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POWER ELECTRONICS

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KEJURUTERAAN ELEKTRIK

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Power Electronics

Suitable for diploma students, this book concise for students to understand the characteristics of converters in electrical engineering. It contains basic theory and practical foundations for power electronics such as uncontrolled rectifiers, controlled rectifiers, three phase rectifiers, choppers, inverters and voltage regulators. Using PSIM software to construct the circuit and waveform. Users are guided how to apply and analyse the techniques.

Chapter

1

Introduction To Power Electronics

Power Electronics is the study of switching electronic circuits in order to control the flow of electrical energy. Its are exciting and challenging for anyone who has an interest in, and aptitude in applied science and mathematics. It is concerned to systems that produce, transmit, control and measure electric power and energy. It can be considered to be an interdisciplinary technology.

1.1 Basic Operation of Switch Mode Power Supply

A switch mode power supply (SMPS) is a power converter that utilises switching devices such as MOSFETs, SCRs, TRIACs and IGBTs that continuously turn on and off at high frequency; and energy storage devices such as the capacitors and inductors to supply power during the non-conduction state of the switching device.

SMPS provide improved efficiency & space saving over traditional linear supplies, but care has to be taken to ensure noise on the output is low. Its widely used in computers and other sensitive electronic equipment.

The basic switch mode power supplies (SMPS) are categorized based on supply input and output voltage. The main four groups are:
AC to DC
DC to DC
DC to AC
AC to AC

The main components of an SMPS are:
• Input rectifier and filter
• Inverter consisting of a high frequency signal and switching devices
• Power transformer
• Output rectifier
• Feedback system and circuit control

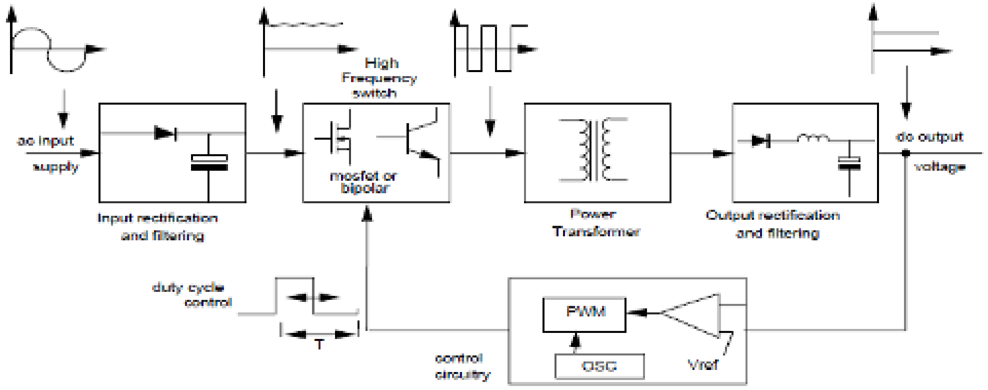


Figure 1.1 Basic Switched Mode Power Supply block diagram
(Source: https://www.sunpower-uk.com/)

Figure 1.2 Gurun HVDC Converter Station
(Source from HVDC Transmission, Gurun)

High Voltage Direct Current (HVDC)

A HVDC electrical power transmission system uses direct current for the bulk transmission of electrical power.
HVDC use converters : AC to DC and DC to AC, 12 pulse circuits consists of bridges and transformer.
For long distance transmission, HVDC systems may be less expensive and suffer lower electrical losses.
In Malaysia, there has one HVDC Converter Station at Gurun, Kedah

1.2 Power Electronics Devices In Industry

In modern systems the conversion is performed with semiconductor switching devices such as diodes, transistors or thyristors. This power devices are used as ON/OFF switches in power control circuit.

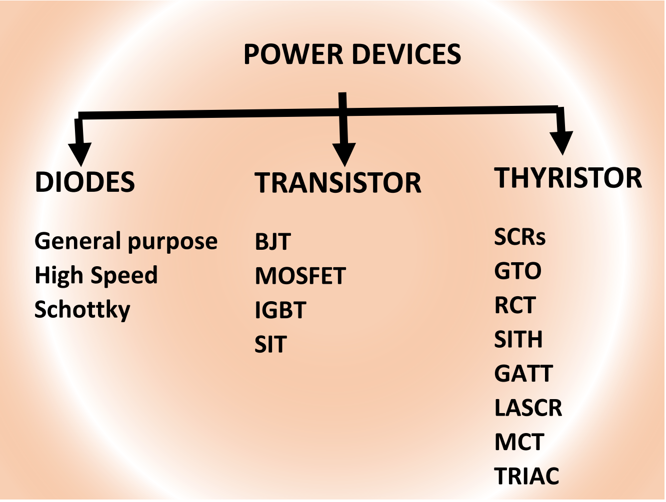


Figure 1.3 Power electronics devices

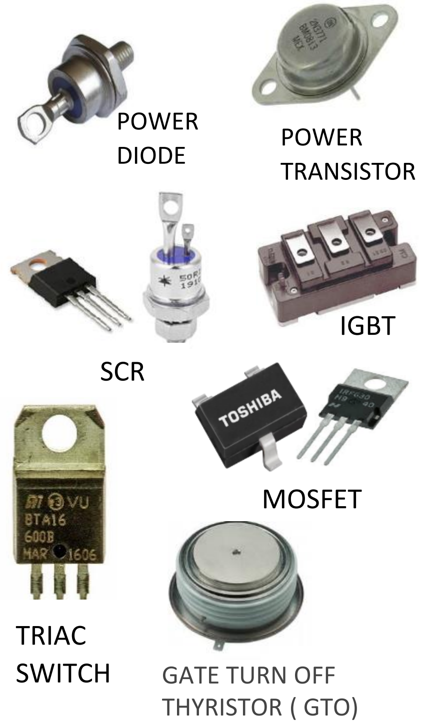


Figure 1.4 Switching devices

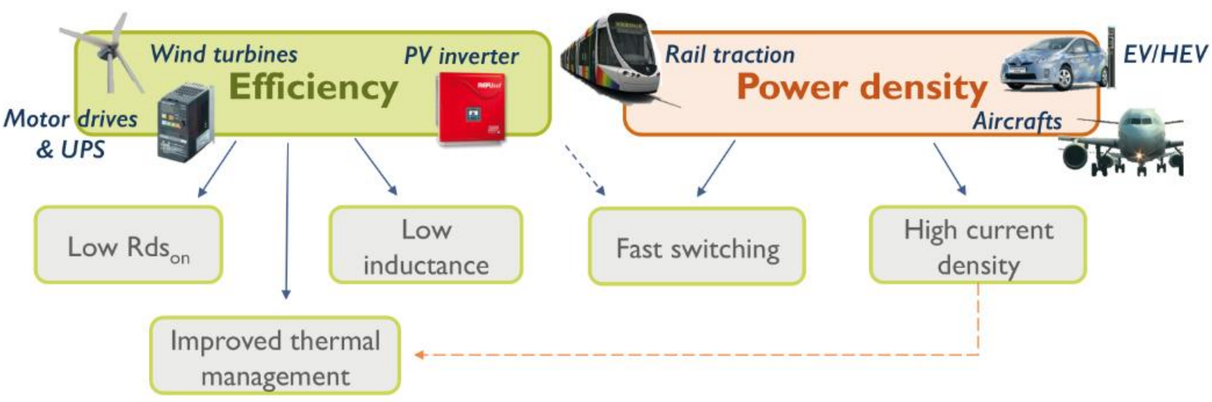


Figure 1.5 Power Generation : efficiency or power density
(Source: Inverter Technology Trends and Market Expectations report, May 2016, Yole Development)

1.3 I-V Characteristic of Devices

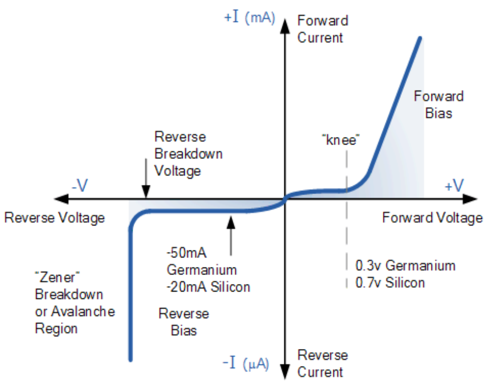


Figure 1.6.1 I-V Characteristic of diode

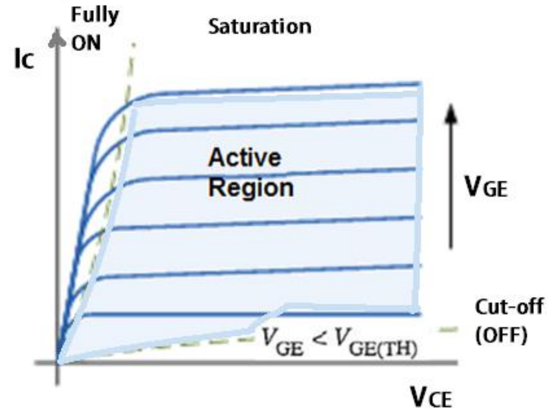


Figure 1.6.2 I-V Characteristics of an N-channel of MOSFET

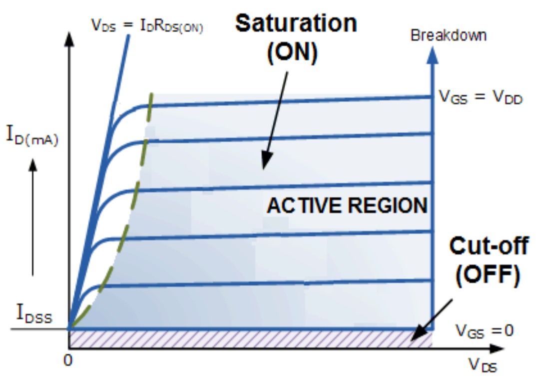


Figure 1.6.4 I-V Characteristics of IGBT

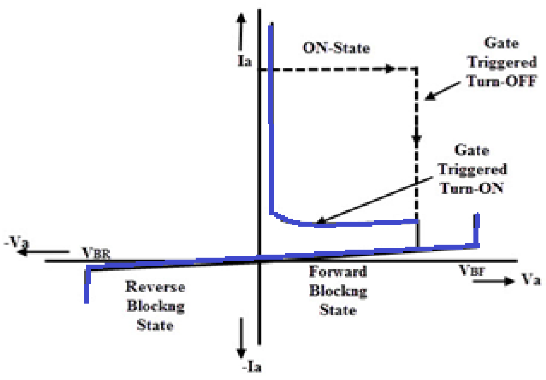


Figure 1.6.3 I-V Characteristics of GTO-SCR

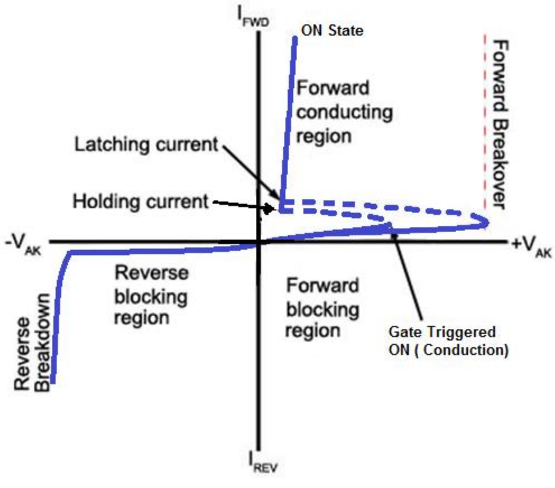


Figure 1.6.5 V-I Characteristics of SCR

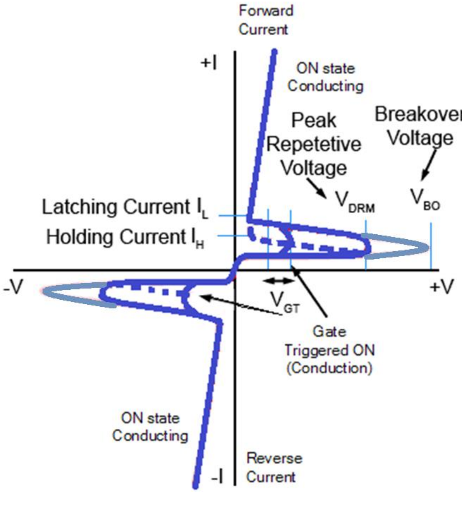


Figure 1.6.6 I-V Characteristics of TRIAC

1.4 Silicon Controlled Rectifier (SCR)

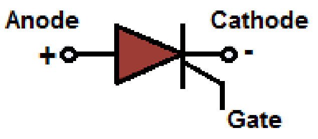


Figure 1.7.1 Symbol of a SCR

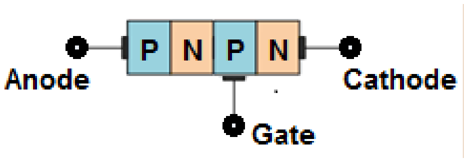


Figure 1.7.2 The structure of a SCR

Turning ON and Turning OFF SCR

From the characteristics of SCR, it can be seen that two condition must be met to turn-on SCR:

i) Anode voltage should be positive with respect to the cathode.
ii) Gate voltage should be positive with respect to the cathode.

The gate has no control over the SCR once it goes into conduction. Turn –off must be achieved in the anode- to – cathode circuit such as:

i) Reversing anode to cathode terminal
ii) Forcing current in the anode circuit in the reverse direction
iii) Decrease forward current (IF) lower than holding current (IH) *(Gate –controlled effect)*

Regeneration Action of SCR - refer to Figure 1.8.3

i) When the switch is closed, a positive triggered voltage is applied to the gate (VGT). The gate current IGT will flow and enough knee voltage, VBE to activate transistor Q1
ii) Collector current, IC1 will flow to the base transistor Q2 (IB2= IC1) and setup the conditions for generations.
iii) Q2 is activated and act as a closed switch. This conditions will generate more current in transistor Q1.
iv) Collector current IC2 will flow to the base of transistor Q1 (IC2 = IB1)
v) The anode current, IA will continue to flow in the SCR even though the positive triggering voltage, VGT is terminated.

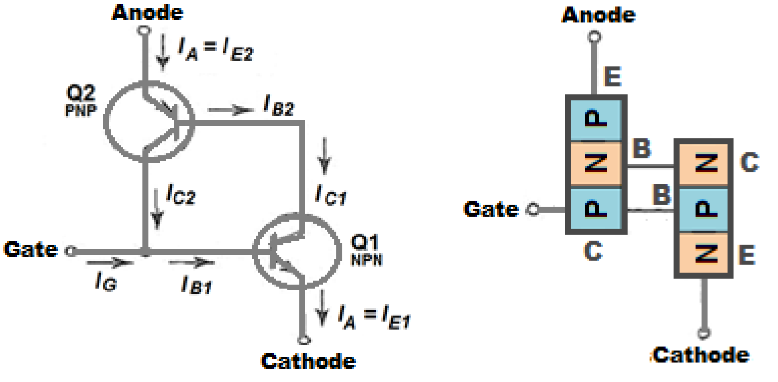


Figure 1.8.3 Two transistor analogy of SCR

1.5 Difference Wave Between Diode, SCR (Thyristor) and TRIAC

Figure 1.9 show Input and output (conduction) waveform from selected devices.

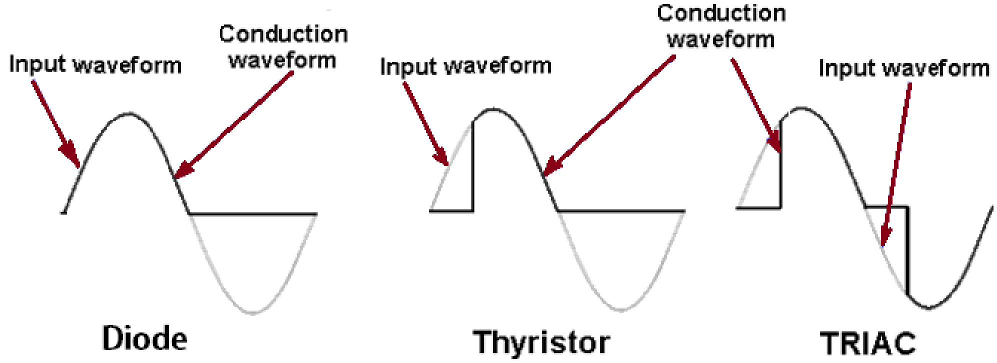


Figure 1.9 Conducion waveform of devices

1.6 Matemathics Equations

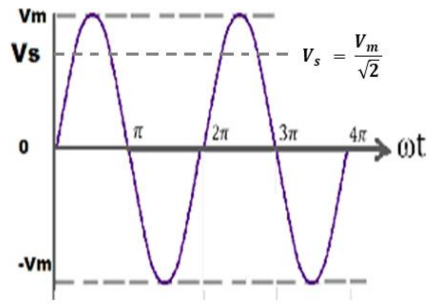


Figure 1.10 Supply waveform

Input voltage (or DC voltage) ,

$$V_{(avg)} = \frac{1}{T}\int_L^U V_m \sin\omega t \, d\omega t \qquad \textbf{(1.1)}$$

$$\boldsymbol{V_s} = \frac{\boldsymbol{V_m}}{\sqrt{2}} \qquad \textbf{(1.2)}$$

RMS input voltage,

$$V_{(RMS)} = \sqrt{\frac{1}{T}\int_L^U (V_m \sin\omega t)^2 \, d\omega t} \qquad \textbf{(1.3)}$$

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

$$= \frac{V_m}{\pi}\int_0^\pi \sin\omega t \, d\omega t$$

$$= \frac{V_m}{\pi}[-\cos\omega t]_0^\pi$$

$$= \frac{V_m}{\pi}[\cos 0 - \cos\pi]$$

$$V_{i\,(avg)} = V_{DC} = \frac{2V_m}{\pi} \qquad \textbf{(1.4)}$$

$$(\sin\omega t)^2 = sin^2\omega t \qquad \textbf{(1.5)}$$

$$sin^2\omega t = 1 - \cos 2\omega t \qquad \textbf{(1.6)}$$

$$V_{i(RMS)} = \sqrt{\frac{1}{T}\int_0^\pi (V_m \sin\omega t)^2 \, d\omega t}$$

$$= \sqrt{\frac{{V_m}^2}{\pi}\int_0^\pi \frac{1}{2}(1 - \cos 2\,\omega t)\, d\omega t}$$

$$= \sqrt{\frac{{V_m}^2}{\pi}\left(\frac{1}{2}\right)\left[\omega t - \frac{\sin 2\,\omega t)}{2}\right]_\alpha^\pi}$$

$$= V_m\sqrt{\frac{1}{2\pi}[(\pi - 0) - (0)]}$$

$$\boldsymbol{V_s} = \frac{\boldsymbol{V_m}}{\sqrt{2}} \qquad \textbf{(1.7)}$$

1.7 Output Equations

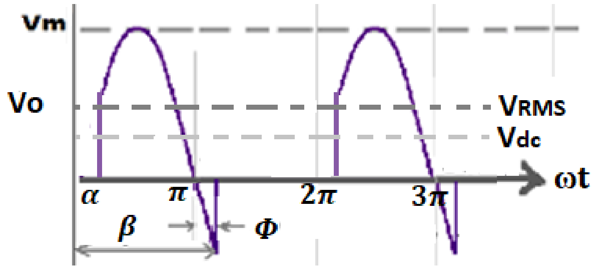


Figure 1.11 Output waveform

Average output voltage (or DC voltage) ,

$$V_{o\,(avg)} = \frac{1}{T}\int_{L}^{U} V_m \sin \omega t \, d\omega t$$

$$V_{o\,(avg)} = \frac{1}{T}\int_{\alpha}^{\beta} V_m \sin \omega t \, d\omega t$$

$$= \frac{V_m}{T}\int_{\alpha}^{\beta} \sin \omega t \, d\omega t$$

$$= \frac{V_m}{T}[-\cos \omega t]_{\alpha}^{\beta}$$

$$= \frac{V_m}{T}[\cos \alpha - \cos \beta] \qquad (1.8)$$

RMS output voltage,

$$V_{o\,(RMS)} = \sqrt{\frac{1}{T}\int_{L}^{U} (V_m \sin \omega t)^2 \, d\omega t}$$

$$V_{o\,(RMS)} = \sqrt{\frac{1}{T}\int_{\alpha}^{\beta} (V_m \sin \omega t)^2 \, d\omega t}$$

$$= \sqrt{\frac{{V_m}^2}{T}\int_{\alpha}^{\beta}\frac{1}{2}(1-\cos 2\,\omega t)\, d\omega t}$$

$$= \sqrt{\frac{{V_m}^2}{T}\left(\frac{1}{2}\right)\left[\omega t - \frac{\sin 2\,\omega t}{2}\right]_{\alpha}^{\beta}}$$

$$= V_m\sqrt{\frac{1}{2T}\left[(\beta-\alpha) - \left(\frac{\sin 2\,\beta}{2} - \frac{\sin 2\,\alpha}{2}\right)\right]} \qquad (1.9)$$

1.8 Types of Power Electronics Circuits

Type of Converter	Function	Application
Uncontrolled rectifier **(AC to DC Converter)**	An uncontrolled rectifier converts a single-phase or three phase AC voltage to a fixed DC voltage. Diodes are used as the rectifying elements to provide power conversion.	➢ DC source for electronic circuits
Controlled rectifier **(AC to DC Converter)**	A controlled rectifier converts a single-phase or three phase fixed AC voltage to a variable DC voltage. SCRs are used as the rectifying elements, providing both power conversion and control.	➢ DC motor speed control from an AC source ➢ Speed control of portable power tools ➢ High-voltage DC transmission ➢ DC Power Supply ➢ Battery charger
DC Chopper **(DC to DC Converter)**	A DC chopper converts a fixed DC voltage to a variable DC voltage	➢ DC motor speed control from a DC source ➢ Switching power supply
Inverter **(DC to AC Converter)**	An inverter converts a fixed DC voltage to a fixed or variable single-phase or three-phase AC voltage and frequency.	➢ Uninterruptible power supply (UPS) ➢ Speed control of three-phase AC motors ➢ Induction heating
AC voltage controller **(AC to AC Converter)**	An AC voltage controller converts a fixed AC voltage to a variable AC voltage at the same frequency. There are two basic methods used in AC voltage controllers – on-off control and phase control.	➢ Light dimmer switch ➢ Control of heaters ➢ Speed control of domestic appliances ➢ Reactive power control ➢ Smooth starting of induction motors
Cycloconverter **(AC to AC Converter)**	Change and control voltage magnitude and frequency	➢ Speed control of AC motors ➢ Constant frequency source for aircraft
Static switch **(AC or DC Converter)**	A power device (SCR and TRIAC) can be operated as an AC or DC switch, thereby replacing traditional mechanical and electromagnetic switches.	➢ Replacement for mechanical and electromagnetic switches

Chapter 2

Uncontrolled Rectifier

Rectification is the process of converting the alternating voltages and currents to direct currents and the device is known as rectifier. **Uncontrolled rectifier** uses only **diodes** to rectify current. There are two different types of uncontrolled rectifiers or diode rectifiers, half wave and full wave rectifiers. Full-wave rectifiers has better performance than half wave rectifiers. But the main advantage of half wave rectifier is its need to less number of diodes than full wave rectifiers.

2.1 Overview of Rectifier

There are two different types rectifiers: Uncontrolled rectifier and Controlled rectifier.

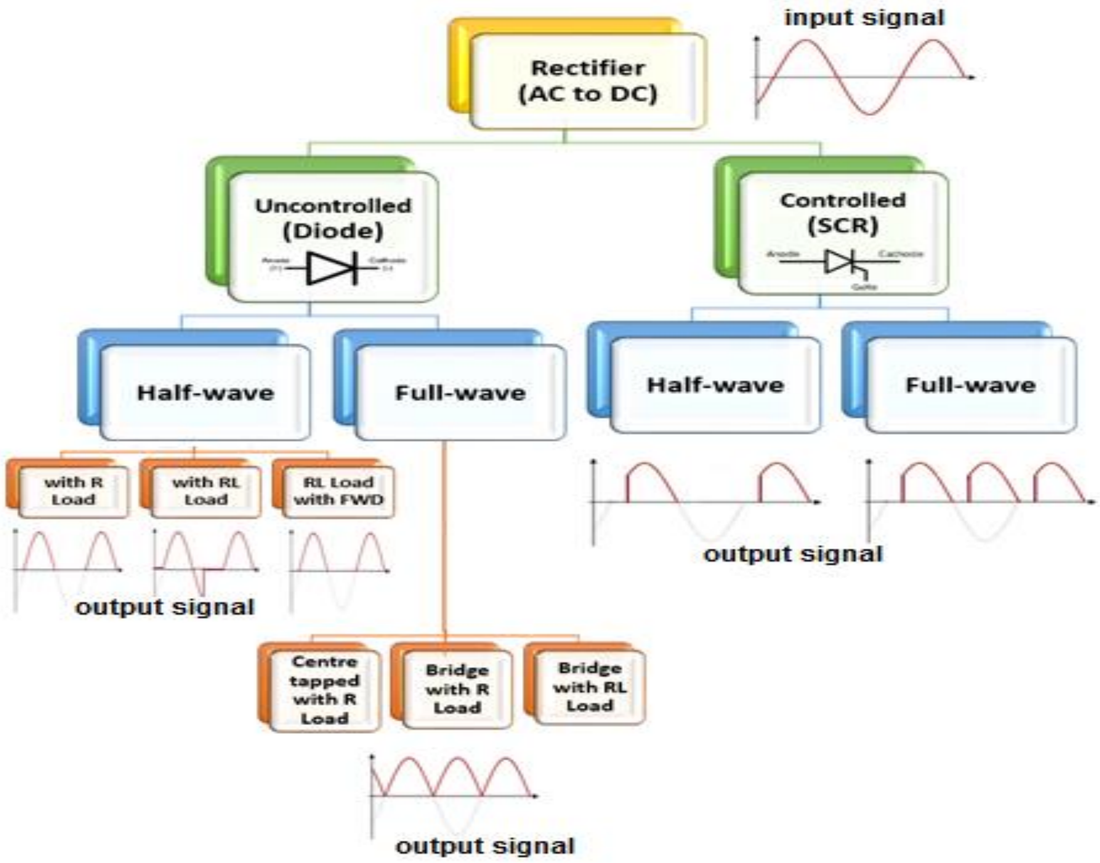


Figure 2.1 Topology of single phase rectifier

2.2 Single-Phase Half-wave Uncontrolled Rectifier R load

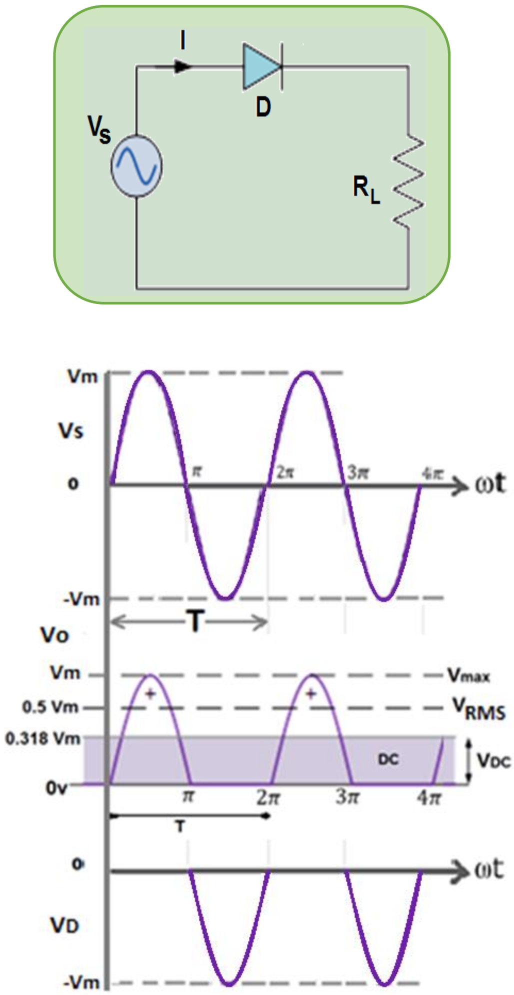


Figure 2.2 Circuit and Waveform of half-wave rectifier with R load

The source voltage is a sine wave with a maximum value V_m and period T .

- During positive half-cycle, diode turns on (anode is positive with respect to cathode), current flow through the load , R_L. Thus , the load voltage V_o follows the positive sine wave.
  $I_m = \frac{V_m}{R_L}$
- During negative half-cycle, diode turns off (anode becomes negative with respect to cathode), no current flow through the load , R_L.
  The half-wave rectifier contain a large ripple, therefore it has limited practical value of high-power applications.

Average output voltage (or DC voltage) ,

$$V_{o\,(avg)} = V_m/\pi = 0.318\,V_m \qquad \textbf{(2.1)}$$

RMS output voltage,

$$V_{o\,(RMS)} = \frac{V_m}{2} \qquad \textbf{(2.2)}$$

The rectifier efficiency is defined as the ratio of DC output power to AC input power: $\eta = \frac{P_{DC}}{P_{AC}}$ **(2.3)**

The AC power input ,

$$P_{AC} = V_{RMS} * I_{RMS} \qquad \textbf{(2.4)}$$

The output DC power, $P_{dc} = V_{dc} * I_{dc}$ **(2.5)**

The output AC power, $P_{ac} = V_{rms} * I_{rms}$ **(2.6)**

$$V_{ac} = \sqrt{V^2{}_{rms} - V^2{}_{dc}} \qquad \textbf{(2.7)}$$

Ripple Factor,

$$RF = \frac{V_{ac}}{V_{dc}} = \sqrt{FF^2 - 1} \qquad \textbf{(2.8)}$$

Example 1:

The rectifier shown in Figure 2.2(a) has a pure resistive load of R .
Determine:
(a) The efficiency,
(b) Form factor
(c) Ripple Factor
(d) Peak Inverse voltage (PIV) of diode D1

Solution:

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{V_{dc} * I_{dc}}{V_{rms} * I_{rms}} = \frac{\frac{V_m}{\pi} * \frac{V_m}{\pi R}}{\frac{V_m}{2} * \frac{V_m}{2R}} = 40.53\%$$

$$FF = \frac{V_{rms}}{V_{dc}} = \frac{\frac{V_m}{2}}{\frac{V_m}{\pi}} = \frac{\pi}{2} = 1.57$$

$$RF = \frac{V_{ac}}{V_{dc}} = \sqrt{FF^2 - 1} = \sqrt{1.57^2 - 1} = 1.211$$

It is clear from Fig 2.2(b) that the PIV is V_m

2.3 Single-Phase Half-wave Uncontrolled Rectifier RL load

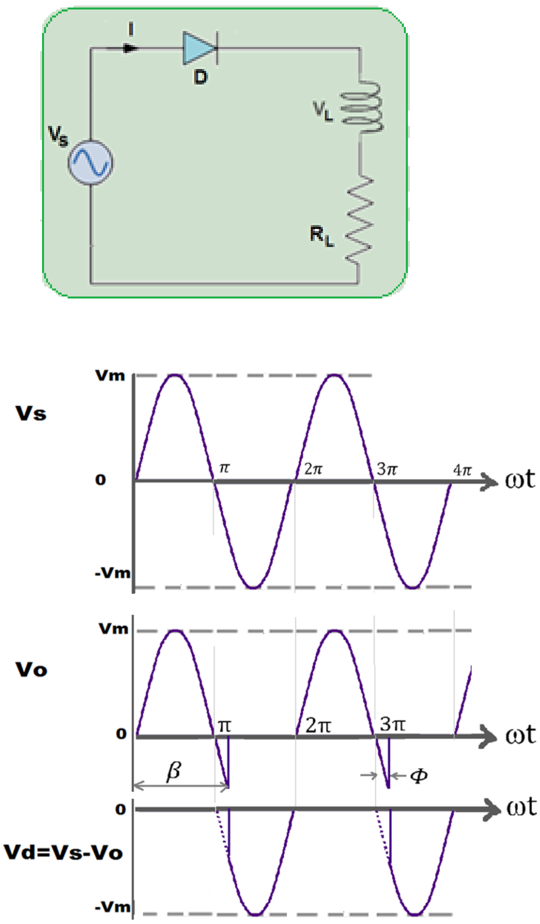


Figure 2.3 Circuit and Waveform of half-wave rectifier with Inductive RL load

Operation:

During positive half cycle:

- Diode D is forward biased, Current flow through R and L. Energy is stored in the electromagnetic field surrounding the inductor.
- Because of inductance, the current I_o keeps on increasing until it reaches maximum value.
- Output vpltage,Vo = Vs.
- At π , the supply –voltage reverse but diode does not turn off, because the inductance does not allow the current to go zero instantly.
- The energy stored in the load inductance is supplied to the main supply and the load itself. The output is negative from π to π + Ø .

During negative half cycle:

- The energy stored in the load inductance is supplied to the main supply and the load itself. The output is negative from π to π +Ø º.
- As soon as the current is zero, Diode D reversed biased. The diode remains off for the rest of the negative cycle.

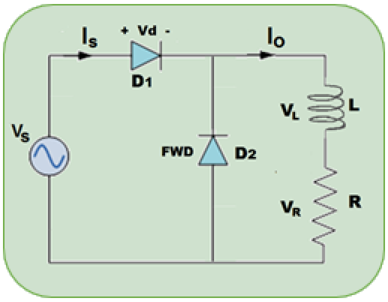
Average output voltage (or DC voltage) ,

$$V_{o\,(avg)} = \frac{V_m}{2\pi}[1 - \cos\beta\ ] \qquad \textbf{(2.9)}$$

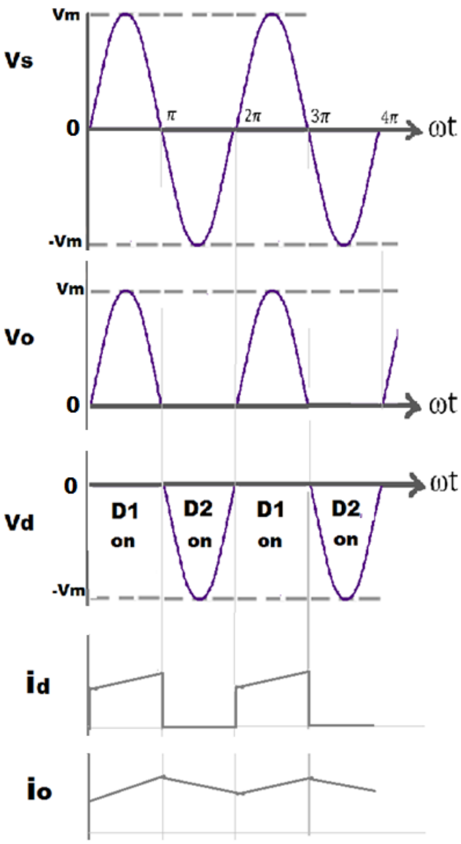
RMS output voltage,

$$V_{o\,(RMS)} = \frac{V_m}{2\sqrt{\pi}}\sqrt{\left((\beta) - \left(\frac{\sin 2\beta\,)}{2}\right)\right)} \qquad \textbf{(2.10)}$$

2.4 Single-Phase Half-wave Uncontrolled Rectifier with Freewheeling Diode (FWD)



(a)



(b)

Figure 2.4 Half-wave rectifier inductive load with a FWD (a) circuit diagram (b) waveforms with large inductive load

Operation:

When positive half cycle:

- Diode D1 forward biased, freewheeling diode D2 is reversed biased
- Vo is same as supply.
- Output current Io increase from zero

When negative half cycle:

- Diode D1 reversed biased, Io tries to go zero, load inductance does not allowed Io drop to zero
- Diode D2 forced to conduct. Output current flows through the freewheeling diode
- Since diode D2 allows the inductor current circulate through L, R and D2 is called freewheeling diode because the current free-wheels through D2.

Average output voltage (or DC voltage) ,

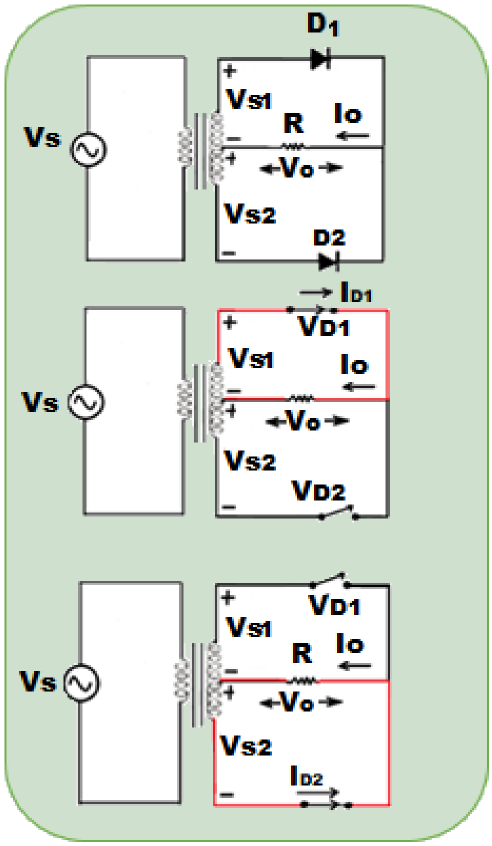
$$V_{o\,(avg)} = V_m / \pi \quad = \quad 0.318\, V_m$$

RMS output voltage,

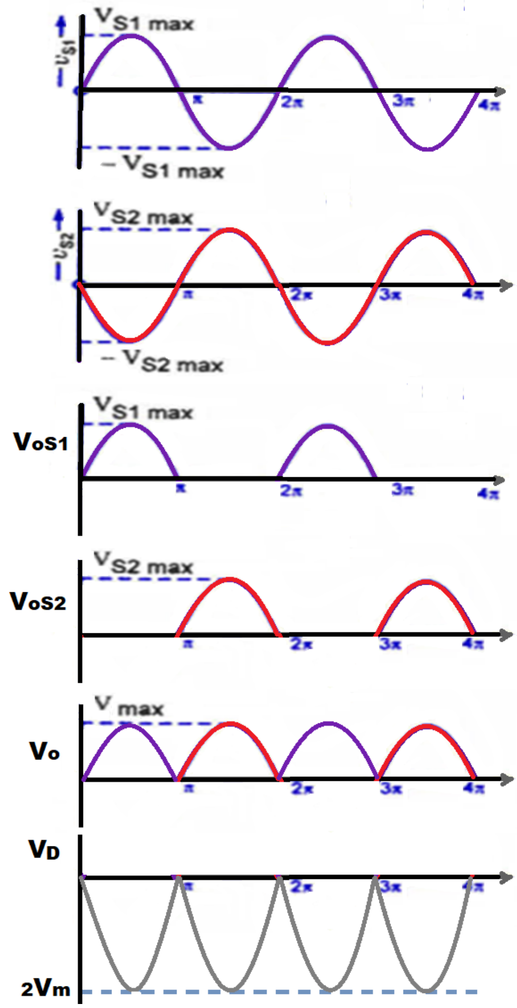
$$V_{o\,(RMS)} = \frac{V_m}{2}$$

A single-phase, half wave rectifier is not very practical due to its low average output voltage, poor efficiency, and high ripple factor. These limitations can be overcome by full-wave rectification. Full-wave rectifiers are more commonly used than half-wave rectifiers, due to their higher average voltages and currents, higher efficiency, and reduced ripple factor. The center tapped full wave rectifier uses a center tapped transformer to convert the input AC voltage into output DC voltage.

2.5 Single-Phase Full-wave Uncontrolled Rectifier (Center Tapped)



(a)



(b)

Figure 2.5 Center tapped Full-wave rectifier resistive load with a FWD
(a) circuit diagram (b) waveforms

During the positive half-cycle

- Diode D1 conducts and D2 is reverse-biased. Current flows through the load, causing a positive drop.

During the negative half-cycle

- Diode D2 conducts and D1 turn off. Current flows through R load, maintaining the same polarity for the voltage across the load.

Average and RMS values are similar to those for the half-wave case:

$$V_{o(avg)} = \frac{2\,V_m}{\pi} = 0.636\,V_m$$

$$I_{oRMS} = \frac{Im}{\sqrt{2}} = 0.707\,Im$$

PIV rating for diodes : ≥ 2 V_m

The average diode current :

$$I_{D1(avg)} = I_{D2(avg)} = I_{o(avg)}/2 = \frac{Im}{\pi}$$

The average or DC power delivered to the load is given by:

$$P_{o(avg)} = \frac{4{V_m}^2}{\pi^2 R} \qquad \textbf{(2.11)}$$

The AC power input is given by

$$P_{AC} = V_{RMS} * I_{RMS} = \frac{{V_m}^2}{2R} \qquad \textbf{(2.12)}$$

The Form factor: $FF = \frac{V_{rms}}{V_{dc}}$

The ripple factor:

$$RF = \frac{V_{ac}}{V_{dc}} = \sqrt{FF^2 - 1}$$

2.6 Single-Phase Full-wave Uncontrolled Rectifier (Center Tapped)

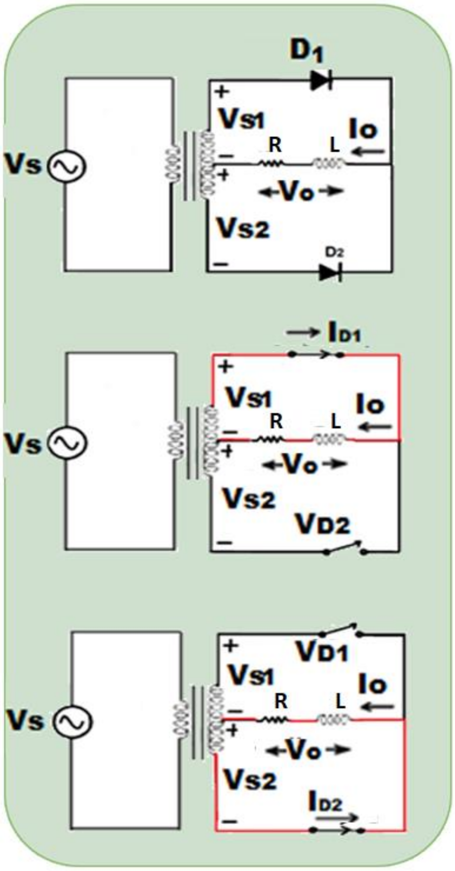


Figure 2.6 shows a center tapped full-wave rectifier with an inductive load.

During the positive half-cycle,

- Diode D1 conducts and D2 is reverse-biased. Current flows through the load, causing a positive drop and energy were stored in its magnetic fields

During the negative half-cycle,

- Diode D2 conducts and D1 turn off. Current flows through R load, maintaining the same polarity for the voltage across the load.

The equation are similar to center tap rectifier with a resistive load.

The average value of the load voltage is:

$$V_{o(avg)} = \frac{2\,V_m}{\pi} = 0.636\,V_m \qquad \textbf{(2.13)}$$

The average value of the load current is:

$$I_{o(avg)} = \frac{2\,V_m}{\pi R} = 0.636\,\frac{V_m}{R} \qquad \textbf{(2.14)}$$

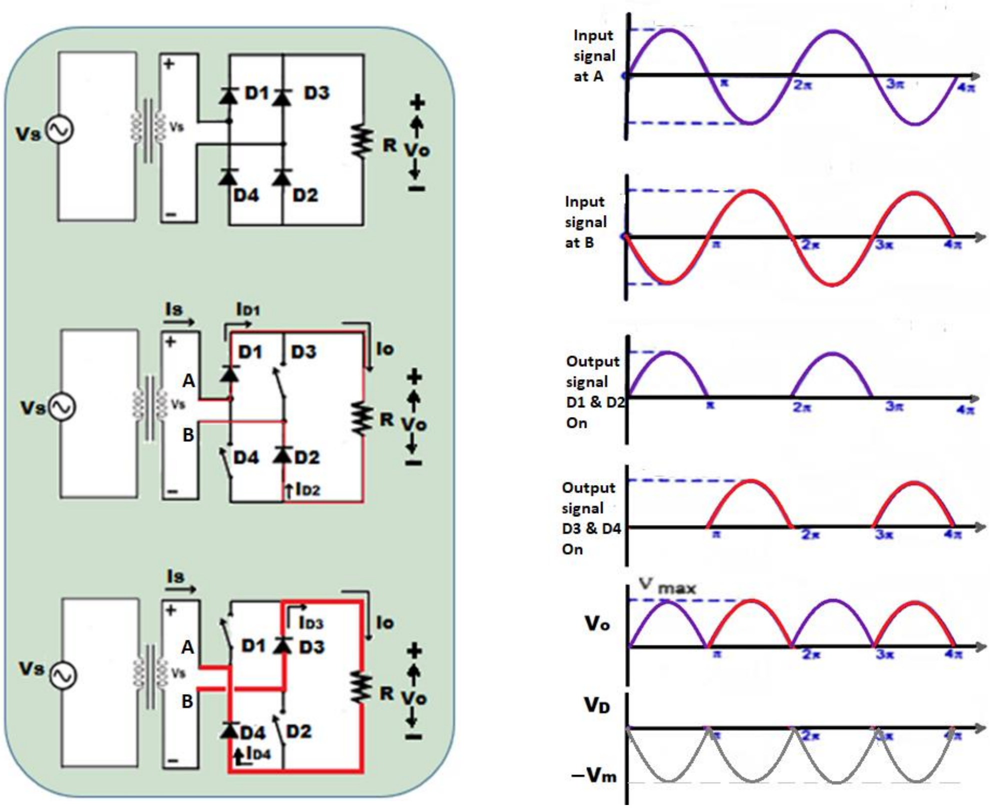
If the load inductance is sufficiently large, the load current is nearly constant.

The RMS value of the load current is:

$$I_{oRMS} = I_{o(avg)} = \frac{V_{o(avg)}}{R}$$

$$I_{D(RMS)} = \frac{I_{o(avg)}}{2} \qquad \textbf{(2.15)}$$

2.7 Single-Phase Full-wave Uncontrolled Bridge Rectifier



(a) (b)

Figure 2.7 Full-wave bridge rectifier resistive load
(a) circuit diagram (b) waveforms

During the positive half cycle,

- The terminal A becomes positive while the terminal B becomes negative. This causes the diodes D_1 and D_2 forward biased and at the same time, it causes the diodes D_3 and D_4 reverse biased.

During the negative half cycle,

- The terminal B becomes positive while the terminal A becomes negative. This causes the diodes D_2 and D_4 forward biased and at the same time, it causes the diodes D_1 and D_3 reverse biased.

The current flow direction during the positive half cycle and negative half cycle is shown in the figure 2.7 (b)

Average and RMS values are similar to those for the full-wave center tap case. However, the waveform of voltage across the diode for each diode equal to V_m only.

$$V_{o(avg)} = \frac{2\,V_m}{\pi} = 0.636\,V_m \qquad \textbf{(2.16)}$$

$$I_{oRMS} = \frac{Im}{\sqrt{2}} = 0.707 \qquad \textbf{(2.17)}$$

The average or DC power delivered to the load is given by:

$$P_{o(avg)} = V_{o(avg)} * I_{o(avg)}$$

$$= \frac{2\,V_m}{\pi} * \frac{2\,I_m}{\pi}$$

$$= \frac{4V_m * V_m}{\pi^2 * R}$$

$$P_{o(avg)} = \frac{4{V_m}^2}{\pi^2 R} \qquad \textbf{(2.18)}$$

2.8 PRACTICAL WORK : UNCONTROLLED RECTIFIER

Using PSIM software, setting the Simulation Control as Figure 2.8.1 , with the guide from Figure 2.8.2, find the Vdc and VRMS. Repeat for Figure 2.8.3 and Figure 2.8.4

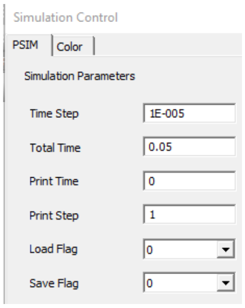


Figure 2.8.1 Simulation Control

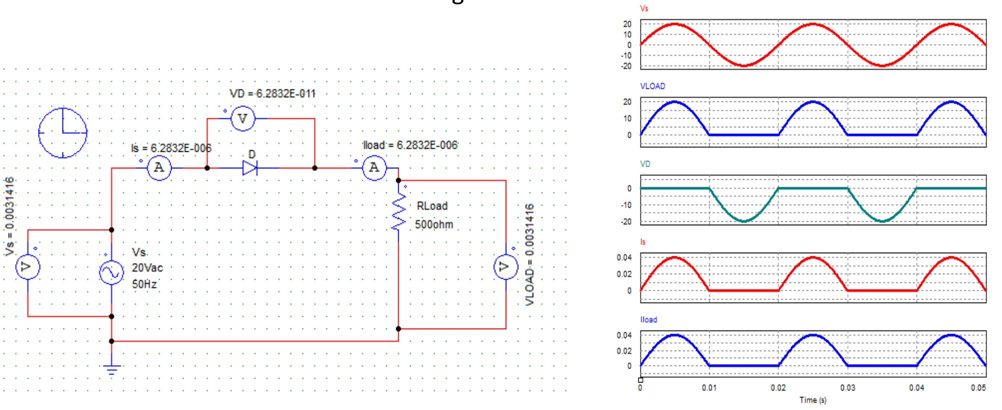


Figure 2.8.2 Half wave Uncontrolled Rectifier (R Load)

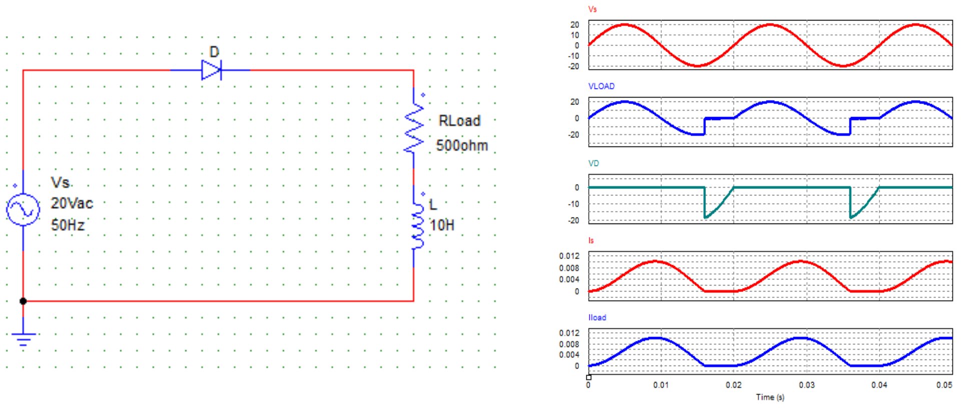
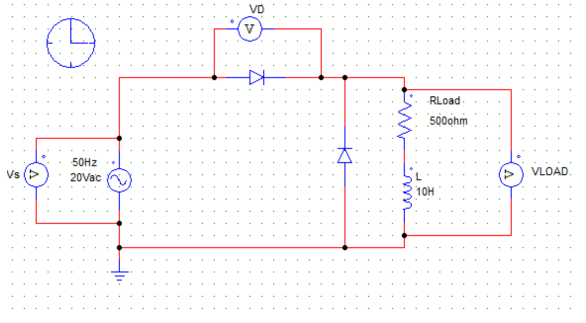


Figure 2.8.3 Half wave Uncontrolled Rectifier (RL Load)



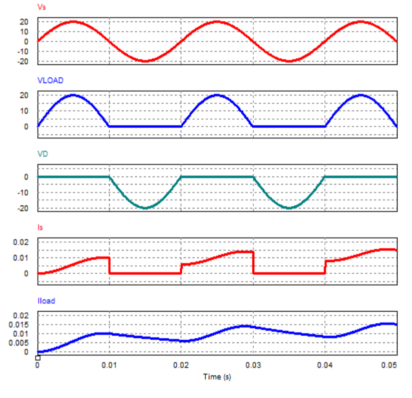


Figure 2.8.3 Half wave Uncontrolled Rectifier
(RL Load with Free wheeling Diode)

2.9 Review Questions

1. Describe the differences between an uncontrolled and a controlled rectifier : The rectifying elemens, DC load voltage, Conduction angle, Required trigger

2. Single phase half wave uncontrolled Rectifier with voltage source 120 sinωt, Calculate output voltage dc (Vdc), Vrms and output current Irms. Given, resistive load is 50Ω.

3. (a) Named the circuit in Figure 2.9
   (b) Based on the figure 2.9 answer the following;
   i. Given VL=120sinωt and Ø=30°, find the value of average output voltage and rms output voltage.
   ii. Sketch the input and output voltage waveform of Figure 2.9.

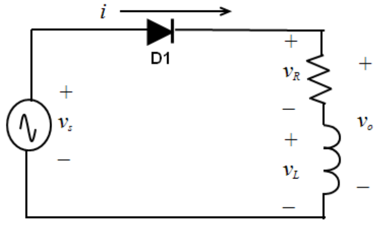


Figure 2.9

4. Referring to Figure 2.10, explain the operation of the circuit.

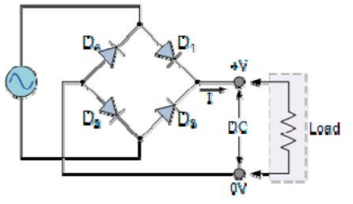


Figure 2.10

Chapter

3 Controlled Rectifier

The simplest controlled rectifier uses a single device, such as a thyristor, to produce variable voltage DC from fixed voltage a.c mains.

3.1 Single Phase Controlled Rectifiers

To build a controlled rectifier, the diodes in the rectifier circuit in Chapter 2 are replaced by SCRs. These circuits produce a variable DC output voltage whose magnitude is varied by controlling the duration of the conduction period by varying the point at which a gate signal is applied to the SCR.

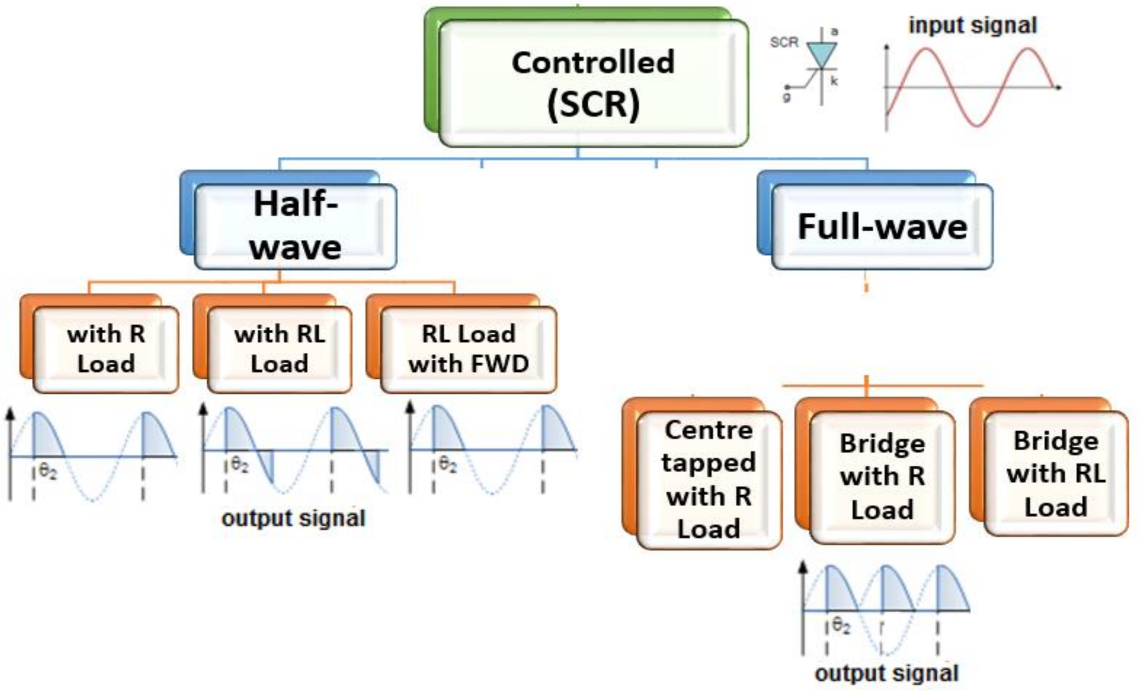


Figure 3.1 Topology of single phase controlled rectifier

The simplest controlled rectifier uses a single device, such as a thyristor to produce variable voltaged.c from fixed voltage a.c. mains.

3.2 Single Phase Half Wave Controlled Rectifiers (R Load)

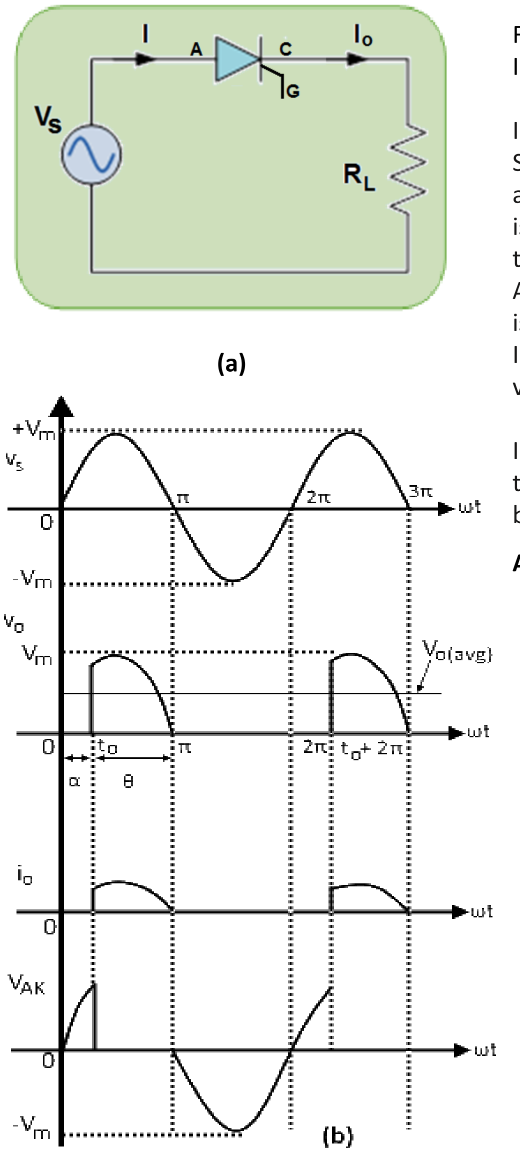


Figure 3.2 Circuit and Waveform of half-wave rectifier with Inductive R load

Figure 3.2 shows of half-wave rectifier with Inductive R load

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 in phase with load voltage.
Inductor stores energy & that generates the voltage.

In negative half cycle,
the voltage developed across inductor, forward biases SCR & maintains its conduction.

Average output voltage (or DC voltage) ,

$$V_{o\,(avg)} = \frac{V_m\ (1+\cos\alpha)}{2\pi} \qquad \textbf{\textit{(3.1)}}$$

RMS output voltage,

$$V_{o\,(RMS)} = \frac{V_m}{2}\sqrt{\left[1-\frac{\alpha}{\pi}+\frac{\sin 2\alpha}{2\pi}\right]} \qquad \textbf{\textit{(3.2)}}$$

Example 3.1

A the single phase half-wave controlled rectifier used to control 100 Ω resistive load with $\alpha = 30^0$ and $V_s = 200 \sin \omega t$. Determine the average output voltage

Solution

$$V_{o\,(avg)} = \frac{V_m}{2\pi}\ (1+\cos\alpha) = \frac{V_m}{2\pi}\ (1+\cos 30)$$

$$= \frac{200}{2\pi}\ (1+0.866) = 59.40\ V$$

3.3 Single Phase Half Wave Controlled Rectifiers (R Load)

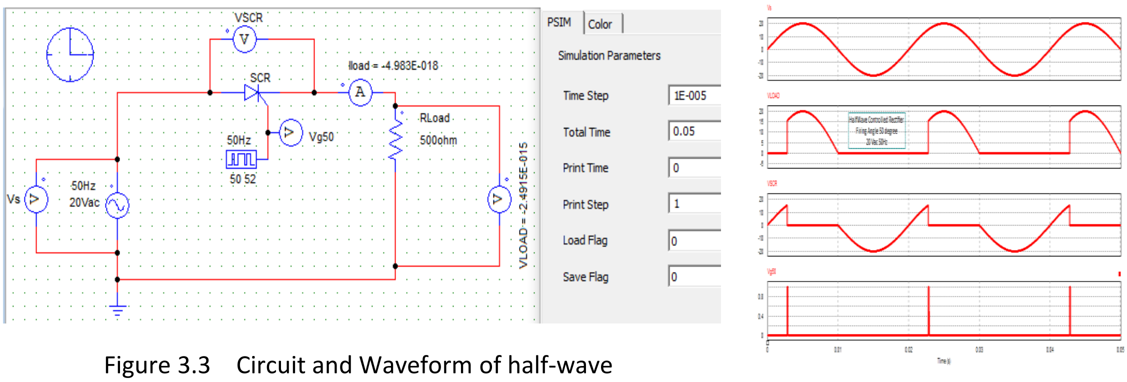


Figure 3.3 Circuit and Waveform of half-wave rectifier with Inductive R load Using PSIM

3.4 Single Phase Half Wave Controlled Rectifiers (RL Load)

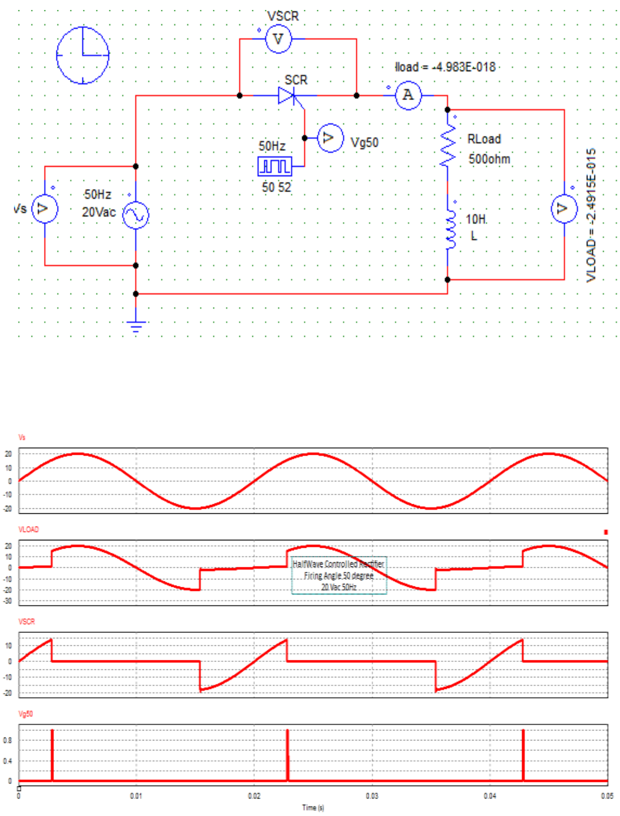


Figure 3.4 Circuit and Waveform of half-wave rectifier with Inductive RL load Using PSIM

Basically Figure 3.4, 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.

Average output voltage (or DC voltage) ,

$$V_{O\,(avg)} = \frac{V_m\,(\cos\alpha - \cos\boldsymbol{\beta})}{2\pi} \qquad \textbf{(3.3)}$$

RMS output voltage,

$$V_{O\,(RMS)} = \frac{V_m}{2}\sqrt{\frac{1}{\pi}\left[(\boldsymbol{\beta} - \boldsymbol{\alpha}\,) - (\frac{\sin 2B}{2\pi} - \frac{\sin 2\alpha}{2\pi})\right]} \qquad \textbf{(3.4)}$$

3.5 Center-Tapped Controlled Rectifiers

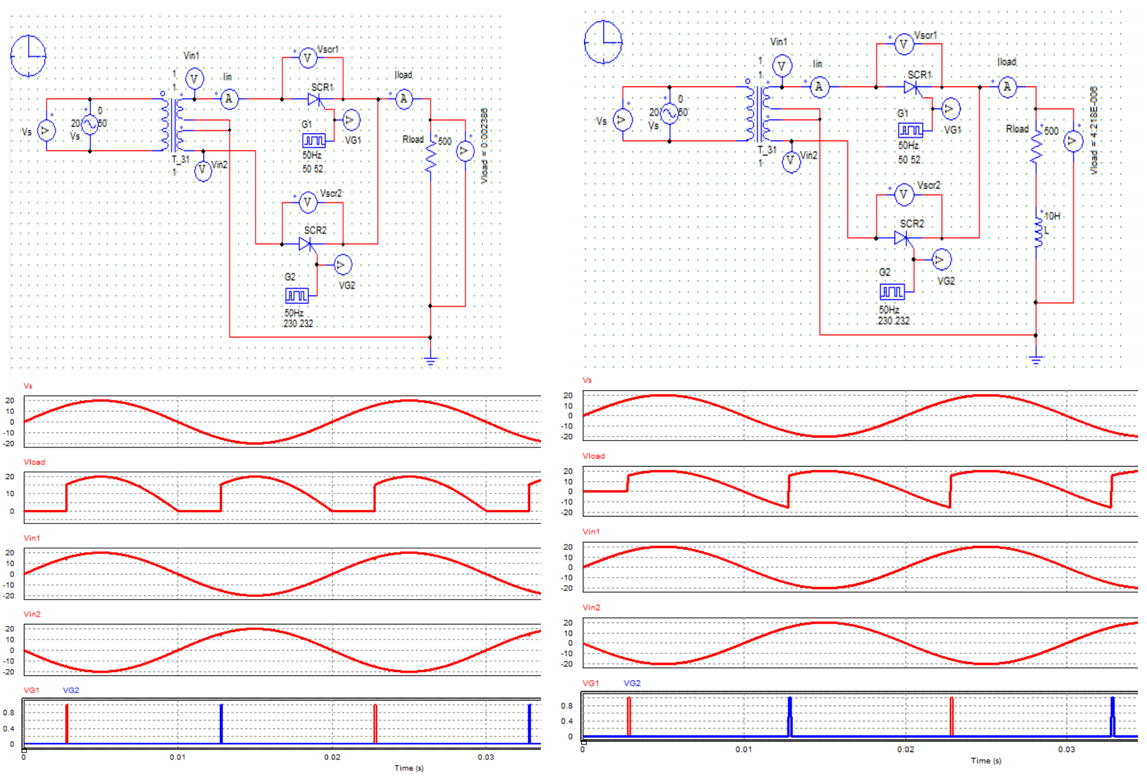
Figure 3.5 (a), In positive half cycle, SCR_1 starts conduction at firing angle α and positive output voltage is produced. In negative half cycle, SCR_2 is forward biased, and start conduct after π + α . Output voltage repeat every half cycle (T = π)

Refer to Figure 3.5 (b), During the positive half cycle of the source, SCR_1 is forward biased and conducts after the gate is triggered at α. During the interval α to π .

SCR_1 are fired at α , hence SCR_1 conduct. The output is positive from α to π. Because of inductance, the current I_o keeps on increasing and become maximum at π. At π the supply –voltage reverse but SCR1 does not turn off. This is because the inductance does not allow the current to go zero instantly. The energy stored in the load inductance is supplied to the main supply and the load itself. The output is negative from π to π + α .

During the interval π + α to 2 π . SCR_2 is fired at π + α, hence SCR_2 conduct. The output is positive from π + α to 2 π. Because of inductance, the load curent I_o keep on increasing.

The similar operation repeats.

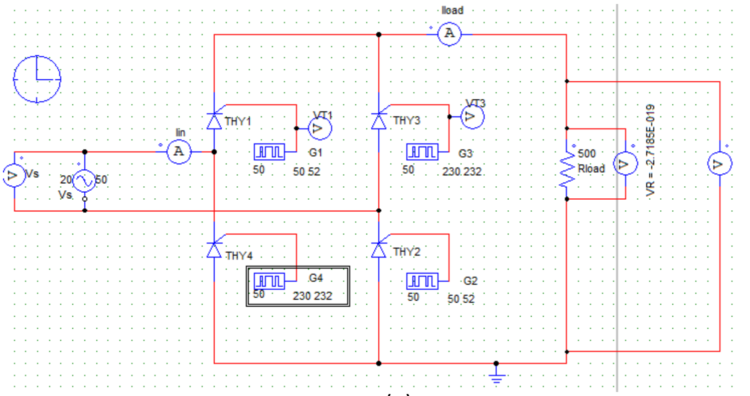


(a) (b)

Figure 3.5 Circuit and Waveform of full-wave Center-tapped rectifier with (a) Resistive Load (b) Inductive R load using PSIM

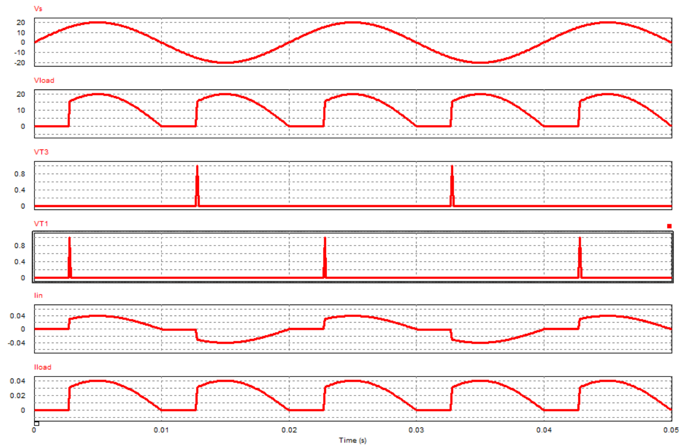
3.6 Bridge Controlled Rectifiers with R Load

Refer to Figure 3.6, During the interval α to π . SCR_1 and SCR_4 are fired at α , hence SCR_1 and SCR_2 conduct. . The output is positive from α to π.
At π the supply –voltage reverse but SCR1 and SCR4 does not turn off.



(a)

During the interval π + α to 2 π . SCR_3 and SCR_4 are fired at π +30°, hence SCR_3 and SCR_4 are conduct. The output is positive from π + α to 2 π
The similar operation repeats.



(b)

Figure 3.6 Circuit and Waveform of Bride rectifier with Resistive load

Average output voltage (or DC voltage) ,

$$V_{o\,(avg)} = \frac{V_m\,(1+\cos\alpha)}{\pi} \qquad \textbf{(3.5)}$$

RMS output voltage,

$$V_{o\,(RMS)} = V_m\sqrt{\frac{1}{2\pi}\left[1-\frac{\alpha}{\pi}+\frac{\sin 2\alpha}{2\pi}\right]} \qquad \textbf{(3.6)}$$

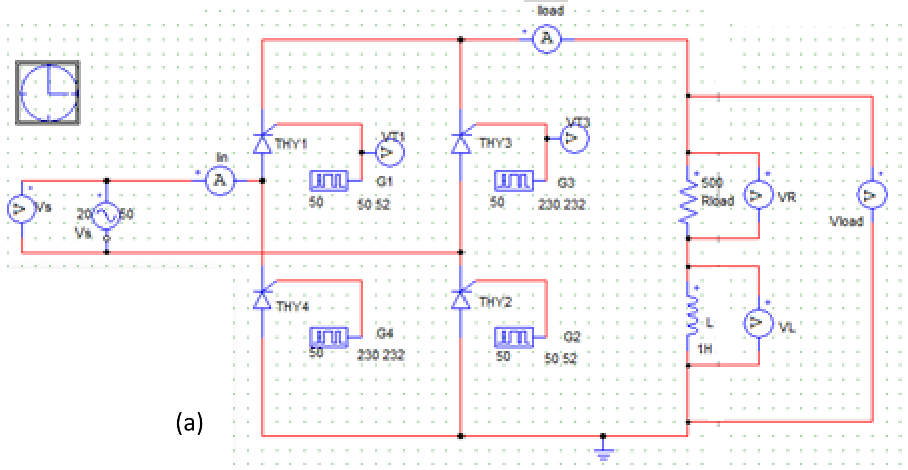
Example 3.2

A single phase fullwave controlled bridge rectifier is supply at 120V. The rectifier is triggered at 30° for highly inductive load. Calculate the average output voltage, Vo(avg) of the rectifier.

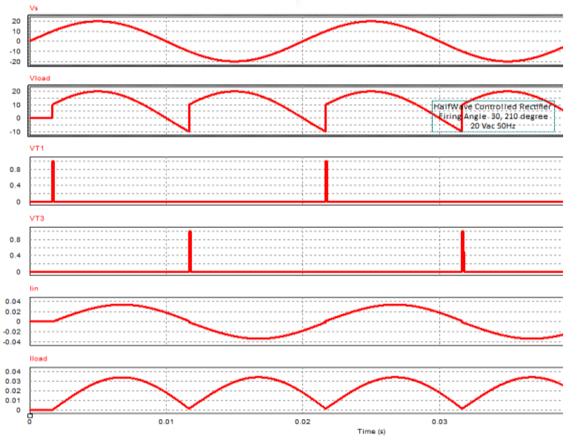
Solution

$V_{o\,(avg)} = \frac{2V_m}{\pi}\,(\cos\alpha)$ = 108.04 cos 30 = 93.56 V

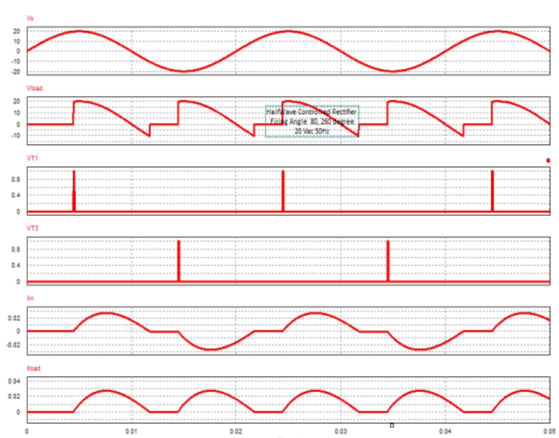
3.7 Bridge Controlled Rectifiers with RL Load



(a)



(b)



(c)

Figure 3.7 Bridge rectifier with Inductive load
(a) Circuit
(b) Waveform for $\alpha < \emptyset$
(c) Waveform for $\alpha > \emptyset$

During the interval α to π .
SCR_1 and SCR_4 are fired at α , hence SCR_1 and SCR_4 conduct. .
The output is positive from α to π.
Because of inductance, the current I_o keeps on increasing and become maximum at π.
At π the supply –voltage reverse but SCR1 and SCR4 does not turn off.
This is because the inductance does not allow the current to go zero instantly.
The energy stored in the load inductance is supplied to the main supply and the load itself.
The output is negative from π to π +30°.
During the interval π + α to 2 π .
SCR_2 and SCR_3 are fired at π +30°, hence SCR_2 and SCR_3 are conduct.
The output is positive from π + α to 2 π
Because of inductance, the load curent I_o keep on increasing.
The similar operation repeats.

Average output voltage (or DC voltage) ,

$$V_{o\,(avg)} = \frac{V_m\ (\cos\alpha - \cos\boldsymbol{\beta})}{\pi}$$

RMS output voltage,

$$V_{o\,(RMS)} = V_m\sqrt{\frac{1}{2\pi}\left[(\beta - \alpha\,) - (\frac{\sin 2B}{2\pi} - \frac{\sin 2\alpha}{2\pi})\right]}$$

3.8 Review Questions

1. A Single phase controlled rectifier half waveshown in Figure 3.8 with R = 10 Ω, L = 20 mH, and Vs = 220 sin 314t and the firing angle α is 30° and β=220°. Determine the current through the load

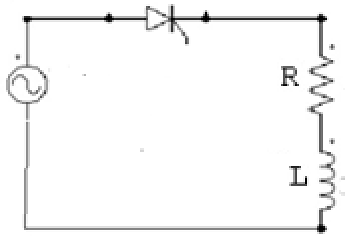


Figure 3.8

2 A single phase full wave controlled rectifier with a supply voltage of 230V is used to control an RL load with advance angle ϕ= 45° Sketch and calculate the average output voltage and rms output voltage for each angle if firing angle :
(i) α = 30°
(ii) α = 60°

3. A single phase rectifier 240V, 50Hz uses four SCRs to control an inductive load, with the triggering angle, α = 60° and the advance angle Ø = 30° , sketch the waveform of the input voltage and the output voltage. Next calculate the average output voltage and the average output current when the resistive and inductive loads are 10 Ω and 20mH. If an additional diode is connected parallel to the load, draw the circuit diagram of the rectifier and sketch the input voltage and output voltage waveform. Calculate the new average output voltage.

Chapter

4 Half Wave Three Phase Rectifier

Three phase converters are 3-phase rectifiers which are used to convert ac input power supply into dc output power across the load.

Its operate from 3 phase ac supply voltage. They provide higher dc output voltage and higher dc output power., also higher output voltage ripple frequency. Requirements are simplified for smoothing out load voltage and load current

4.1 Three Phase Rectifiers

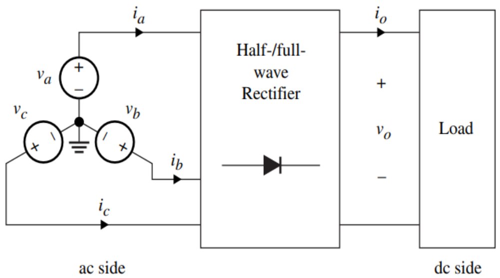


Figure 4.1 Three-phase rectifier

Advantages three phase rectifiers compared with single phase rectifier

1. Higher output voltage for a given input voltage
2. Lower amplitude ripples (although they never fall to zero) i.e smoother DC output
3. Higher frequency ripples, simplifying filtering
4. Higher overall efficiency

4.2 Three Phase Half Bridge Uncontrolled Rectifiers

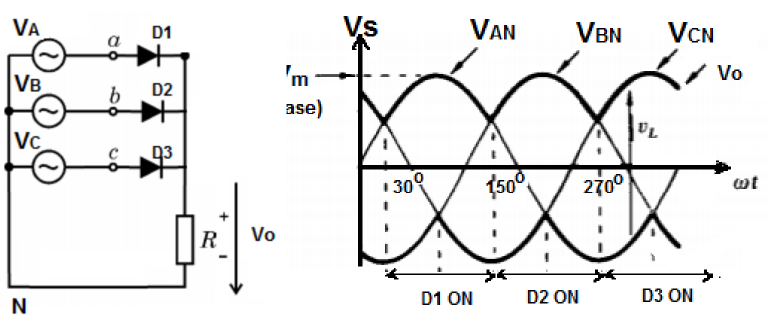


Figure 4.2 Three-phase half-wave rectifier (a) circuit diagram (b) output voltage waveform

Table 4.1

Period	ON diode	OFF diodes	Diode voltages		
			V_{D1}	V_{D2}	V_{D3}
0 to 30°	D_3	D_1 and D_2	V_{AC}	V_{BC}	0
30 to 150°	D_1	D_2 and D_3	0	V_{BA}	V_{CA}
150 to 270°	D_2	D_3 and D_1	V_{AB}	0	V_{CB}
270 to 390°	D_3	D_1 and D_2	V_{AC}	V_{BC}	0

Average output voltage (or DC voltage) ,

$$V_{o\,(avg)} = \frac{1}{T}\int_{\frac{\pi}{6}}^{\frac{5\pi}{6}} V_m \sin\omega t \, d\omega t \qquad T = \frac{2\pi}{3} = 120°$$

$$V_{o\,(avg)} = \frac{3\sqrt{3}}{2\pi} V_m$$

4.3 Three Phase Half-wave Controlled Rectifier R Load

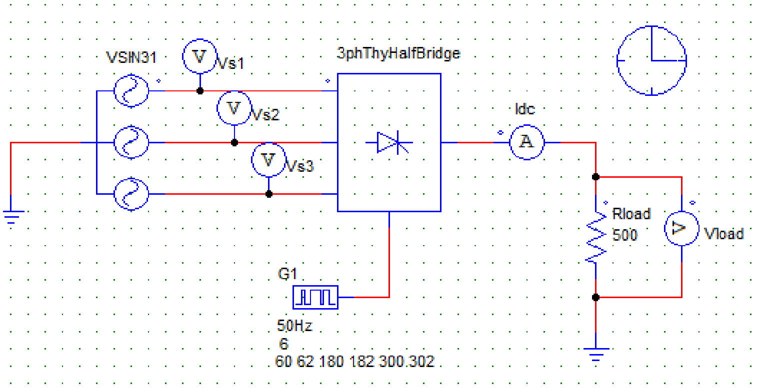
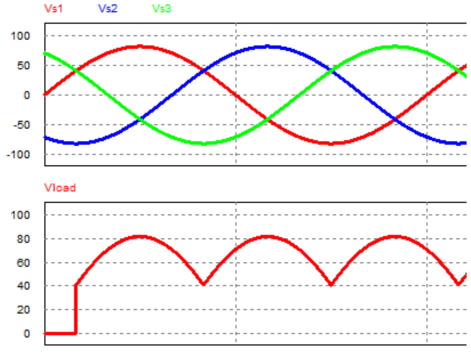
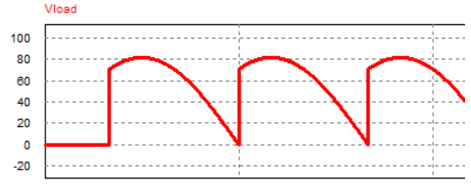


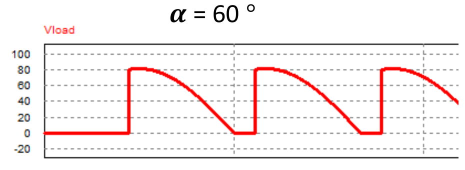
Figure 4.2(a) Circuit of three phase controlled rectifier with resistive load



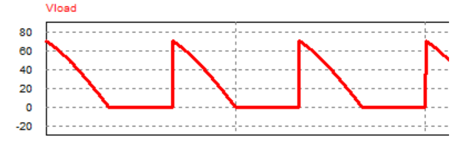
α = 30 °



α = 60 °



α = 80 °



α = 120 °

Figure 4.3(b) Waveform of three phase controlled rectifier with resistive load

The 3-phase half wave converter combines three single phase half wave controlled rectifiers in one single circuit feeding a common load. The thyristor S1 in series with one of the supply phase windings 'a-n' acts as one half wave controlled rectifier. The second thyristor S2 in series with the supply phase winding 'b-n' acts as the second half wave controlled rectifier. The third thyristor S3 in series with the supply phase winding acts as the third half wave controlled rectifier.

Average output voltage (or DC voltage) ,

$$V_{o\,(avg)} = \frac{3\sqrt{3}}{2\pi} V_m \cos \boldsymbol{\alpha}$$

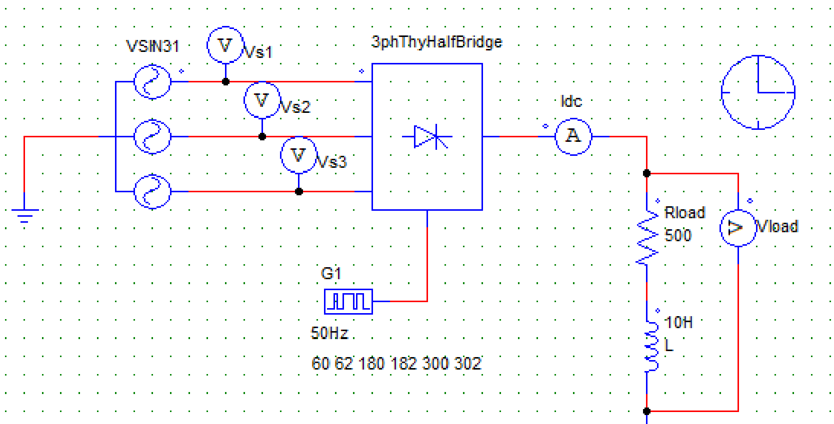
Construct a circuit as Figure 4.2(a) , run simulation and find Avg and RMS value then fill in the table 4.2 below

:

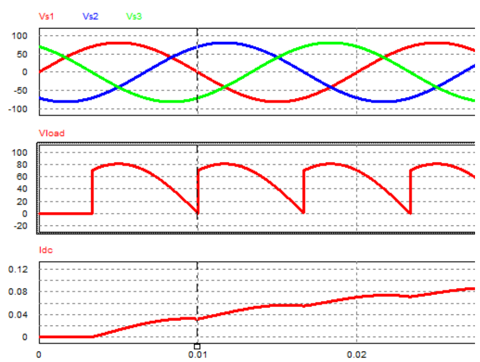
Table 4.2

	VoAvg	IoAvg	VoRMS	IoRMS
60				
80				
120				

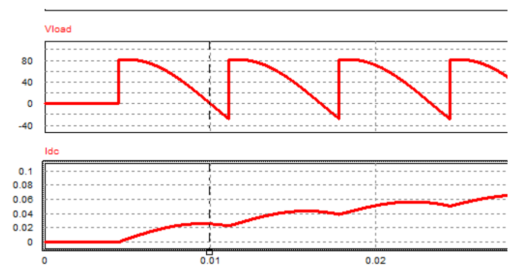
4.4 Three Phase Half-wave Controlled Rectifier RL Load



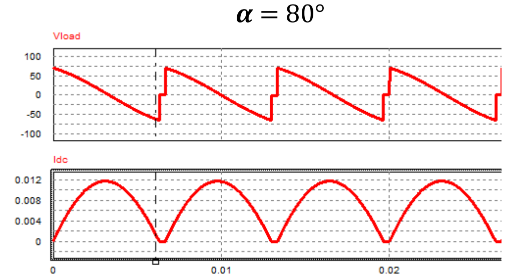
(a) circuit



$\alpha = 60°$



$\alpha = 80°$



$\alpha = 120°$

Average output voltage (or DC voltage) ,

$$V_{o\,(avg)} = \frac{1}{T}\int_{\frac{\pi}{6}}^{\frac{5\pi}{6}} V_m \sin \omega t \, d\omega t$$

$$V_{o\,(avg)} = \frac{3\sqrt{3}}{2\pi} V_m$$

(b) waveform

Figure 4.3 Three-phase half-wave rectifier (a) circuit diagram (b) output voltage waveform

Setting the Simulation Control, construct a circuit as Figure 4.3 (a), find the Avg and RMS value as per table 4.3

Table 4.3

Firing Angle, α (degree)	VoAvg	IoAvg	VoRMS	IoRMS
60				
80				
120				

4.5 Review Questions

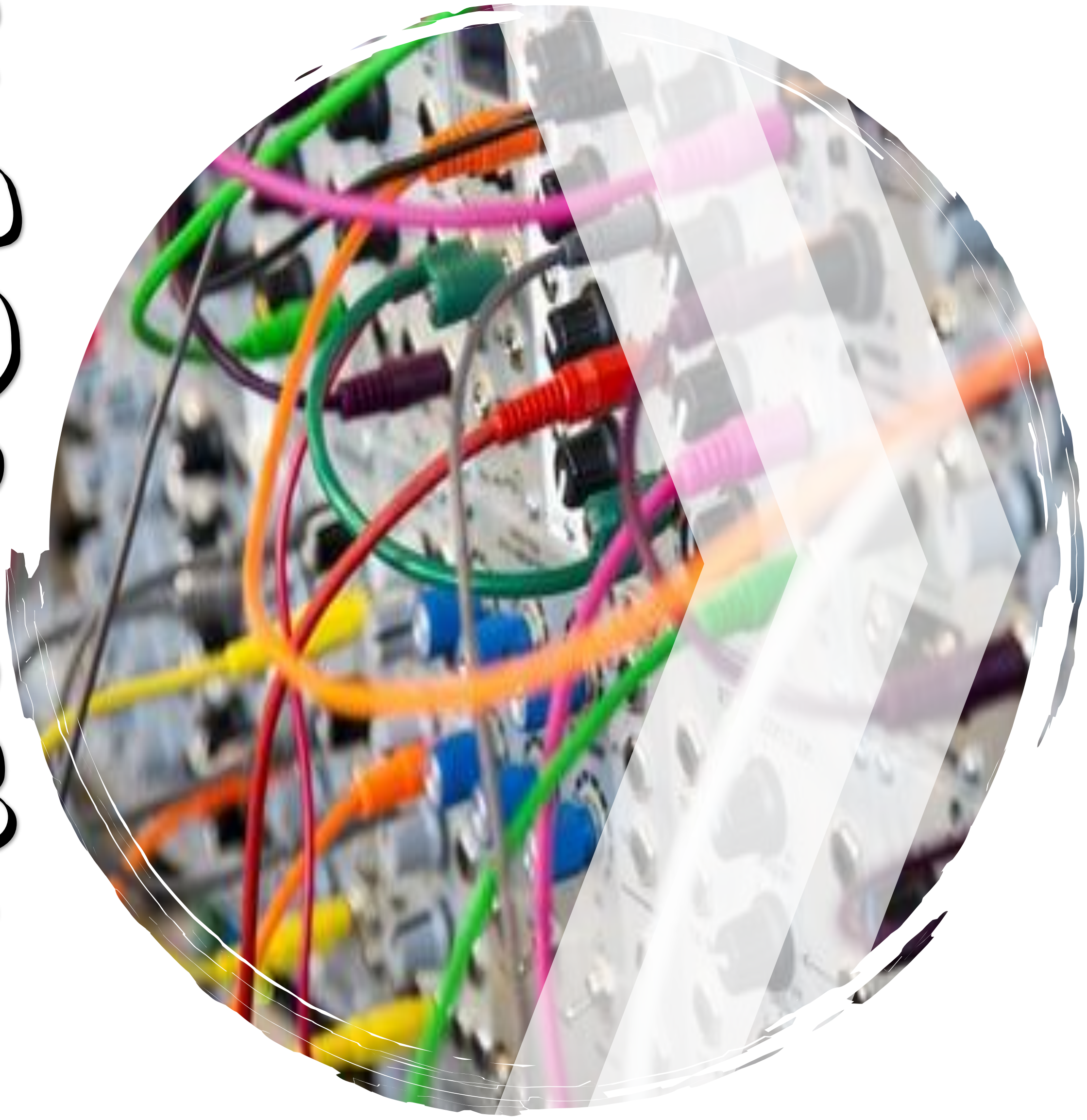
1. A 3-phase half-wave bridge converter is operated from a three-phase Y-connection 220V, 60 Hz supply and load resistor R= 10 Ω. Calculate the average output voltage for $\alpha = \frac{\pi}{6}$

2. A three phase half wave controlled rectifier is connected to 260 V, If the firing angle, α= 20º, explain the circuit operation for the whole cycle (0º to 360º) for the period stated in Table 4.4. By using appropriate scale, sketch the average output voltage $Vo_{(avg)}$. Calculate the $Vo_{(avg)}$; if the load is purely resistive.

Table 4.4.

	Duration period	S1	S2	S3	Vout
1	0º – 20º				
2	20º – 30º				
3	30º – 120º				
4	120º – 140º				
5	140º – 150º				
6	150º – 240º				
7	240º – 160º				
8	260º – 170º				
9	270º – 360º				

Chapter



5 DC Chopper

Dc-dc converters are power electronic circuits that convert a dc voltage to a different dc voltage level, often providing a regulated output. For a good DC-to-DC converter may have an inductor, a capacitor, and a freewheeling diode, and an electronic switch.

Power Electronics

5.1 Introduction To DC Chopper

DC to DC converter (known as DC Chopper) is is used to convert a fixed DC voltage into a variable DC voltage , refer to Figure 5.1

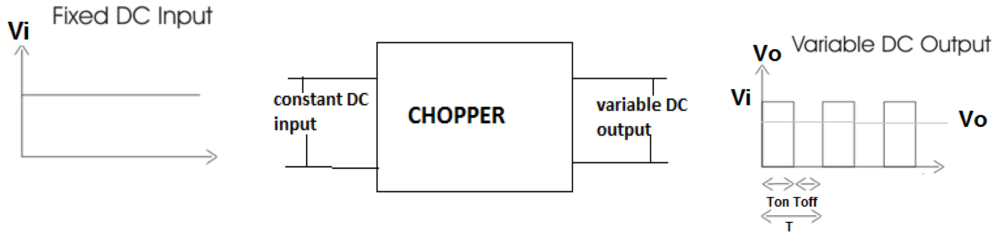


Figure 5.1 Block diagram of DC Chopper

There are three types of basic DC choppers topologies, Figure 5.2 :

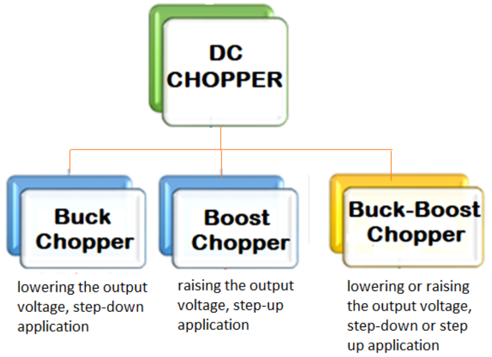
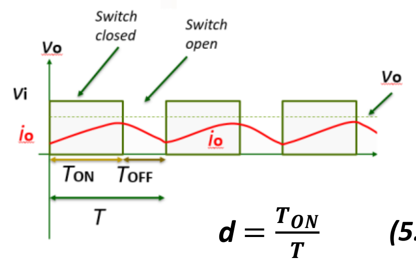


Figure 5.2 DC choppers topologies



$$d = \frac{T_{ON}}{T} \qquad (5.1)$$

where d is duty cycle

Figure 5.3 Basic switching converter

The DC output voltage of the chopper can be varied by varying the duty cycle. The average output voltage can be varied in one of the following ways:

1. Pulse-width modulation (PWM). In this method , the pulse width T_{ON} is varied while the overall switching period T is kept constant.
2. Pulse-frequency modulation (PFM). In this method T_{ON} or T_{OFF} is kept constant while the period

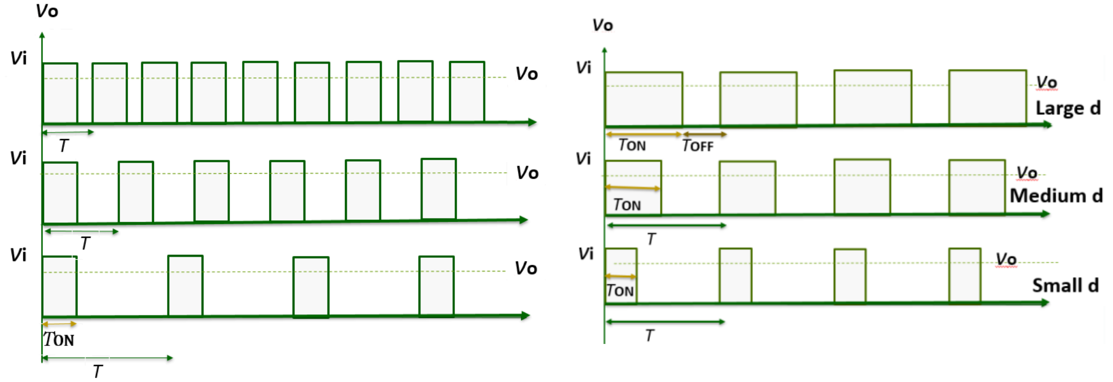


Figure 5.4 Output voltage waveforms with switching frequency (a) PWM (b) PFM

5.2 Buck (or Step-Down) Chopper

The buck chopper is a DC to DC converter Figure 5.4 uses a battery as a DC source. The cicuit consist of switching component, free wheeling diode and loads. The output voltage is less than the input voltage.

$$V_0 = DV_i \qquad (5.2)$$

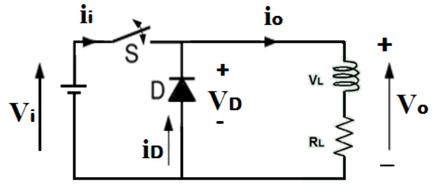


Figure 5.2(a) Buck choppers

Mode 1: when switch is closed

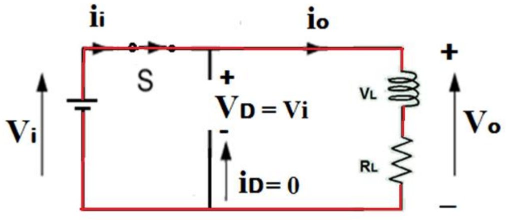


Figure 5.2(b) ON State Buck Chopper

1. Switch S is closed, FWD D reversed biased, D OFF

$$V_0 = \frac{T_{ON}}{T} V_i \qquad (5.3)$$

1. Current flows through inductor L and the Load (R).
2. Vo = Vi
3. Switch S ON for a time TON

The average value of the inductor current

$$I_L = \frac{I_{max} + I_{min}}{2} \qquad (5.4)$$

$$I_L = I_o = \frac{V_o}{R} \qquad (5.5)$$

$$I_{max} + I_{min} = 2\frac{V_o}{R} \qquad (5.6)$$

The voltage across the inductor:

$$V_L = V_0 = L\frac{di_o}{dt} \qquad (5.7)$$

Mode 2: when switch is opened

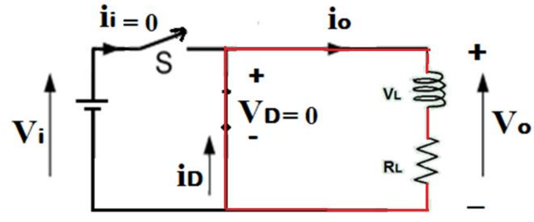


Figure 5.2(c) OFF State Buck Chopper

1. Switch S is opened,
2. Current through inductor L starts decaying to zero (not change instantaneously)
3. This causes an induced voltage with opposite polarity across the inductor.
4. Diode D forward biased.
5. The current flowing freewheels through D and R
6. The energy in L is delivered to the load.

$$\Delta i_o = I_{max} - I_{min} = \frac{V_o}{L} T_{OFF} \qquad (5.8)$$

$$2\, I_{max} = 2\frac{V_o}{R} + \frac{V_o}{L} T_{OFF} \qquad (5.9)$$

Maximum and minimum current:

$$I_{max} = \frac{V_o}{R} + \frac{V_o}{2L} T_{OFF} \qquad (5.10)$$

$$I_{min} = \frac{V_o}{R} - \frac{V_o}{2L} T_{OFF} \qquad (5.11)$$

Peak to peak ripple current:

$$I_{p-p} = I_{max} - I_{min} \qquad (5.12)$$

$$I_{p-p} = \frac{V_o}{L} T_{OFF} \qquad (5.13)$$

The output voltage and output current of buck chopper :

$$P_i = P_O \qquad (5.14)$$

$$V_i\, I_i = V_O\, I_o \qquad (5.15)$$

$$I_0 = \frac{I_i}{d} \qquad (5.16)$$

5.3 Practical of Buck Chopper

Setting the Simulation Control, construct a buck chopper as Figure 5.5, find the voltage output with the duty cycle as Table 5.1 by setting the gating block.

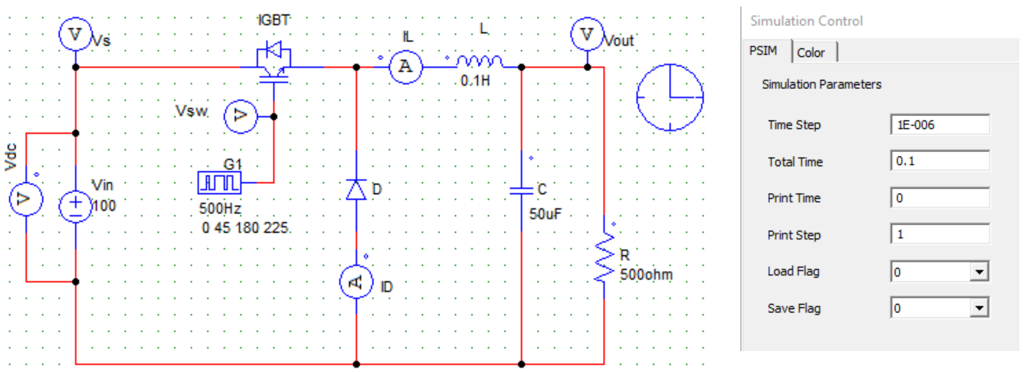


Figure 5.5 Buck choppers

Table 5.1

Duty cycle	Waveform	Voltage input and output
D=0.5 0 90 180 270		Vdc = Vs = Vout =
D=0.25 0 45 180 225		Vdc = Vs = Vout =

Example 5.1

A buck converter is supplied from a 100 V battery source. Given L =100 mH,, R=10 Ω, fs=1 kHz and the on time is 0.5 ms . If the average source current is 1A, Calculate;

i. The average load voltage

$T = 1/fs$ = 1/1000 = 1ms

$D = \frac{T_{ON}}{T} = \frac{0.5}{1}$ = 0.5 or 50%

$V_0 = dV_i$ = (0.5) (100) = 50V

ii. The output current

$I_0 = \frac{I_i}{d} = \frac{1}{0.5}$ = 2A

iii. The output power

$P_0 = V_O I_O$ = (50V) (2A) = 100W

iii. The minimum value of required

$T_{OFF} = T - T_{ON}$ = 0.5 ms

$L = \frac{T_{OFF} R}{2}$

$= \frac{(0.5x10^{-3})(10)}{2}$ = 2.5 mH

5.4 Boost Chopper

In the step-up (boost chopper) circuit, the output voltage can be varied several times from the source voltage. The basic circuit is shown in Figure 5.4.

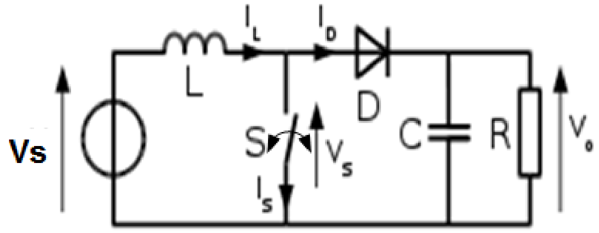


Figure 5.4 Buck chopper

Mode 1: when switch is closed (ON-state)

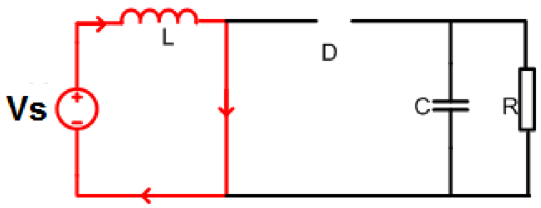


Figure 5.4.1 ON state of Buck chopper

Mode 2: when switch is opened (OFF-state)

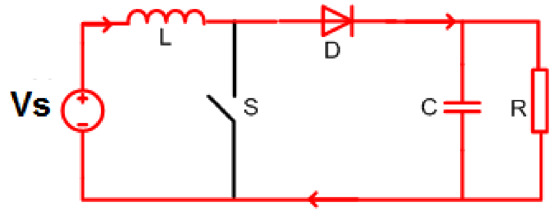


Figure 5.4.2 OFF state of Buck chopper

When switch ON, the inductor connect to supply, Current through inductor,increase linearly and stores energy in the magnetic field.

The voltage across the inductor:

$$V_L = V_s = L\frac{di_o}{dt} \qquad (5.17)$$

$$\frac{di_o}{dt} = \frac{V_o}{L} \qquad (5.18)$$

$$I_L = \frac{I_{max} + I_{min}}{2} \qquad (5.19)$$

Now $I_L = I_i$

$$\frac{I_{max} + I_{min}}{2} = I_i$$

$$I_{max} + I_{min} = 2I_i$$

Voltage across Inductor:

$$V_L = V_i = L\frac{di_o}{dt} \qquad (5.20)$$

$$\frac{di_i}{dt} = \frac{V_i}{L} \qquad (5.21)$$

When switch OFF, current collapses and the energy stored in the inductor is transferred to the capacitor through diode D.
The induced voltage VL across the inductor reversed, and the inductor voltage adds to the source voltage to increased the output voltage, the energy stored in the inductor is released to the load.

Energy transferred by inductance during TOFF must equal the energy gained by it during the period TON

$$W_{ON} = W_{OFF} \qquad (5.22)$$

$$V_O = V_i = V_i\frac{T_{ON}}{T_{OFF}} \qquad (5.23)$$

$$= V_i\,(1 + \frac{T_{ON}}{T_{OFF}}) \qquad (5.24)$$

$$V_0 = V_i\,(\frac{1}{1 - \frac{T_{ON}}{T}})$$

$$V_0 = V_i\,(\frac{1}{1 - d}), \qquad (5.26)$$

5.5 Boost Chopper

With the switch open (T_{OFF})

$$\Delta i_i = \frac{V_i}{L} \Delta t \quad (5.26)$$

$$I_{max} - I_{min} = \frac{V_o}{L} T_{OFF} \quad (5.27)$$

$$2\, I_{max} = 2I_i + \frac{V_i}{L} T_{ON} \quad (5.28)$$

$$I_{max} = I_i + \frac{V_i}{2L} T_{ON} \quad (5.29)$$

$$= \frac{V_i}{(1-d)^2 R} + \frac{V_i}{2L} T_{ON}$$

$$I_{max} = V_i \left[\frac{1}{(1-d)^2 R} + \frac{T_{ON}}{2L}\right] \quad (5.30)$$

$$I_{min} = V_i \left[\frac{1}{(1-d)^2 R} - \frac{T_{ON}}{2L}\right] \quad (5.31)$$

The peak to peak current:

$$I_{p-p} = I_{max} - I_{min} = \frac{V_i}{L} T_{ON} \quad (5.32)$$

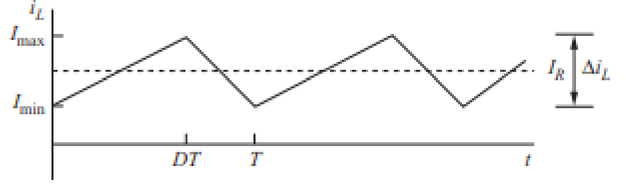


Figure 5.5 Minimum and maximum current of choppers

The output current of boost chopper :

$$P_i = P_O \quad (5.33)$$

$$V_i\, I_i = \frac{{V_O}^2}{R} \quad (5.34)$$

From **(5.26)**

$$I_i = \frac{V_i}{(1-d)^2 R} \quad (5.35)$$

$$I_o = I_i \frac{T_{OFF}}{T} = I_i\, (1\text{-}d) \quad (5.36)$$

For continuous current condition, the minimum value of inductance required is obtained by setting

$$I_{min} = V_i \left[\frac{1}{(1-d)^2 R} - \frac{T_{ON}}{2L}\right] = 0, \quad (5.37)$$

$$\frac{1}{(1-d)^2 R} = \frac{T_{ON}}{2L}, \quad (5.31)$$

solve for $L = \frac{T_{ON}}{2}(1-d)^2 R$ **(5.31)**

5.6 Practical of Boost Chopper

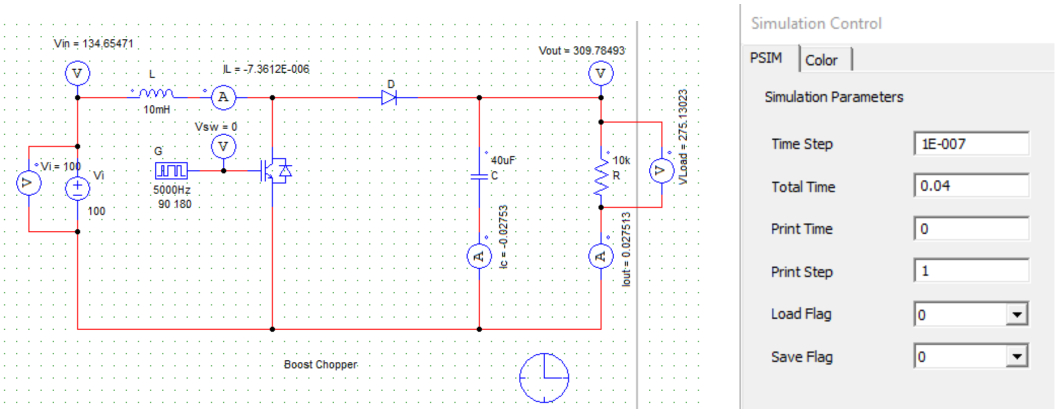


Figure 5. 6 Boost choppers

Setting the Simulation Control, construct a circuit as Figure 5.6, find the voltage output with the duty cycle as Table 5.2 by setting the gating block.

Table 5.2

Duty cycle	Waveform	Voltage input and output
D=0.5 90 180 270 360		Vi = Vout =
D=0.25 135 180 315 360		Vi = Vout =

Example 5.1

A boost converter is supplied by a 12 V DC source and the output voltage is 30 V. The circuit is connected to a load with resistance of 50 Ω and the operating switching frequency is 25 kHz. Determine;

i. The duty cycle of the converter
ii. The minimum value of inductance to ensure continuous conduction mode of operation
iii. The minimum and maximum values of inductor current if the inductor used have a value of 120 μH.

Solution:

i. $D = 1 - \frac{V_i}{V_O} = (1 - 12/30) = 0.6$

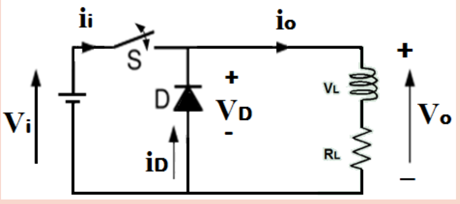
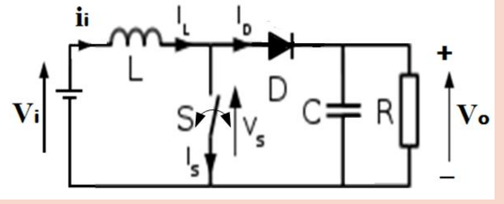
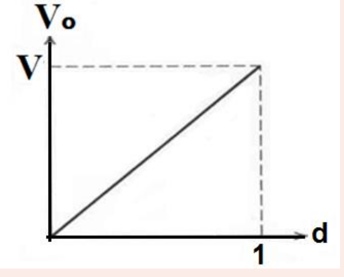
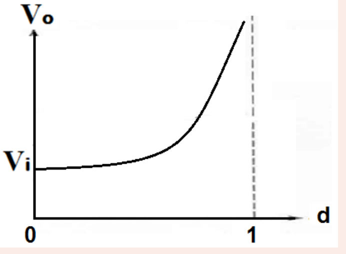
ii. $L = \frac{T_{ON}}{2}(1-d)^2 R = 96\ \mu H$

iii.

$$I_{max} = V_i\left[\frac{1}{(1-d)^2 R} + \frac{T_{ON}}{2L}\right] = 1.508A$$

$$I_{min} = V_i\left[\frac{1}{(1-d)^2 R} - \frac{T_{ON}}{2L}\right] = 1.500\ A$$

5.7 Reflexion

	Buck Chopper	Boost Chopper
Circuit		
average load voltage , V_0	$V_0 = \frac{T_{ON}}{T} V_i$ $V_0 = d\, V_i$	$V_0 = V_i \left(\frac{T}{T_{OFF}}\right) = V_i \left(\frac{T}{T - T_{ON}}\right)$ $V_0 = V_i \left(\frac{1}{1-d}\right)$
Duty cycle, d	$D = \frac{V_0}{V_i}$	$D = \frac{V_0 - V_i}{V_o} = 1 - \frac{V_i}{V_o}$
		
Inductor , L	$L = \frac{T_{OFF} R}{2}$	$L = \frac{T_{ON}}{2} (1-d)^2 R$
Max Current, I_{max}	$I_{max} = \frac{V_o}{R} + \frac{V_o}{2L} T_{OFF}$	$I_{max} = V_i \left[\frac{1}{(1-d)^2 R} + \frac{T_{ON}}{2L}\right]$
Minimum Current, I_{min}	$I_{min} = \frac{V_o}{R} - \frac{V_o}{2L} T_{OFF}$	$I_{min} = V_i \left[\frac{1}{(1-d)^2 R} - \frac{T_{ON}}{2L}\right]$
I_{p-p}	$I_{p-p} = I_{max} - I_{min}$ $= \frac{V_o}{L} T_{OFF}$	$I_{p-p} = I_{max} - I_{min}$ $= \frac{V_i}{L} T_{ON}$

5.8 Review Questions

1. In a buck chopper, the source voltage is 220V DC. The resistive load is 20Ω , L is 400 μF and duty cycle is 0.4. If the chopper is operating at a frequency of 20kHz, calculate the average load voltage, and the maximum and minimum inductor current.

2. Refer to Figure 5.2(a) , the switching frequency is 25 Hz and T_{ON} = 3 ms. If the average value of the output current is 40 A, determine the average source current.

3. A step up chopper has an input voltage of 150V.The voltage output needed is 450V. Given that the thyristor has a conducting time of 150μS.

4. A DC Buck chopper operates at frequency of 1 KHz from a 100 V DC source supplying a 10 Ω resistive load. The inductive component of the load is 50 mH. If the average output is 50 V, find

Chapter

6 Inverter

Inverters are used in a wide range of applications, from small switching power supplies in computers, to large electric utility applications that transport bulk power.
Switching devices in inverter circuits such as SCRs, BJTs, GTOs, IGBTs and MOSFETs. There are many technique can be used to controlling the output voltage such as Pulse width modulation, Single Pulse Width modulation, Multiple Pulse width modulation.

6.1 Introduction to Inverter

Definition of inverter is to convert a fixed DC supply voltage source to AC output *voltage at fixed or variable frequencies and magnitudes. It can be a single phase or a three phase voltage system.*

TYPICAL APPLICATIONS:

1. DC Power Utilization
2. Uninterruptible power supply (UPS)
3. Induction heating
4. High voltage direct current (HVDC) power transmission
5. Variable-speed ac motor drives
6. Electric vehicle drives
7. In refrigeration compressor
8. Use in power generation systems such as electric utility companies or solar generating systems to convert DC power to AC power

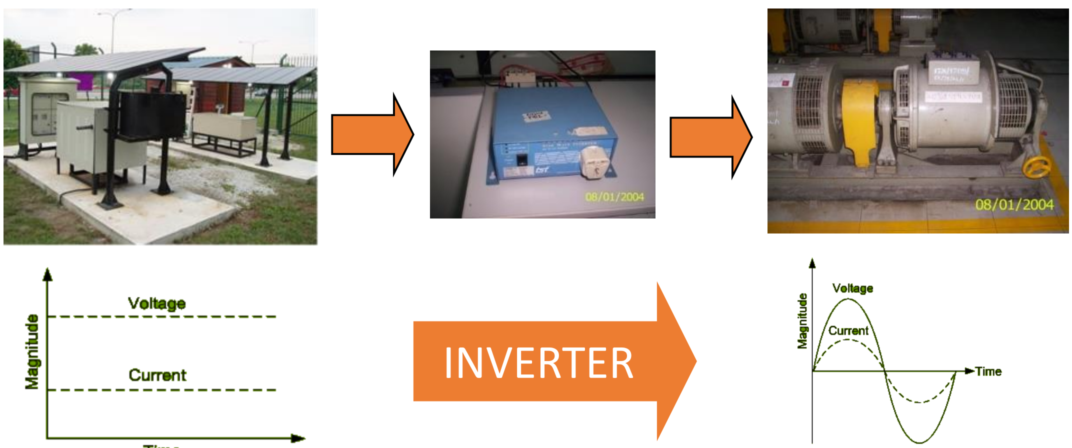


Figure 6.1 Inverter

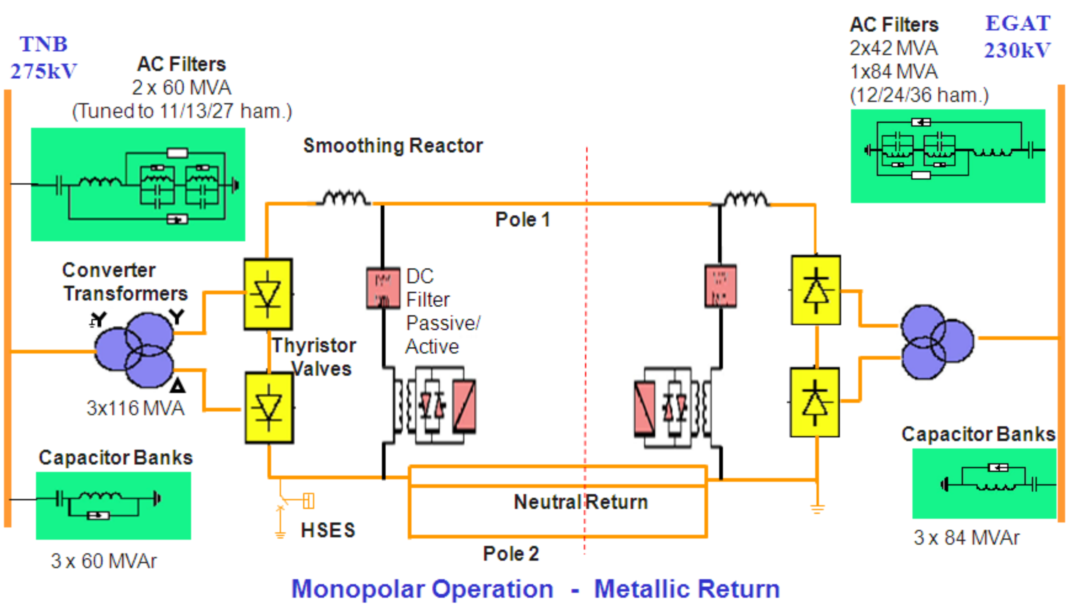


Figure 6.2 One-line diagram of HVDC interconnection between Malaysia and Thailand
(Source from HVDC Transmission, Gurun)

6.2 Classes of Inverter

a. Voltage source inverter (VSI)

b. Current source inverter (CSI)

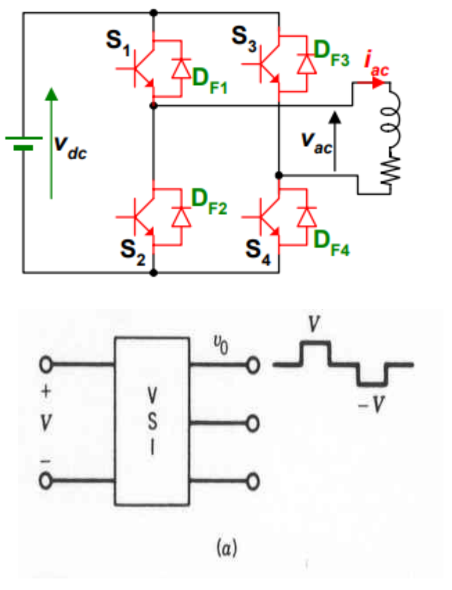


Figure 6.3 Voltage source inverter keeps the voltage constant

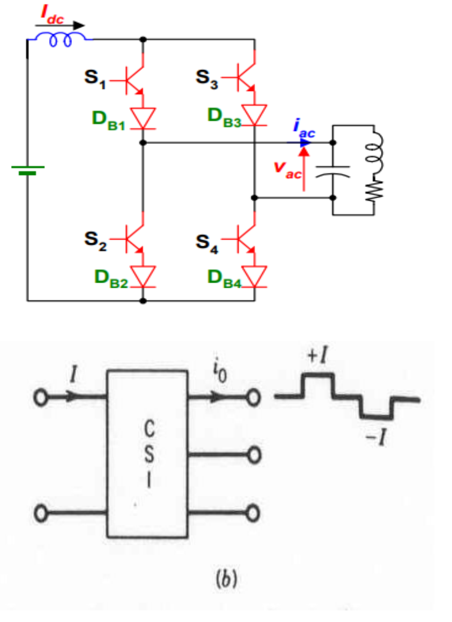


Figure 6.4 Current source inverter keeps the current constant

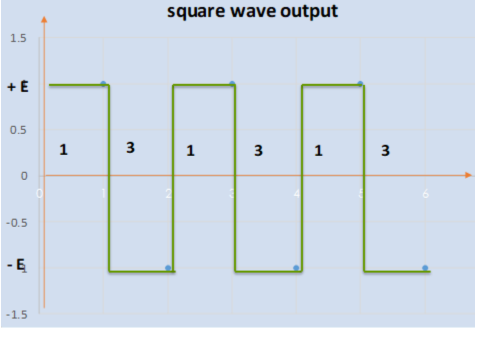


Figure 6.5 Switching sequence in the Half bridge inverter (square wave output)

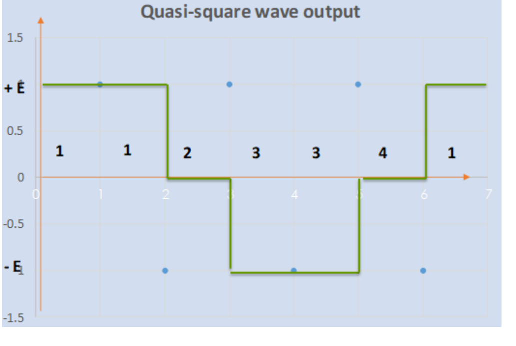


Figure 6.6 Switching sequence in the H-bridge inverter (step-wave / quasi-square wave output)

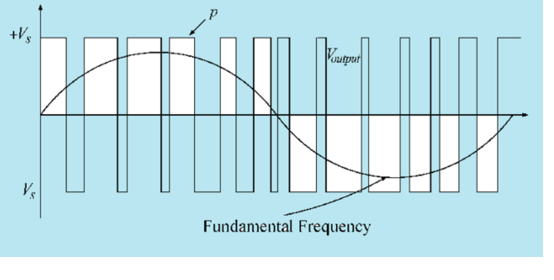


Figure 6.7 Sinosoidal PWM signal

6.3 Half Bridge Inverter

It has two identical dc voltage sources connected in series, two static switches, and two diodes.
If switches S1 and S2 are each closed for an interval TON, the half-wave average output voltage is

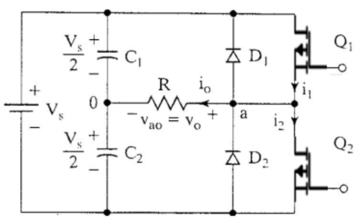
$$V_{o(avg)} = 2dV_s \qquad \textbf{(6.1)}$$

The RMS value of the output voltage is:

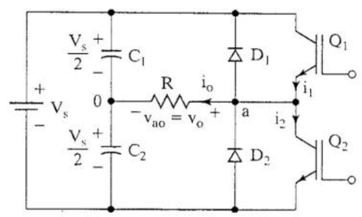
$$V_{o(RMS)} = \sqrt{2d}V_s \qquad \textbf{(6.2)}$$

The average power absorbed by the load is:

$$P_L = \frac{V_{o(RMS)}{}^2}{R} = 2d\,\frac{V_s{}^2}{R} \qquad \textbf{(6.3)}$$



using MOSFET



using IGBT

Figure 6.8 Half bridge inverter

6.4 Practical of Half Bridge Inverter

Construct a half bridge inverter circuit and setting the simulation control as Figure 6.9, simulate and get the voltage output at the load.

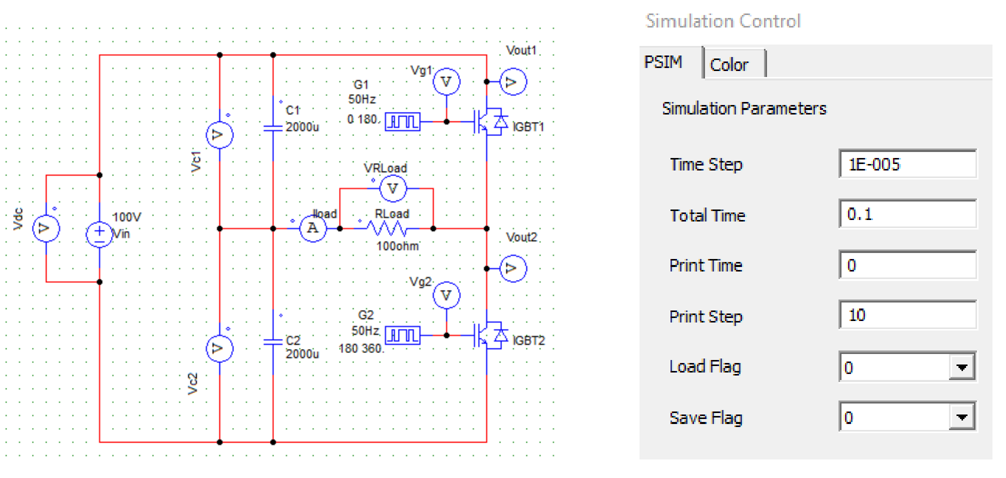


Figure 6.9 Circuit of Half bridge inverter and simulation control

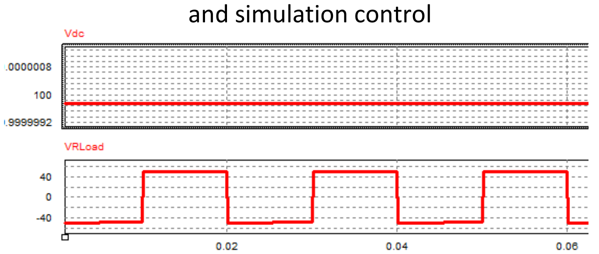


Figure 6.10 Circuit and waveform of Half bridge inverter using PSIM

6.5 Full Bridge Inverter

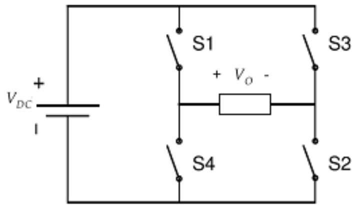
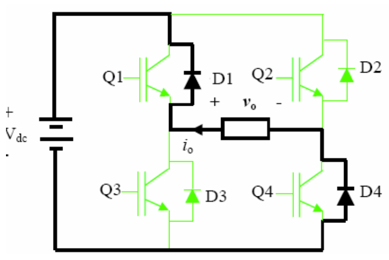


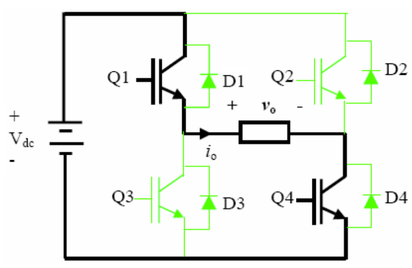
Figure 6.9 Equivalent circuit for square-wave inverter

The output voltage as shown Figure 6.10 will have harmonics components in addition to the fundamental components.

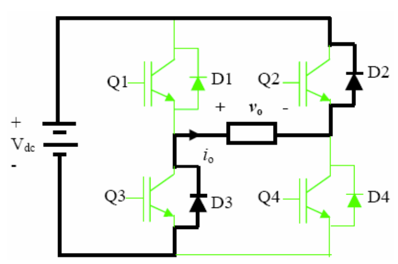
The square wave output voltage having a significant low-order of harmonic component as shown in the frequency spectrum



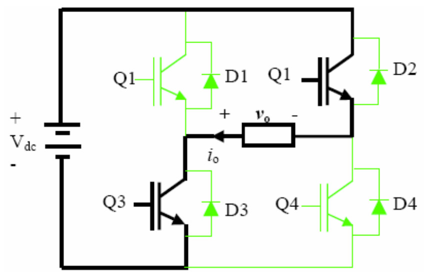
i) When diode D1 and D4 conducted,



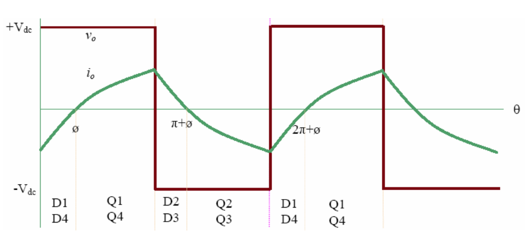
ii) When switch Q1 and Q4 operated,



iii) When diode D2 and D3 conducted,



iv) When switch Q2 and Q3 operated,



v) The output of FW inverter with square wave switching scheme

Figure 6.9 Switching Schemes Topology for Square Wave (SW) Output

Example 6.1

A single phase full bridge inverter, produces a step wave output, as shown, across a resistive load. E = 200 V, d = 50% and load resistance R = 2 Ω, Find

a) the average load current
b) the average switch current
c) the power delivered to the load
d) the average source current

Solution

- The average output voltage over half cycle is: $V_{o(avg)} = 2E\ d$
- The average load current : $I_{o(avg)} = V_{o(avg)} / R$
- Average current in the switch = average load current /2
- The RMS value of the output voltage is $V_{o(RMS)} = \sqrt{2d}E$

6.6 Three Phase Inverter

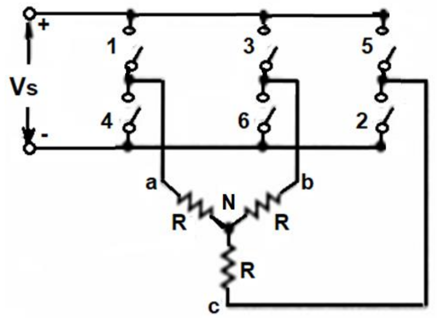


Figure 6.10 Basic circuit 3-phase inverter

A three-phase inverter circuit changes DC input voltage to a three-phase variable frequency variable-voltage output. The basic circuit is shown in Figure 6.10. It can be seen in the output graphs of both 120º and 180º switching cases that we have achieved an alternating three-phase voltage at the three output terminals.

A three phase inverter is classified on the basic of conduction period of a switch:

a) 120° Conduction Mode
b) 180° Conduction Mode

THREEPHASE INVERTER –120° Conduction Mode

Table 6.1 120° Conduction Mode

Interval	Duration period	S1	S2	S3	S4	S5	S6	VAN	VBN	VCN
1	0° – 60°	ON	OFF	OFF	OFF	OFF	ON	+Vs/2	-Vs/2	0
2	60° – 120°	ON	ON	OFF	OFF	OFF	OFF	+Vs/2	0	-Vs/2
3	120° – 180°	OFF	ON	ON	OFF	OFF	OFF	0	+Vs/2	-Vs/2
4	180° – 240°	OFF	OFF	ON	ON	OFF	OFF	-Vs/2	+Vs/2	0
5	240° – 300°	OFF	OFF	OFF	ON	ON	OFF	-Vs/2	0	+Vs/2
6	300° – 360°	OFF	OFF	OFF	OFF	ON	ON	0	-Vs/2	+Vs/2

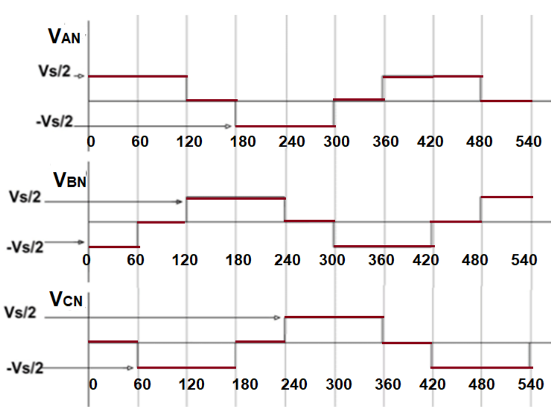


Figure 6.11 Output phase voltage

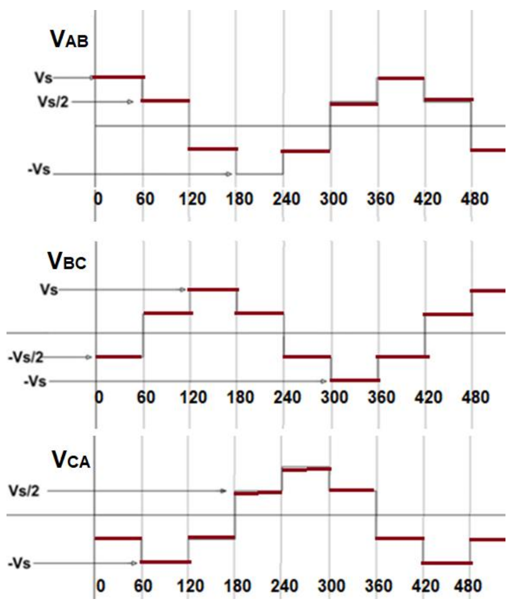


Figure 6.12 Output line voltage

$V_{AB} = V_{AN} - V_{BN}$
$V_{BC} = V_{BN} - V_{CN}$
$V_{CA} = V_{CN} - V_{AN}$

$V_{BA} = V_{BN} - V_{AN}$
$V_{CB} = V_{CN} - V_{BN}$
$V_{AC} = V_{AN} - V_{CN}$

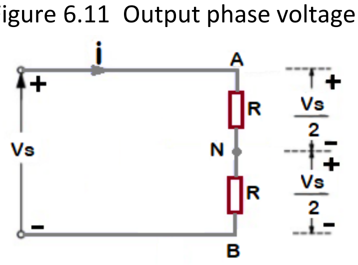


Figure 6.13 120° Conduction Equivalent circuit for 0° – 60°

6.7 Three Phase Inverter

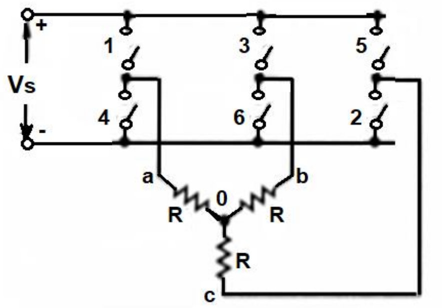


Figure 6.14 Basic circuit 3-phase inverter

A three-phase inverter circuit changes DC input voltage to a three-phase variable frequency variable-voltage output. The basic circuit is shown in Figure 6.10

THREEPHASE INVERTER –180° Conduction Mode

Table 6.2 180° Conduction Mode

Interval	Duration period	S1	S2	S3	S4	S5	S6	VAN	VBN	VCN
1	0° – 60°	ON	OFF	OFF	OFF	ON	ON	+Vs/3	-2Vs/3	+Vs/3
2	60° – 120°	ON	ON	OFF	OFF	OFF	ON	2Vs/3	- Vs/3	- Vs/3
3	120° – 180°	ON	ON	ON	OFF	OFF	OFF	+Vs/3	+Vs/3	-2Vs/3
4	180° – 240°	OFF	ON	ON	ON	OFF	OFF	- Vs/3	+2Vs/3	- Vs/3
5	240° – 300°	OFF	OFF	ON	ON	ON	OFF	-2Vs/3	+Vs/3	+Vs/3
6	300° – 360°	OFF	OFF	OFF	ON	ON	ON	- Vs/3	- Vs/3	+2Vs/3

$V_{AB} = V_{AN} - V_{BN}$
$V_{BC} = V_{BN} - V_{CN}$
$V_{CA} = V_{CN} - V_{AN}$

$V_{BA} = V_{BN} - V_{AN}$
$V_{CB} = V_{CN} - V_{BN}$
$V_{AC} = V_{AN} - V_{CN}$

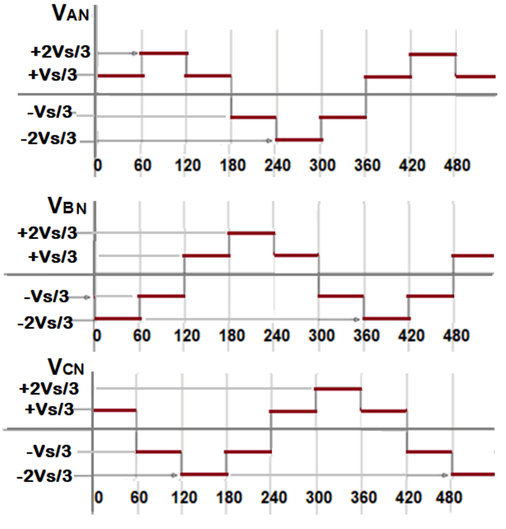


Figure 6.15 Output phase voltage

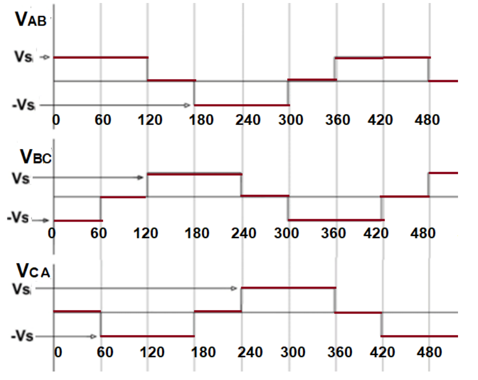


Figure 6.16 Output line voltage

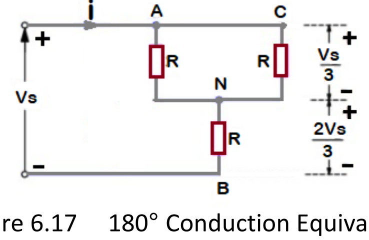


Figure 6.17 180° Conduction Equivalent circuit for 0° – 60°

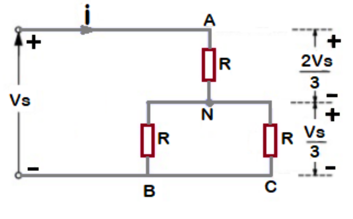


Figure 6.18 180° Conduction Equivalent circuit for 60° – 120°

6.8 Review Questions

1. By using transistors, draw a Single Phase Half Bridge DC-AC Inverter with R load circuit. Explain the operation of switching sequence and draw the waveform input voltage Vin and output voltage Vo and output current Io. Calculate the rms output Voltage $Vo_{(rms)}$, if the Single Phase Half Bridge Inverter has DC input, Vin= 100V, and the load resistance value is 20 Ω.

2. A single phase full bridge inverter in Figure 6.10 has an RL load with R=100Ω. The inverter frequency is 60Hz and DC input voltage Vs=220V. Calculate the RMS output current.

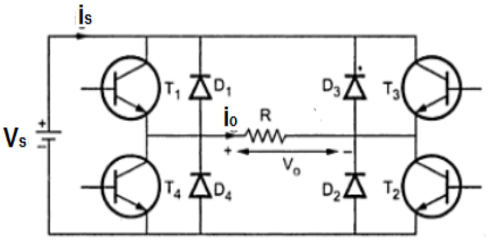


Figure 6.10

3. Sketch a circuit diagram of a three phase bridge inverter with resistive load from a star connected source. Then cornplete fhe conduction table given in Table 18 a and sketch the output line voltage waveforms on the assumption that each thyristor conducts for 180^o.

Table 6.1

Duration	Switch mode	V_{AN}	V_{BN}	V_{CN}	V_{AB}	V_{BC}	V_{CA}
0^o – 60^o	S5,S6,S1	$\frac{Vs}{3}$	$\frac{-2Vs}{3}$	$\frac{Vs}{3}$			
60^o – 120^o	S6,S1, S2	$\frac{2Vs}{3}$	$\frac{-Vs}{3}$	$\frac{-Vs}{3}$			
120^o – 180^o	S1, S2, S3	$\frac{Vs}{3}$	$\frac{Vs}{3}$	$\frac{-2Vs}{3}$			
180^o – 240^o	S2, S3, S4	$\frac{-Vs}{3}$	$\frac{2Vs}{3}$	$\frac{-Vs}{3}$			
240^o – 300^o	S3, S4, S5	$\frac{-2Vs}{3}$	$\frac{Vs}{3}$	$\frac{Vs}{3}$			
300^o – 360^o	S4, S5, S6	$\frac{-Vs}{3}$	$\frac{-Vs}{3}$	$\frac{2Vs}{3}$			

Chapter

7 AC Voltage Controller

AC/AC converters connect an AC source to AC loads by controlling amount of power supplied to the load. This converter converts the AC voltage at one level to the other by varying its magnitude as well as frequency of the supply voltage
These are used in different types of applications including uninterrupted power supplies, high power AC to AC transmission, adjustable speed drives, renewable energy conversion systems and aircraft converter systems.

7.1 Introduction to AC Voltage Controller

AC to AC converter is used to obtain a variable AC output voltage from a fixed AC voltage. It is used to change the AC voltage from one level to another. The AC to AC converter is also called as **AC regulator** or **AC voltage controller**

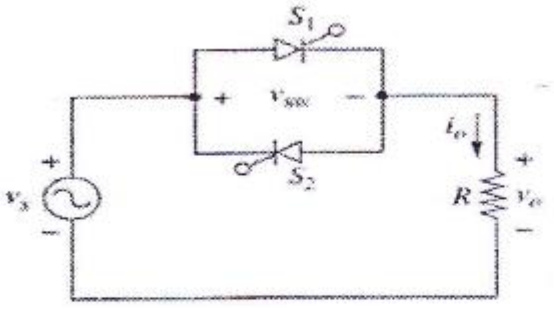


Figure 7.1 Single phase bidirectional controller

The SCRs cannot conduct simultaneously. The load voltage is the same as the source voltage when either SCR is on. The load voltage is zero when both SCRs are off.

S_1 conducts if a gate signal is applied during the positive half cycle of the so-urce, r A gate signal is applied to S_2 during the negative halfcycle of the source, providing a path for negative load current.

There are **two different types of switching control techniques** used in practice to control the AC output voltage:

a) Phase angle control

b) Integral-cyclecontrol(ON-OFFcontrol)

Each type of controller subdivided into:

a) Uni-directional or half wave AC voltage controller

b) Bi-directional or full wave AC voltage controller

7.2 Common applications of AC voltage controller

- Lighting control
- AC magnet control
- Domestic and industrial heating
- On-load transformer tap changing
- Starting three phase induction motors
- Speed control of (fan, pump)
- Static VAR generator
- UPS
- Microwave heating
- Electronic ballast
- Flexible AC Transmission line
- Variable speed drives

7.3 Type of AC voltage controller

Integral-cycle control

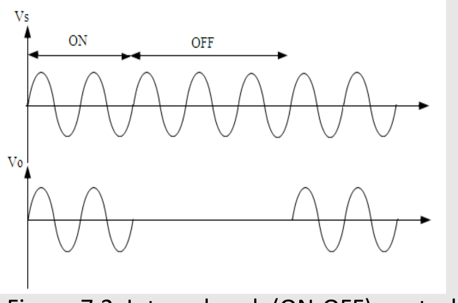


Figure 7.2 Integral-cycle(ON-OFF) control

- Suitable for systems with a large time constant
- The average power to the load can be controlled from 0% - 100%
- Such as temperature control system
- If the input voltage is connected to load for 'n'cycles and disconnected for 'm'cycles,

The RMS value of output voltage

$$V_{o(RMS)} = \frac{V_m}{\sqrt{2}}\sqrt{\frac{T_{ON}}{T}} = V_S\sqrt{\frac{T_{ON}}{T}} = V_{S_i}\sqrt{D} \qquad \textbf{(7.1)}$$

Average load power

$$P_{o(avg)} = \frac{V_S{}^2 T_{ON}}{R\ T} = \frac{V_S{}^2}{R} D = P_{o(max)} D \qquad \textbf{(7.3)}$$

Power factor , $PF = \sqrt{D}$ **(7.5)**

Phase angle control

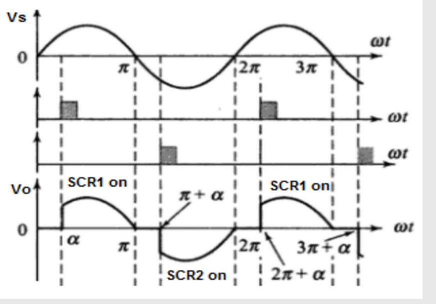


Figure 7.3 Phase angle control

- Suitable for systems with a short time constant
- The voltage at the load can be varied by altering the firing angle for each half-cycle of a period
- if α = 0, the output voltage is maximum (vo = vi)
- if α = π, the output voltage is minimum (vo = 0)
- Such as lighting control & motor speed control

By controlling the phase angle or the trigger delay angle 'α' (firing angle), the AC output voltage across the load can be controlled.

$$V_{o\,(RMS)} = V_S\sqrt{\frac{1}{\pi}\left[(\pi - \alpha) + \left(\frac{\sin 2\alpha}{2}\right)\right]} \qquad \textbf{(7.2)}$$

$$P_{o(max)} = \frac{V_S{}^2}{R} \qquad \textbf{(7.4)}$$

$$P_{o(avg)} = \frac{V_{o(RMS)}{}^2}{R}$$

$$PF = \frac{active\ power}{apparent\ power} = \frac{P_O}{V_S \times I_S} = \frac{V_{O\,(RMS)}}{V_S} \qquad \textbf{(7.6)}$$

$$PF = \sqrt{\frac{1}{\pi}\left[(\pi - \alpha) + \left(\frac{\sin 2\alpha}{2}\right)\right]}$$

7.4 Practical of Phase Angle Control

Build a phase angle control circuit as Figure 7.4, simulate and find the voltage output and current output at the load.

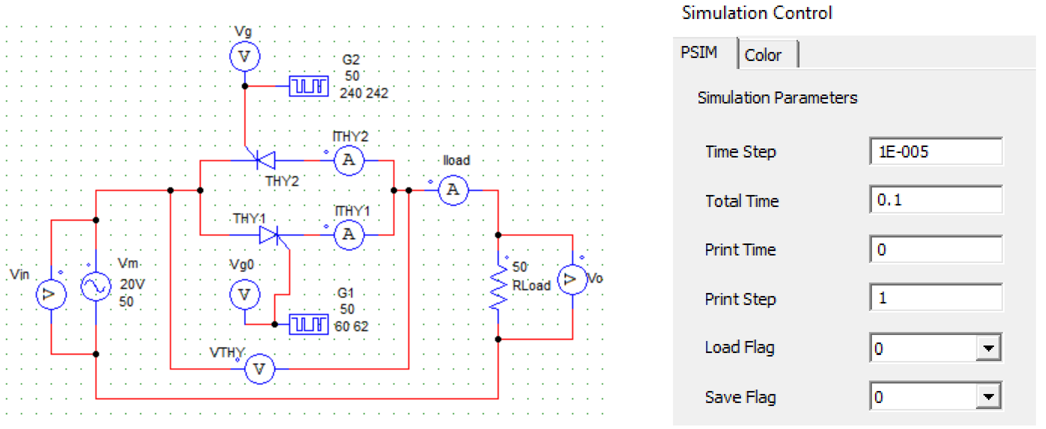


Figure 7.4 Circuit of phase angle control and and simulation control

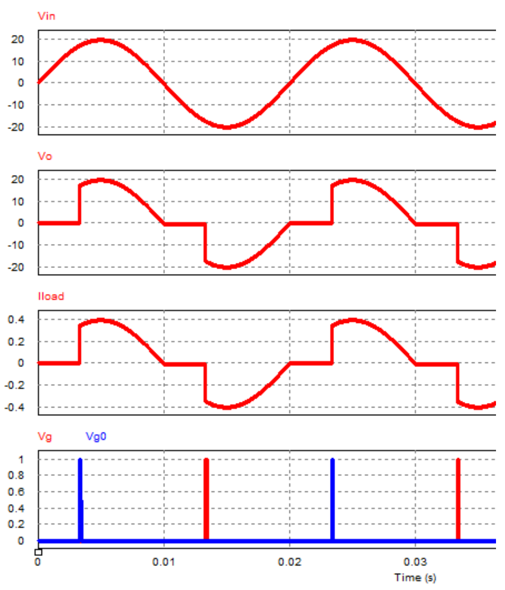


Figure 7.5 Waveform of phase angle control and and simulation control

Example 7.1

A single-phase 120 V AC source controls power to a 5 Ω resistive load using integral cycle control. Find

a) the average value of output current
b) the maximum switch current
c) the maximum power produced
d) the duty cycle and the value of TON to produce 1 kW power
e) the power factor for part (d)

Solution:

a) *the average value of output current over any number of complete conduction cycles is 0*

b) the maximum switch current

$I_{o(RMS)} = \frac{V_s}{R} = \frac{120}{5}$ =24 A

$I_m = \sqrt{2}\ I_{o(RMS)} = \sqrt{2}$ (24) = 33.9 A

c) the maximum power will be produced when the switch is always on

$P_{o(max)} = V_s \times I_{o(RMS)}$ = (120)(24) = 2880W

d) the duty cycle and the value of TON to produce 1 kW power

for $P_{o(avg)} = 1000W$,

$$d = \frac{T_{ON}}{T} = \frac{P_{o(avg)}}{P_{o(max)}} = \frac{1000}{2880} = 0.35$$

e) the power factor for part (d)

PF = $\sqrt{d} = \sqrt{0.35} = 0.59$

Example 7.2

A single-phase 120 V AC source controls power to a 5 Ω resistive load using integral cycle control. If T_{ON} = 2 cycles and T = 4 cycles Find

a) the output power
b) the delay angle required if the phase control method is used to produce the same power
c) the output power , if the load is always connected to the source

Solution:

a) *the average output power*

$$P_{o(avg)} = \frac{V_i^2 T_{ON}}{R\ T} = \frac{(120)^2(2)}{(5)(4)} = 1440W$$

b) the delay angle required if the phase control method is used to produce the same power

$$P_{o(avg)} = \frac{V_s^2}{R}\{\frac{1}{\pi}\left[(\pi - \alpha) + (\frac{\sin 2\alpha}{2})\right]\} = 1440W$$

$$\frac{1}{\pi}\left[(\pi - \alpha) + (\frac{\sin 2\alpha}{2})\right] = 0.5$$

$$\alpha = \frac{\pi}{2} = 90°$$

c) the output power , if the load is always connected to the source

$$P_{o(avg)} = \frac{V_s^2}{R} = \frac{(120)^2}{(5)} = 2880\ W$$

7.5 Cycloconverter

Refer to Figure 7.5, during positive half cycle of the input voltage, positive converter (bridge-1) is turned ON and it supplies the load current. During negative half cycle of the input, negative bridge is turned ON and it supplies load current. Both converters should not conduct together that cause short circuit at the input.

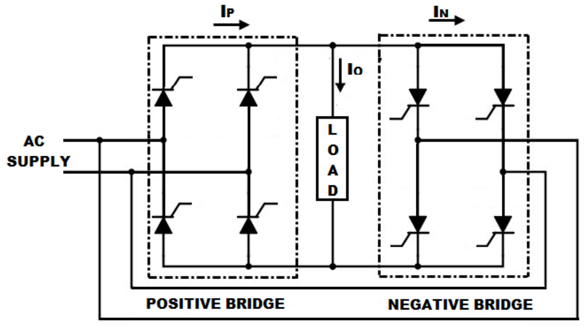


Figure 7.5 Basic Circuit of cycloconverter

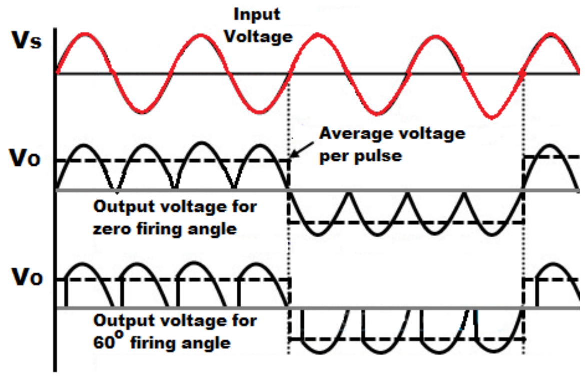


Figure 7.6 Waveform of cycloconverter

To avoid this, triggering to thyristors of bridge-2 is inhibited during positive half cycle of load current, while triggering is applied to the thyristors of bridge-1 at their gates. During negative half cycle of load current, triggering to positive bridge is inhibited while applying triggering to negative bridge.

By controlling the switching period of thyristors, time periods of both positive and negative half cycles are changed and hence the frequency. This frequency of fundamental output voltage can be easily reduced in steps, i.e., 1/2, 1/3, 1/4 and so on.

7.6 Review Questions

1. An AC voltage controller has a resistive load of R = 30Ω and rms input voltage of Vs=200V, 50Hz. The thyristor switch on time is 15 cycles and off time is 15 cycles. Calculate:
   i. Duty cycle, d
   ii. The rms output voltage, Vo_{rms}, and the rms output current, Io_{rms}

2. A resistive load of 5Ω is fed through a single phase full wave AC voltage controller from 230V, 50 Hz source. If firing angle of thyristor is π/2 calculate:
   i. The RMS output voltage, V_{0RMS}
   ii. The RMS output current, I_{0RMS}
   iii. The load power, P_o

3. A single-phase Uni-directional AC voltage controller has a resistive load of R=50 ohm and the input voltage is Vs=240V, 50Hz. The delay angle of thyristor is α= 30° . Determine ;
   i. The RMS value of output voltage
   ii. The output power
   iii. The RMS load current

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ANSWERS

Chapter 2

1

	Uncontrolled rectifier	Controlled rectifier
The rectifying elemens	only diodes	Are SCRs
DC load voltage	a fixed DC	A variable DC output
Conduction angle	The conduction angle is 180° or π radians, each diode conducts for a duration of one half-cycle	Varied from 0° to 180°
Required trigger	Not required	Required trigger for firing SCR

2 $$Vdc = \frac{Vm}{\pi} = \frac{120}{\pi} = 38.2\ V$$

$$Vrms = \frac{Vm}{\sqrt{2}} = \frac{120}{\sqrt{2}} = 84.853\ v$$

$$Irms = \frac{Vrms}{R} = \frac{84.853\ v}{50\ \Omega} = 1.7\ Amp$$

3 *(a) Single phase half wave uncontrolled Rectifier with inductive load*

(b)(i) $V_{o\,avg} = \frac{1}{2\pi}\int_0^{\pi+\beta} V_m \sin\omega t\, d\omega t$

$= \frac{V_m}{2\pi}\left[-\cos\omega t\right]_0^{\pi+\beta}$

$\pi+\beta = 180^o + 30^o = 210^o$

$= \frac{120}{2\pi}\left[-\cos\omega t\right]_0^{210}$

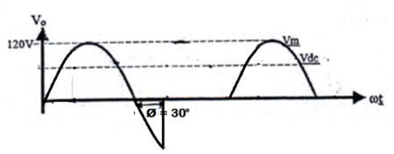
$= \frac{120}{2\pi}\left(-(\cos(210) - \cos 0)\right)$

$= \frac{120}{2\pi}(1+\cos 30)$

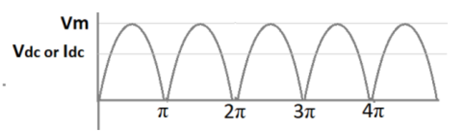
$= \frac{120}{2\pi}(1+0.866)$

$= 35.63\ V$

(ii)



4 The bridge rectifier is constructed by using 4 diodes.
During the positive half cycle
the diodes D1 and D3 are in forward biased.
And the diodes D2 & D4 will not conduct.
And vice versa during the negative half cycle of secondary input



Chapter 3

1 $$Z = \sqrt{10^2 + (314 \times 20 \times 10^{-3})^2} = 11.8\ \Omega$$

$\boldsymbol{\alpha}$ =30° , $\alpha = \frac{1}{6}\pi$ rad

β , 220° $\beta = \frac{11}{9}\pi$ rad

$$Vo(RMS) = \sqrt{\frac{Vm^2}{2}\left[-\left(\frac{\sin 2\beta)}{2\pi} - \frac{\sin 2\alpha)}{2\pi}\right)\right]}$$

$$= \sqrt{\frac{(220)^2}{2}\left[\left(\frac{\frac{11}{9}\pi - \frac{1}{6}\pi}{\pi}\right) - \left(\frac{\sin 2(220)}{2\pi} - \frac{\sin 2(30)}{2\pi}\right)\right]}$$

= 158.4 V

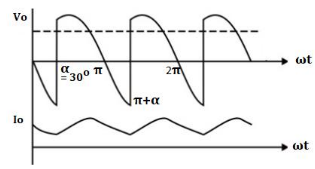
$$Io(RMS) = \frac{Vo(RMS)}{Z} = 13.42\ A$$

2 i. For α = 30° and ϕ = 45°

$V_m = \sqrt{2}\ Vs = \sqrt{2}\ (230) = 325.27$ V

$$Vo(avg) = \frac{2V_m \cos\alpha}{\pi} = \frac{2\sqrt{2}\,(230)\cos 30^o}{\pi} = 179.33V$$

$$Vo(rms) = \frac{V_m}{\sqrt{2}} = \frac{\sqrt{2}(230)}{\sqrt{2}} = 230V$$

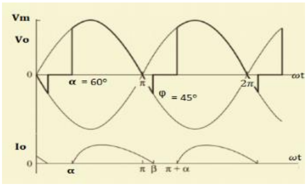


ii. $\beta = = 225^{o}$ $= \frac{5\pi}{4}$ rad , α =60° = $\frac{\pi}{3}$

$$Vo(avg) = \frac{V_m\,(\cos\alpha - \cos\beta)}{\pi} == 124.97\ V$$

$$Vo(rms) = \sqrt{\frac{Vm^2}{2}\left[\frac{(\beta-\alpha)}{\pi} - \left(\frac{\sin 2\beta)}{2\pi} - \frac{\sin 2\alpha)}{2\pi}\right)\right]}$$

= 307.89 V



3 The average output voltage:

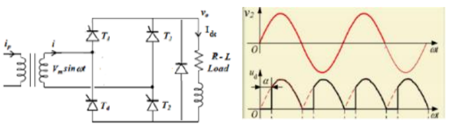
$$Vo(avg) = \frac{V_m\,(\cos\alpha - \cos\beta)}{\pi} = \frac{V_m\,(\cos\alpha - \cos\beta)}{\pi}$$

$$= \frac{(339.4)(0.5-(-0.866))}{\pi} = \frac{(339.4)1.366}{\pi} = 463.62\ V$$

The average output current:

$$Io(avg) = \frac{Vo(avg)}{R} = \frac{463.62}{10} = 46.36\ V$$

The circuit diagram with freewheeling diode:



The new average output voltage:

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

α = 60° = $\frac{\pi}{3}$

$$V_{o\,(avg)2} = \frac{463.62}{\pi}[1 + \cos 60^o] = 221.6\ V$$

ANSWERS

Chapter 4

1 The average output voltage is given

$$\text{Vo(avg)} = V_{DC} = \frac{3\sqrt{3}V_m\,(\cos\alpha)}{2\pi}$$

V_m is the maximum phase voltage.

$$\textit{The line voltage is given as } 220V, \textit{hence } V_L = \sqrt{3}V_{ph}$$

$$V_{ph} = \frac{V_L}{\sqrt{3}} = \frac{220}{\sqrt{3}} = 127.02\,V$$

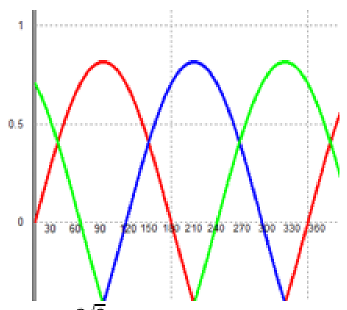
And $V_m = \sqrt{2}V_{ph} = \sqrt{2}\,(127.02) = 179.63\text{V}$. (maximum phase voltage)

a) For $\alpha = \frac{\pi}{6}$ rad $= 30°$

$$\text{Vo(avg)} = V_{DC} = \frac{3\sqrt{3}V_m\,(\cos\frac{\pi}{6}rad)}{2\pi} = 128.65\text{V}$$

2

Interval	Duration period	S1	S2	S3	Vout
1	0° – 20°	Forward Biased/ Not Triggered	OFF	ON	VCN
2	20° – 30°	ON	OFF	ON	VCN
3	30° – 120°	ON	OFF	OFF	VAN
4	120° – 140°	ON	Forward Biased/ Not Triggered	OFF	VAN
5	140° – 150°	ON	ON	OFF	VAN
6	150° – 240°	OFF	ON	OFF	VBN
7	240° – 160°	OFF	ON	Forward Biased/ Not Triggered	VBN
8	260° – 170°	OFF	ON	ON	VBN
9	270° – 360°	OFF	OFF	ON	VCN



$$T = \frac{2\pi}{3}$$

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

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

$If\ \alpha = 20°$, and Vs = 260 V, hence Vphase $= \frac{260}{\sqrt{3}} = 150$ V

$$V_m = \sqrt{2}\,(150) = 212\text{ V}$$

$$V_{o\,(avg)} = \frac{3\sqrt{3}}{2\pi}(212)\cos(20) = 164.7\,V$$

Chapter 5

1

The average load voltage:

$$V_0 = dV_i$$

$$= (0.4)\,(220) = 88\text{V}$$

The maximum inductor current

$$I_{max} = \frac{V_o}{R} + \frac{V_o}{2L}T_{OFF}$$

$$= \frac{88}{20} + \frac{88}{2(400\,\mu F)}(0.3\text{x}10^6)$$

$$= 7.7A$$

The maximum inductor current

$$I_{max} = \frac{V_o}{R} + \frac{V_o}{2L}T_{OFF}$$

$$= \frac{88}{20} - \frac{88}{2(400\,\mu F)}(0.3\text{x}10^6)$$

$$= 1.1\,A$$

$$T_{OFF} = \frac{(1-0.4)}{20kHz}$$

$$= 0.3\text{x}10^6$$

2

$$Ii = D\,Io$$

$$Ii = \frac{Ton}{Ton + T\,off}\,Io$$

$$Ii = \frac{Ton}{T}\,Io$$

$$Ii = Ton\,(fc)\,Io$$

$$Ii = 0.003\,x\,25\,\,x\,40 = 3A$$

3

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

$$(1-D) = \frac{150}{450}$$

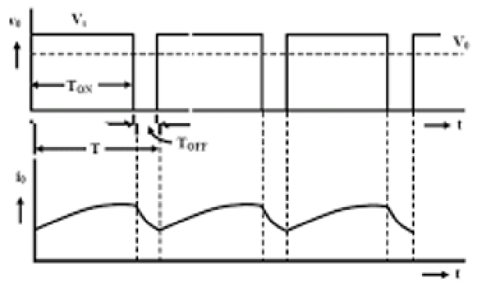
$$D = \frac{2}{3} = 0.67$$

$$D = \frac{Ton}{T}$$

$$T = \frac{150\mu s}{0.67} = 225\ \mu s$$

$$f = \frac{1}{225\ \mu s} = 4.44\text{kHz}$$

4



a. The duty cycle

$$D = \frac{Vo}{Vi} = \frac{50}{100} = 0.5 = 50\%$$

b. T_{ON}

$$T_{ON} = TD = (1ms)(0.5) = 0.5\,ms$$

c. The RMS value of the load current

$$V_{o(RMS)} = V_i\sqrt{D} = 100\sqrt{0.5} = 70.7\,V$$

d. The average value of the load current

$$I_o = \frac{V_o}{R} = \frac{50}{10} = 5\,A$$

e. I_{max} and I_{min}

$$I_{max} = \frac{V_o}{R} + \frac{V_o}{2L}T_{OFF}$$

$$I_{max} = 5 + \frac{50*0.5(10^{-3})}{2*50(10^{-3})} = 5 + 0.25 = 5.25$$

$$I_{min} = I_o - \frac{V_o}{2L}T_{OFF}$$

$$I_{min} = 5 - 0.25 = 4.75\,A$$

f. The peak to peak ripple current

$$I_{p-p} = I_{max} + I_{min} = 5.25 - 4.75 = 0.5\,A$$

g. The peak to peak ripple current if the frequency is increased to 5 kHz

$$T = \frac{1}{5(10^3)} = 200\mu s$$

$$T_{ON} = T_{OFF} = 100\mu s$$

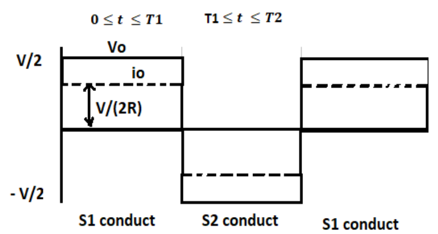
$$I_{max} = 5 + \frac{100(10^{-6}) * 50}{2 * 50(10^{-6})} = 5 + 0.5 = 5.05\text{ A}$$

ANSWERS

Chapter 6

1 • The operation and switching sequence of DC – AC inverters

- The current entering node a is considered to be positive
- The switches Q1 and Q2 are unidirectional, i.e. they conduct current in one direction.
- The current through Q1 is denoted as i1 and the current through Q2 is i2.
- Switch Q1 is on for the time duration $0 \le t \le T1$ and the switch Q1 is on for the time duration $T1 \le t \le T2$. When switch Q1 is turned on, the instantenous voltage across the load is Vo = Vs/2
- When switch Q2 is turned on, the voltage across the load is Vo =- Vs/2
- For a resistive load, the current io = Vo/R



Vout = Vin/2 = 120/2 = 60V

Iout = Vo/R = 60 /25 = 2.4 A

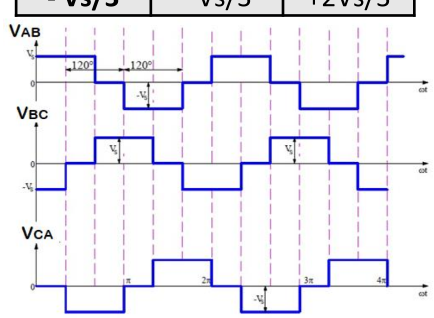
2 $Vo(RMS) = \frac{1}{2\pi}\int_{\alpha}^{2\pi} \sqrt{{V_s}^2\ \omega t\ d\omega t} = Vs$

$Vo(RMS) = Vs$

$Io(RMS) = \frac{Vs}{2R} = \frac{220}{2(100)} = 1.1\ A$

3

VAN	VBN	VCN
+Vs/3	-2Vs/3	+Vs/3
2Vs/3	- Vs/3	- Vs/3
+Vs/3	+Vs/3	-2Vs/3
- Vs/3	+2Vs/3	- Vs/3
-2Vs/3	+Vs/3	+Vs/3
- Vs/3	- Vs/3	+2Vs/3



Chapter 7

1 i. Duty cycle,

d = 15/(15+15)= 50%

ii. The rms output voltage, Vo_{rms},

$Vo(RMS) = Vs\sqrt{d} = 200\sqrt{0.50} = 141.4$ V

and the rms output current, Io_{rms}

$Io(RMS) = \frac{Vo(RMS)}{R} = 4.71$ A

2 i.The RMS output voltage

$$V_{o\,(RMS)} = V_m\sqrt{\frac{1}{2\pi}\left[(\pi-\alpha) - \left(\frac{\sin 2\pi)}{2} - \frac{\sin 2\alpha\,)}{2}\right)\right]}$$

$$V_{o\,(RMS)} = V_m\sqrt{\frac{1}{2\pi}\,[(\pi/2)\,]}$$

$$= V_m\sqrt{\frac{1}{2\pi}\,[(\pi - \pi/2) - (0-0)]}$$

ii.The RMS output current

$$V_{o\,(RMS)} = V_m\sqrt{\left[1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha\,)}{2}\right]} = V_m\sqrt{\left[1 - \frac{1}{2} + 0\right]}$$

$= V_m\sqrt{0.5}$ = 169.7 V

$I_{o\,(RMS)} = \frac{V_{o\,(RMS)}}{R} = 6.788$ A

iii. The load power, $P_o = V_{o\,(RMS)}$ x $I_{o\,(RMS)}$ = 1.152 kW

3 i. The RMS value of output voltage

$$V_{0(RMS)} = V_s\sqrt{\frac{1}{2\pi}\left[(2\pi - \alpha) + \frac{\sin 2\alpha}{2}\right]}$$

$$= 240\sqrt{\frac{1}{2\pi}\left[\left(2\pi - \frac{\pi}{6}\right) + \frac{\sin 2(30)}{2}\right]}$$

$$= 240\sqrt{[(0.9167) + 0.0689]}$$

$V_{0(RMS)} = 240\sqrt{[0.993]}$ = 238.27 V

ii. The output power

$P_{o(max)} = \frac{{V_o}^2}{R} = \frac{238.27^2}{50}$ = 1.135 kW

iii. The RMS load current

$I_{0(RMS)} = \frac{V_{O(RMS)}}{R} = \frac{238.27}{50}$ = 4.77A

Terbitan

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