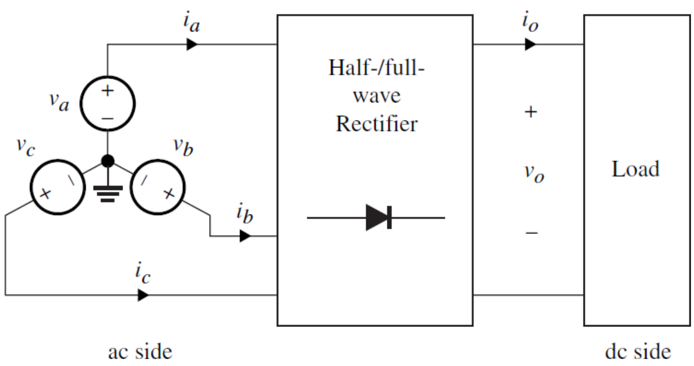
Lecture -1-

Three -phase rectifiers

➢ Uncontrolled Three -phase rectifiers

Many industrial applications require high power that a single-phase system is unable to provide. Three-phase diode rectifier circuits are used widely in high-power applications with low output ripple. It is important that we understand the basic concepts of a three-phase rectifier circuit. In this section, we will cover both half- and full-wave rectifier circuits under resistive and high inductive loads.

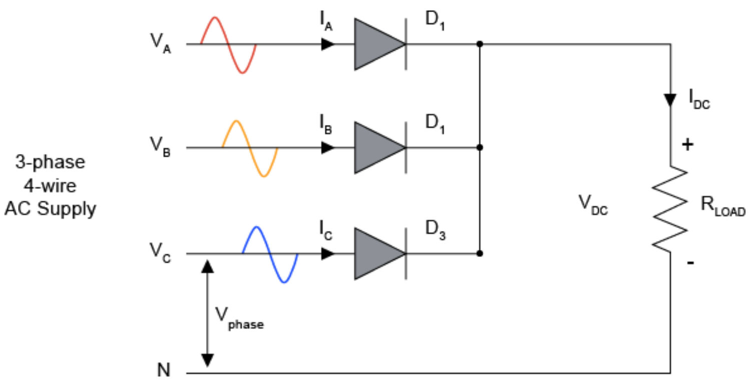


1) Half-Wave Rectifiers

Three-phase half-wave rectifiers are utilized in power electronics applications where the conversion of three-phase AC power to DC power is required. It is widely used in power supply systems, motor drives, and various other applications due to its efficient and reliable performance.

The three-phase half-wave rectifier is simple since it requires only three diodes, the circuit is called also a ***three-pulse rectifier***. the ac connection consists of three single phases (Red, Yellow, and Blue colored wires are used to represent each of the three phases) with a phase difference of 120° connected to the load. The circuit works at any time the voltage of any one of the phases is greater than zero, therefore machines operate at a better efficiency.

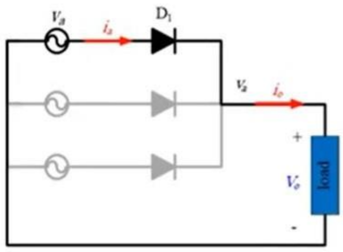
$$v_a = V_s \sin \omega t \qquad v_b = V_s \sin(\omega t - 120°) \qquad v_c = V_s \sin(\omega t - 240°)$$



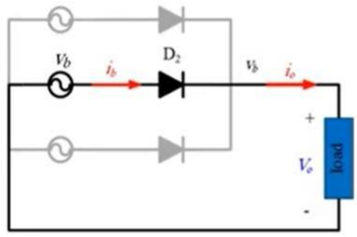
- **Voltage at (R- Load)**

The anode of each diode is connected to one phase of the AC voltage source, while the other terminals (the cathodes of the three diodes) are connected together to the same positive point. This common point becomes the positive (+) terminal for the load while the negative (-) terminal of the load is connected to the neutral (N) of the power supply.

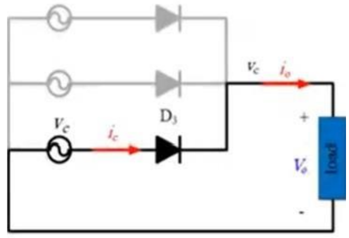
In each phase, only one diode will be ON (forward) while the others are forced to be off (reversed). The waveform of the voltage at the output of the rectifier (on the load) is depicted in the figures below.



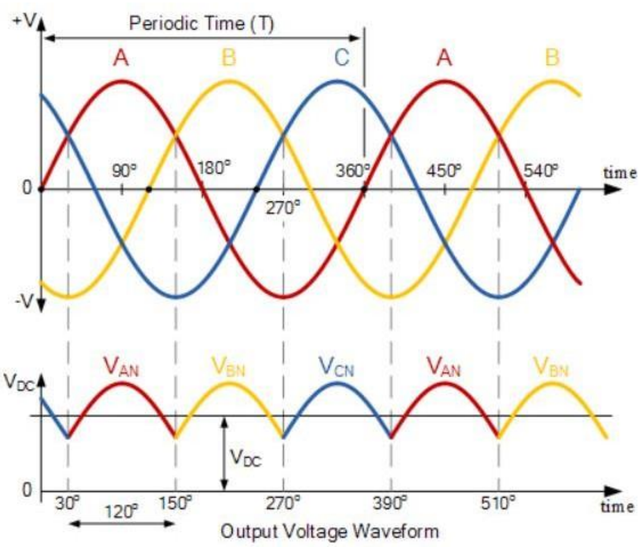
$\pi/6 \le \omega t \le 5\pi/6$



$5\pi/6 \le \omega t \le 3\pi/2$



$3\frac{\pi}{2} \le \omega t \le 2\pi + \pi/6$



Let's assume that phase voltage V_A starts at 0°. During the time interval between 0° and 30° the voltage at the diode D_3 anode is the highest one ($V_C > V_A > V_B$). Hence, diode D_3 conducts, and forces diodes D_1 and D_2 to turn off. Thereafter, during the time interval between 30° and 150° the voltage at the diode D_1 anode is the highest one (30°-90°: $V_A > V_C > V_B$; 90°-150°: $V_A > V_B > V_C$). Hence, diode D_1 conducts, and diodes D_2 and D_3 don't. And so on…
we can see, for three-phase rectification, whichever diode has a more positive voltage at its anode compared to the other two diodes will automatically start to conduct.

The output waveform(V_{dc})in the figure above applies if the load is R or RL.

The average value of the load voltage $\left(\cos 150 = -\frac{\sqrt{3}}{2}\right)$

$$V_{DC(load)} = \frac{3}{2\pi}\int_{\pi/6}^{5\pi/6} V_m \sin(wt)\, dwt$$

$$\boxed{V_{DC(load)} = \frac{3\sqrt{3}\, V_{m(Phase)}}{2\pi}}$$

drive it ??

The average value of the load current:

$$I_{DC(load)} = \frac{V_{DC}}{R}$$

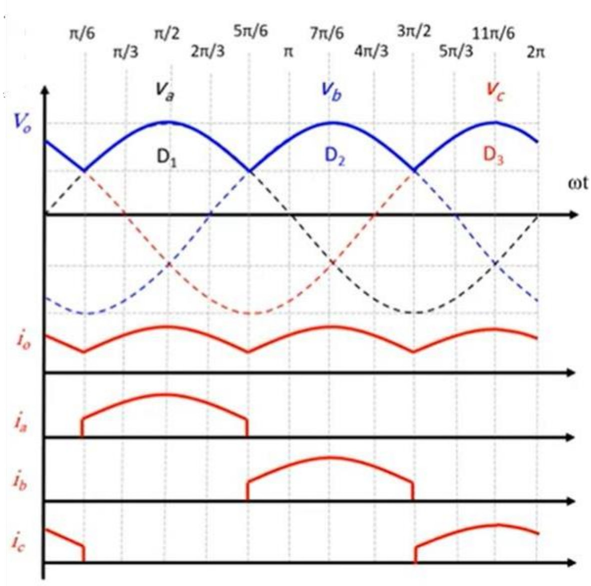
$$\boxed{I_{DC(load)} = \frac{3\sqrt{3}\, V_{m(Phase)}}{2\pi R}}$$

The rms value of the output voltage and current:

$$V_{RMS(load)} = \sqrt{\frac{3}{2\pi}\int_{\pi/6}^{5\pi/6} [V_m \sin(wt)]^2\, dwt} = 0.84 V_{m(Phase)}$$

$$I_{RMS(load)} = \frac{V_{RMS}}{R}$$

Current at (R- Load)



$$\mathbf{I_{D,avg}} = \frac{\mathbf{I_{o,avg}}}{\mathbf{3}} \qquad (\textbf{diode current})$$

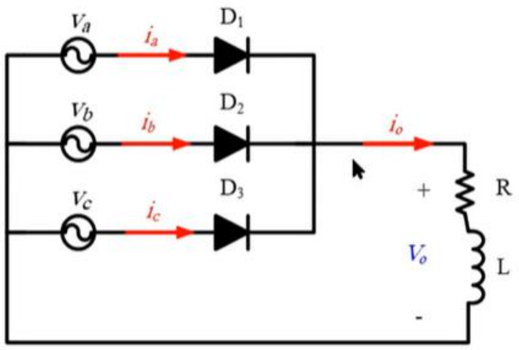
$$\mathbf{P_o} = \mathbf{I_{o,rms}} * \boldsymbol{R} \qquad (\textbf{output power})$$

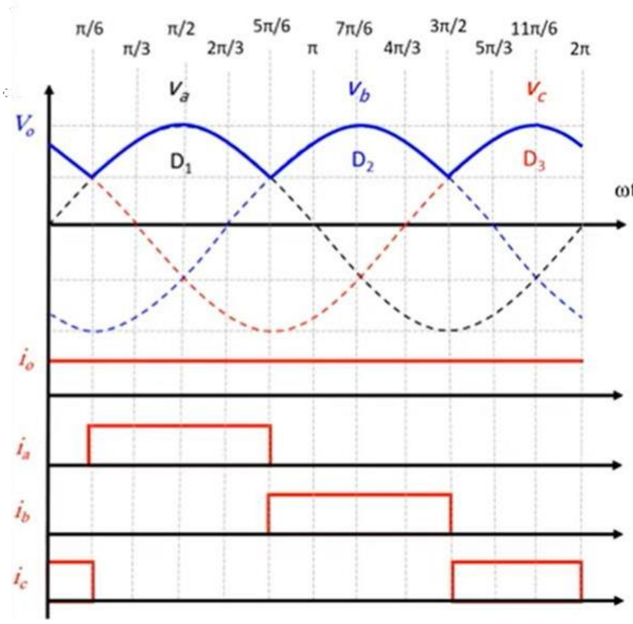
$$\boldsymbol{S} = \mathbf{3\ V_{o,rms}} * \mathbf{I_{o,rms}} \qquad (\textbf{apparent power})$$

$$\boldsymbol{P.F} = \frac{\mathbf{P_o}}{\boldsymbol{S}} \qquad (\boldsymbol{power\ factor})$$

- **Current at (RL- Load)**

Adding an inductance in series with the load resistance changes the current waveform. If **L** is much higher than **R** (L>>>R), the load time constant L/R is very high and can be considered infinity. Consequently, the load current is assumed constant as shown by the waveforms in Figure:





All previous formulas apply to (RL-Load) except for Irms, since

$$\boldsymbol{I_{o,rms} = I_{DC} = I_{o,avg} = \frac{3\sqrt{3}\,Vm}{2\pi R}}$$

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***Applications of Half Wave Rectifier**

Half-wave rectifiers are widely used in electrical and electronic circuits. Some of such circuits are:

- Pulse generating circuits
- Signal demodulation circuits
- Signal peak circuits
- AC to DC converters
- Low-power DC chargers

Example

Power is supplied to heavily inductive load from a three-phase supply, using a three-phase half-wave rectifier. If the phase voltage is 220 Vrms and the resistance of the load is 100 Ω, determine the DC load voltage and current.

Solution:

$$V_{s,RMS(Phase)} = 220\,V, \quad R = 100\,\Omega, \quad L \gg R$$

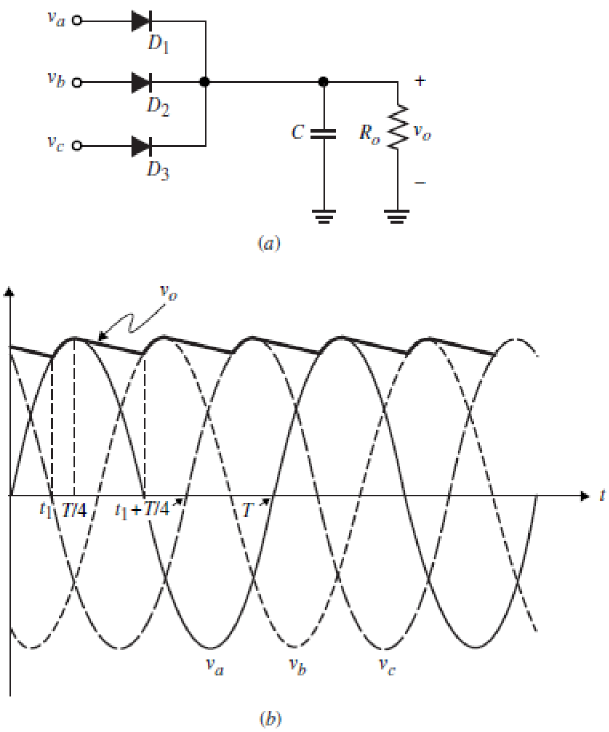
$$V_{DC(load)} = \frac{3\sqrt{3}\,V_{m(Phase)}}{2\pi}, \qquad V_{m(phase)} = 220\sqrt{2}$$

$$V_{DC(load)} = \frac{(3\sqrt{3})(220\sqrt{2})}{2\pi} = 257.4\,V$$

$$I_{DC(load)} = \frac{V_{DC}}{R}$$

$$I_{DC(load)} = \frac{257.4}{100} = 2.6\,A$$

Three-phase Half-wave capacitive-load rectifiers



(a) Three-phase half-wave capacitive-load rectifier. (b) Output voltage waveform.

The output voltage ripple is given by:

$$\Delta Vo = \frac{Vm}{3fRC}$$

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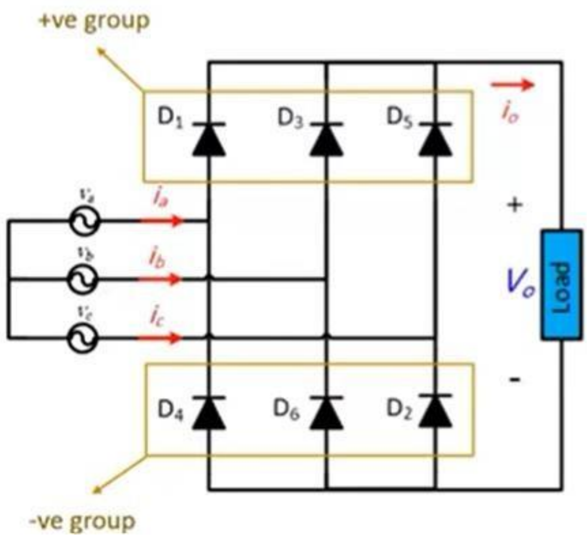
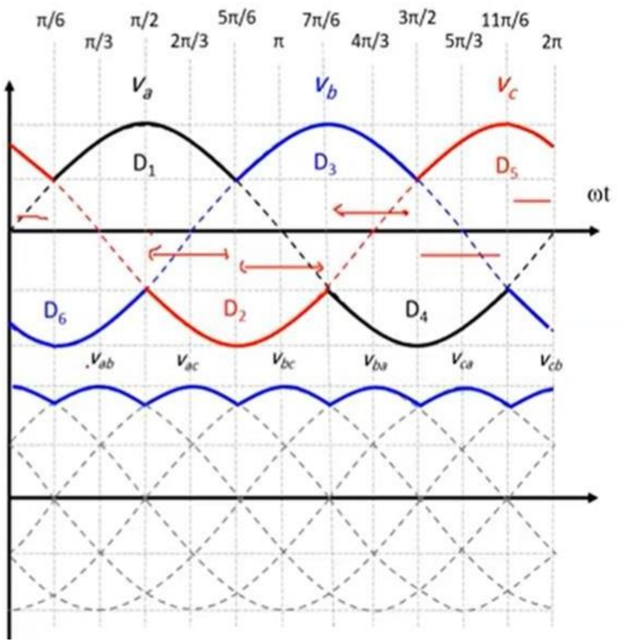
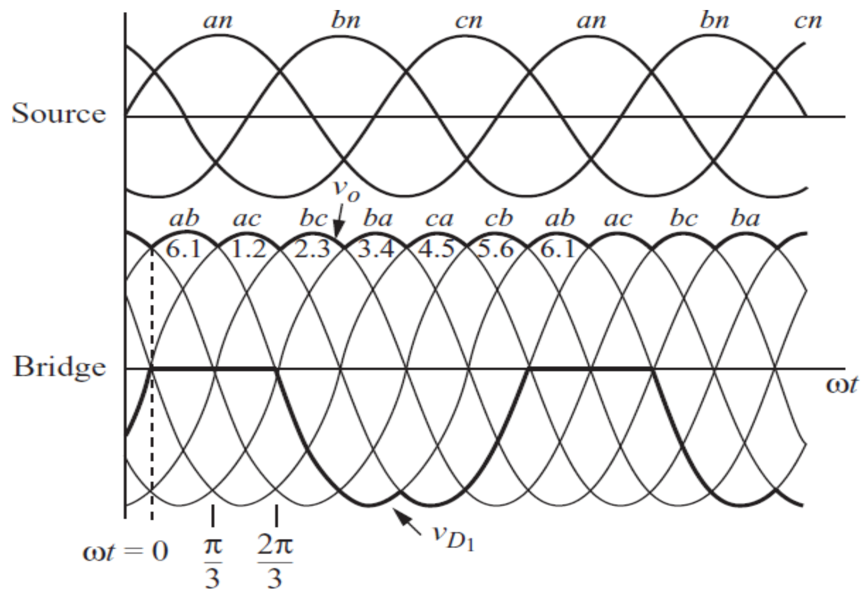
1) *Full-Wave Rectifiers*

Three-phase rectifiers are commonly used in industry to produce a dc voltage and current for large loads. The three-phase voltage source is balanced and has phase sequence *abc*. The source and the diodes are assumed to be ideal in the initial analysis of the circuit.



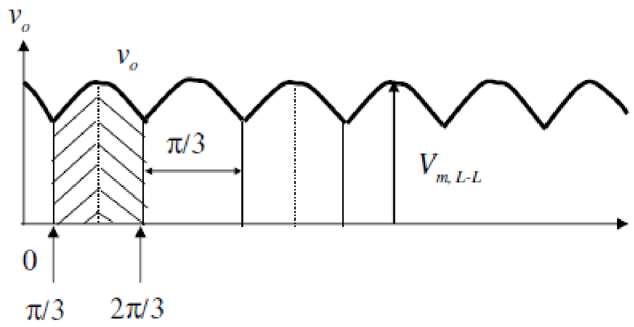




Some basic observations about the circuit are as follows:

1. only one diode in the top half of the bridge may conduct at one time (D1, D3, or D5). The anode of the conducting diode will have the highest voltage at that instant.
2. only one diode in the bottom half of the bridge may conduct at one time (D2, D4, or D6). the cathode of the conducting diode will have the lowest voltage at that instant.
3. The output voltage across the load is one of the line-to-line voltages of the source. For example, when $D1$ and $D2$ are on, the output voltage is VAC.
4. There are six combinations of line-to-line voltages (three phases taken two at a time). Considering one period of the source to be 360°, a transition of the highest line-to-line voltage must take place every 360°/6 = 60°. Because of the six transitions that occur for each period of the source voltage, the circuit is called a ***six-pulse rectifier.***
5. The diodes conduct in pairs (1,6), (1,2), (3,2), (3,4), (5,4), (5,6), (1,4).

6. The fundamental frequency of the output voltage is 6ω, where ω is the frequency of the three-phase source



The average or dc value of the output voltage is

$$\boxed{V_0 = \frac{1}{\pi/3}\int_{\pi/3}^{2\pi/3} V_{m,L-L}\sin(\omega t)\,d(\omega t) = \frac{3V_{m,L-L}}{\pi} = 0.955\,V_{m,L-L}}$$

Or

$$V_{m,L-L} = \sqrt{3}\,V_{m(phase)}$$

$$V_{DC(load)} = \frac{3\sqrt{3}\,V_{m(Phase)}}{\pi}$$

$$I_o = \frac{V_o}{R}$$

where $V_{m,L-L}$ is the peak line-to-line voltage of the three-phase source, which is $\sqrt{2}V_{L-L,\text{rms}}$. The amplitudes of the ac voltage terms are

$$V_n = \frac{6V_{m,L-L}}{\pi(n^2-1)} \qquad n = 6, 12, 18, \ldots$$

Since the output voltage is periodic with period one-sixth of the ac supply voltage, the harmonics in the output are of order $6k\omega$, $k = 1, 2, 3 \ldots$ An advantage of the three-phase rectifier over the single-phase rectifier is that the output is inherently like a dc voltage, and the high-frequency low-amplitude harmonics enable filters to be effective.

$$I_{o,rms} = I_{DC} = I_{o,avg} = \frac{3V_{m,L-L}}{\pi R} \qquad \text{for } (L >> R)$$

$$S = \sqrt{3}(V_{L-L,\text{rms}})(I_{s,\text{rms}})$$

$$I_{D,\text{avg}} = \frac{1}{3} I_{o,\text{avg}}$$

$$I_{D,\text{rms}} = \frac{1}{\sqrt{3}} I_{o,\text{rms}}$$

$$I_{s,\text{rms}} = \sqrt{\frac{2}{3}}\, I_{o,\text{rms}}$$

Example:

A three-phase Uncontrolled full wave rectifier is supplied by a 480-V rms line-to-line 60-Hz source, feeding a highly inductive load with a 50 Ω resistor. Determine (a) the average load current, (b) the rms load current, (c) the rms source current, and (d) the power factor.

Solution:

a) output voltage across the load

$$\boxed{V_0 = \frac{1}{\pi/3} \int_{\pi/3}^{2\pi/3} V_{m,L-L} \sin(\omega t) d(\omega t) = \frac{3 V_{m,L-L}}{\pi} = 0.955\, V_{m,L-L}}$$

$$= 0.955 * 482\sqrt{2} = 648.2\ v$$

$$I_o = \frac{V_o}{R}$$

$$I_o = \frac{648.2}{50} = 12.96\ A$$

b) the rms load current

$$I_{o,rms} \cong I_o = 12.96\ A$$

the rms source current

$$I_{s,\text{rms}} = \left(\sqrt{\frac{2}{3}}\right) I_{o,\text{rms}}$$

$$I_{s,rms} \cong \sqrt{\frac{2}{3}} * 12.96 = 10.58\ A$$

c) the power factor

$$\text{p.F} = \frac{\text{P}}{\text{S}} = \frac{(I_{o,rms})^2 * R_.}{\sqrt{3} * \text{V}_{\text{L-L,rms}} * I_{s,rms}} = \frac{(12.96)^2 * 50}{\sqrt{3} * 480 * 10.58} = \frac{8398.08}{8796.04} = 0.95$$

Example:
A three-phase Uncontrolled bridge rectifier is supplied by a 480-V rms line-to-line 60-Hz source. The RL load is a 100- Ω resistor in series with a 15-mH inductor. Determine (a) the average and rms load currents, (b) the average and rms diode currents, (c) the rms source current, and (d) the power factor.

Solution:

(a) the average and rms load currents,

$$V_o = \frac{3V_{m,L-L}}{\pi} = \frac{3\sqrt{2}\,(480)}{\pi}$$

$$= 648.2\ v$$

$$I_o = \frac{V_o}{R}$$

$$I_o = \frac{648.2}{100} = 6.482\ A$$

The first ac voltage term is / $V_n = \dfrac{6V_{m,L-L}}{\pi(n^2-1)}$ $\quad n = 6, 12, 18, \ldots$

$$V_6 = \frac{6V_m}{\pi(6^2 - 1)} \qquad = 37.04\ \text{v}$$

$$Z_6 = \sqrt{R^2 + (6\omega L)^2} \qquad = 105.6\ \Omega$$

$$I_6 = \frac{V_6}{Z_6}$$

$$I_6 = \frac{37.04}{105.6} = 0.35\ A$$

$$I_{o,rms} = \sqrt{(I_o)^2 + (\frac{I_6}{\sqrt{2}})^2}$$

$$I_{o,rms} = \sqrt{(6.482)^2 + (\frac{0.35}{\sqrt{2}})^2} = 6.486\ A$$

Note/I_6 and other ac terms are much smaller than the dc term and can be neglected.

(b) the average and rms diode currents,

$$I_{D,\text{avg}} = \frac{1}{3} I_{o,\text{avg}}$$

$$I_D = \frac{1 * 6.482}{3} = 2.16\ A$$

$$I_{D,\text{rms}} = \frac{1}{\sqrt{3}} I_{o,\text{rms}}$$

$$I_{D,rms} = \frac{1 * 6.486}{\sqrt{3}} = 3.74\ A$$

(c) the rms source current,

$$I_{s,\text{rms}} = \sqrt{\frac{2}{3}}\, I_{o,\text{rms}}$$

$$I_{s,rms} = \sqrt{\frac{2}{3}} * 6.486 = 5.3\ A$$

(d) the power factor

$$\text{p.F} = \frac{\text{P}}{\text{S}} = \frac{(I_{o,rms})^2 * R_.}{\sqrt{3} * \text{V}_{\text{L-L,rms}} * I_{s,rms}} = \frac{(6.486)^2 * 100}{\sqrt{3} * 480 * 5.3} = \frac{4206.82}{4406.33} = 0.95$$