6.334 Power Electronics
Spring 2007

Chapter 1

Introduction and Analysis Methods

1.1 Switching Power Electronics

Read Chapter 1 of "Principles of Power Electronics" (KSV) by J. G. Kassakian, M. F. Schlecht, and G. C. Verghese, Addison-Wesley, 1991.

Linear Regulator

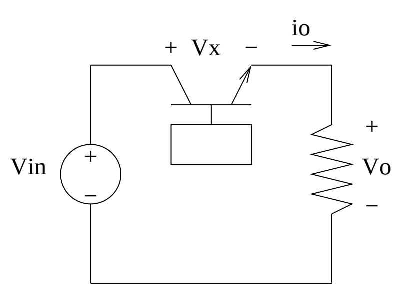

Figure 1.1: Linear Regulator

Control v_x such that $V_o = V_{o,REF}$: Simple, accurate, high-bandwidth, but

$$\begin{aligned} P_{diss} &= < v_x i_o > \quad > 0 & (1.1)\\ \eta &= \frac{P_{out}}{P_{in}} \\ &= \frac{V_o i_o}{V_{in} i_o} \\ &= \frac{V_o}{V_{in}} & (1.2) \end{aligned}$$

$$@ \ V_{in} = 15v, V_o = 5v \rightarrow \eta = 33\% \tag{1.3}$$

For efficiency we will consider switching power converters:

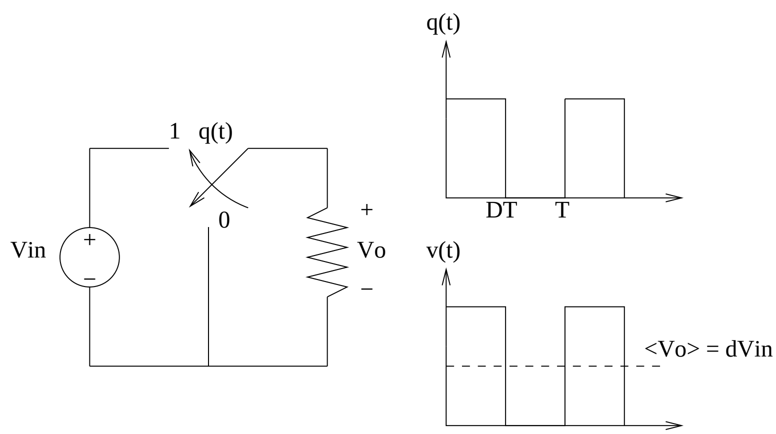

Figure 1.2: Considering Switching Power Convertor

Add filtering:

NOTE: Only lossless elements. L, C (energy storage).

Use semiconductors as switches. Switches: Block V, carry I, but NOT at the same time!

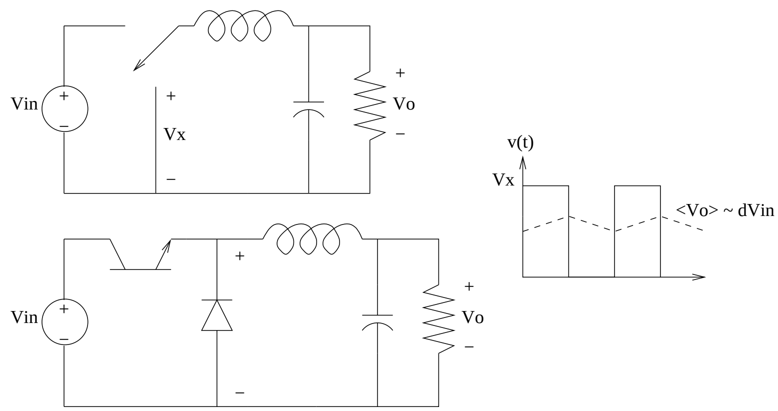

Figure 1.3: Add Filtering

1.2 Analysis Techniques

1.2.1 Methods of Assumed States

Semiconductor switches are typically not fully controllable. Let's consider how to analyze a switching circuit in time domain:

Simple Rectifier

Example: (trivial but fundamental)

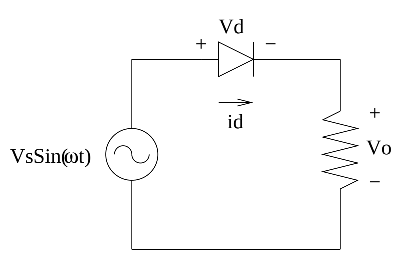

Figure 1.4: Simple Rectifier

Diodes: Uncontrolled

- Cannot sustain positive voltage (will turn on)

- Cannot sustain negative Current (will turn off)

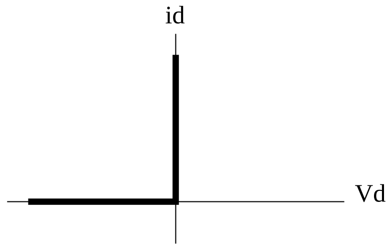

Figure 1.5: Diode

The method of assumed states allows us to figure out which un/semi-controlled switches are on as a function of time.

1. Assume a state (on/off) for all un/semi-controlled switches.
2. Calculate voltages and currents in the system (linear circuit theory).
3. See if any switch conditions are violated (e.g., “on” diode has negative current and “off” diode has positive voltage.)
4. If no violations, then done, else if violation assume a new set of states go back to step 1.

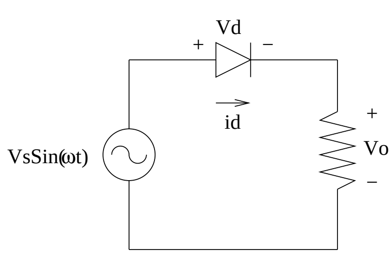

Figure 1.6: Simple Rectifier

- If $V_s \sin(\omega t) > 0$ and we assume diode off: $v_d > 0$, since this is not possible diode must be on during this condition.

- If $V_s \sin(\omega t) < 0$ and we assume diode on: $i_d < 0$, since this is not possible diode must be off during this condition.

$V_s \sin(\omega t) > 0 \rightarrow$ diode on:

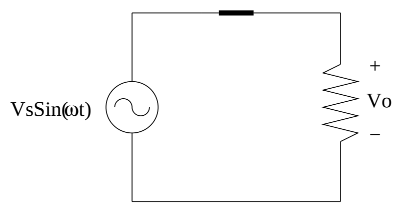

Figure 1.7: Simple Rectifier with Diode On

$V_s \sin(\omega t) < 0 \rightarrow$ diode off:

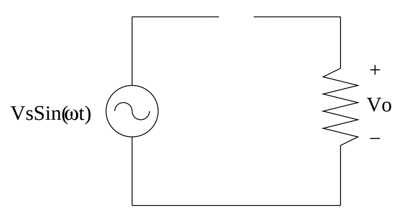

Figure 1.8: Simple Rectifier with Diode Off

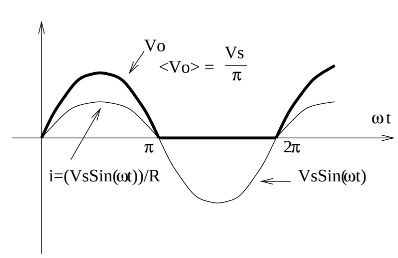

Figure 1.9: Rectifier Waveform

Very simple example but principle works in general.

1.2.2 Periodic Steady State

In power electronics we are often interested in the periodic steady state. In periodic steady state the system returns to the same point at the end of cycle (beginning matches end), so things are operating cyclicly.

In periodic steady state (P.S.S.):

$$\begin{aligned}
V &= L\frac{di}{dt} \\
< V > &= < L\frac{di}{dt} > \\
&= L < \frac{di}{dt} > \\
\text{since } < \frac{di}{dt} >= 0 \rightarrow < V > &= 0
\end{aligned} \tag{1.4}$$

Therefore, in P.S.S.:

- Inductor $< V_L >= 0 \rightarrow$ average $\frac{di_L}{dt} = 0$
- Capacitor $< V_C >= 0 \rightarrow$ average $\frac{dV_C}{dt} = 0$

The P.S.S. conditions are useful for analysis. Consider adding a filter to smooth the ripple current in our simple rectifier:

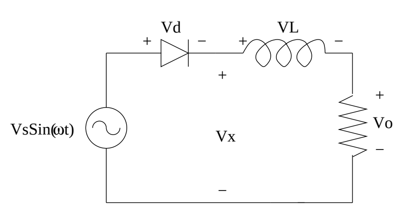

Figure 1.10: Simple Rectifier with Filter

If we assume diode is always on in P.S.S., then:

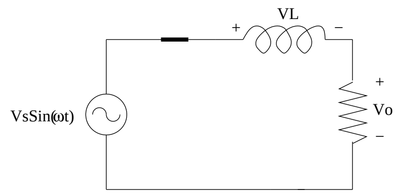

Figure 1.11: Simple Rectifier with Filter and Diode On

$$
\begin{aligned}
V_s \sin(\omega t) - V_L - v_o &= 0 \\
< V_s \sin(\omega t) > &= 0 \text{ in P.S.S.} \\
< V_L > &= 0 \text{ in P.S.S.} \\
v_o &= 0 \qquad (1.5)
\end{aligned}
$$

If diode were always on $< V_o >= 0$ and i_o must be < 0 part of the time. We know diode must turn off during part of cycle by the method of assumed states. What happens:

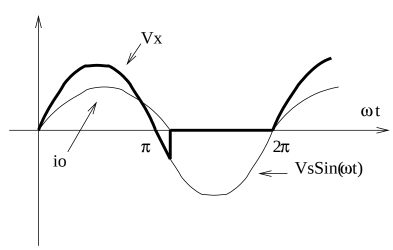

Figure 1.12: Rectifier with Filter Waveform

Negative voltage for part of cycle drives $i \rightarrow 0$. Exact analysis in KSV, Section 3.2.2. Good for review of time-domain analysis.

Main point: Method of assumed states and P.S.S. condition are useful tools to determine system behavior.

Now, in P.S.S. $< V_x > = < V_o >$, since $< V_L > = 0$. $< V_x >$ is *pos* $\frac{1}{2}$ sin plus some *neg* $\frac{1}{2}$ sin, so we lose some voltage as compared to a *pos* $\frac{1}{2}$ sin.

Solution: Free-wheeling diode → Half-wave Rectifier.

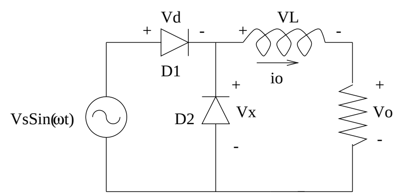

Figure 1.13: Simple Rectifier with Free Wheeling Diode

D_2 clamps so that V_x never goes negative. i_o "free-wheels".

Using method of assumed states:

- D_1 conducts when $V_s \sin \omega t > 0$.
- D_2 conducts when $V_s \sin \omega t < 0$.

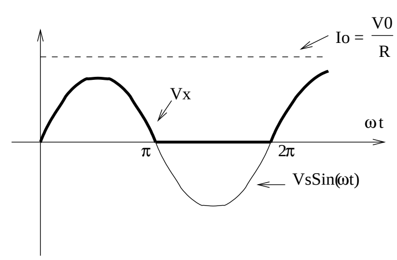

Figure 1.14: Rectifier with Free Wheeling Diode Waveform

$$
\begin{aligned}
< V_L > &= 0 \; in \; P.S.S. \\
< V_o > &= < V_x > \\
&= \frac{1}{2\pi} \int_0^{\pi} V_s \sin(\phi) d\phi
\end{aligned}
$$

$$= \frac{V_s}{\pi} \tag{1.6}$$

NOTE: This circuit is rarely used in line applications today for several reasons, but the analysis technique is the key point. Full-wave rectifier is more common.

NOTE: For analyzing output current, output voltage, etc., we can do an equivalent-source replacement. Linear circuit with sum of fourier sources.

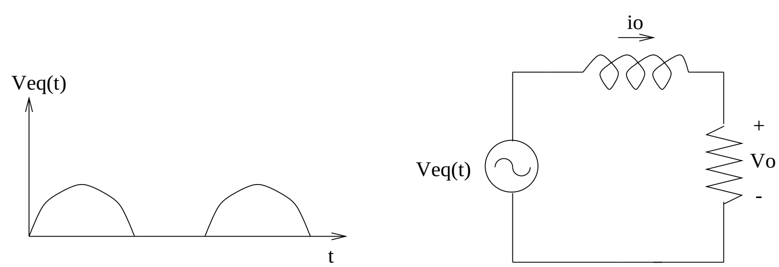

Figure 1.15: Linear Circuit with Sum of Fourier Sources

$$V_{eq} = \sum_{n=0}^{\infty} B_n \cos(n\omega t + \phi_n) \tag{1.7}$$

$$\text{If } H(\omega) = \frac{v_o(\omega)}{v_x(\omega)} \Rightarrow V_o = \sum_n |H(n\omega)| B_n \cos(n\omega t + \phi_n + < H(n\omega)) \tag{1.8}$$

Main point: We can replace difficult to handle part of circuit with an equivalent voltage source, then use linear circuit theory to analyze from there.

Summary of analysis thechniques:

- Method of assumed states
- Periodic Steady State
- Equivalent source replacement