M]

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Code No: R1631025 **R16** SET - 3

III B. Tech I Semester Regular/Supplementary Examinations, October/November - 2019

POWER ELECTRONICS

(Electrical and Electronics Engineering)

Time: 3 hours Max. Marks: 70

Note: 1. Question Paper consists of two parts (**Part-A** and **Part-B)**
2. Answer **ALL** the question in **Part-A**
3. Answer any **FOUR** Questions from **Part-B**

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PART –A **(14 Marks)**

1. a) Why protection is required during the operation of SCR? [2M]
   b) Calculate power delivered to a 1 kW heater which is connected to a single phase half wave controlled rectifier when $\alpha = 30^0$, Supply voltage = 220V. [2M]
   c) Give the conduction periods of lower group thyristors in 6 pulse converters for 60 Hz frequency with $\alpha = 60^0$. [2M]
   d) Write the advantages of buck-boost converter. [3M]
   e) Mention the advantages of pulse width modulation control strategy. [3M]
   f) Draw the waveforms of single phase unidirectional ac voltage controller with RL load with $\alpha = 30^0$. [2M]

PART –B **(56 Marks)**

2. a) Describe the switching characteristics of power MOSFET and what are the requirements of gate drive to get less turn OFF and turn ON times? [7M]
   b) Explain the design of snubber circuit used for a SCR, how it provides different voltage protections? [7M]

3. a) Explain the operation of single phase full-wave controlled rectifier using center tapped transformer having R-L load and freewheeling diode under discontinuous and continuous conduction modes with the help of wave forms. [7M]
   b) A single phase fully controlled bridge converter is supplied from 230 V, 50 Hz ac supply and it is fed to load consisting of R = 10 Ω and large inductance such that load current is constant. When the firing angle is 45^0, i) calculate average and rms current ii) if the source inductance of 1.5 mH is connected find the average voltage and overlap angle at the same firing angle. [7M]

4. a) Derive the average and rms voltage expressions of three phase half-wave controlled rectifier having R load operated on discontinuous conduction mode. [7M]
   b) A three phase full converter is fed by 230 V, 50 Hz, three phase supply, the average load current is 25A and the load is highly inductive. For firing angle of 60^0 find average, rms and peak current through the SCR's. [7M]

5. a) Explain the operation of buck converter in the DCM mode and obtain the expression for amplitude of ripple current. [7M]
   b) A buck-boost converter has the input voltage of 24 V and it operates at 30 kHz, when the duty cycle is 0.25, L = 300 μH, C= 150 μF and the average load current is 1.5 A. Determine average output voltage, peak to peak ripple current through the inductor, peak to peak ripple voltage and critical values of L and C. [7M]
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6. a) Draw a neat circuit diagram for single phase full bridge inverter feeding inductive load. What is the function of feedback diodes? [7M]
   b) Explain the working of a current source inverter with a neat circuit diagram and waveforms. [7M]

7. a) A single phase voltage controller has input voltage of 230 V, 50 Hz; the load consists of a resistance 30 Ω in series with inductance 15 mH, for 6 cycles off and 4 cycles on. Determine the output voltage and input power factor. [7M]
   b) Explain the synchronous connection charge control of a Single–phase transformer connection charger. [7M]

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Code No: R1631025 **R16** SET - 4

III B. Tech I Semester Regular/Supplementary Examinations, October/November - 2019

POWER ELECTRONICS

(Electrical and Electronics Engineering)

Time: 3 hours Max. Marks: 70

Note: 1. Question Paper consists of two parts (**Part-A** and **Part-B)**
2. Answer **ALL** the question in **Part-A**
3. Answer any **FOUR** Questions from **Part-B**

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PART –A **(14 Marks)**

1. a) What is meant by reverse recovery time of a SCR? [2M]
   b) Calculate power delivered to a 1 kW heater which is connected to a single phase full wave controlled bridge rectifier, when $\alpha = 90^0$, Supply voltage = 220V? [2M]
   c) Give the conduction periods of upper group thyristors in 6 pulse converters for 60 Hz frequency with $\alpha = 30^0$. [2M]
   d) What is meant by fly back mode of operation of buck-boost converter? [3M]
   e) Mention the advantages of sinusoidal pulse width modulation control. [3M]
   f) Draw the static V – I characteristics of a TRIAC. [2M]

PART –B **(56 Marks)**

2. a) Describe the switching characteristics of power IGBT and what are the requirements of gate drive to get less turn OFF and turn ON times? [7M]
   b) Discuss about the different turn ON methods of a SCR. [7M]

3. a) Explain the operation of single phase half-wave controlled rectifier having R-L load and freewheeling diode under discontinuous and continuous conduction modes with the help of wave forms. [7M]
   b) A single phase full converter is used to deliver a constant load current, it is operated such that overlap angle is 15^0 for a firing angle, $\alpha = 0^0$. Determine the overlap angles for firing angles $\alpha = 30^0$, $\alpha = 45^0$ and $\alpha = 60^0$. [7M]

4. a) Describe the operation of three phase full converter feeding an R load and draw the wave forms for any firing angle which is more than the 90^0. [7M]
   b) A three-phase three pulse controlled rectifier with freewheeling diode D_F is fed from three phase, 400 V, 50 Hz ac supply and it is connected with a constant current load of 90 A at firing angle of $\alpha = 45^0$. Calculate dc output voltage, rms output voltage, average and rms current of free-wheeling diode. [7M]

5. a) Explain the working of buck converter in continuous conduction mode. Derive the expression for output voltage. [7M]
   b) A boost converter has the input voltage of 24 V and it operates at 20 kHz, when the average output voltage is 12 V, the average load current is 1.2 A, it is having L = 300 μH, C= 150 μF. Find duty cycle, ripple current through the inductor, ripple voltage and critical values of L and C ? [7M]
~~~~~~

6. a) Explain the working of a three phase inverter with 120^0 mode of conduction with three phase delta connected resistive load. [7M]

   b) A 50 Hz PWM inverter employs sinusoidal pulse width modulation based on sine-triangle comparison. If the triangular carrier frequency is 15 kHz, what will be the number of pulses per half period in the output waveform and with 80% modulation index what will be the width of the longest pulse? [7M]

7. a) Describe the operation of single phase full wave ac regulator feeding resistive load. Derive the expression for output voltage. [7M]

   b) A single phase ac voltage controller is employed for controlling the power flow from 230 V, 50 Hz source in to a load circuit consisting of $R = 4\ \Omega$ and $\omega L = 3\ \Omega$. Calculate: i) the control range of Firing angle; ii) the maximum power delivered to load and power factor; iii) the maximum values of average and rms SCR currents. [7M]

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Code No: R1631025 **R16** SET - 1

III B. Tech I Semester Supplementary Examinations, October/November - 2020

POWER ELECTRONICS

(Electrical and Electronics Engineering)

Time: 3 hours Max. Marks: 70

Note: 1. Question Paper consists of two parts (**Part-A** and **Part-B)**
2. Answer **ALL** the question in **Part-A**
3. Answer any **FOUR** Questions from **Part-B**

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PART –A **(14 Marks)**

1. a) Define Latching Current. [2M]
b) Why power factor of semi converter is better than full converter? [2M]
c) Draw the circuit diagram of three phase M-3 controlled converter. [2M]
d) List the applications of step up choppers. [3M]
e) What is shoot through fault? Explain. [3M]
f) A 1-phase voltage controller has input voltage of 230 V, 50 Hz for 6 cycles on and 4 cycles off. Determine RMS output voltage. [2M]

PART –B **(56 Marks)**

2. a) Explain the operation of snubber circuit and also design the parameters of snubber circuit. [7M]
b) Draw the two-transistor analogy of a SCR? Explain SCR operation with this analogy. [7M]

3. a) Explain the operation of single phase two pulse midpoint converter with relevant voltage and current waveforms and also derive the expression for average output voltage. [7M]
b) A single phase semi converter is delivering power to RLE load with R= 5Ω, L= 10 mH and E = 80 V. The ac source voltage is 230 V, 50 Hz. For continuous conduction, find the average value of output current for a firing angle of 50^0. If one of the SCR is damaged and open circuited find the new value of average output current on the assumption to continuous conduction. Also sketch the output voltage and current waveforms? [7M]

4. a) Explain the working of three-phase half wave uncontrolled rectifier with relevant wave forms for 'R' load. [7M]
b) A Three phase fully controlled bridge converter is connected to a supply voltage of 230 V per phase and frequency of 50 Hz. The source inductance is 3 mH. The load current on dc side is constant at 15 A. If load consists of a dc source voltage of 400 V having an internal resistance of 1 **Ω**. Find the firing angle and overlap angle. [7M]

5. a) Explain the principle of operation and working of buck converter with relevant waveforms in CCM mode. [10M]
b) A boost regulator has an input voltage of Vs = 5 V. The average output voltage Va = 15 V and the average load current Ia = 0.5 A. The switching frequency is 25 kHz. If L = 150 µH and C = 220 µF, determine (i) the duty cycle, (ii) the ripple current of inductor ΔI, (iii) the critical values of L and C. [4M]
~~~~~~

6\. a) With necessary waveforms explain the working of single phase half bridge inverter with RL load and also derive the expression for RMS value of output voltage. [7M]

b) Single phase full bridge inverter has a resistive load of R= 2.4 ohms and DC input voltage of 48 volts. Calculate: i) RMS output voltage at fundamental frequency, ii) output power, iii) Average and peak current of each thyristors. [7M]

7\. a) Explain the operation of a single phase AC voltage controller with a neat circuit diagram and output wave forms with respect to source voltage waveforms at $\alpha = 60$ degrees for R-load. [7M]

b) Explain the principle of integral cycle control with relevant waveforms and also derive the expression for rms value of output voltage, power delivered to load and input power factor. [7M]

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