3.6 Limiting and Clamping Circuits

Reading Assignment: pp. 184-187 (i.e., neglect section 3.6.2)

Another application of junction diodes →

Q: What is a limiter?

A: A 2-port device that restricts (i.e., limits) the voltage across a device to some specified region.

HO: Diode Limiters

Q:  

A: HO: Steps for Analyzing Limiter Circuits

Example: A Diode Limiter
Often, a voltage source (either DC or AC) is used to supply an electronic device that is very expensive and/or very sensitive.

In this case, we may choose insert a diode limiter between the source and the device—this limiter will provide over-voltage protection!

To see how, we should first consider a typical transfer function for a junction diode limiter:

\[
\begin{align*}
V_O(t) &= K \left( V_I(t) - \frac{L}{K} \right) \\
&= K \left( V_I(t) - \frac{L_+}{K} \right)
\end{align*}
\]
Note that this transfer function indicates that the output voltage \( v_O \) can never be more than a maximum voltage \( L_+ \), nor less than a minimum voltage \( L_- \).

\* Thus, the device places some limits on the value of the output voltage:

\[
L_- < v_O < L_+ \quad \text{for any } v_I
\]

\* The limits \( L_- \) and \( L_+ \) provide a safe operating value for \( v_O \), the voltage across our “sensitive” electronic device.

\* Presumably, if no limiter were present, we might find that \( v_O > L_+ \) or \( v_O < L_- \), resulting in damage to the device!

\* Note although \( L_+ > L_- \), the values of \( L_- \) and \( L_+ \) may be both positive, both negative, or even zero.

For example, a limiter with \( L_- = 0 \) \((L_+ > 0)\) would prevent the voltage from ever becoming negative (positive). We find that for many devices, the wrong voltage polarity can be destructive!

To illustrate, let’s consider an example input voltage \( v_I(t) \), and the resulting output voltage when passed through a limiter with values \( L_- = 0 \) and \( L_+ = 20 \text{ V} \) \((K=1)\). I.E.:

\[
v_O = \begin{cases} 
0 & \text{if } v_I < 0 \\
 v_I & \text{if } 0 < v_I < 20 \\
20 & \text{if } v_I > 20 
\end{cases}
\]
Note there are a couple of “hiccups” in the input voltage that take the voltage value outside the “safety” range of the sensitive device. However, the limiter does in fact limit these excursions, such that the voltage across the sensitive device always remains between 0 and 20 Volts.

**Q:** Why would these “hiccups” occur?

**A:** There are many possible reasons, including:

1. A power surge (e.g., lightning strike)
2. Static discharge
3. Switching transients (e.g., at power up or down).
Perhaps the most **prevalent** reason, however, is **operator error**.

→ Someone connects the **wrong** source to the sensitive device!

Thus, limiters are often used on expensive/sensitive devices to make them “**fool-proof**”.

Your book has many **examples** of limiter circuits, including:
Steps for Analyzing Limiter Circuits

The junction diodes in most limiter circuits can/will be in forward bias, or reverse bias, or breakdown modes! Thus, the distinction between a Zener diode and a “normal” junction diode is essentially meaningless.

But, this presents us with a big problem—what diode model do we use to analyze a limiter? Recall that none of the diode models that we studied will provide accurate estimates for all three junction diode modes!

The solution we will use is to change the diode model we implement, as we consider each of the possible junction diode modes. Specifically:

<table>
<thead>
<tr>
<th>Junction Diode Mode</th>
<th>Junction Diode Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward Bias</td>
<td>CVD model with ideal diode f.b.</td>
</tr>
<tr>
<td>Reverse Bias</td>
<td>Ideal diode model with ideal diode r.b.</td>
</tr>
<tr>
<td>Breakdown</td>
<td>Zener CVD model with ideal diode f.b.</td>
</tr>
</tbody>
</table>
**Step 1:**

Assume that the limiter diode is **forward biased**, so replace

![Diode Forward Biased Diagram]

with a **CVD model**, where the **ideal** diode is **forward biased**:

![CVD Model Diagram]

Now, using this model, determine:

1. The **output voltage** \( v_O \) in terms of input voltage \( v_I \).

2. The **ideal diode current** \( i_D' \) in terms of input voltage \( v_I \).

Finally, we solve the **inequality** \( i_D' > 0 \) for \( v_I \), thus determining **when** (i.e., for what values of \( v_I \)) this assumption, and thus the derived expression for output voltage \( v_O \), is true.

**Step 2:**

Assume that the limiter diode is in **breakdown**, so replace

![Diode Breakdown Diagram]

or

![Diode Breakdown Diagram]
with a Zener CVD model, where the ideal diode is forward biased:

\[ i_D^f \]

\[ A \quad -V_{ZK} \quad + \quad C \]

Now, using this model, determine:

1. The output voltage \( v_O \) in terms of input voltage \( v_I \).

2. The ideal diode current \( i_D^f \) in terms of input voltage \( v_I \).

Finally, we solve the inequality \( i_D^f > 0 \) for \( v_I \), thus determining when (i.e., for what values of \( v_I \)) this assumption, and thus the derived expression for output voltage \( v_O \), is true.

**Step 3:**

Assume that the limiter diode is reverse biased, so replace

\[ A \quad \text{or} \quad C \]

with an Ideal Diode model, where the ideal diode is reversed biased:

\[ A \quad + \quad v_D^i \quad - \quad C \]
Now, using this model, determine the output voltage \( v_O \) in terms of input voltage \( v_I \).

Q: What about \( v_D^i \)? Don't we need to likewise determine its value, and then determine when \( v_D^i < 0 \)?

A: Actually, no. If the junction diode is not forward biased and it is not in breakdown, then it must be reverse biased! As obvious as this statement is, we can use it to determine when the junction diode is reverse biased—it's when the junction diode is not in forward bias and when it is not in reverse bias.

For example, say that we find that the junction diode is forward biased when:

\[
v_I > 20 \text{ V},
\]

and that the junction diode is in breakdown when:

\[
v_I < -15 \text{ V}.
\]

We can thus conclude that the junction diode is reverse biased when:

\[
-15 \text{ V} < v_I < 20 \text{ V}
\]

**Step 4:**

We take the result of the previous 3 steps and form a continuous, piecewise linear transfer function (make sure it's continuous, and that it's a function!).
Example: A Diode Limiter

Consider the following junction diode circuit:

This circuit is a junction diode limiter!

Perhaps that would be clearer if we *redrew* this circuit as:

This is the *same* circuit as above!
Now, let’s determine the transfer function of this limiter. To do this, we must follow the 4 steps detailed in the previous handout!

**Step1:** Assume junction diode is forward biased

Replace the junction diode with a CVD model. ASSUME the ideal diode is forward biased, ENFORCE $v_D^i = 0$.

We find that the output voltage is simply:

$$v_o = 5.0 + 0.7 = 5.7 \text{ V}$$

while the ideal diode current is more difficult to determine.

From KCL:

$$i_D^i = i_1 + i_2$$

where from Ohm’s Law:
\[ i_1 = \frac{v_I - 5.7}{1} = v_I - 5.7 \]

and:
\[ i_2 = \frac{0 - 5.7}{1} = -5.7 \]

Thus, the ideal diode current is:
\[ i_D^{ii} = i_1 + i_2 = \nu_I - 5.7 - 5.7 = \nu_I - 11.4 \]

Now, for our assumption to be correct, this current must be positive (i.e., \( i_D^{ii} > 0 \)). Thus, we solve this inequality to determine when our assumption is true:
\[ \nu_I - 11.4 > 0 \]
\[ \nu_I > 11.4 \text{ V} \]

So, from this step we find:
\[ v_O = 5.7 \text{ V} \quad \text{when} \quad \nu_I > 11.4 \text{ V} \]

**Step2:** Assume the junction diode is in breakdown

Replace the junction diode with a Zener CVD model. ASSUME the ideal diode is forward biased, ENFORCE \( v_D^{i} = 0 \).
We find that the output voltage is simply:

\[ v_O = 5 - 10 = -5.0 \text{ V} \]

while the ideal diode current is more difficult to determine.

From KCL:

\[ i_D^i = i_1 + i_2 \]

where from Ohm's Law:

\[ i_1 = \frac{-5 - v_I}{1} = -v_I - 5.0 \]

and:

\[ i_2 = \frac{0 - 5.0}{1} = -5.0 \text{ V} \]

Thus, the ideal diode current is:
\[ i_D^i = i_1 + i_2 \]
\[ = -v_I - 5.0 - 5.0 \]
\[ = -v_I - 10.0 \]

Now, for our assumption to be correct, this current must be positive (i.e., \( i_D^i > 0 \)). Thus, we solve this inequality to determine when our assumption is true:

\[ -v_I - 10.0 > 0 \]
\[ -v_I > 10.0 \text{ V} \]
\[ v_I < -10.0 \text{ V} \]

So, from this step we find:

\[ v_O = -5.0 \text{ V} \quad \text{when} \quad v_I < -10.0 \text{ V} \]

**Step 3:** Assume the junction diode is reverse biased

Replace the junction diode with the Ideal Diode model. ASSUME the ideal diode is reverse biased, ENFORCE \( i_D^i = 0 \).

\[ \text{A voltage divider!} \]
Thus the output voltage is:

\[ v_O = \frac{v_I (1)}{1 + 1} = \frac{v_I}{2} \]

This output voltage is true when the junction diode is neither forward biased nor in breakdown. Thus, using the results from the first two steps, we can infer that it is true when:

\[-10.0 < v_I < 11.4\]

**Step 4:** Determine the continuous transfer function

Combining the results of the previous 3 steps, we get the following continuous, piece-wise linear transfer function:

\[ v_O = \begin{cases} 
5.7 \text{ V} & \text{if } v_I > 11.4 \text{ V} \\
\frac{v_I}{2} & \text{if } -10.0 < v_I < 11.4 \text{ V} \\
-5.0 \text{ V} & \text{if } v_I < -10.0 \text{ V}
\end{cases} \]
Note that at $v_i = -10$:

$$v_o = \frac{v_i}{2} = \frac{-10}{2} = -5.0 \text{ V}$$

and at $v_i = 11.4$:

$$v_o = \frac{v_i}{2} = \frac{11.4}{2} = 5.7 \text{ V}$$

Thus, this function is continuous!