8 Basic Diode Circuits

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8.2

Introduction

Basic applications of the diode will be introduced, with circuits such as the rectifier, and the limiter. Lastly, with the use of so-called breakdown diodes, we can design circuits that act as voltage regulators – i.e. circuits that provide a steady output voltage when subjected to a wide range of input voltages and output load currents.

8.1 Diode Models

Why we model the diode

The curve describing the diode's terminal characteristics is non-linear. How can we use this curve to do circuit analysis? We only know how to analyze linear circuits. There is therefore a need for a linear circuit model of the diode.

The concept of modelling

When we model something, we transform it into something else – usually something simpler – which is more amenable to analysis and design using mathematical equations. Modelling mostly involves assumptions and simplifications, and the only requirement of a model is for it to "work" reasonably well. By "work" we mean that it agrees with experimental results to some degree of accuracy.

Models are sometimes only valid under certain operating conditions, as we shall see when modelling the diode.

8.1.1 The Ideal Diode Model

As a first approximation, we can model the diode as an ideal switch:

The diode as an ideal (controlled) switch

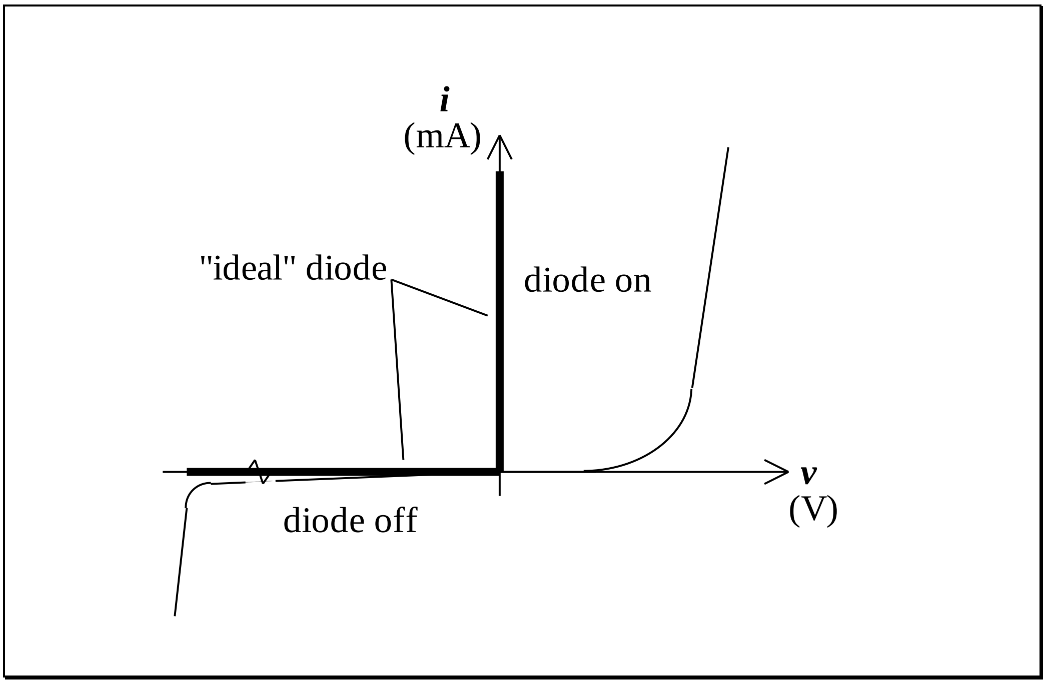


Figure 8.1 – The Ideal Diode Model

The characteristic in this case is approximated by two straight lines – the vertical representing the "on" state of the diode, and the horizontal representing the "off" state. To determine which of these states the diode is in, we have to determine the conditions imposed upon the diode by an external circuit. This model of the diode is used sometimes where a quick "feel" for a diode circuit is needed. The above model can be represented symbolically as:

The ideal diode model

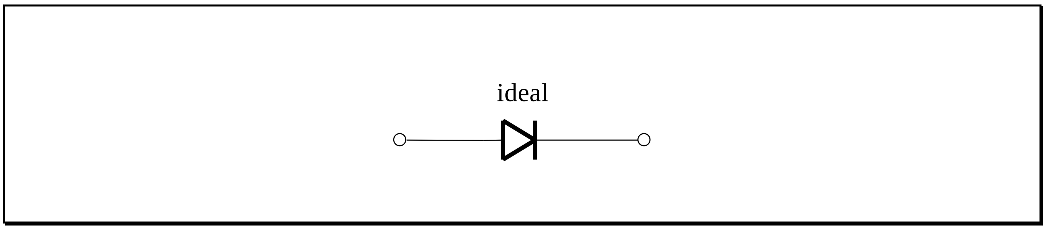
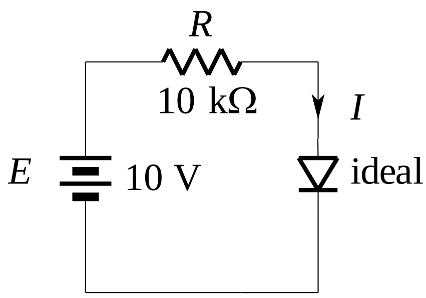


Figure 8.2

EXAMPLE 8.1 Analysis Using the Ideal Diode

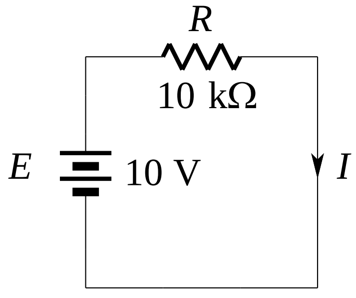
(i) Find the current, *I*, in the circuit shown below, using the ideal diode model.

(ii) If the battery is reversed, what does the current become?



(i) Firstly, we must determine whether the diode is forward biased or reverse biased. In this circuit, the positive side of the battery is connected (via the resistor) to the anode. Therefore, the anode is positive with respect to the cathode, and the diode is *forward biased*. In order to use the ideal diode model, the diode is simply replaced by the ideal diode model (forward bias model), and the simplified circuit is analysed accordingly.

The *equivalent circuit* is shown below, where the diode has now been replaced by a short circuit.



$$I = \frac{E}{R} = \frac{10}{10\text{ k}} = 1\text{ mA}$$

Ohm's Law may be used to determine the current, *I*, as shown:

(ii) If the battery is reversed, the diode becomes *reverse biased*. In this case, the diode is replaced by the ideal diode model for reverse bias. Since the reverse biased ideal diode model is simply an *open circuit*, there is no current, i.e. $I = 0$.

8.1.2 The Constant Voltage Drop Model

A model that takes into account the forward voltage drop

A better model is to approximate the forward bias region with a vertical line that passes through some voltage called e_{fd}:

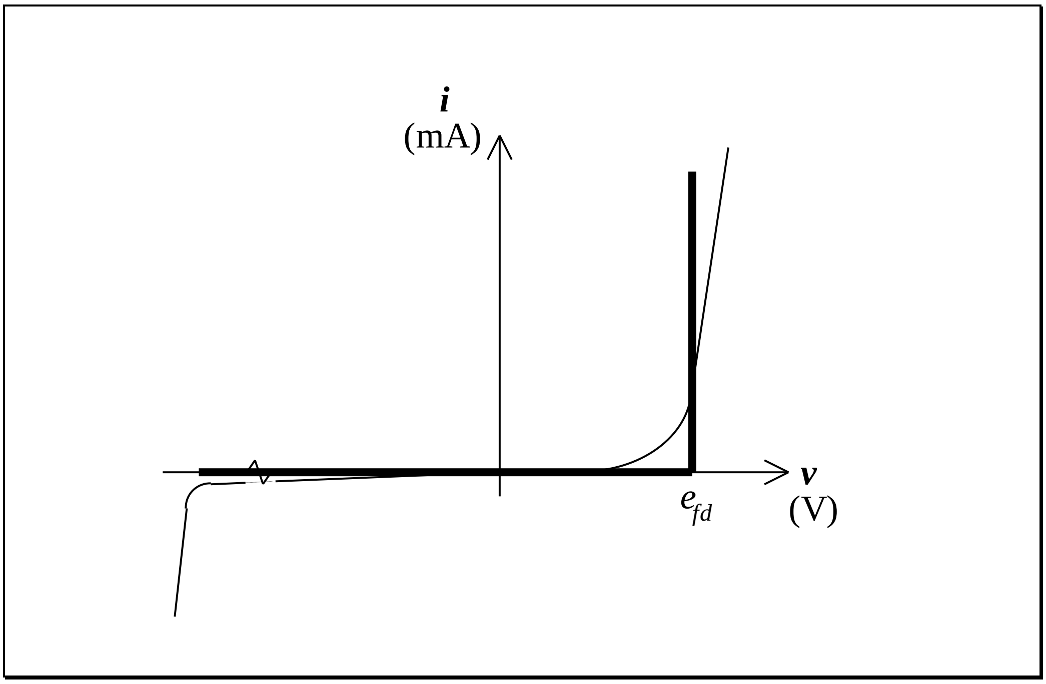


Figure 8.3 – The Constant Voltage Drop Diode Model

The constant voltage drop diode model

This "constant voltage drop" model is better than the ideal model because it more closely approximates the characteristic in the forward bias region. The "voltage drop" is a model for the barrier voltage in the *p*-*n* junction. The model of the diode in this case is:

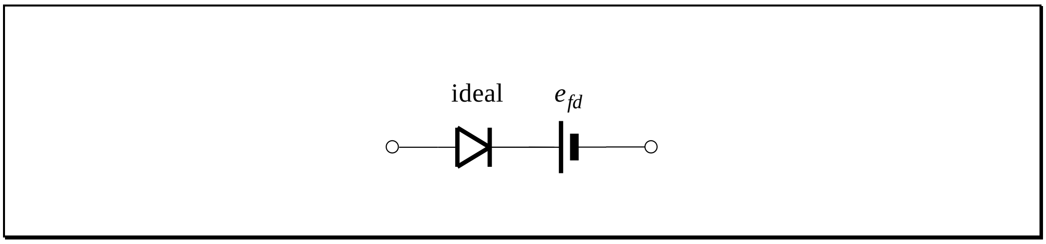


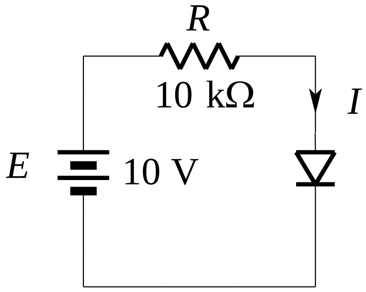
Figure 8.4

This model is the one of the simplest and most widely used. It is based on the observation that a forward-conducting diode has a voltage drop that varies in a relatively narrow range, say 0.6 V to 0.8 V. The model assumes this voltage to be constant, say, 0.7 V. The constant voltage drop model is the one most frequently employed in the initial phases of analysis and design.

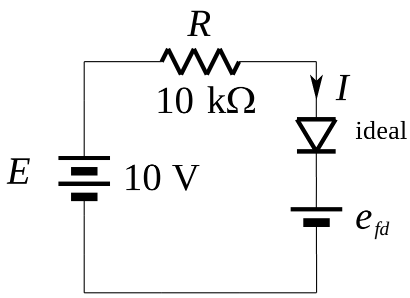
EXAMPLE 8.2 Analysis Using the Constant Voltage Drop Model

(i) Find the current, *I*, in the circuit shown below, using the constant voltage drop model of the diode (assume $e_{fd} = 0.7\ \text{V}$).

(ii) If the battery is reversed, what does the current become?



(i) Analysis proceeds in exactly the same manner as the previous example, except that the constant voltage drop diode model is used instead. The diode is again forward biased, and so the equivalent circuit is shown below, along with the calculation for *I*.



$$I = \frac{E - e_{fd}}{R} = \frac{10 - 0.7}{10\text{k}} = 0.93\ \text{mA}$$

(ii) If the battery is reversed, the diode becomes *reverse biased*, resulting in no current, i.e. $I = 0$.

8.1.3 The Piece-Wise Linear Model

An even better approximation to the diode characteristic is called a "piece-wise" linear model. It is made up of pieces, where each piece is a straight line:

A model that approximates the characteristic by using straight lines

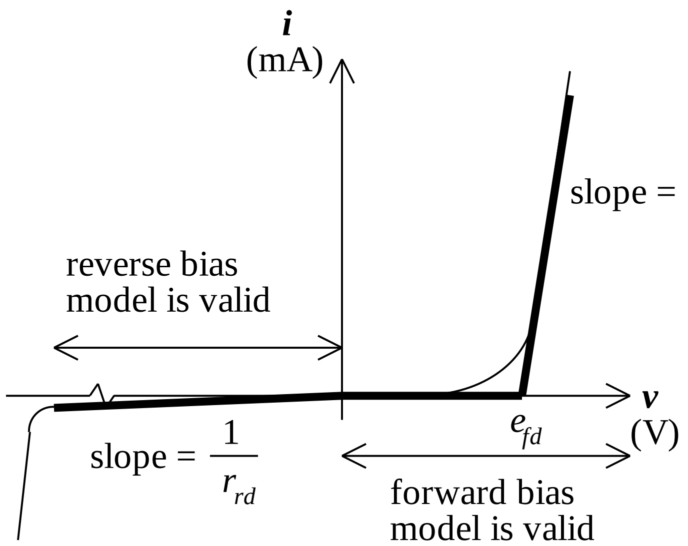


Figure 8.5 – The Piece-Wise Linear Diode Model

For each section, we use a different diode model (one for the forward bias region and one for the reverse bias region):

The piece-wise linear diode model

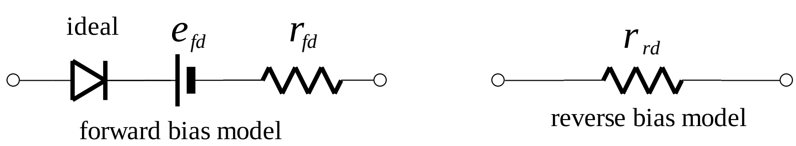


Figure 8.6

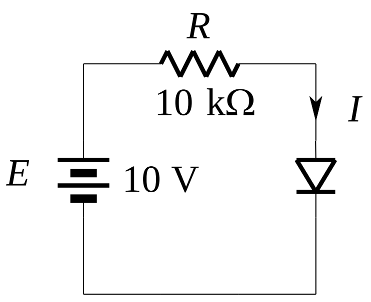
Typical values for the resistances are $r_{fd} = 5\,\Omega$ and $r_{rd} > 10^9\,\Omega$.

Notice how we have done away with the ideal diode part of the model for when the diode is reverse biased. This is because there is a separate equivalent circuit for the forward bias and reverse bias regions, so an ideal diode is not necessary (we apply one equivalent circuit or the other).

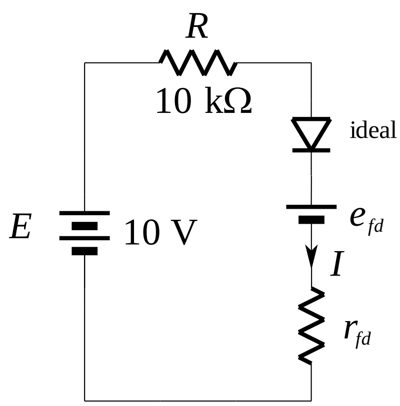
EXAMPLE 8.3 Analysis Using the Piece-Wise Linear Model

(i) Find the current, I, in the circuit shown below, using the piece-wise linear model of the diode (assume $e_{fd} = 0.7\text{ V}$, $r_{fd} = 5\,\Omega$ and $r_{rd} = 10^9\,\Omega$).

(ii) If the battery is reversed, what does the current become?



(iii) Analysis proceeds in exactly the same manner as the previous example, except that the piece-wise linear diode model is used instead. The diode is again forward biased, and so the equivalent circuit is shown below, along with the calculation for I.



$$I = \frac{E - e_{fd}}{R + r_{fd}} = \frac{10 - 0.7}{10\text{k} + 5} = 0.9295\text{ mA}$$

(iv) If the battery is reversed, the diode becomes *reverse biased*, and the diode is replaced by the piece-wise linear model for the reverse region, which is just the resistance r_{rd}. Since $r_{rd} = 10^9\,\Omega$, the reverse current is:

$$I = \frac{E}{R + r_{rd}} = \frac{10}{10^9 + 10^4} \approx 10\text{ nA}$$

which is negligible, i.e. $I \approx 0$.

8.2 Basic Diode Circuits

There are many diode circuits that are used in a wide variety of applications. The most important are summarised below.

8.2.1 Half-Wave Rectifier

A rectifier is a circuit that converts a bipolar (AC) signal into a unidirectional one. The figure below shows a diode rectifier fed by a sine-wave voltage source v_i.

The half-wave rectifier

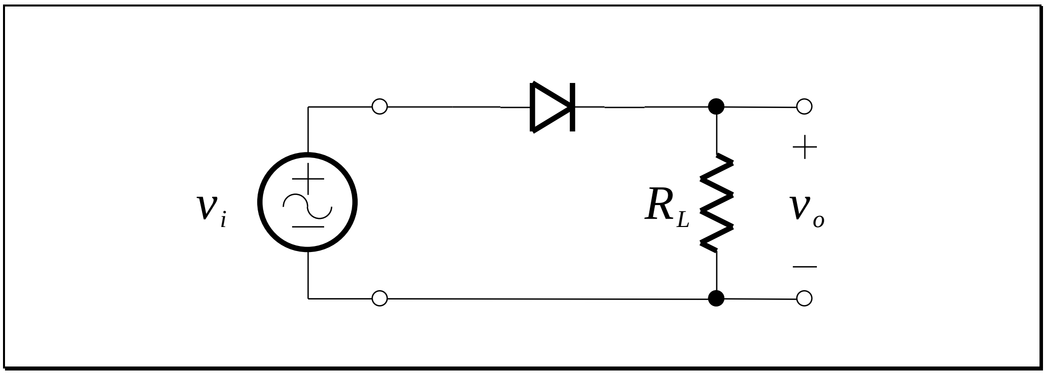


Figure 8.7

A sinusoidal input waveform, and the resulting output waveform v_o that appears across the "load resistor", R_L, are shown below:

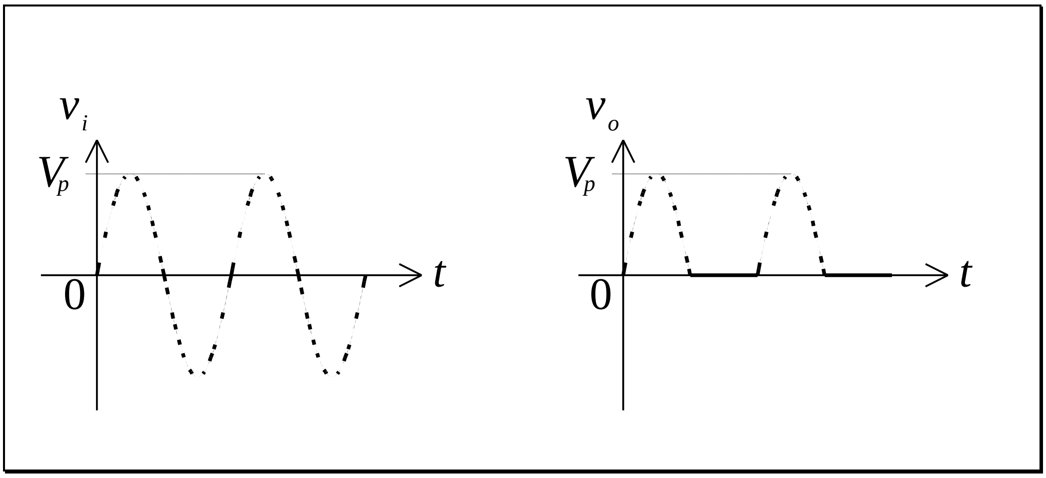


Figure 8.8

Operation of the circuit is straightforward when we assume the diode is ideal: When v_i is positive the diode conducts and acts as a short-circuit. The voltage v_i appears directly at the output – that is, $v_o = v_i$, and the diode forward current is equal to v_i / R_L. On the other hand, when v_i is negative the diode *cuts off* – that is, there is no current. The output voltage v_o will be zero, and the diode becomes reverse-biased by the value of the input voltage v_i. It follows that the output voltage waveform will consist of the positive half cycles of the input sinusoid. Since only half-cycles are utilized, the circuit is called a *half-wave rectifier*.

It should be noted that while the input sinusoid has a zero average value, the output waveform has a finite average value or DC component. Therefore, rectifiers are used to generate DC voltages from AC voltages.

The *transfer characteristic* is often used to describe non-linear circuits – it is simply a plot of the output, v_o, versus the input, v_i. The figure below shows the transfer characteristic of the half-wave rectifier:

Half-wave rectifier transfer characteristic

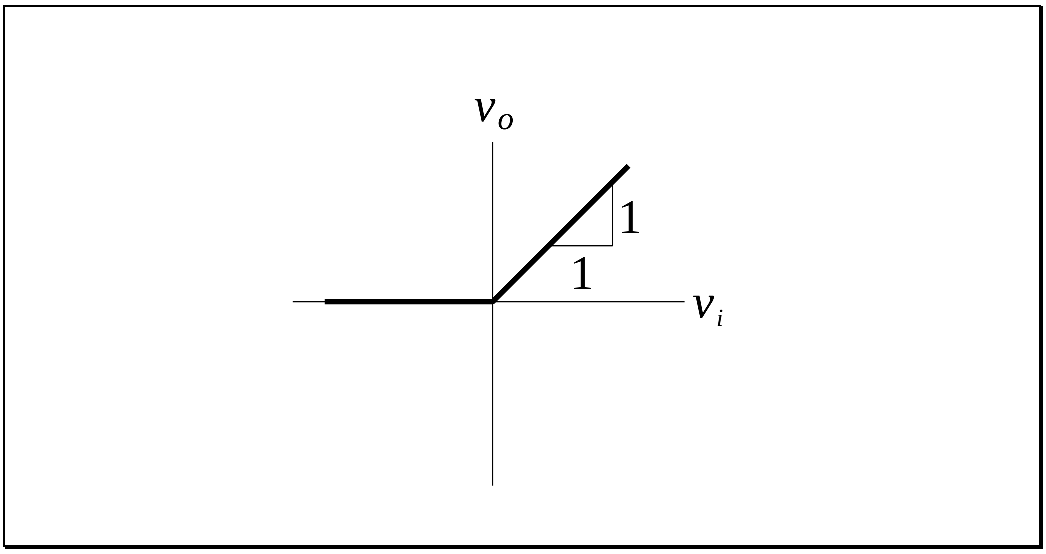


Figure 8.9

As can be seen, the half-wave rectifier produces an output voltage equal to the input voltage when the input voltage is positive and produces zero output voltage when the input voltage is negative.

8.2.2 Full-Wave Rectifier

The full-wave rectifier utilizes both halves of the input signal – it inverts the negative halves of the waveform. One popular implementation is shown below, where the diodes are connected in a bridge configuration:

A full-wave "bridge rectifier"

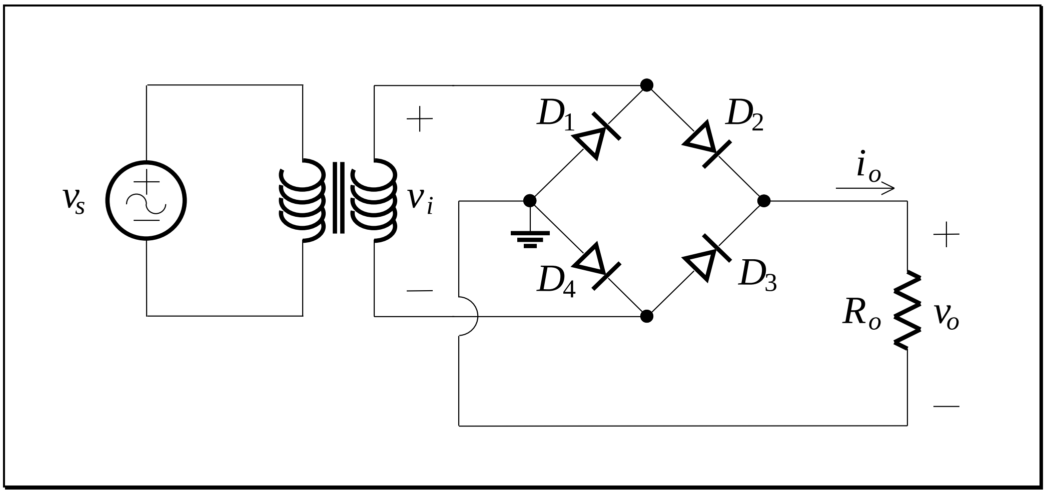


Figure 8.10

We can perform the usual analysis quickly. In the positive half cycle of the input voltage, D_2 and D_4 are on. Meanwhile, D_1 and D_3 will be reverse biased. In the negative half cycle of the input voltage, D_1 and D_3 are on, and D_2 and D_4 are off. The important point to note is that during both half-cycles, the current through the resistor R_o is in the same direction (down), and thus v_o will always be positive. The waveforms are shown below:

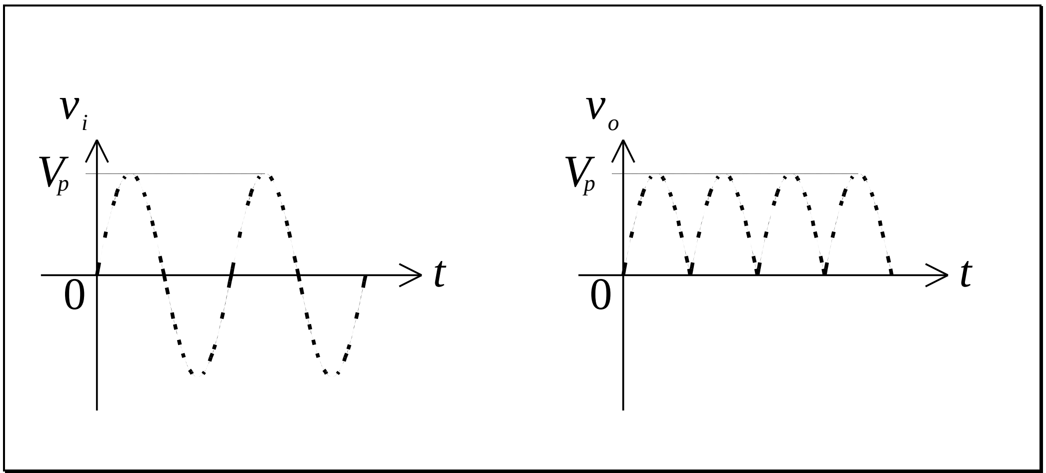
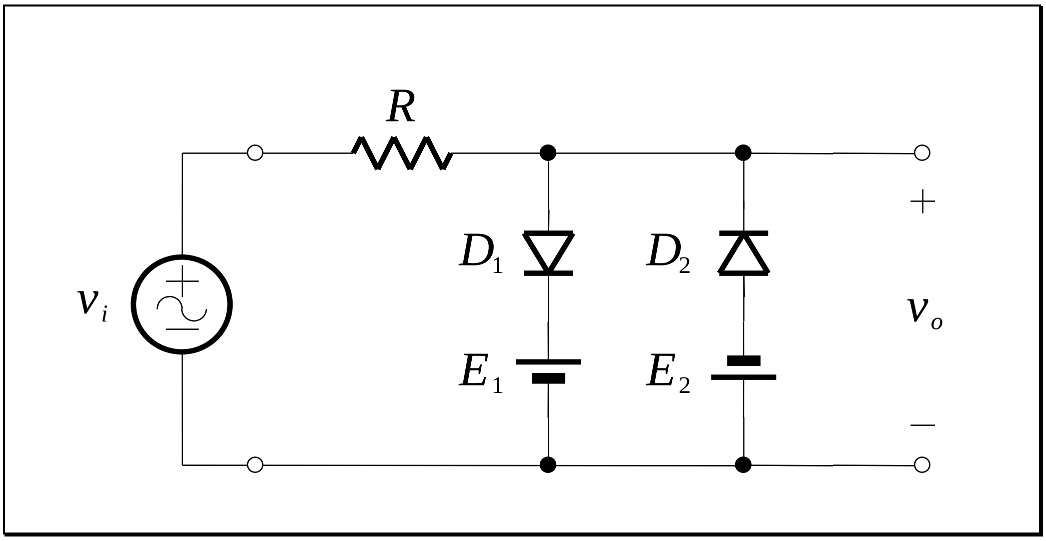


Figure 8.11

8.2.3 Limiter Circuits

Consider the following circuit:



A limiting circuit

Figure 8.12

The circuit works very simply. Assume both diodes are off. KVL then gives:

$$v_o = v_i \tag{8.1}$$

If the output voltage is greater than E_1, then diode D_1 will be on. This limits or clamps the output voltage to E_1:

$$v_o = E_1 \quad \text{for } v_i > E_1 \tag{8.2}$$

If the output voltage is less than $-E_2$ then diode D_2 will be on, limiting the output voltage to $-E_2$:

$$v_o = -E_2 \quad \text{for } v_i < -E_2 \tag{8.3}$$

8.14

A graph of the output is shown below for a sinusoidal input:

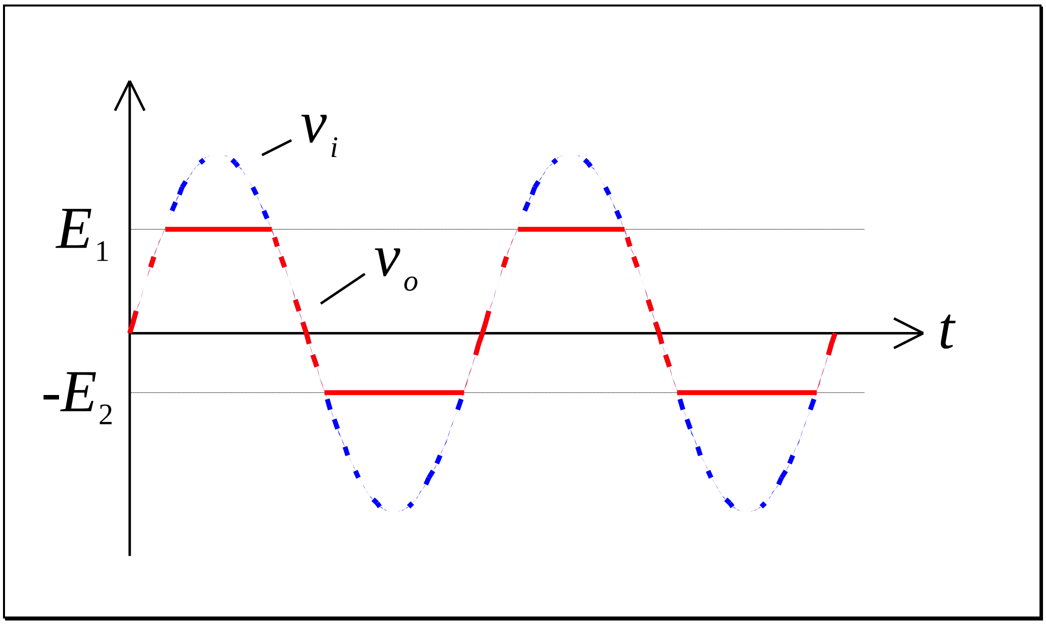


Figure 8.13

The transfer characteristic of this limiter is shown below:

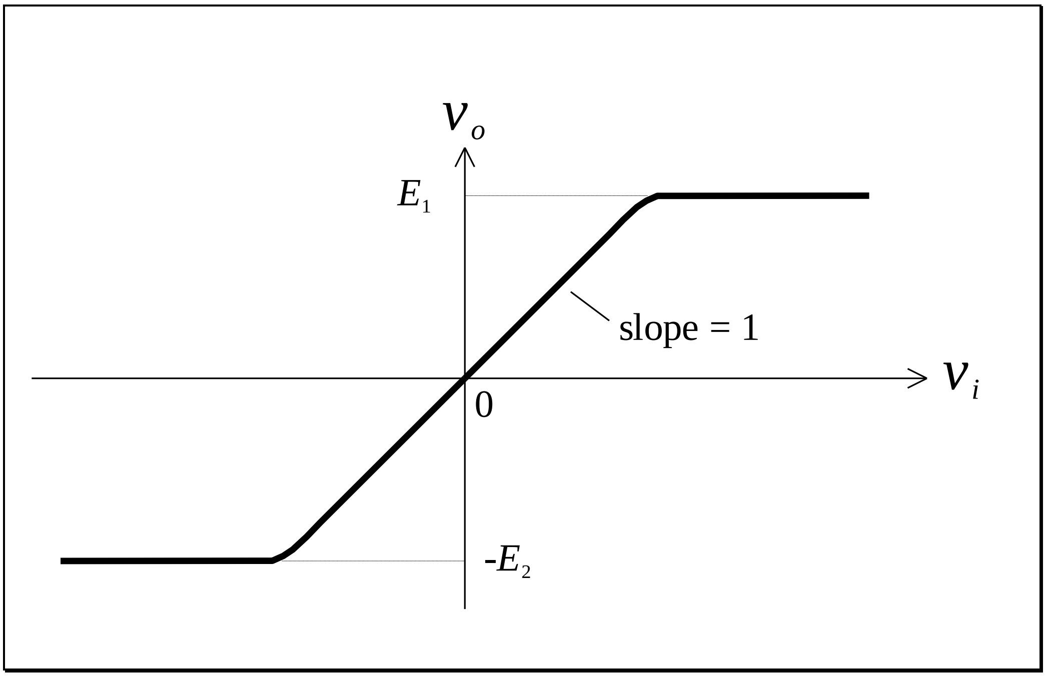


Figure 8.14

8.2.4 The Zener Regulator

A Zener diode is a diode that exhibits Zener breakdown when it is reverse biased. Zener breakdown occurs when the electric field in the depletion layer is strong enough to generate hole-electron pairs, which are accelerated by the field. This increases the reverse bias current. It gives rise to a sharper transition and steeper curve than forward biased conduction. An typical Zener diode characteristic is shown below:

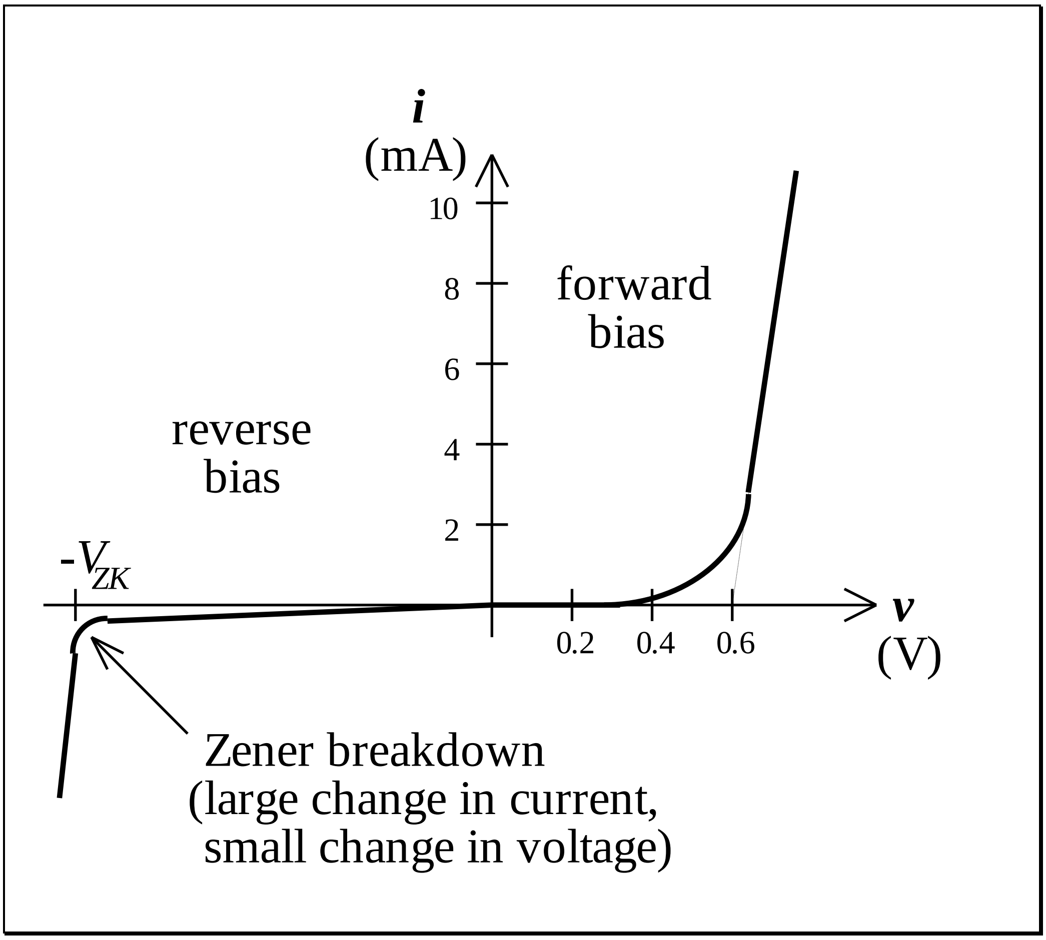


Figure 8.15

8.16

Zener diodes can be used to create simple regulators. They are designed so that the “operating point” of the Zener diode always lies in the near-vertical part of the breakdown region – hence the voltage across the diode is roughly constant and equal to the breakdown voltage of the particular device, usually labelled V_{ZK} . A typical Zener regulator circuit is shown below:

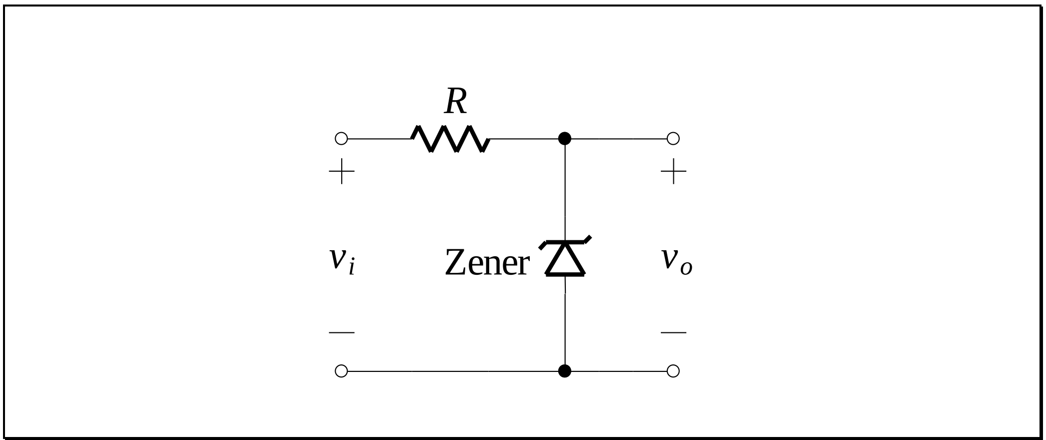


Figure 8.16

Analysis of such a circuit is relatively straight forward – you assume that the Zener diode is operating in the breakdown region so that it’s voltage is constant at V_{ZK} , and then check whether the assumption is correct.

The circuit above can also be used as a limiting circuit, since the Zener diode acts as a normal diode when it is forward-biased. The transfer characteristic of the circuit above is shown below:

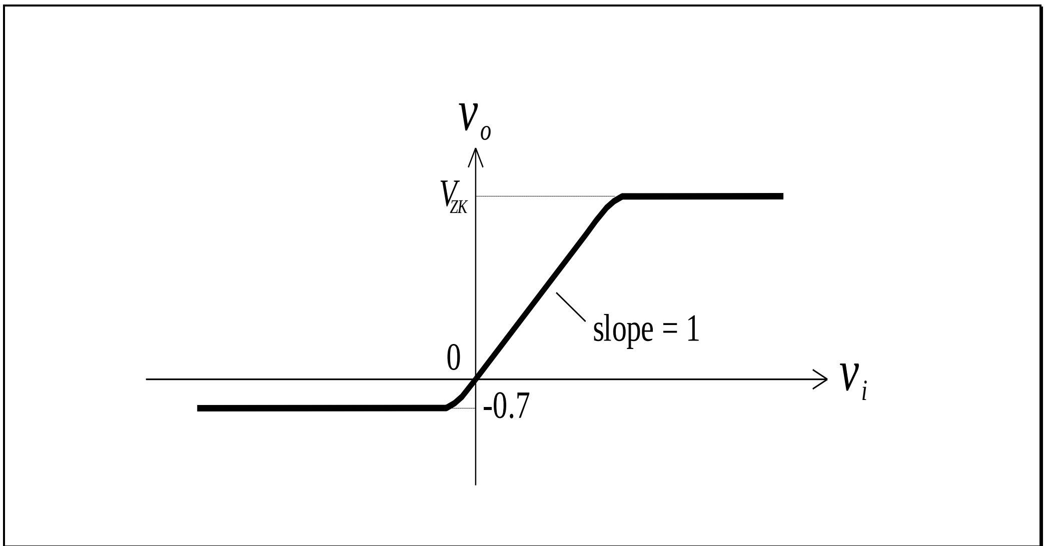


Figure 8.17

8.3 Summary

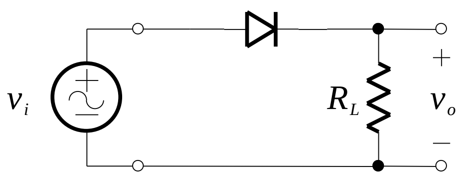
- A hierarchy of diode models exists, with the selection of an appropriate model dictated by the application.

- In the forward direction, the ideal diode conducts any current forced by the external circuit while displaying a zero voltage drop. The ideal diode does not conduct in the reverse direction; any applied voltage appears as reverse bias across the diode.

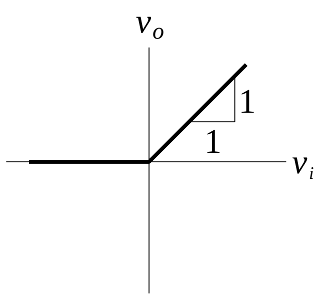
- In many applications, a conducting diode is modelled as having a constant voltage drop, usually approximately 0.7 V.

- The unidirectional-current property makes the diode useful in the design of a variety of circuits, such as the half-wave rectifier, the full-wave rectifier, limiting circuits, and many others.

- The half-wave rectifier is:

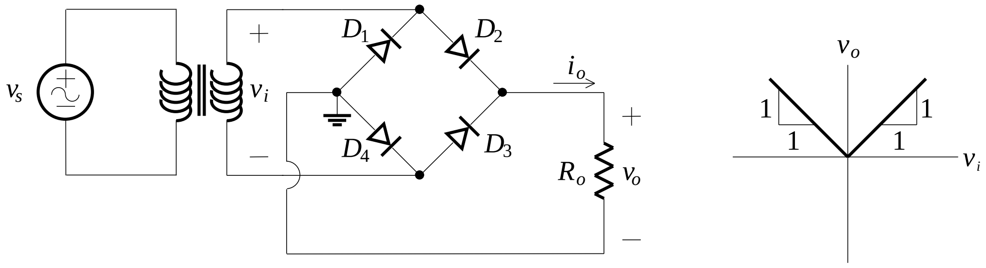


(a) circuit



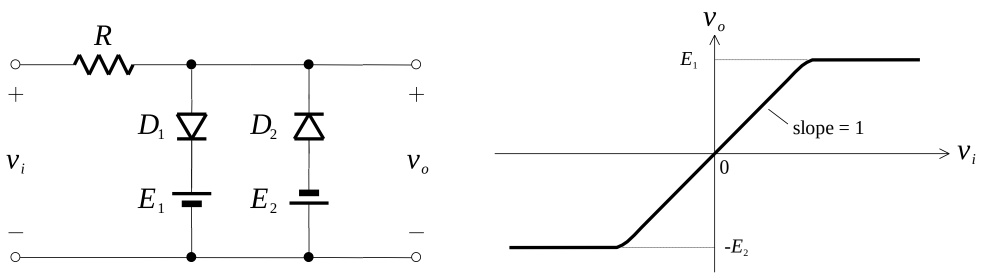
(b) transfer characteristic

- The full-wave rectifier is:



(a) circuit (b) transfer characteristic

- A limiting circuit is:



(a) circuit (b) transfer characteristic

- A Zener regulator circuit is:

(a) circuit (b) transfer characteristic

8.4 References

Sedra, A. and Smith, K.: *Microelectronic Circuits*, Saunders College Publishing, New York, 1991.