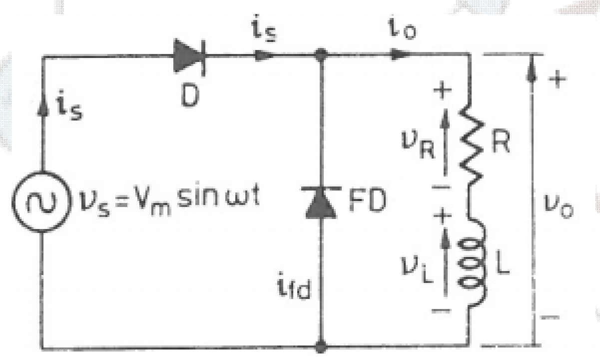
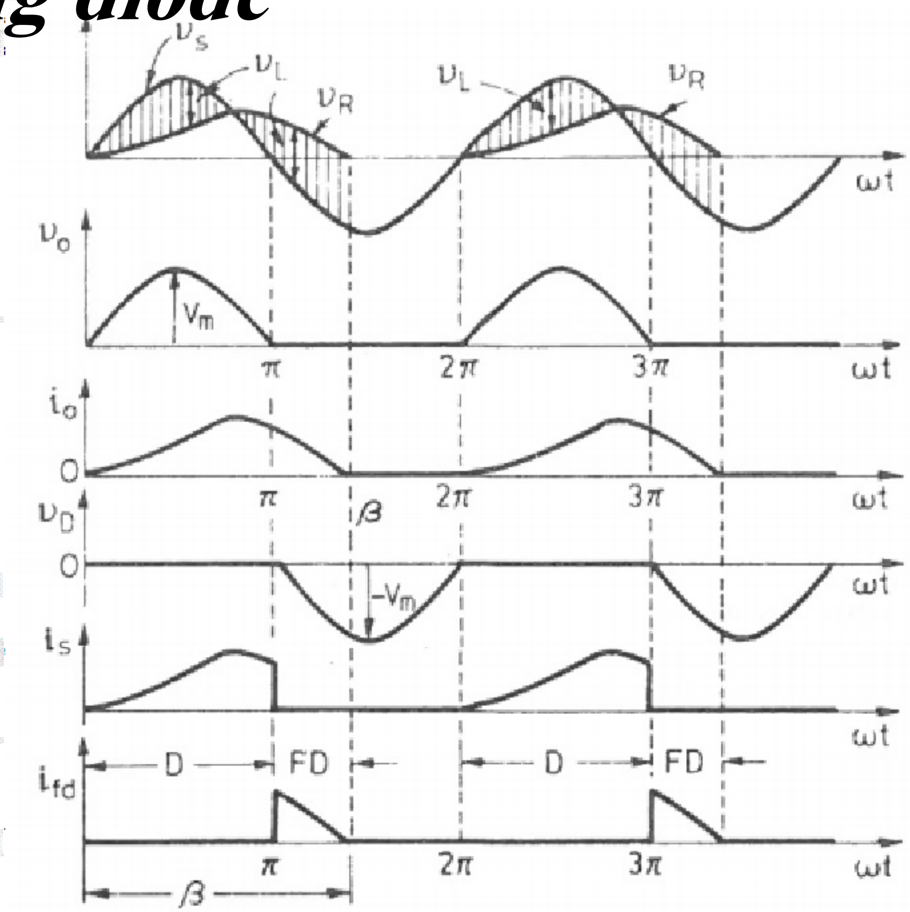
RL Load with freewheeling diode





Output voltage is $v_0 = v_s$ for $0 \le \omega t \le \pi$. At $\omega t = \pi$, source voltage v_s is zero, but output current i_0 is not zero because of L in the load circuit. Just after $\omega t = \pi$, as v_s tends to reverse, negative polarity of v_s reaches cathode of FD through conducting diode D, whereas positive polarity of v_s reaches anode of FD direct. Freewheeling (or flywheel) diode FD, therefore, gets forward-biased. As a result, load current i_0 is immediately transferred from D to FD as v_s tends to reverse. After $\omega t = \pi$, diode current $i_s = 0$ and it is subjected to reverse voltage with PIV equal to V_m.

After $\omega t = \pi$, current freewheels through circuit RL and FD. The energy stored in L is now dissipated in R. When energy stored in L = energy dissipated in R, current falls to zero at $\omega t = \beta < 2\pi$. Depending upon the value of R and L, the current may not fall to zero even when $\omega t = 2\pi$, this is called continuous conduction. load current decays to zero before $\omega t = 2\pi$; load current is therefore discontinuous.

The effects of using freewheeling diode are as under :

(*i*) It prevents the output (or load) voltage from becoming negative.

(*ii*) As the energy stored in L is transferred to load R through FD, the system efficiency is improved.

(*iii*) The load current waveform is more smooth, the load performance is therefore improved.

average output voltage, $$V_0 = \frac{1}{2\pi}\int_0^{\pi} V_m \sin \omega t \, d(\omega t) = \frac{V_m}{\pi}$$

and average load current, $$I_0 = \frac{V_m}{\pi R}$$

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The effect of this diode is to prevent a negative voltage appearing across the load; and as a result, the magnetic stored energy is increased. At $t = t_1 = \pi/\omega$, the current from D_1 is transferred to D_m and this process is called *commutation* of diodes

Depending on the load time constant, the load current may be discontinuous. Load current i_0 is discontinuous with a resistive load and continuous with a very high inductive load. The continuity of the load current depends on its time constant $\tau = \omega L/R$.

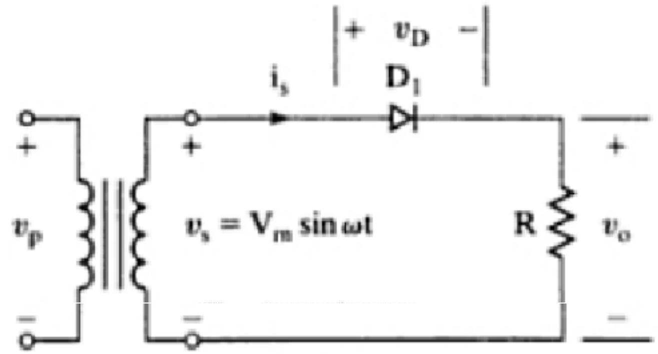
The performance of a half-wave rectifier that is measured by certain parameters is poor. The load current can be made continuous by adding an inductor and a freewheeling diode. The output voltage is discontinuous and contains harmonics at multiples of the supply frequency.

Example Finding the Fourier Series of the Output Voltage for a Half-Wave Rectifier

The single-phase half-wave rectifier of Figure is connected to a source of $V_s = 120$ V, 60 Hz. Express the instantaneous output voltage $v_0(t)$ in Fourier series.

Solution

The rectifier output voltage v_0 may be described by a Fourier series as



$$v_0(t) = V_{dc} + \sum_{n=1,2,\ldots}^{\infty} (a_n \sin n\omega t + b_n \cos n\omega t)$$

$$V_{dc} = \frac{1}{2\pi}\int_0^{2\pi} v_0 \, d(\omega t) = \frac{1}{2\pi}\int_0^{\pi} V_m \sin \omega t \, d(\omega t) = \frac{V_m}{\pi}$$

$$a_n = \frac{1}{\pi}\int_0^{2\pi} v_0 \sin n\omega t \, d(\omega t) = \frac{1}{\pi}\int_0^{\pi} V_m \sin \omega t \sin n\omega t \, d(\omega t)$$

$$= \frac{V_m}{2} \qquad \text{for } n = 1$$

$$= 0 \qquad \text{for } n = 2, 3, 4, 5, 6, \ldots$$

$$b_n = \frac{1}{\pi}\int_0^{2\pi} v_0 \cos n\omega t \, d(\omega t) = \frac{1}{\pi}\int_0^{\pi} V_m \sin \omega t \cos n\omega t \, d(\omega t)$$

$$= \frac{V_m}{\pi} \frac{1 + (-1)^n}{1 - n^2} \qquad \text{for } n = 2, 4, 6, \ldots$$

$$= 0 \qquad \text{for } n = 1, 3, 5, \ldots$$

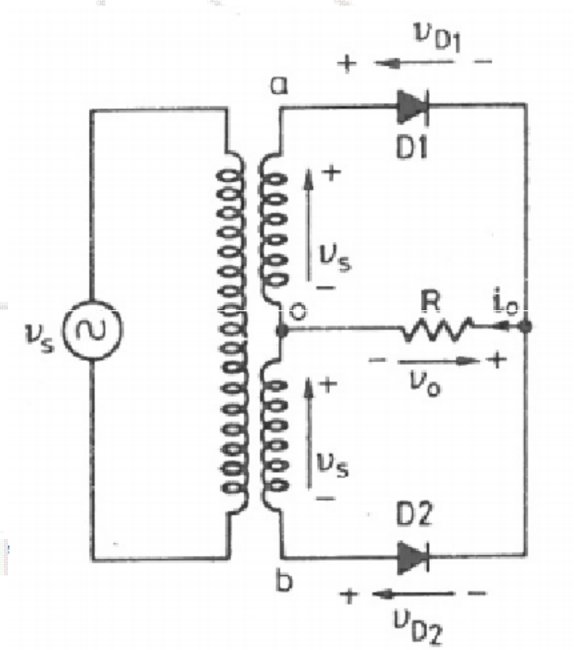
Substituting a_n and b_n, the instantaneous output voltage becomes

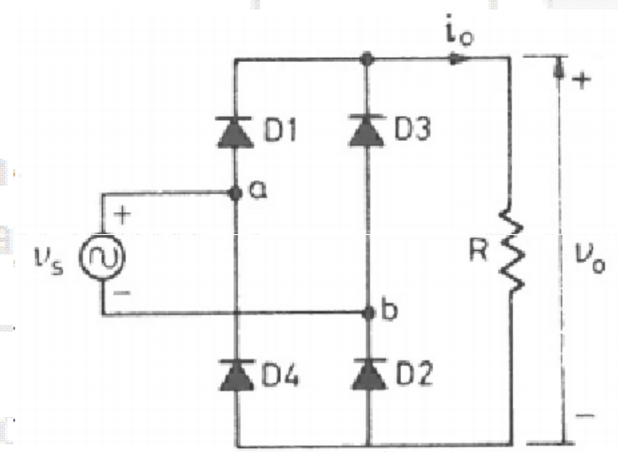
$$v_0(t) = \frac{V_m}{\pi} + \frac{V_m}{2}\sin \omega t - \frac{2V_m}{3\pi}\cos 2\omega t - \frac{2V_m}{15\pi}\cos 4\omega t - \frac{2V_m}{35\pi}\cos 6\omega t - \cdots$$

where $V_m = \sqrt{2} \times 120 = 169.7$ V and $\omega = 2\pi \times 60 = 377$ rad/s.

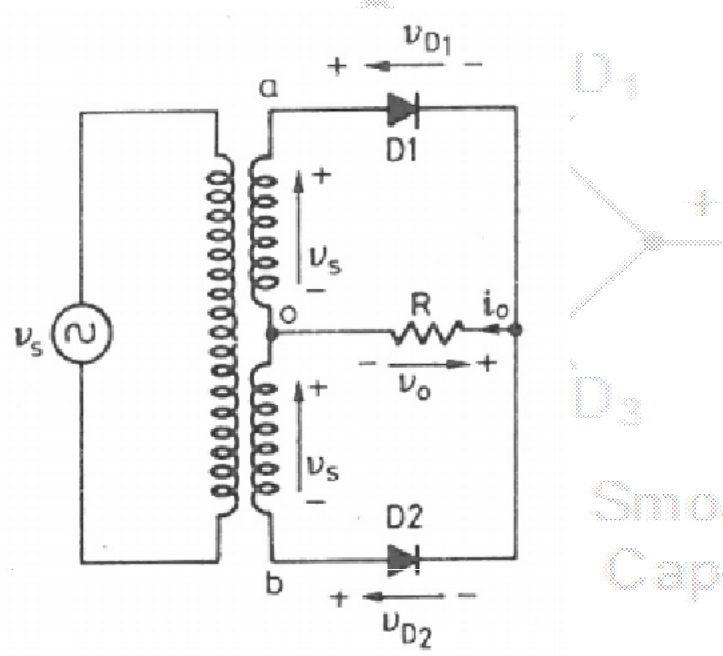
Single Phase Full Wave Diode Rectifiers

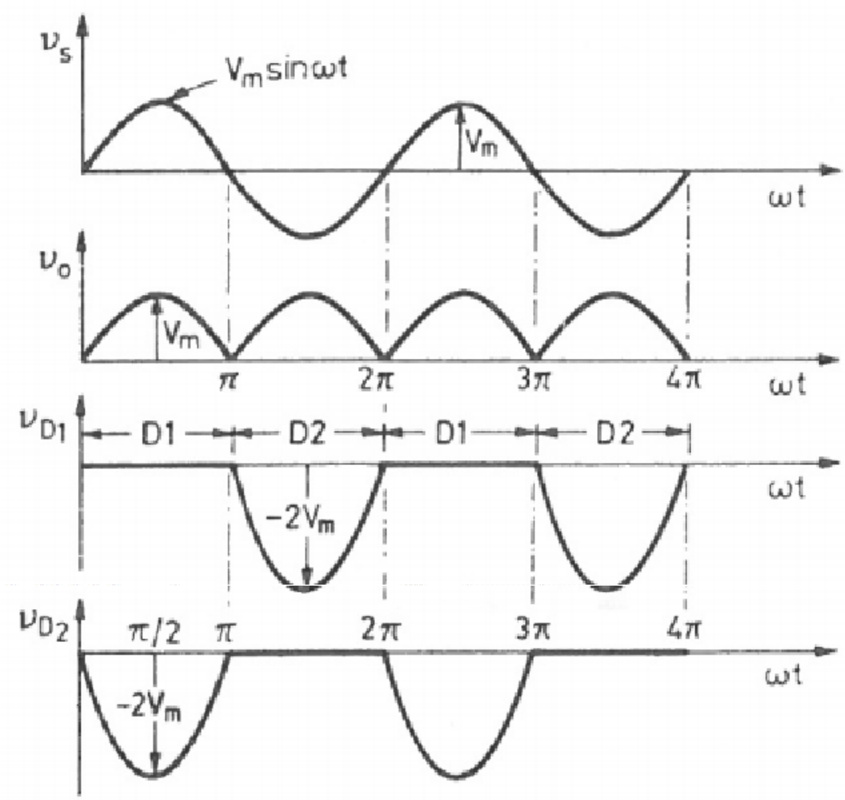
There are two types of full-wave diode rectifiers, one is centre-tapped (or mid-point) full-wave diode rectifier and the other is full-wave diode bridge rectifier. These are now described briefly.





Single Phase Full Wave mid point Diode Rectifiers





Each half of the transformer with its associated diode acts as a half-wave rectifier

The turns ratio from each secondary to primary is taken as unity for simplicity. When '*a*' is positive with respect to '*b*' ; diode D1 conducts for π radians. In the next half cycle, '*b*' is positive with respect to '*a*' and therefore diode D2 conducts.

The waveform for output current i_0 (not shown in the figure) is similar to v_0 waveform. When '*a*' is positive with respect to '*b*', diode D2 is subjected to a reverse voltage of $2v_s$. In the next half cycle, diode D1 experiences a reverse voltage of $2v_s$. Thus, for diodes

D1 and D2, peak inverse voltage is $2V_m$.

for one cycle

of source voltage, there are two pulses of output voltage. So single-phase full-wave diode rectifier can also be called *single-phase two-pulse* diode rectifier.

Average output voltage

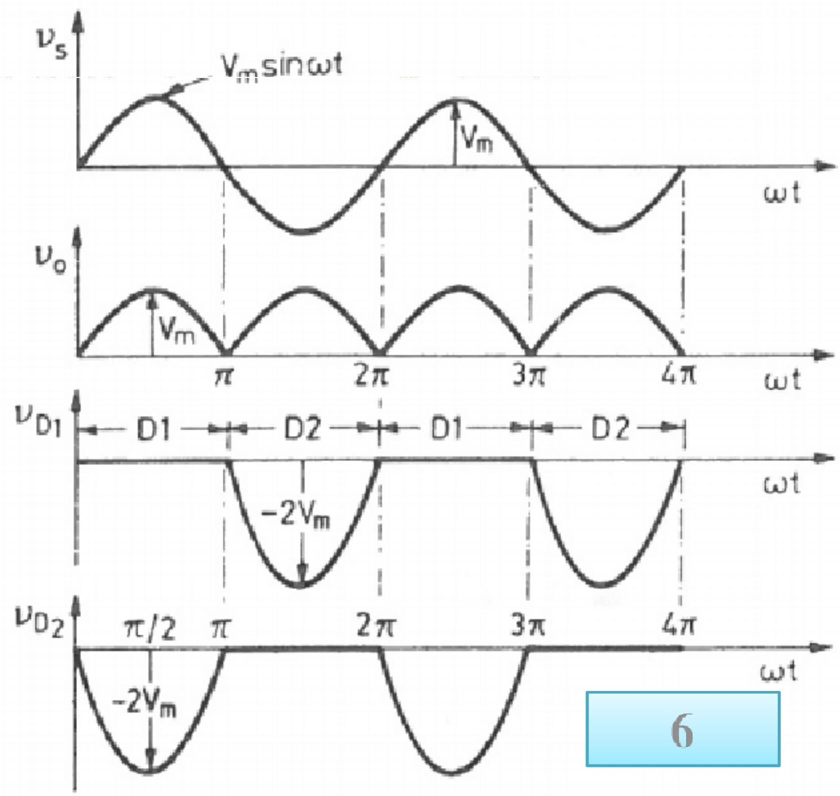
$$V_0 = \frac{1}{\pi}\int_0^{\pi} V_m \sin \omega t \, d(\omega t) = \frac{2V_m}{\pi}$$

Average output current, $I_0 = \dfrac{V_0}{R}$

Rms value of output voltage,

$$V_{or} = \left[\frac{1}{\pi}\int_0^{\pi} V_m^2 \sin^2 \omega t \, d(\omega t)\right]^{1/2}$$

$$= \frac{V_m}{\sqrt{2}} = V_s$$

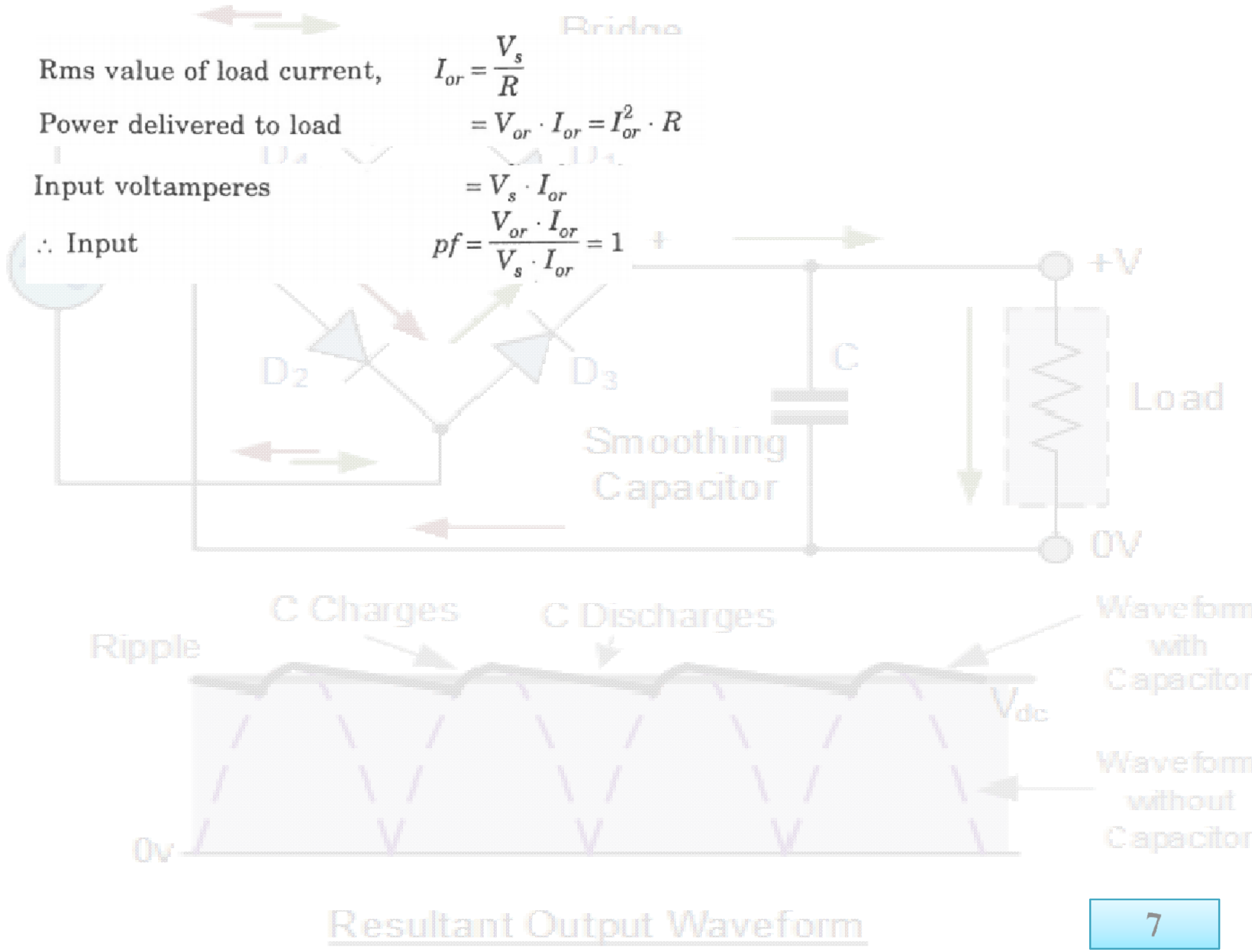


Rms value of load current, $I_{or} = \frac{V_s}{R}$

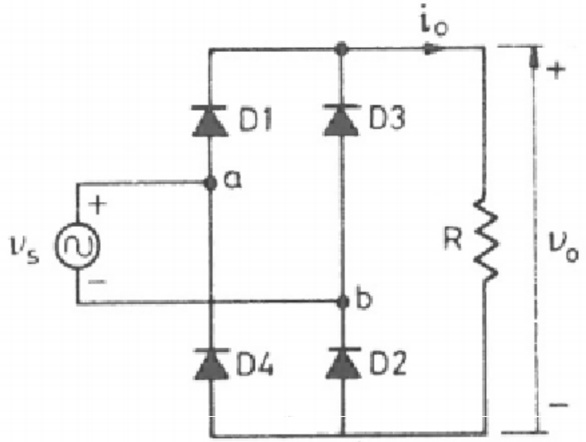
Power delivered to load $= V_{or} \cdot I_{or} = I_{or}^2 \cdot R$

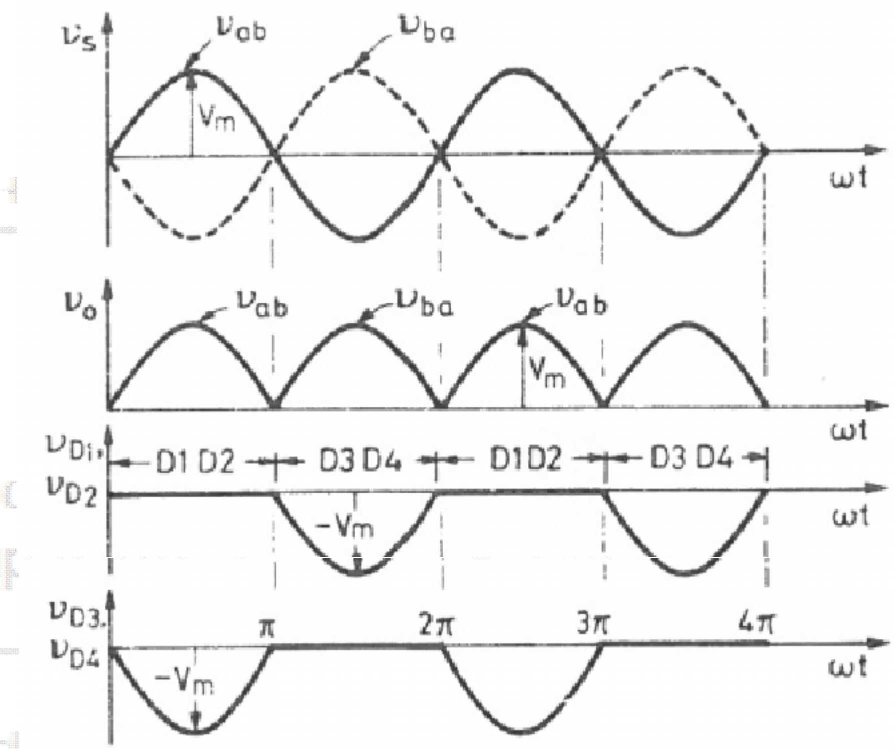
Input voltamperes $= V_s \cdot I_{or}$

$\therefore$ Input $pf = \frac{V_{or} \cdot I_{or}}{V_s \cdot I_{or}} = 1$



Single Phase Full Wave Diode Bridge Rectifiers





When 'a' is positive with respect to 'b', diodes D1, D2 conduct together so that output voltage is v_{ab}. Each of the diodes D3 and D4 is subjected to a reverse voltage of v_s , When 'b' is positive with respect to 'a', diodes D3, D4 conduct together and output voltage is v_{ba}. Each of the two diodes D1 and D2 experience a reverse voltage of v_s as shown.

a diode in mid-point full-wave rectifier is subjected to PIV of $2V_m$ whereas a diode in full-wave bridge rectifier has PIV of V_m only.

Example *In a single-phase full-wave diode bridge rectifier, the diodes have a reverse recovery time of 40 μs. For an ac input voltage of 230 V, determine the effect of reverse recovery time on the average output voltage for a supply frequency of (a) 50 Hz and (b) 2.5 kHz.*

If reverse recovery time is taken into consideration, the diodes D1 and D2 will not be off at $\omega t = \pi$, but will continue to conduct until $t = \dfrac{\pi}{\omega} + t_{rr}$

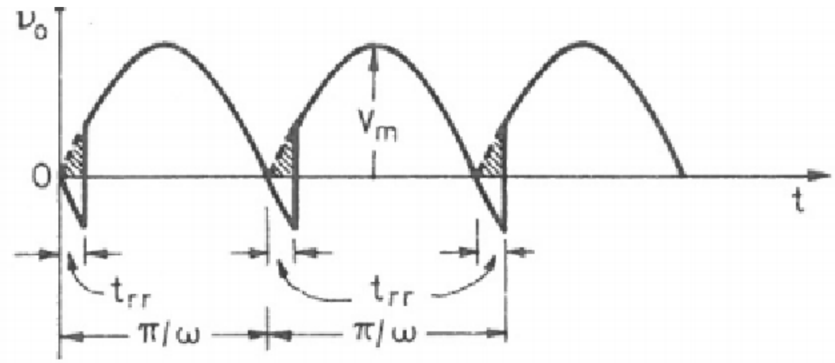
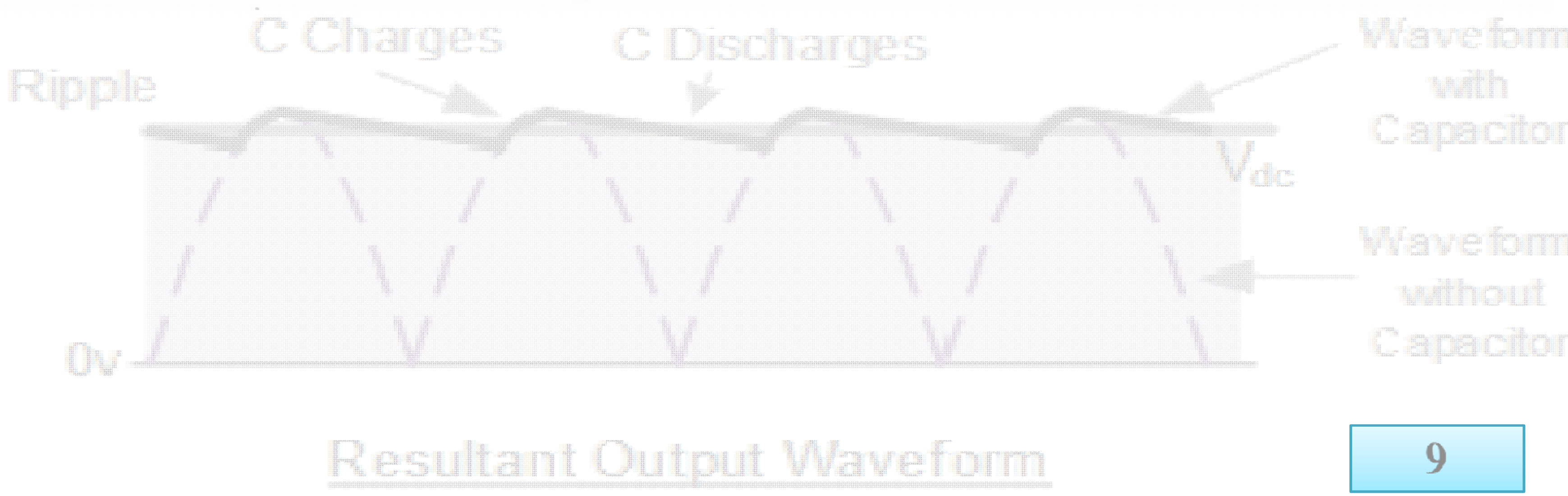


Fig. 3.20. Effect of reverse recovery time on output voltage.

The reduction in output voltage is given by the cross-hatched area. Average value of this reduction in output voltage is given by

$$V_r = \frac{1}{\pi}\int_0^{t_{rr}} V_m \sin \omega t \, d(\omega t)$$



$$= \frac{V_m}{\pi}(1 - \cos \omega t_{rr})$$

With zero reverse recovery time, average output voltage, is

$$V_0 = \frac{2\sqrt{2} \times 230}{\pi} = 207.04 \text{ V}$$

(*a*) For $f = 50$ Hz and $t_{rr} = 40$ μs, the reduction in the average output voltage, is

$$V_r = \frac{V_m}{\pi}(1 - \cos 2\pi f t_{rr})$$

$$= \frac{\sqrt{2} \times 230}{\pi}\left(1 - \cos 2\pi \times 50 \times 40 \times 10^{-6} \times \frac{180}{\pi}\right)$$

$$= 8.174 \text{ mV}$$

Percentage reduction in average output voltage

$$= \frac{8.174 \times 10^{-3}}{207.04} \times 100 = 3.948 \times 10^{-3}\%$$

(*b*) For $f = 2500$ Hz, the reduction in the average output voltage, is

$$V_r = \frac{\sqrt{2} \times 230}{\pi}\left(1 - \cos 2\pi \times 2500 \times 40 \times 10^{-6} \times \frac{180}{\pi}\right)$$

$$= 19.77 \text{ V}$$

Percentage reduction in average output voltage $= \frac{19.77}{207.04} \times 100 = 9.594\%$.

It is seen from above that the effect of reverse recovery time is negligible for diode operation at 50 Hz, but for high-frequency operation of diodes, the effect is noticeable.

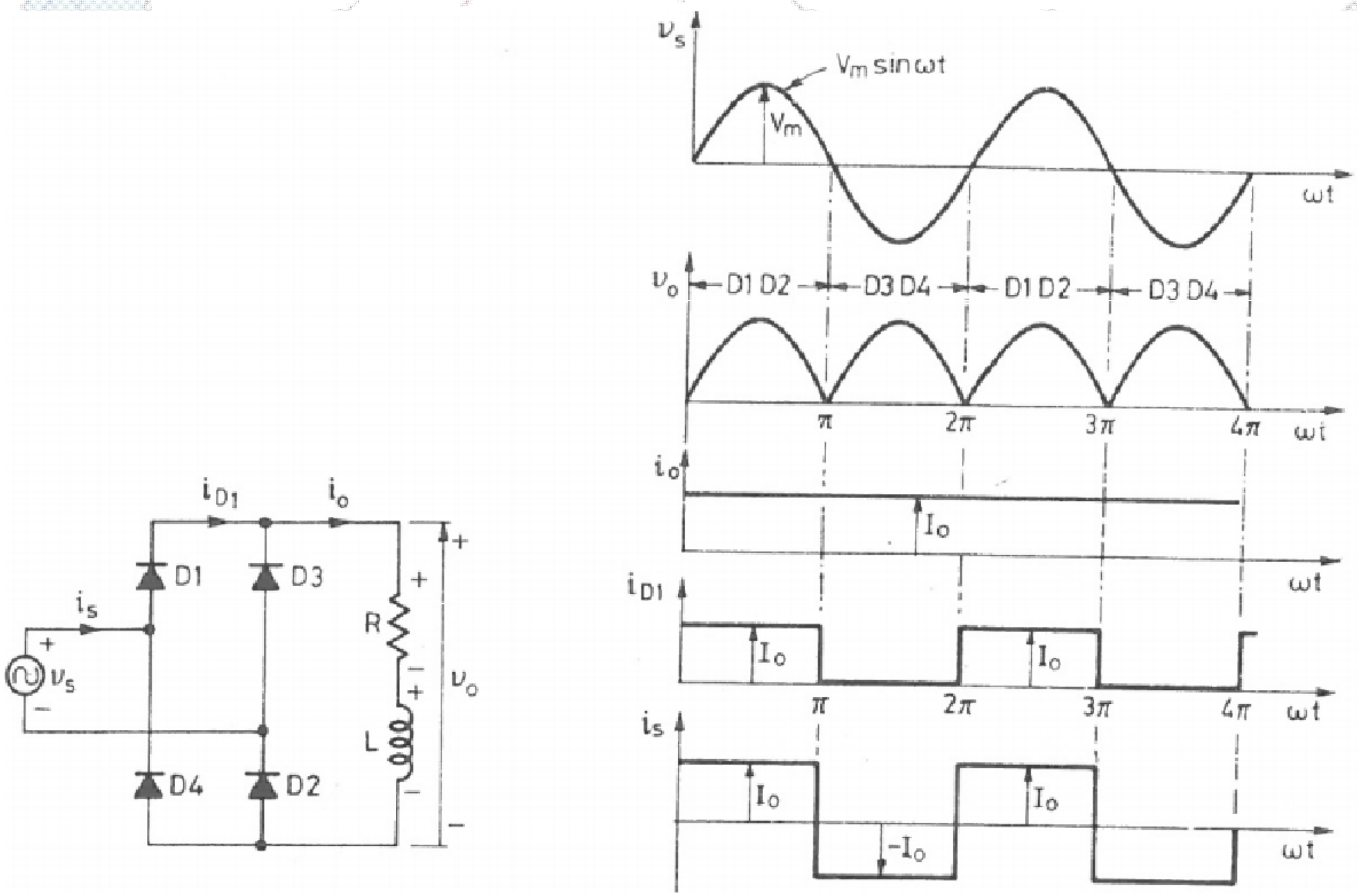
Resultant Output Waveform

Example *A single-phase full bridge diode rectifier is supplied from 230 V, 50 Hz source. The load consists of $R = 10\ \Omega$ and a large inductance so as to render the load current constant. Determine*

(a) average values of output voltage and output current,

(b) average and rms values of diode currents,

(c) rms values of output and input currents, and supply pf.



(*a*) Average value of output voltage,

$$V_0 = \frac{2V_m}{\pi} = \frac{2\sqrt{2} \times 230}{\pi} = 207.04 \text{ V}$$

Average value of output current,

$$I_0 = \frac{V_0}{R} = \frac{207.04}{10} = 20.704 \text{ A}$$

(*b*) Average value of diode current,

$$I_{DAV} = \frac{I_0 \cdot \pi}{2\pi} = \frac{I_0}{2} = \frac{20.704}{2} = 10.352 \text{ A}$$

Rms value of diode current, $I_{Dr} = \sqrt{\dfrac{I_0 \, \pi}{2\pi}} = \dfrac{I_0}{\sqrt{2}} = \dfrac{20.704}{\sqrt{2}} = 14.642 \text{ A}$

As load, or output, current is ripple free, rms value of output current

$= \text{average value of output current} = I_0 = 20.704 \text{ A}$

Rms value of source current, $I_s = \sqrt{\dfrac{I_0^2 \, \pi}{\pi}} = I_0 = 20.704 \text{ A}$

Load power $= V_0 I_0 = 207.04 \times 20.704 \text{ W}$

Input power $= V_s I_s \cos\phi$

$\therefore \quad 230 \times 20.704 \times \cos\phi = 207.04 \times 20.704$

$\therefore$ Supply pf $= \cos\phi = \dfrac{207.04}{230} = 0.90$ lagging.

Example Finding the Fourier Series of the Output Voltage for a Full-Wave Rectifier

The rectifier in Figure 3.5a has an RL load. Use the method of Fourier series to obtain expressions for output voltage $v_0(t)$.

Solution

The rectifier output voltage may be described by a Fourier series (which is reviewed in Appendix E) as

$$v_0(t) = V_{dc} + \sum_{n=2,4,\ldots}^{\infty} (a_n \cos n\omega t + b_n \sin n\omega t)$$

$$V_{dc} = \frac{1}{2\pi}\int_0^{2\pi} v_0(t)\, d(\omega t) = \frac{2}{2\pi}\int_0^{\pi} V_m \sin \omega t\, d(\omega t) = \frac{2V_m}{\pi}$$

$$a_n = \frac{1}{\pi}\int_0^{2\pi} v_0 \cos n\omega t\, d(\omega t) = \frac{2}{\pi}\int_0^{\pi} V_m \sin \omega t \cos n\omega t\, d(\omega t)$$

$$= \frac{4V_m}{\pi} \sum_{n=2,4,\ldots}^{\infty} \frac{-1}{(n-1)(n+1)} \qquad \text{for } n = 2, 4, 6, \ldots$$

$$= 0 \qquad \text{for } n = 1, 3, 5, \ldots$$

$$b_n = \frac{1}{\pi}\int_0^{2\pi} v_0 \sin n\omega t\, d(\omega t) = \frac{2}{\pi}\int_0^{\pi} V_m \sin \omega t \sin n\omega t\, d(\omega t) = 0$$

Substituting the values of a_n and b_n, the expression for the output voltage is

$$v_0(t) = \frac{2V_m}{\pi} - \frac{4V_m}{3\pi}\cos 2\omega t - \frac{4V_m}{15\pi}\cos 4\omega t - \frac{4V_m}{35\pi}\cos 6\omega t - \cdots$$