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RECTIFIERS

Rectification :-

Rectification is the process of converting alternating current (ac) into direct current(dc).

Rectifier :-

Rectifier is a device that converts ac (alternating current) into dc (direct current). Semiconductor diodes are used as rectifying elements.

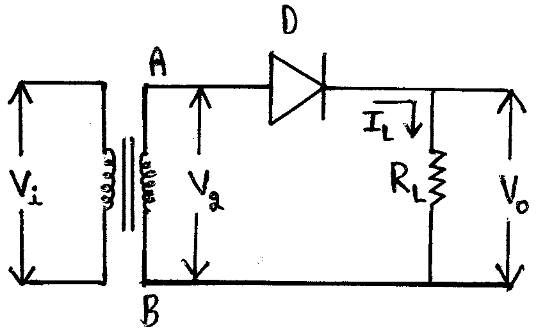
Rectifiers are classified into :

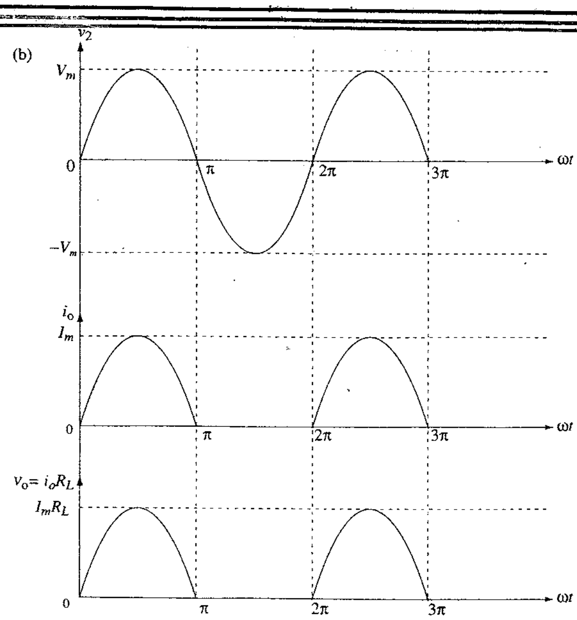
1. **Half wave rectifier (HWR)**
2. **Full wave rectifier (FWR)**

Full wave rectifier can be built in two ways :

1. **Full – wave rectifier using two diodes and a centre tapped transformer**
2. **Full-wave bridge rectifier using four diodes and an ordinary transformer. (FWBR)**

HALFWAVE RECTIFIER (HWR):-





(a) Half-wave rectifier. (b) Waveforms of transformer secondary voltage, load current and load voltage.

Half wave rectifier consists of a single diode in series with load resistance. The ac voltage across the secondary winding A & B changes polarities after half cycle.

Operation :-

During positive half cycle of the ac input voltage, end A becomes positive with respect to end B, the diode 'D' is forward biased and acts as a short circuit, thus the current flows in the circuit, Figure 2. The load voltage is given by $\boxed{V_O = I_L R_L}$.

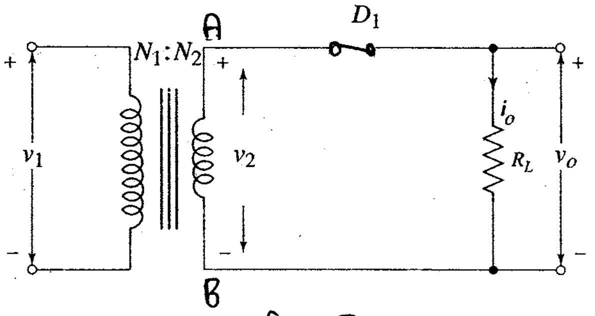


Fig ②

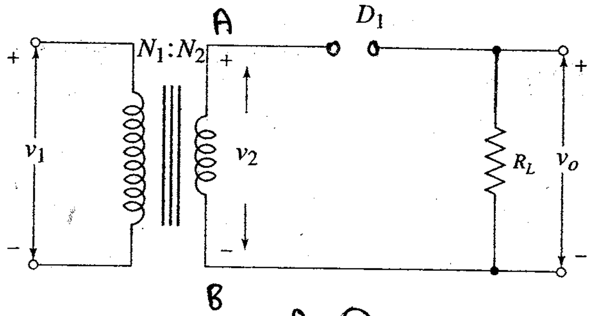


Fig ③

During negative half cycle of the ac input voltage, end A becomes negative with respect to end B, the diode 'D' is reverse biased and acts as a open circuit, thus **NO current** flows in the circuit, Figure 3. The load voltage is given by $V_O = 0 \times R_L$.

Therefore $\boxed{V_O = 0v}$

The dc output waveform is **expected** to be a **straight line** but the half wave rectifier gives output in the form of positive sinusoidal pulse. Hence the output is called **pulsating dc**.

The load current is given by :

$$I_L = \begin{cases} I_m \sin\omega t & 0 \leq \omega t \leq \pi \\ 0 & \pi \leq \omega t \leq 2\pi \end{cases}$$

Where $\boxed{I_m = \frac{V_m}{R_L}}$

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1) Average or dc load current (I_{dc} or I_{av}) :-

$$I_{dc} = \frac{1}{2\pi}\int_0^{2\pi} I_L \, d\omega t$$

$$= \frac{1}{2\pi}\int_0^{2\pi} I_m \sin\omega t \, . \, d\omega t$$

$$= \frac{1}{2\pi}\left[\int_0^{\pi} I_m \sin\omega t \, . \, d\omega t + \int_{\pi}^{2\pi} 0 \, d\omega t\right]$$

$$= \frac{I_m}{2\pi}\int_0^{\pi} \sin\omega t \, . \, d\omega t$$

$$= \frac{I_m}{2\pi}\Big[-\cos\omega t\Big]_0^{\pi}$$

$$= -\frac{I_m}{2\pi}\Big[\cos(\pi) - \cos(0)\Big]$$

$$= -\frac{I_m}{2\pi}\Big[-1 - 1\Big]$$

$$= -\frac{I_m}{2\pi}(-2)$$

$$= \frac{2 I_m}{2\pi}$$

$$\boxed{I_{dc} = \frac{I_m}{\pi}}$$

2) Average dc load voltage (V_{dc}) :-

$$\boxed{I_{dc} = \frac{I_m}{\pi}}$$

$$V_{dc} = I_{dc} R_L$$

$$= \frac{I_m}{\pi} R_L$$

$$\boxed{I_m = \frac{V_m}{R_L}}$$

$$= \frac{V_m}{R_L \cdot \pi} R_L$$

$$\boxed{V_{dc} = \frac{V_m}{\pi}}$$

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3) RMS value of load current (I_{RMS}) :-

$$I_{RMS} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} I_L^2 \, d\omega t}$$

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

$$= \sqrt{\frac{1}{2\pi}\int_0^{2\pi} I_m^2 \sin^2\omega t \, . \, d\omega t}$$

$$\sin^2\theta = \frac{1-\cos 2\theta}{2}$$

$$\int \cos 2\theta = \frac{\sin 2\theta}{2}$$

$$= \sqrt{\frac{I_m^2}{2\pi}\int_0^{2\pi} \frac{1-\cos 2\omega t}{2} \, . \, d\omega t}$$

$$= \sqrt{\frac{I_m^2}{4\pi}\left[\int_0^{\pi} 1-\cos 2\omega t \, . \, d\omega t + \int_{\pi}^{2\pi} 1-\cos 2\omega t \, . \, d\omega t\right]}$$

$$= \sqrt{\frac{I_m^2}{4\pi}\left[\theta - \frac{\sin 2\omega t}{2}\right]_0^{\pi}}$$

$$= \sqrt{\frac{I_m^2}{4\pi}\left\{[\theta]_0^{\pi} - \left[\frac{\sin 2\omega t}{2}\right]_0^{\pi}\right\}}$$

$$= \sqrt{\frac{I_m^2}{4\pi}\left\{[\pi - 0] - \left[\frac{\sin 2(\pi)}{2} - \frac{\sin 2(0)}{2}\right]\right\}}$$

$$= \sqrt{\frac{I_m^2}{4\pi} . \pi} = \sqrt{\frac{I_m^2}{4}}$$

$$I_{RMS} = \frac{I_m}{2}$$

4) RMS value of the load voltage (V_{RMS}) :-

$$V_{RMS} = I_{RMS} R_L$$

$$= \frac{I_m}{2} R_L$$

$$I_{RMS} = \frac{I_m}{2}$$

$$I_m = \frac{V_m}{R_L}$$

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$$= \frac{V_m}{2R_L} \cdot R_L$$

$$\boxed{V_{RMS} = \frac{V_m}{2}}$$

5) DC output power (P_{dc}) :-

$$P_{dc} = I_{dc}^2 R_L$$

$$= \left(\frac{I_m}{\pi}\right)^2 R_L = \frac{I_m^2}{\pi^2} R_L$$

$$= \left(\frac{V_m}{R_L}\right)^2 \cdot \frac{1}{\pi^2} R_L$$

$$= \frac{V_m^2}{R_L^2 \pi^2} \cdot R_L$$

$$\boxed{P_{dc} = \left(\frac{V_m}{\pi}\right)^2 \cdot \frac{1}{R_L}}$$

6) AC output power (P_{ac}) :-

$$P_{ac} = I_{RMS}^2 R_L$$

$$\boxed{P_{ac} = \left(\frac{I_m}{2}\right)^2 R_L}$$

7) Rectification efficiency (η):-

The rectifier efficiency is defined as the ratio of output dc power to input ac power.

$$\eta = \frac{\text{DC o/p power}}{\text{AC I/p power}} = \frac{P_{dc}}{P_{ac}} = \frac{\frac{I_m^2}{\pi^2} R_L}{\frac{I_m^2}{4} R_L} = \frac{\frac{1}{\pi^2}}{\frac{1}{4}} = \frac{1}{\pi^2} \times \frac{4}{1}$$

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$\eta = 0.406$

$$\boxed{\% \eta = 40.6\%}$$

In HWR, maximum 40.6% ac power gets converted to dc power in the load.

8) Ripple factor (γ):-

Ripple factor is defined as the ratio of RMS value of the ac component present in the rectified output to the dc component present in the rectified output.

$$\gamma = \frac{\text{RMS value of ac Component of o/p}}{\text{dc Component of o/p}}$$

$$\boxed{\gamma = \frac{I_{ac}}{I_{dc}}} \longrightarrow ①$$

WKT $I_{RMS} = \sqrt{I_{ac}^2 + I_{dc}^2}$

$$I_{RMS}^2 = I_{ac}^2 + I_{dc}^2$$

$$I_{ac}^2 = I_{RMS}^2 - I_{dc}^2$$

$$\boxed{I_{ac} = \sqrt{I_{RMS}^2 - I_{dc}^2}} \longrightarrow ②$$

WKT $\boxed{I_{dc} = \frac{I_m}{\pi}} \longrightarrow ③$

Substituting eq ② & ③ in eq ①, we get

$$\gamma = \frac{I_{ac}}{I_{dc}} = \frac{\sqrt{I_{RMS}^2 - I_{dc}^2}}{I_{dc}} = \sqrt{\frac{I_{RMS}^2 - I_{dc}^2}{I_{dc}^2}} = \sqrt{\frac{I_{RMS}^2}{I_{dc}^2} - \frac{I_{dc}^2}{I_{dc}^2}}$$

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$$= \sqrt{\frac{I_{RMS}^2}{I_{dc}^2} - 1} = \sqrt{\frac{(I_m/2)^2}{(I_m/\pi)^2} - 1}$$

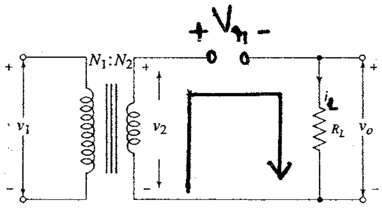
$$= \sqrt{\frac{\frac{1}{4}}{\frac{1}{\pi^2}} - 1} = \sqrt{\frac{\pi^2}{4} - 1}$$

$$\boxed{\gamma = 1.21}$$

This indicates that the **amount of ac present in the output is 121 % of the dc voltage.**

Peak Inverse voltage (PIV) :-

PIV is the maximum voltage across the diode, when the diode is reverse biased.



Applying kvl to the circuit, we get

$-V_2 + V_r - I_L R_L = 0$ $\qquad$ $I_L = 0$

$-V_2 + V_r - 0 \times R_L = 0$

$-V_2 + V_r = 0$

$V_r = V_2$ $\qquad$ $V_2 = V_m \sin wmt$

$V_{r(max)} = (V_m \sin wmt)_{max}$ $\qquad$ $\boxed{V_{rmax} = V_m}$, $\quad (\sin wt)_{max} = 1$

$V_{r(max)} = V_m$

Therefore for HWR $\boxed{PIV = V_m}$

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Advantages of HWR :-

1. Only one diode is required.
2. No centre-tap is required on the transformer.
3. PIV is same as secondary output voltage.

Disadvantages or demerits of HWR :-

1. The ripple factor is too high i.e. =1.21
2. Rectification efficiency is low i.e. 40.6%.

FWR with centre-tapped transformer :-

❖ **Explain with the help of a circuit diagram the working of a full wave rectifier. Derive expressions for**

i) I_{dc} ii) I_{rms} iii) V_{dc} iv) Ripple factor v) Rectifier efficiency.

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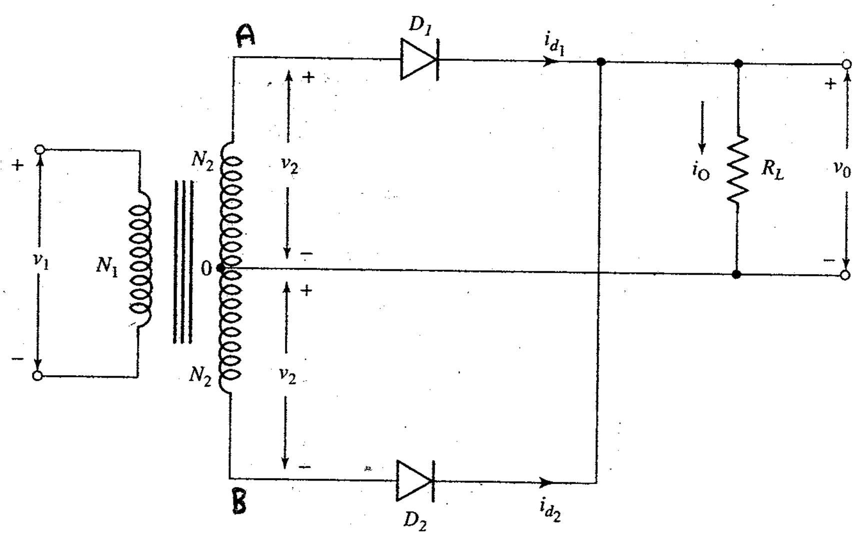

Figure 1. FWR using two diodes & a centre-tapped transformer.

Operation :-

During +ve half cycle :-

❖ During +ve half cycle of the ac input voltage, end A becomes +ve with respect to end B, the diode 'D_1' is forward biased and conducts while the

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diode D_2 is reverse biased and acts as open circuit and will not conduct as shown in fig 2.

- The diode **D_1 supplies** the **load current**. The conventional **current flow** is through diode **D_1**, load resistor **R_L** & the **upper half** of **secondary winding** as shown by the **dotted arrows.**

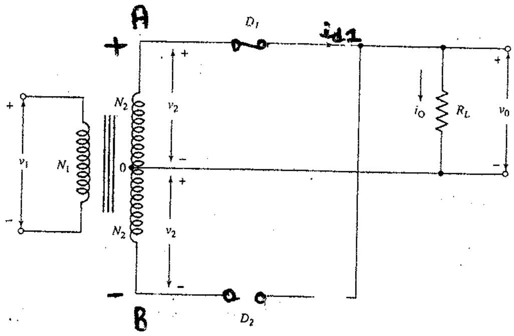


Fig 2.

<u>During -ve half cycle</u> :-

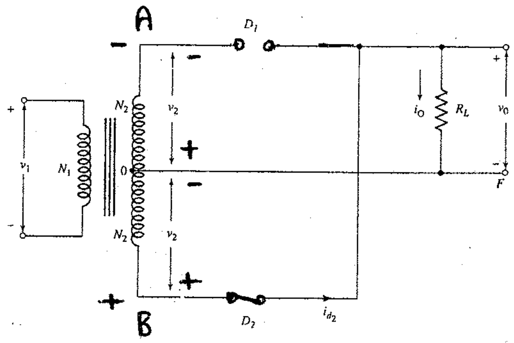


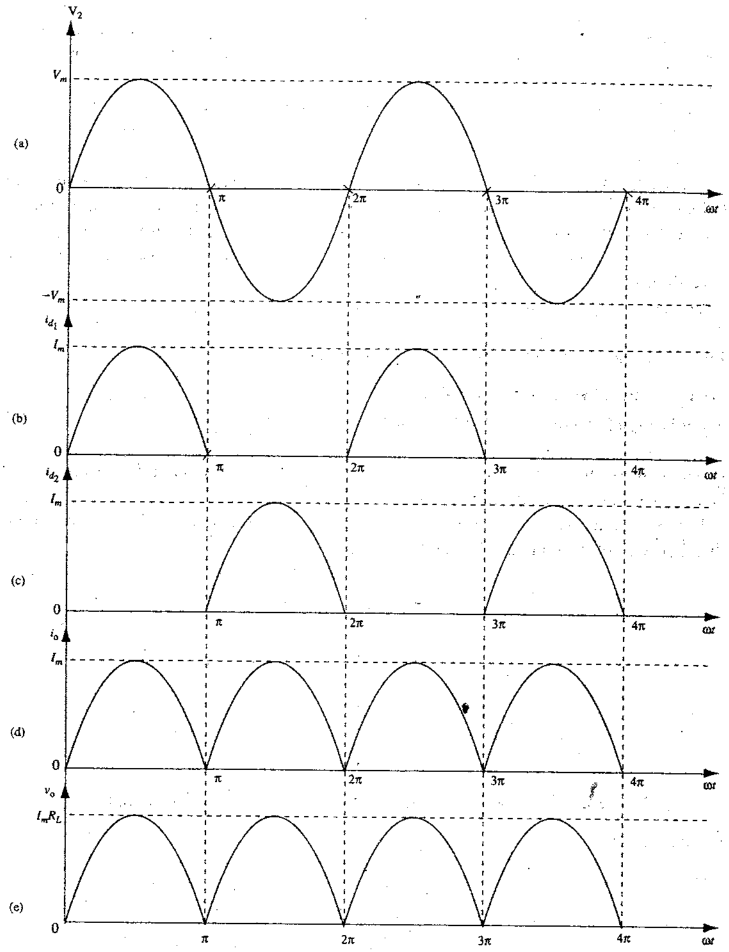
Fig 3.

- During <u>-ve half cycle</u> of the ac input voltage, end A becomes -ve with respect to end B, the diode 'D_2' is forward biased and conducts while the diode D_1 is reverse biased and acts as open circuit and will not conduct as shown in fig 3.

- The diode **D_2 supplies** the **load current**. The conventional **current flow** is through diode **D_2**, load resistor **R_L** & the **lower half** of **secondary winding** as shown by the **solid arrows.**

- From fig 2 & 3 it can be observed that **current** in the **load R_L** is in the **same direction** for **both half cycles** of **ac input voltage**.
  - For both the half cycles the current flows through load in the same direction. Hence we get two half cycles for one complete input signal.

I/O Waveforms



Voltage and current waveforms. (a) Secondary voltage waveform, (b) & (c) Diode current waveforms, (d) load current waveform, (e) load voltage waveform.

1) Average or dc load current (I_{dc} or I_{av}) :-

Consider one cycle of the load current I_L from 0 to π to obtain the average value which is dc value of load current.

$$I_{dc} = \frac{1}{\pi}\int_0^{\pi} I_L \, d\omega t$$

$$= \frac{1}{\pi}\int_0^{\pi} I_m \sin\omega t \, d\omega t$$

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

$$= \frac{I_m}{\pi}\Big[-\cos(\pi) - \{-\cos(0)\}\Big]$$

$$= \frac{I_m}{\pi}[1+1]$$

$$I_{dc} = \frac{2I_m}{\pi}$$

2) Average dc load voltage (V_{dc}) :-

$$V_{dc} = I_{dc} R_L$$

$$= \frac{2I_m}{\pi} R_L$$

$$= \frac{2V_m}{\pi R_L} \cdot R_L$$

$$V_{dc} = \frac{2V_m}{\pi}$$

$$I_{dc} = \frac{2I_m}{\pi}$$

$$I_m = \frac{V_m}{R_L}$$

3) RMS value of load current (I_{RMS}) :-

$$I_{RMS} = \sqrt{\frac{1}{\pi}\int_0^{\pi} I_L^2 \, d\omega t} = \sqrt{\frac{1}{\pi}\int_0^{\pi} I_m^2 \sin^2 \omega t \, d\omega t}$$

$$= I_m\sqrt{\frac{1}{\pi}\int_0^{\pi}\left(\frac{1-\cos 2\omega t}{2}\right) \cdot d\omega t}$$

$$\because \sin^2\theta = \frac{1-\cos 2\theta}{2}$$

$$= I_m\sqrt{\frac{1}{2\pi}\left\{\int_0^{\pi} 1 \, d\omega t - \int_0^{\pi}\cos 2\omega t \, d\omega t\right\}}$$

$$\because \int \cos 2\theta \, d\theta = \frac{\sin 2\theta}{2}$$

$$= I_m\sqrt{\frac{1}{2\pi}\left\{[\omega t]_0^{\pi} - \left[\frac{\sin 2\omega t}{2}\right]_0^{\pi}\right\}}$$

$$= I_m\sqrt{\frac{1}{2\pi}\left\{[\pi - 0] - \frac{1}{2}[\sin 2(\pi) - \sin 2(0)]\right\}}$$

$$= I_m\sqrt{\frac{1}{2\pi}\left\{\pi - \frac{1}{2}[0-0]\right\}}$$

$$= I_m\sqrt{\frac{\pi}{2\pi}}$$

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$$I_{RMS} = \frac{I_m}{\sqrt{2}}$$

4) RMS value of the load voltage (V_{RMS}) :-

$$V_{RMS} = I_{RMS} R_L$$

$$V_{RMS} = \frac{I_m}{\sqrt{2}} R_L$$

5) DC output power (P_{dc}) :-

$$P_{dc} = I_{dc}^2 R_L$$

$$= \left(\frac{2I_m}{\pi}\right)^2 R_L$$

$$P_{dc} = \frac{4}{\pi^2} I_m^2 R_L$$

$$I_{dc} = \frac{2I_m}{\pi}$$

$$I_m = \frac{V_m}{R_L}$$

6) AC output power (P_{ac}) :-

$$P_{ac} = I_{RMS}^2 R_L$$

$$= \left(\frac{I_m}{\sqrt{2}}\right)^2 R_L$$

$$P_{ac} = \frac{I_m^2}{2} R_L$$

$$I_{RMS} = \frac{I_m}{\sqrt{2}}$$

The rectifier efficiency is defined as the ratio of output dc power to input ac power.

7) Rectification efficiency (η):-

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{\frac{4}{\pi^2} I_m^2 R_L}{\frac{I_m^2}{2} R_L} = \frac{\frac{4}{\pi^2}}{\frac{1}{2}} = \frac{4}{\pi^2} \times \frac{2}{1} = 0.812$$

$$\% \eta = 81.2\%$$

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8) Ripple factor (γ):-

$$\gamma = \sqrt{\frac{I_{RMS}^2}{I_{dc}^2} - 1}$$

$$\gamma = \sqrt{\left[\frac{\left(\frac{I_m}{\sqrt{2}}\right)^2}{\left(\frac{2I_m}{\pi}\right)^2}\right] - 1} = \sqrt{\left[\frac{\frac{I_m^2}{2}}{\frac{4I_m^2}{\pi^2}}\right] - 1} = \sqrt{\left(\frac{\frac{1}{2}}{\frac{4}{\pi^2}}\right) - 1}$$

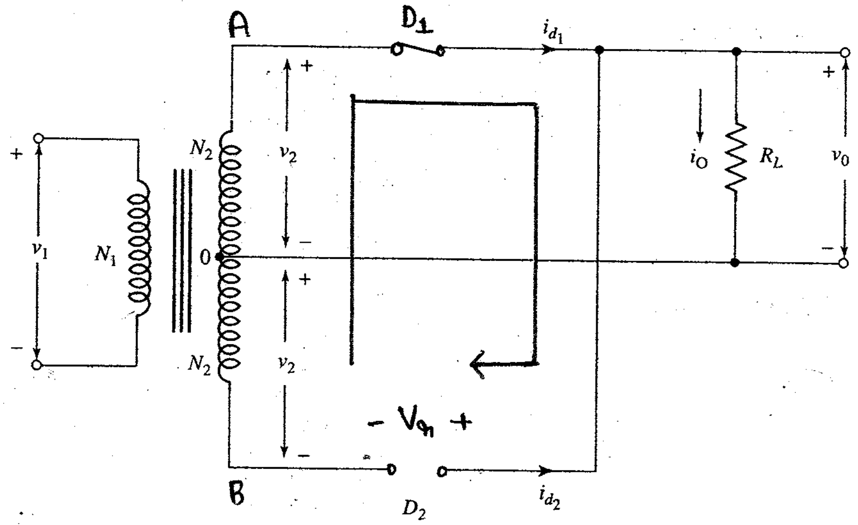
$$= \sqrt{\left(\frac{1}{2} \times \frac{\pi^2}{4}\right) - 1} = \sqrt{\frac{\pi^2}{8} - 1}$$

$$\boxed{\gamma = 0.48}$$

This indicates that the amount of ac present in the output is 0.48 % of the dc voltage.

Peak Inverse voltage (PIV) :-

PIV is the maximum voltage across the diode, when the diode is reverse biased.



Full-wave rectifier, using two diodes and a centre-tapped transformer.

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Applying kvl to the circuit, we get

$$+V_2 + V_2 - V_r = 0$$

$$V_r = 2V_2 \qquad V_2 = V_m \sin wmt$$

$$V_r = 2(V_m \sin wmt) \qquad \boxed{V_{2(max)} = V_m} \qquad (\sin wt)_{max} = 1$$

$$V_{r(max)} = 2V_m$$

Therefore for HWR $\boxed{PIV = 2V_m}$

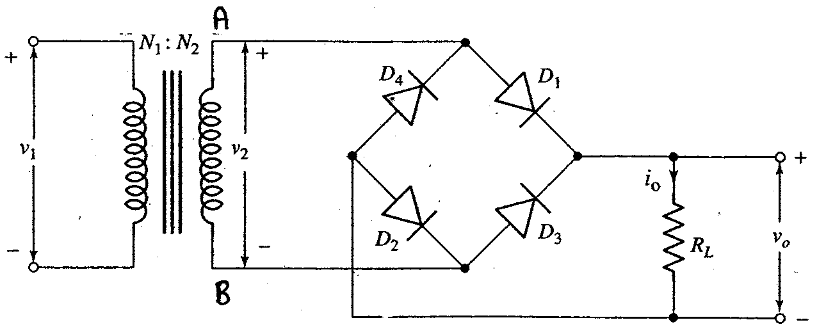
Advantages of FWR :-

1. The efficiency is twice that of HWR i.e. 81.2%
2. The ripple factor is much less than that of HWR
3. The dc output voltage and load current value are twice than HWR.
4. Large dc power output.

Disadvantages of FWR :-

1. PIV of diode the is higher.
2. Cost of centre-tap transformer is higher.
3. Output voltage is half of the secondary voltage.

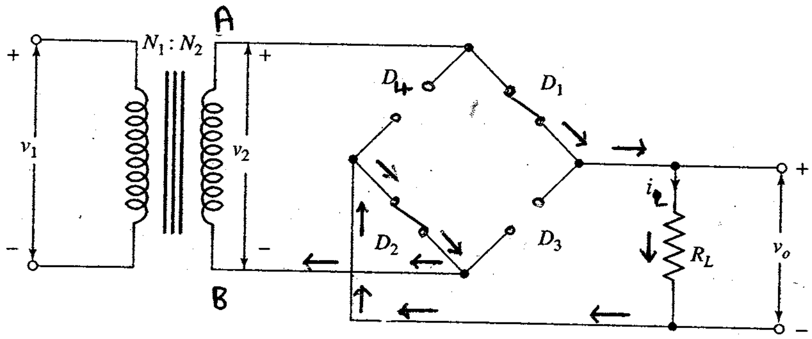
FULL WAVE BRIDGE Rectifier (FWBR) :-



Full-wave bridge rectifier.

Operation :-

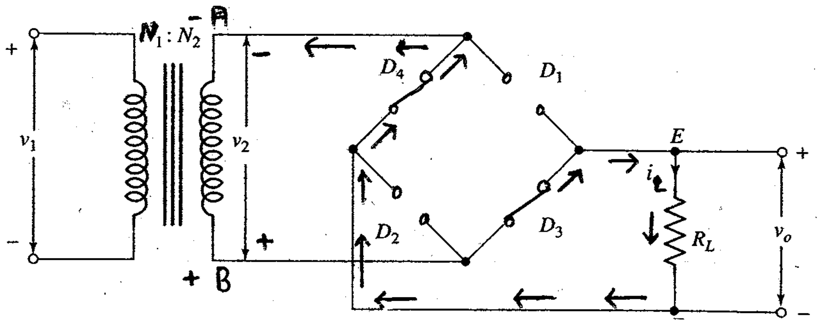
During +ve half cycle :-



- During <u>+ve half cycle</u> of the ac input voltage, end A becomes +ve with respect to end B. This makes diodes ***D_1 & D_2 forward biased***, while ***D_3 & D_4 are reverse biased.***

Therefore only **diodes D_1 & D_2 conducts**. The conventional ***current flows*** through the ***load resistance R_L*** and is shown by the **arrows.**

During –ve half cycle :-



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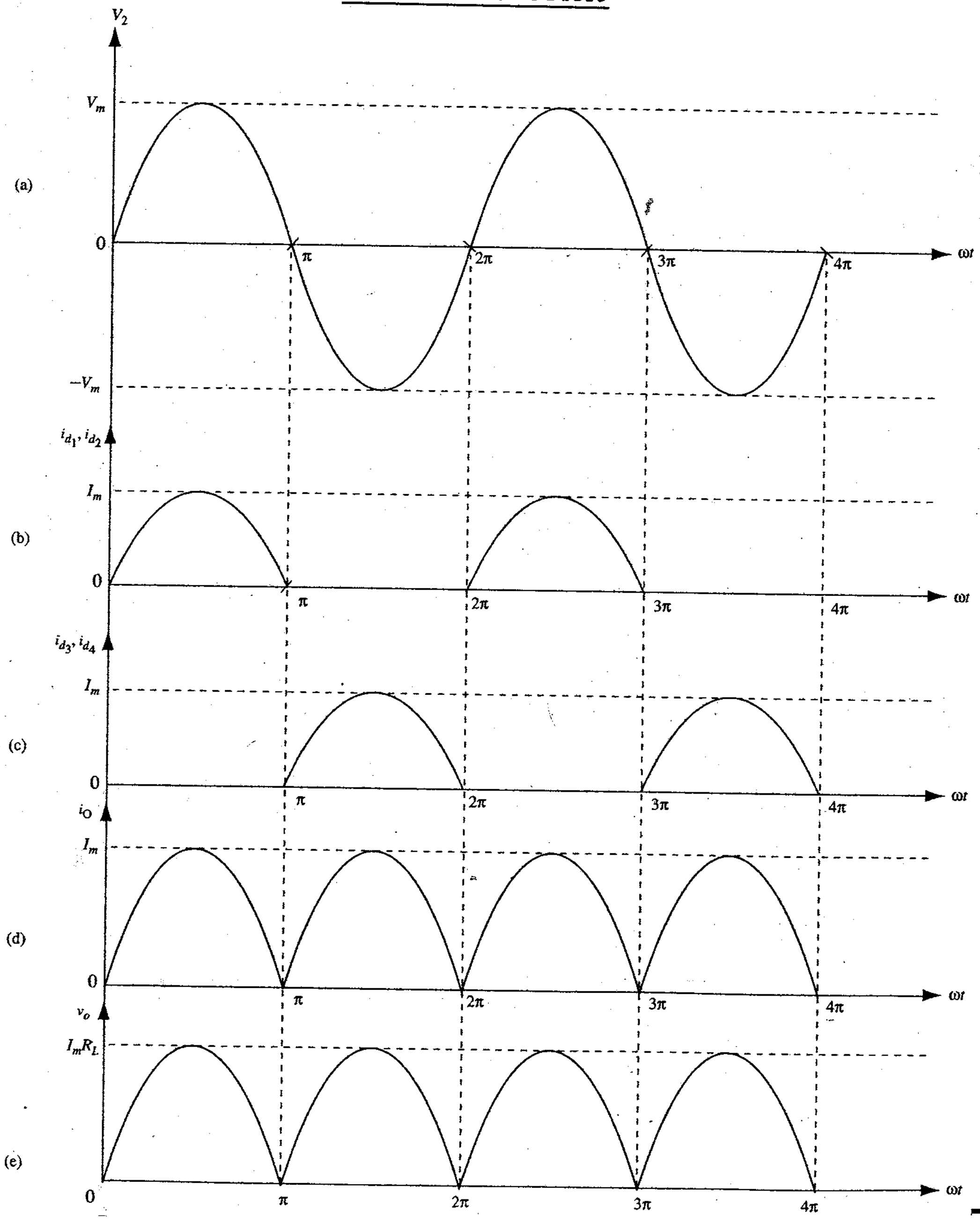
- During **-ve half cycle** of the ac input voltage, end A becomes -ve with respect to end B. This makes diodes ***D_3 & D_4 forward biased***, while ***D_1 & D_2 are reverse biased.***

Therefore only **diodes D_3 & D_4 conducts**. The conventional ***current flows*** through the ***load resistance R_L*** and is shown by the **arrows.**

- For both the half cycles the current flows through load in the same direction. Hence we get two half cycles for one complete input signal.

I/O Waveforms



Voltage and current waveforms in full-wave bridge rectifier.

1) Average or dc load current (I_{dc} or I_{av}) :-

Consider one cycle of the load current I_L from 0 to π to obtain the average value which is dc value of load current.

$$I_{dc} = \frac{1}{\pi}\int_0^{\pi} I_L \, d\omega t$$

$$= \frac{1}{\pi}\int_0^{\pi} I_m \sin\omega t \, d\omega t$$

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

$$= \frac{I_m}{\pi}\left[-\cos(\pi) - \{-\cos(0)\}\right]$$

$$= \frac{I_m}{\pi}\left[1+1\right]$$

$$\boxed{I_{dc} = \frac{2I_m}{\pi}}$$

2) Average dc load voltage (V_{dc}) :-

$$V_{dc} = I_{dc} R_L$$

$$= \frac{2I_m}{\pi} R_L$$

$$= \frac{2V_m}{\pi R_L} \cdot R_L$$

$$\boxed{V_{dc} = \frac{2V_m}{\pi}}$$

$I_{dc} = \frac{2I_m}{\pi}$
$I_m = \frac{V_m}{R_L}$

3) RMS value of load current (I_{RMS}) :-

$$I_{RMS} = \sqrt{\frac{1}{\pi}\int_0^{\pi} I_L^2 \, d\omega t} = \sqrt{\frac{1}{\pi}\int_0^{\pi} I_m^2 \sin^2\omega t \, d\omega t}$$

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$$= I_m \sqrt{\frac{1}{\pi}\int_0^{\pi}\left(\frac{1-\cos 2\omega t}{2}\right) \cdot d\omega t}$$

$\because \sin^2\theta = \frac{1-\cos 2\theta}{2}$

$$= I_m \sqrt{\frac{1}{2\pi}\left\{\int_0^{\pi} 1\, d\omega t - \int_0^{\pi} \cos 2\omega t\, d\omega t\right\}}$$

$\because \int \cos 2\theta\, d\theta = \frac{\sin 2\theta}{2}$

$$= I_m \sqrt{\frac{1}{2\pi}\left\{[\omega t]_0^{\pi} - \left[\frac{\sin 2\omega t}{2}\right]_0^{\pi}\right\}}$$

$$= I_m \sqrt{\frac{1}{2\pi}\left\{[\pi - 0] - \frac{1}{2}\left[\sin 2(\pi) - \sin 2(0)\right]\right\}}$$

$$= I_m \sqrt{\frac{1}{2\pi}\left\{\pi - \frac{1}{2}[0-0]\right\}}$$

$$= I_m \sqrt{\frac{\pi}{2\pi}}$$

$$I_{RMS} = \frac{I_m}{\sqrt{2}}$$

4) RMS value of the load voltage (V_{RMS}) :-

$$V_{RMS} = I_{RMS} R_L$$

$$V_{RMS} = \frac{I_m}{\sqrt{2}} R_L$$

5) DC output power (P_{dc}) :-

$$P_{dc} = I_{dc}^2 R_L$$

$$= \left(\frac{2I_m}{\pi}\right)^2 R_L$$

$$P_{dc} = \frac{4}{\pi^2} I_m^2 R_L$$

$I_{dc} = \frac{2I_m}{\pi}$

$I_m = \frac{V_m}{R_L}$

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6) AC output power (P_{ac}) :-

$$I_{RMS} = \frac{I_m}{\sqrt{2}}$$

$$P_{ac} = I^2_{RMS} R_L$$

$$= \left(\frac{I_m}{\sqrt{2}}\right)^2 R_L$$

$$P_{ac} = \frac{I^2_m}{2} R_L$$

The rectifier efficiency is defined as the ratio of output dc power to input ac power.

7) Rectification efficiency (η):-

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{\frac{4}{\pi^2} I^2_m R_L}{\frac{I^2_m}{2} R_L} = \frac{\frac{4}{\pi^2}}{\frac{1}{2}} = \frac{4}{\pi^2} \times \frac{2}{1} = 0.812$$

$$\% \eta = 81.2\%$$

8) Ripple factor (γ):-

$$\gamma = \sqrt{\frac{I^2_{RMS}}{I^2_{dc}} - 1}$$

$$\gamma = \sqrt{\left[\frac{\left(\frac{I_m}{\sqrt{2}}\right)^2}{\left(\frac{2I_m}{\pi}\right)^2}\right] - 1} = \sqrt{\left[\frac{\frac{I^2_m}{2}}{\frac{4I^2_m}{\pi^2}}\right] - 1} = \sqrt{\left(\frac{\frac{1}{2}}{\frac{4}{\pi^2}}\right) - 1}$$

$$= \sqrt{\left(\frac{1}{2} \times \frac{\pi^2}{4}\right) - 1} = \sqrt{\frac{\pi^2}{8} - 1}$$

$$\gamma = 0.48$$

This indicates that the amount of ac present in the output is 0.48 % of the dc voltage.

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Advantages of FWBR :-

1. The need for centre-tapped transformer is eliminated.
2. The PIV is only V_m
3. The transformer is less costly.

Disadvantages of FWBR :-

1. It requires four diodes.

Peak Inverse voltage (PIV) :-

PIV is the maximum voltage across the diode, when the diode is reverse biased.

Therefore for FWBR **PIV = V_m**

Applications of rectifiers :-

1. In power supply circuits.
2. In rectifier type meter to convert ac voltage to be measured to dc.

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