Chapter 4: Power Semiconductor Diodes, Rectifier Circuits and DC Power Supply

Learning Objectives

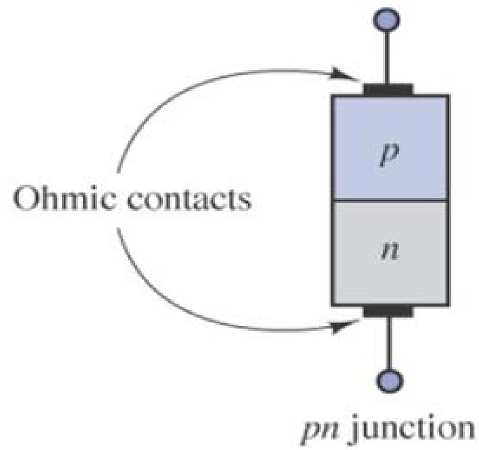
- Understanding of voltage-current characteristics of a power semiconductor diode
- Understanding of half-wave and full-wave bridge-type rectifier circuits
- Understanding of voltage and currents in rectifier circuits
- Analysis of the rectifier circuits
- Analysis of the bridge rectifier circuit with capacitive filter
- Design of DC power supplies

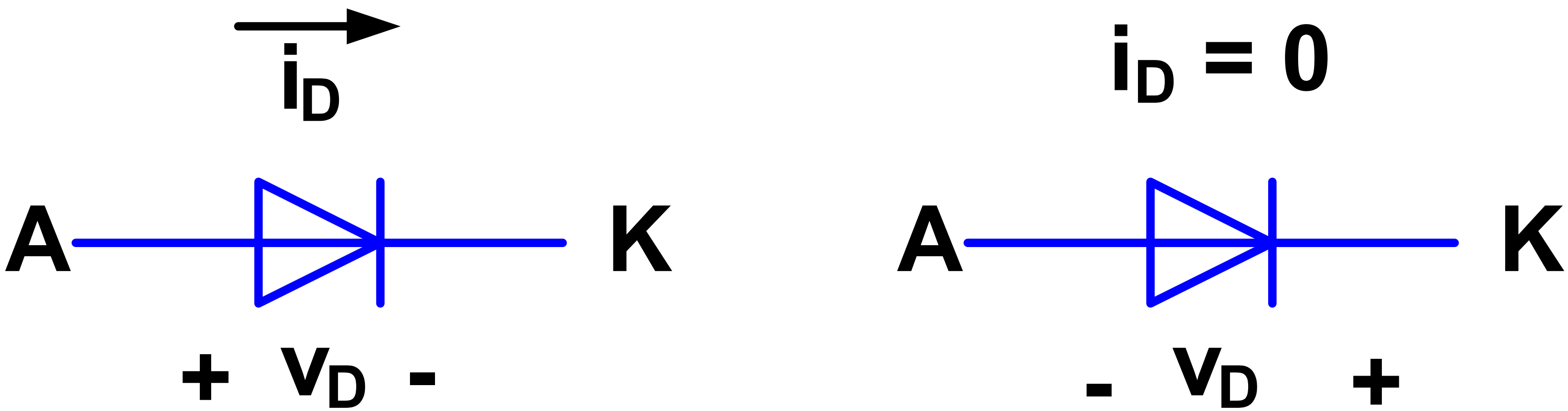
Introduction to Semiconductor Diodes

- Semiconductor diodes are active devices and can be considered as non-linear circuit element exhibiting non-linear voltage-current characteristics.
- They are equivalent of mechanical valves and can be used as an electronic switch that can be closed or open depending on the circuit operating conditions.
- Diode is considered as an uncontrolled electronic switch and circuit operating conditions decide if it is ON of OFF.
- Power diodes regulate the flow of electrical energy in electric circuits mainly from the source to the load.
- Diodes are used in converting AC power to DC power and widely used in regulated DC power supplies.

Semiconductor Diodes

- Semiconductor diode is a two terminal device and made up of *p* - and *n* - type of silicon semiconductor material.
- When the anode (A) terminal is made more positive w.r.t. the cathode (K) terminal, the diode is said to be forward biased and current flows only in one direction i.e. from anode to cathode.
- In the forward biased condition, the semiconductor switch is considered to be ON and the circuit is "closed".
- The symbol of the diode is shown in Fig. 4.1 and the corresponding V-I characteristic is as shown in Fig. 4.2.





forward biased diode **reverse biased diode**

Figure 4.1: Diode operation (a) forward-biased and (b) reverse-biased.

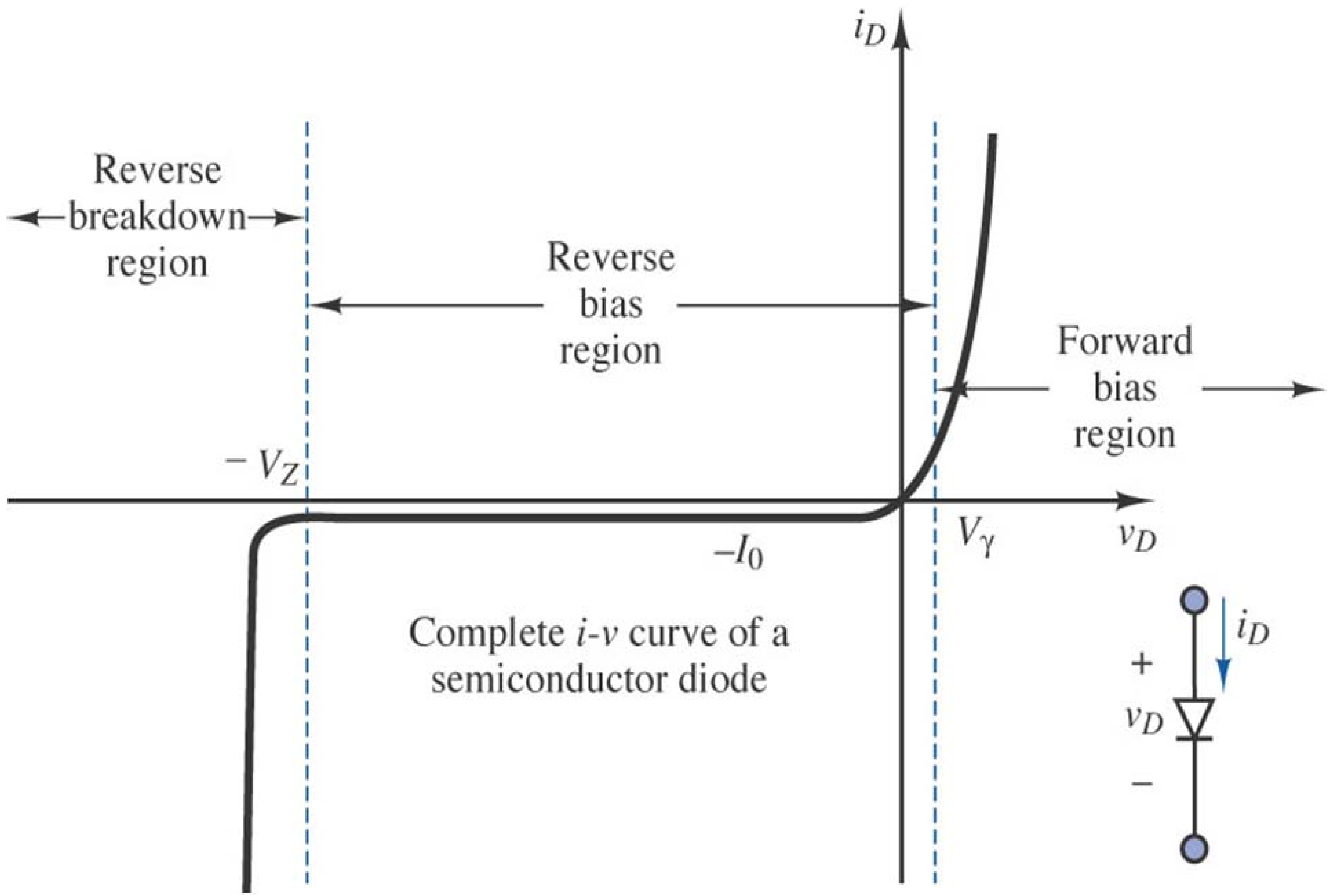


Figure 4.2: V-I characteristics of diode.

- When the anode is made –ve w.r.t. the cathode terminal, the diode is reverse biased and blocks the voltage.
- Only a very small leakage current, I_O of the order of hundreds of μA flows through it.
- The forward voltage drop, v_D of silicon signal diode is of the order of 0.7 V, while that for power diode can be of the order of 1 - 3 V.
- The maximum reverse biased voltage the diode can withstand safely is called peak-inverse-voltage (PIV) and can be of the order of 1–2kV.

Ideal-diode

- Ideal diode has $v_D = 0$ and $I_O = 0$.
- It acts as a short-circuit when forward biased and open-circuit when reverse biased.

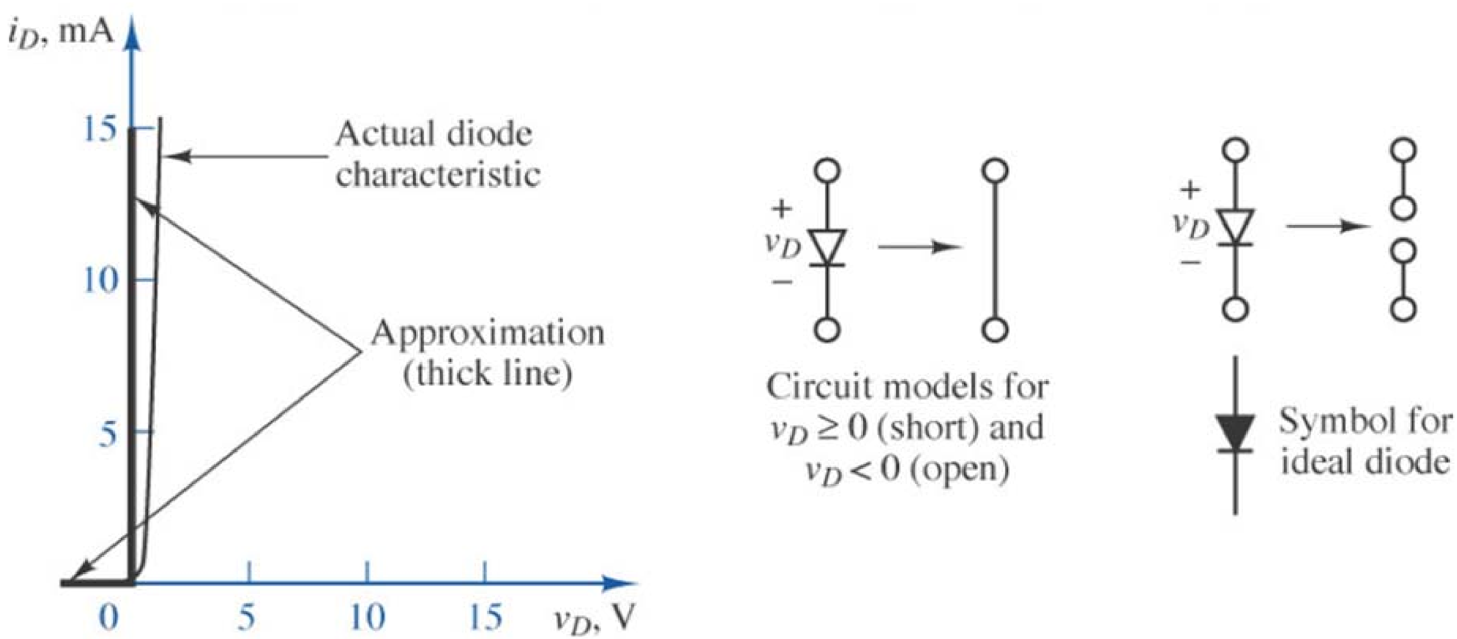


Figure 4.3: Ideal diode model.

Rectifier Circuits

- A rectifier circuit converts AC power into DC power.
- Classification:
  - Half-wave Rectifier
  - Full-wave Rectifier
    - Bridge type
    - Centre-tap type
- Rectifier circuits are extensively used in regulated DC power supplies.

Half-wave Rectifier Circuit

- A half-wave rectifier circuit feeding a resistive load is shown in Fig. 4.4.

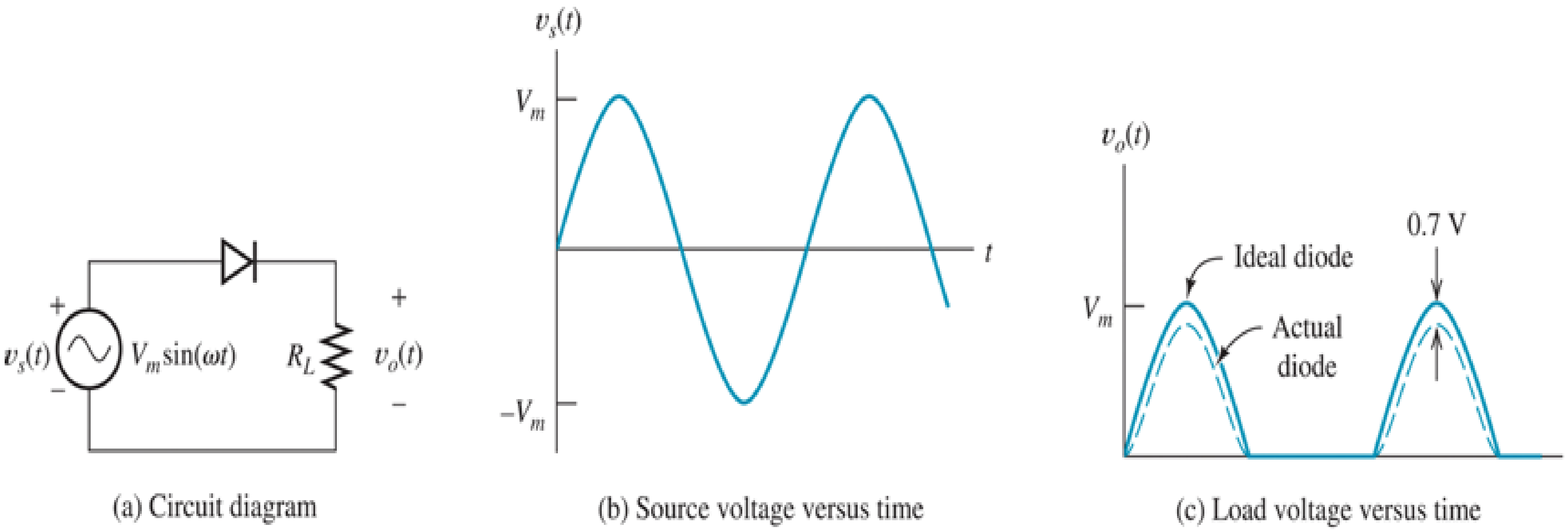


Figure 4.4: Half-wave rectifier with resistive load .

- Assuming the source voltage, v_s to be sinusoidal, the average output voltage, $V_{o,avg}$ is given by

$$V_{o,avg} = \frac{1}{2\pi}\left[\int_0^{\pi} V_m \sin(\omega t)\, d(\omega t) + \int_{\pi}^{2\pi} 0\, d(\omega t)\right] = \frac{V_m}{\pi} \quad (2.1)$$

- Average load current, $I_{L,avg}$ is given by

$$I_{L,avg} = \frac{V_{o,avg}}{R_L} \quad (2.2)$$

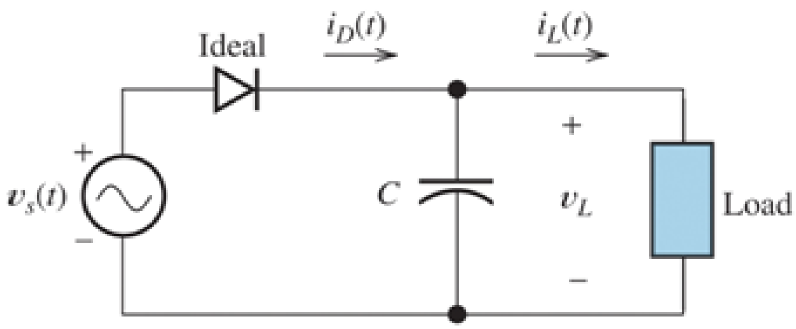
- During the –ve half-cycle, the diode blocks the source voltage and the PIV is given by

$$PIV = V_m \quad (2.3)$$

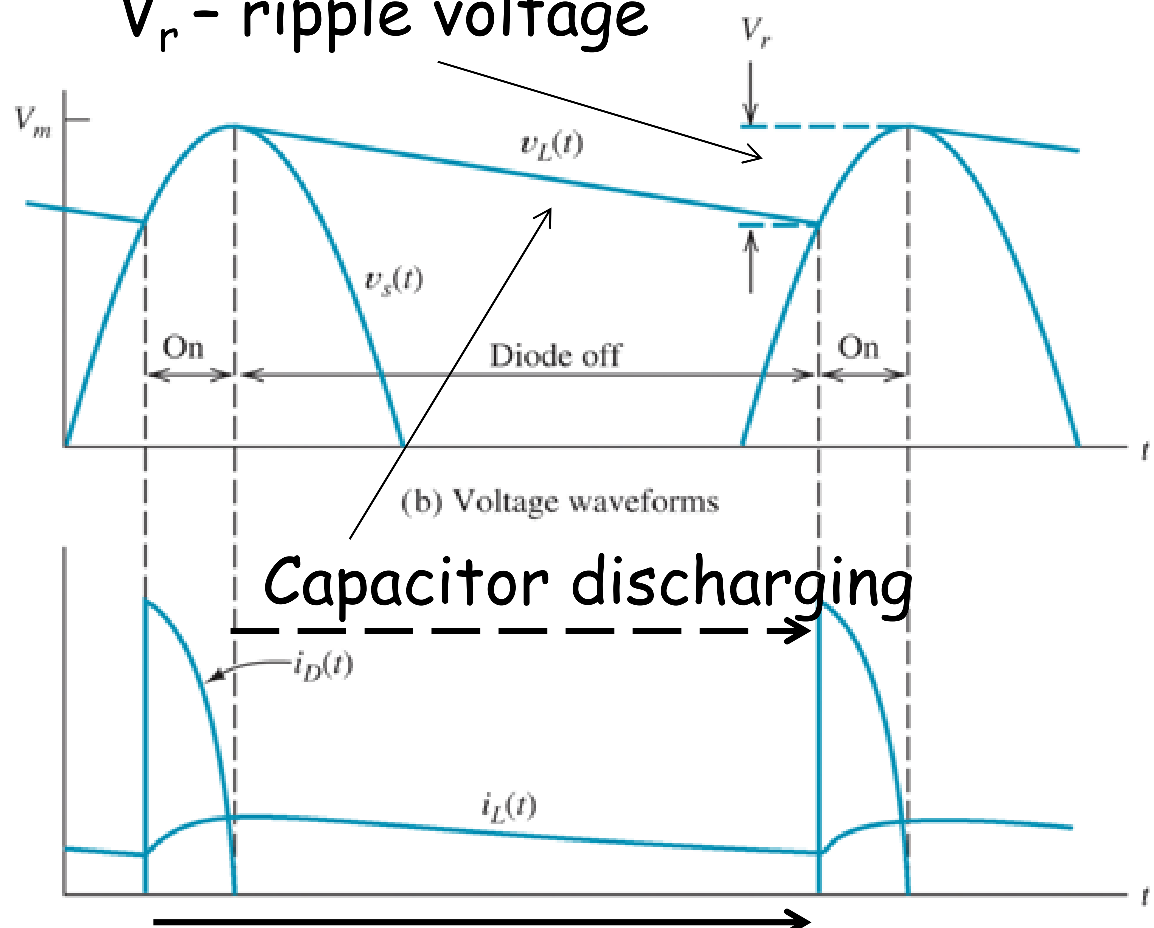
Half-wave Rectifier with Smoothing Capacitor

- The peak-to-peak ripple voltage is V_m and considered to be large for many practical applications.
- By putting a capacitive filter the ripple voltage can be reduced to a large extent.
- The half-wave rectifier circuit with a smoothing capacitor feeding a resistive load is shown in Fig. 4.5.
- During +ve half-cycle when $v_s > (v_c = v_L)$ the diode becomes forward biased and capacitor gets charged as shown in Fig.4.5.

V_r – ripple voltage



(a) Circuit diagram



(b) Voltage waveforms

(c) Current waveforms

T– time period for one electrical cycle

Figure 4.5: Half-wave rectifier with smoothing capacitor.

- When the diode is reverse biased the capacitor discharges to the load.
- The charge removed by the capacitor approximately is given by $Q \cong I_L \times T \;\; (2.4)$

where Q - charge removed from the capacitor, I_L - average load current and (T = 1/ f) - time period of one electrical cycle of supply voltage.

- The charge removed from capacitor can also be written as $Q = V_{pk-pk} \times C \;\; (2.5)$

$$I_L \times T = V_{pk-pk} \times C \;\; \Rightarrow C = \frac{I_L T}{V_{pk-pk}} = \frac{I_L}{V_{pk-pk} \times f} \;\; (2.6)$$

- Large C as well as higher f would reduce pk-to-pk ripple voltage.

Example 4.1: A half-wave rectifier circuit as shown in Fig. 2.4(a) is used to provide a DC supply to a 50 Ω resistive load. If the AC source voltage is 230 V rms at 50 Hz, find the peak and average current in the load. Also determine the percentage of the peak-to-peak ripple in the output voltage. Assume the diode to be ideal.

Solution:

The peak load current is given by

$$i_{L,pk} = \frac{V_m}{R_L} == \frac{230\sqrt{2}}{50} = 6.5\ A$$

- The average load current is given by

$$i_{L,avg} = \frac{V_{o,avg}}{R_L} = \frac{V_m/\pi}{50} = \frac{230\sqrt{2}}{50 \times \pi} = 2.1\ A$$

- The peak-to-peak ripple voltage is given by

$$V_{pk-pk} = V_m = \sqrt{2} \times V_{s,rms} = \sqrt{2} \times 230 = 325.3\ V,$$

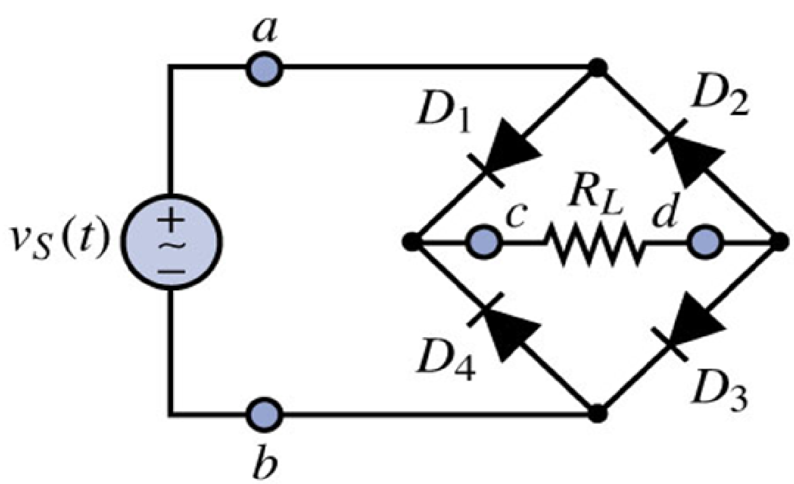
- The percentage ripple voltage is given by

$$\text{Percentage ripple} = \frac{V_{pk-pk}}{V_{o,avg}} \times 100\% = \frac{325.3}{103.5} \times 100\% = 314.2\%$$

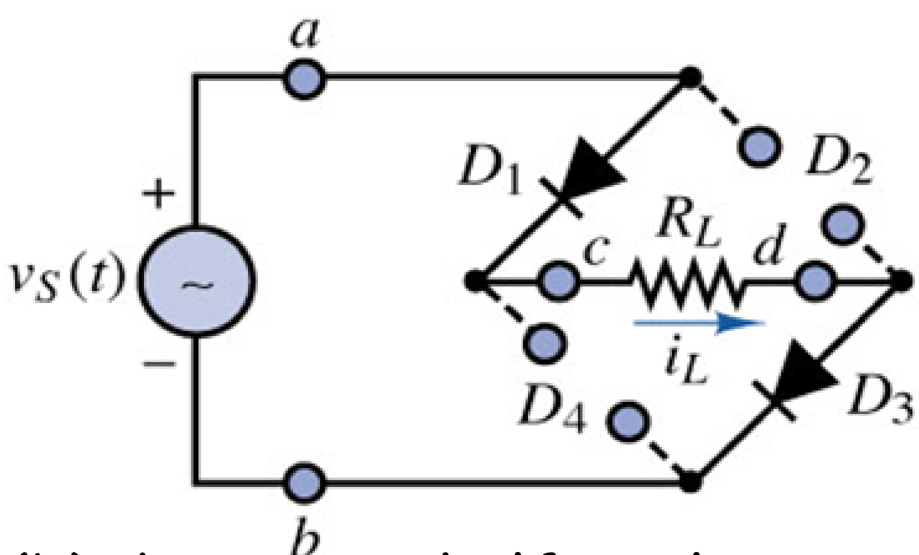
- It is called a half-wave circuit as it preserves only + ve half of the AC voltage waveform – not an efficient circuit as –ve half-cycle is not preserved - can be overcome by using full-wave rectifier

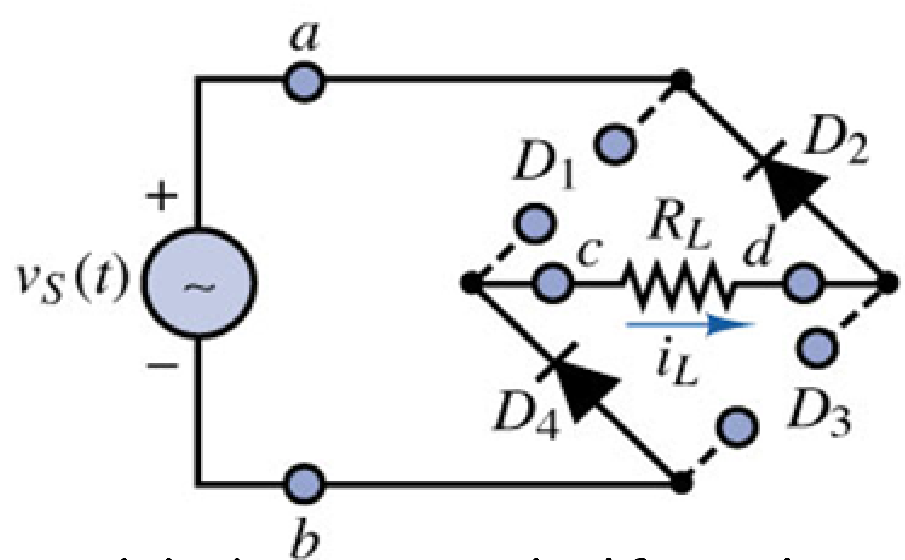
Full-wave Bridge Rectifier

- The full-wave rectifier provides substantial improvement in efficiency over the half-wave rectifier and therefore widely accepted in the industry.
- Consider the full-wave bridge type of rectifier circuit as shown in Fig. 4.6.
- During +ve half-cycle diodes D_1 and D_3 conduct while during the –ve half-cycle diodes D_2 and D_4 conduct and current always flows from *c* to *d* in the load.



Bridge rectifier





(b) during +ve half-cycle (c) during -ve half-cycle

Figure 4.6: Full-wave bridge rectifier circuit with resistive load.

- The source and load voltage waveforms are as shown in Fig. 4.7.

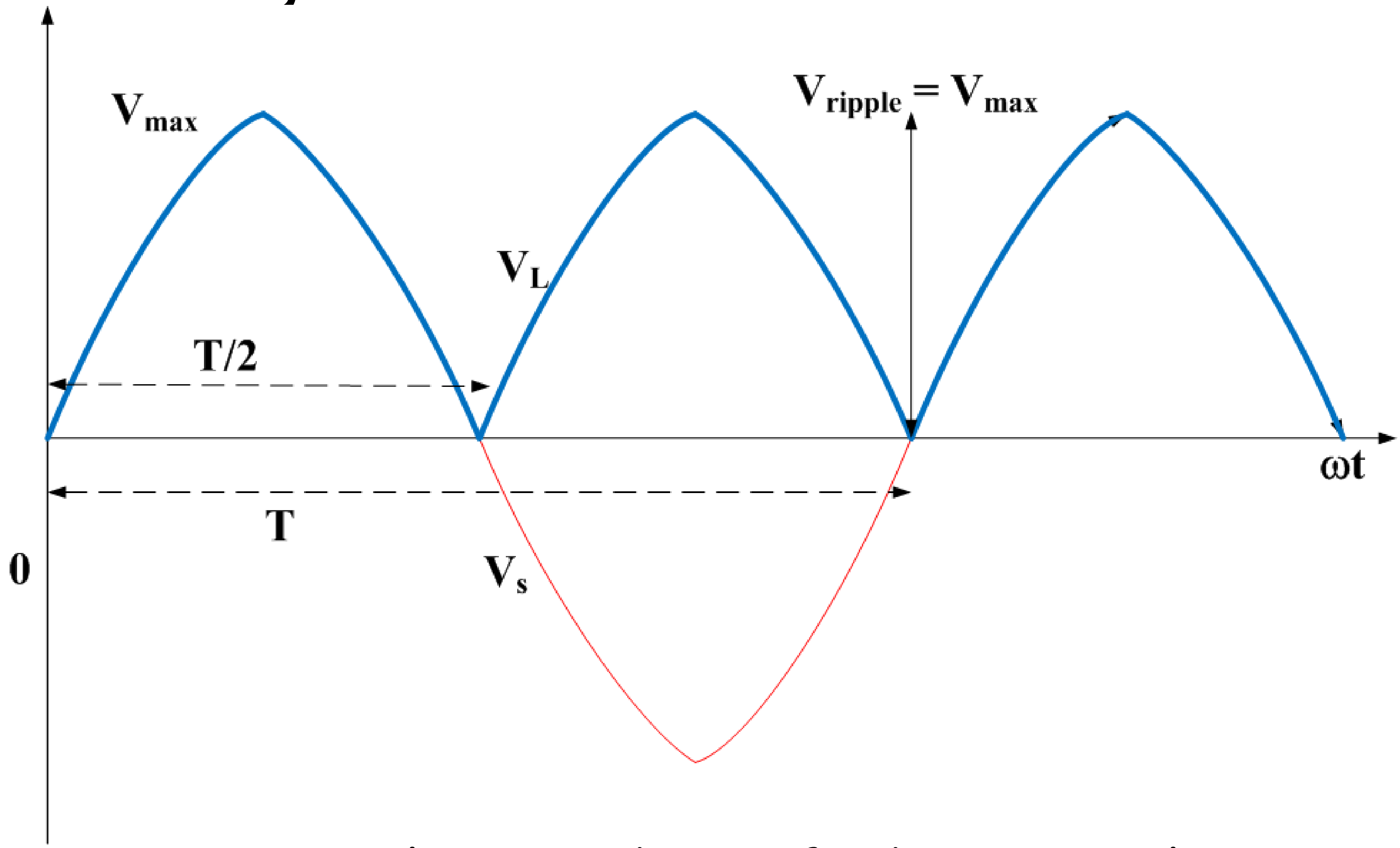


Figure 4.7: Source voltage and rectified output voltage (assuming ideal diode).

- The average output voltage is given by

$$V_{o,avg} = \frac{1}{\pi}\left[\int_0^{\pi} V_m \sin(\omega t)\, d(\omega t)\right] = \frac{2V_m}{\pi} \quad (2.7)$$

- The output has two pulses in one electrical cycle of the ac source voltage and is therefore more efficient than half-wave rectifier. Also the average output voltage is twice that of the half-wave rectifier.
- However the ripple voltage is V_m same as that of half-wave rectifier but ripple frequency is twice that of supply voltage frequency.

Bridge Rectifier with Smoothing Capacitor

- A simple yet effective way to eliminate the ripples in the output voltage is to make use of a capacitive filter circuit as shown in Fig. 4.8.

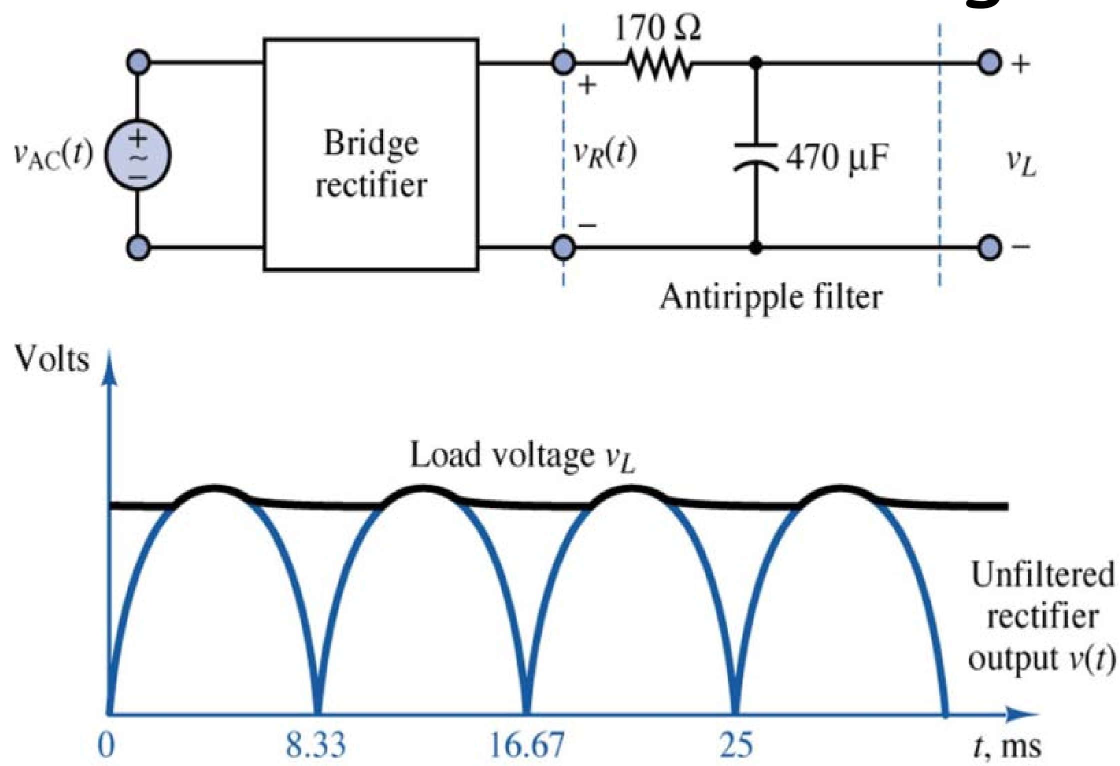


Figure 4.8: Full-wave bridge rectifier with filter circuit.

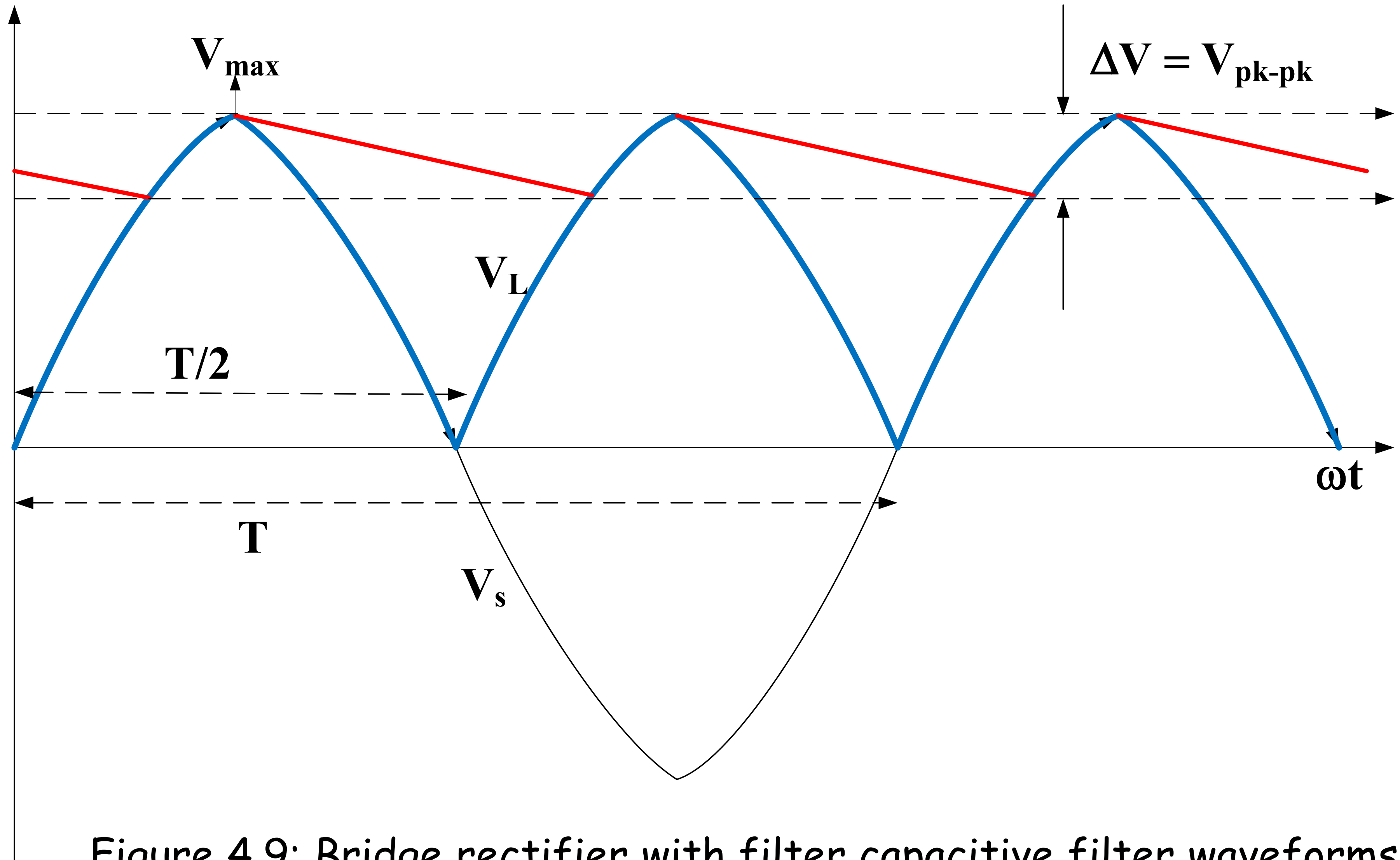


Figure 4.9: Bridge rectifier with filter capacitive filter waveforms.

- The value of the smoothing capacitor required to reduce the ripple voltage is given by

$$Q \cong I_L \times \frac{T}{2} = V_{pk-pk} \times C \Rightarrow C = \frac{I_L \times T}{2 \times V_{pk-pk}} = \frac{I_L}{2 \times f_s \times V_{pk-pk}} \quad (2.8)$$

- Note that the capacitor discharges only for half-cycle rather than full-cycle as in half-wave rectifier circuit.
- For a good DC power supply, a typical voltage ripple of less than 1% is desirable.

Example 4.2: A DC power-supply circuit is needed to deliver 0.1 A with an average voltage of 15 V. The ac source has a frequency of 50 Hz. Assume that a full-wave rectifier circuit is used. The peak-to-peak ripple voltage is to be less than 0.4 V. Instead of assuming ideal diode, allow a forward voltage drop of 0.7 V across the diode. Determine the peak value of the source voltage needed and also the smoothing capacitor.

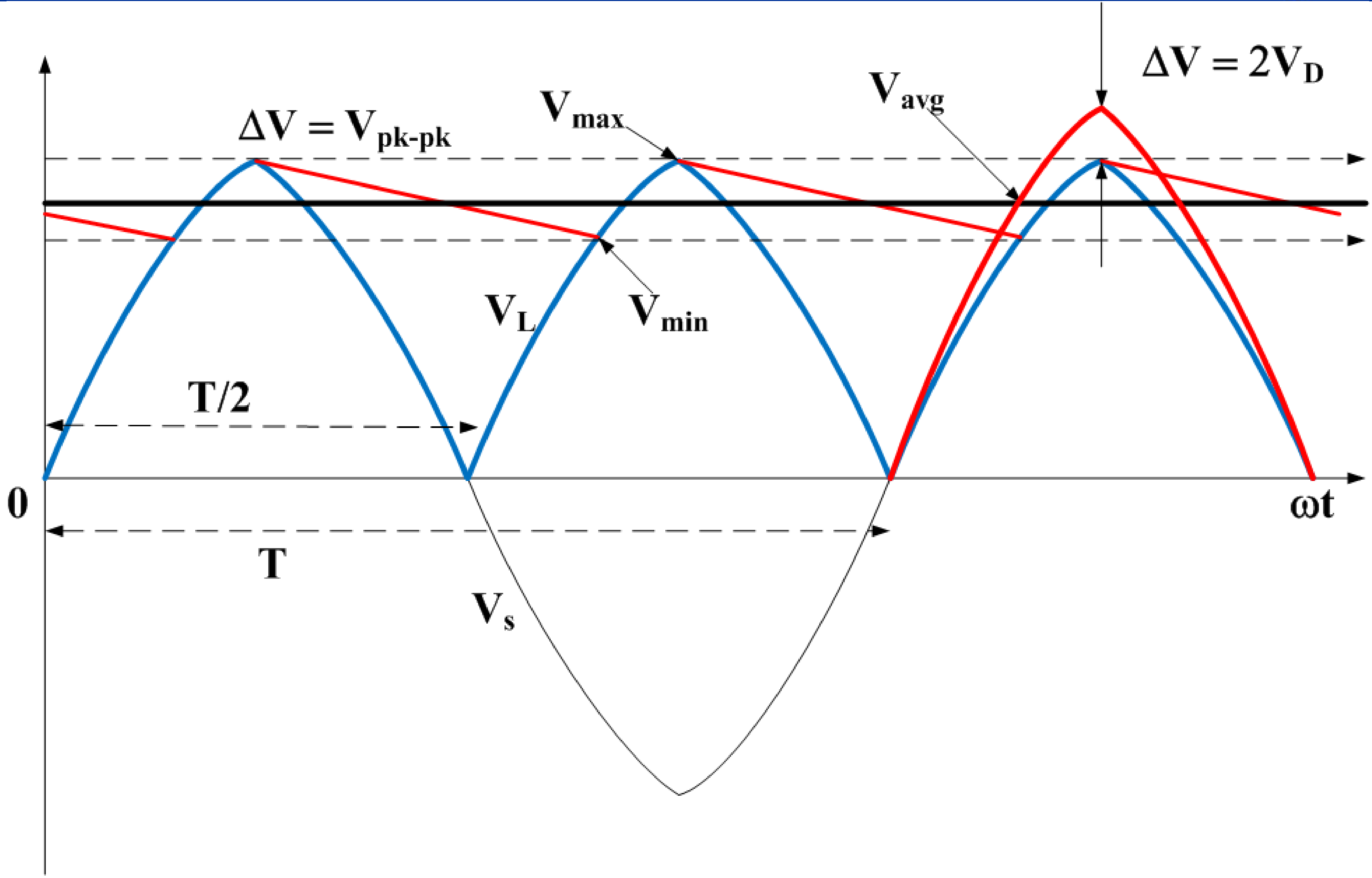
Solution:

- The peak-value of the source voltage is given by

$$V_m = V_{o,avg} + 2 \times v_D + \frac{V_{pk-pk}}{2} = 15 + 2 \times 0.7 + \frac{0.4}{2} = 16.6\,V$$

- The approximate value of the smoothing capacitor is given by

$$C = \frac{I_L}{2 \times f_s \times V_{pk-pk}} = \frac{0.1\,A}{2 \times 50\,Hz \times 0.4\,V} = 2500\ \mu F$$


$\Delta V = 2V_D$
V_{avg}
V_{max}
$\Delta V = V_{pk\text{-}pk}$
V_L
V_{min}
T/2
0
ωt
T
V_s

DC Power Supplies and Voltage Regulation

- A typical regulated DC power supply circuit is as shown in Fig. 4.10.
- It consists of components such as step-down transformer, bridge rectifier circuit, filter circuit and voltage regulator that are used to maintain the output voltage constant at the desired value irrespective of the voltage variation from the source side or load impedance variation.

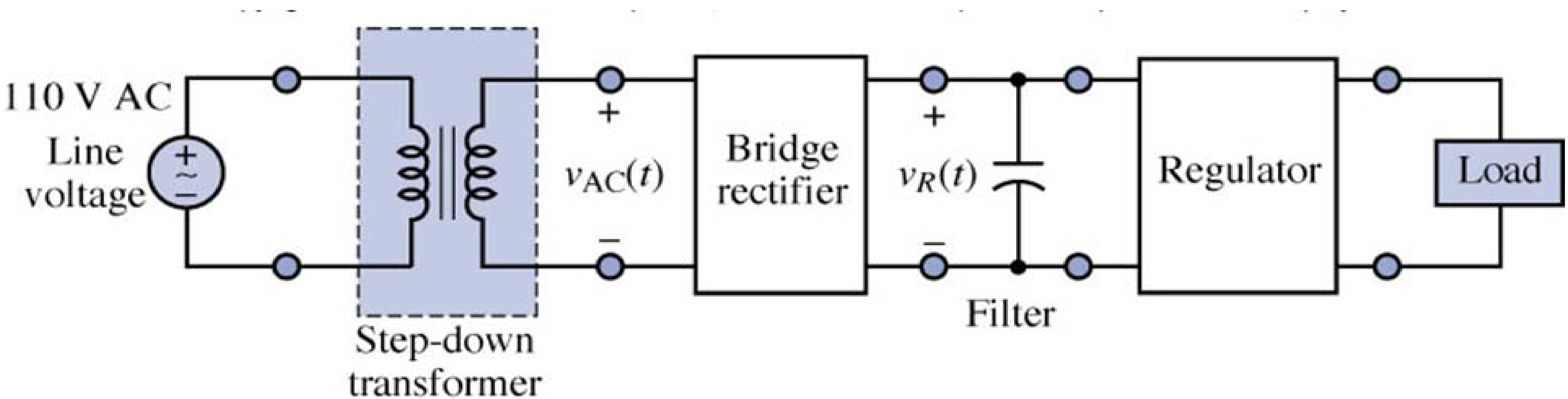


Figure 4.10: Regulated DC power supply.

- In the project you need 5 V DC power supply for the logic circuit and the voltage regulator IC 7805 would be used to provide 5 V DC.

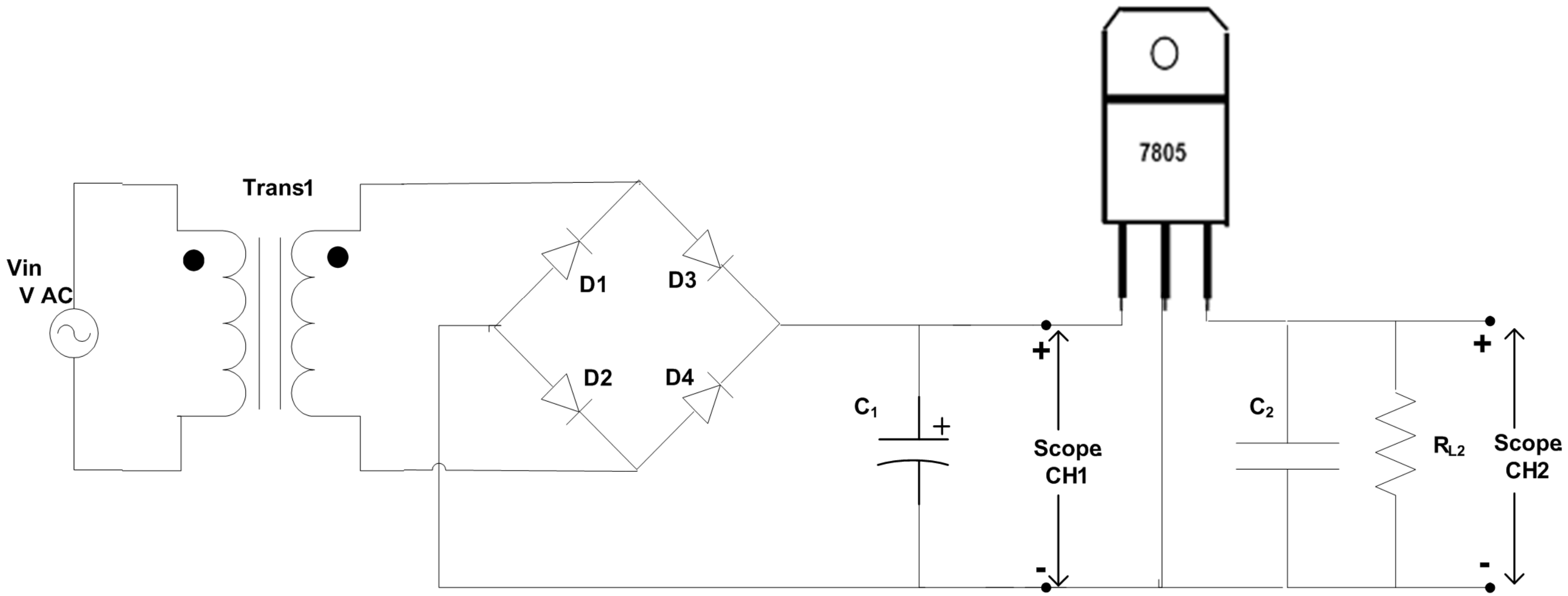


Fig. 4.11 Regulated DC power supply for logic circuits

Summary

- A p-n-junction diode is a two terminal device that conducts current easily in one direction i.e. from anode to cathode, but not in the opposite direction.
- The V-I characteristic has three regions of operation: forward bias, reverse biased and reverse breakdown regions.
- The rectifier circuits can be either half-wave or full-wave rectifiers. A full-wave rectifier is more desirable than half-wave rectifiers as it has two pulses per cycle and therefore more efficient as compared to half-wave rectifier circuit.
- The output voltage of the rectifier circuit consists of a DC component and also and an AC component, this AC component is undesirable and is referred to as ripples in output voltage.
- The ripples can be minimized by using a capacitive filter circuit.

References

1. "Electrical Engineering Principles and Applications", - Allan R. Hambley, Pearson – Prentice Hall, 5th Edition 2005, Chapter 10.
2. "Principles and Applications of Electrical Engineering" – Giorgio Rizonni, Mc Graw Hill, 5th Edition 2007, Chapters 9.