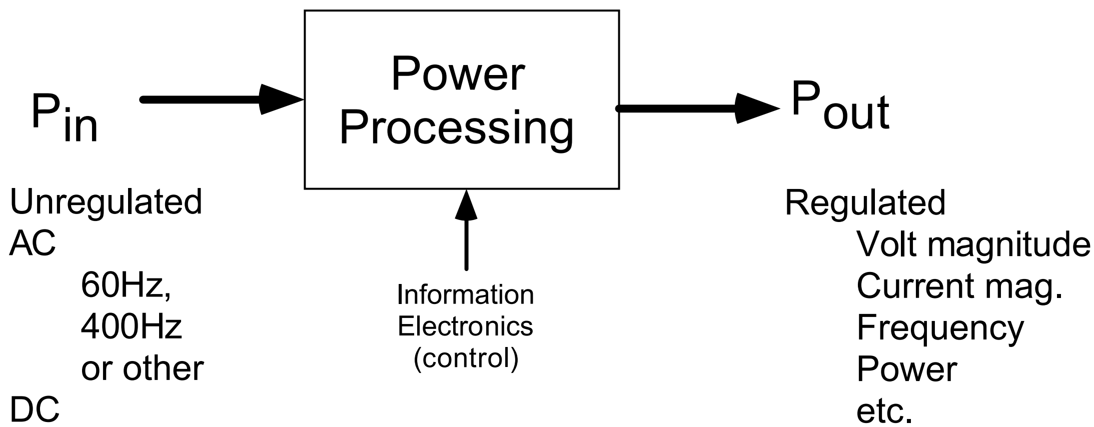
ECE 320: Lectures 30 and 31

Notes

Power Electronic Circuits:

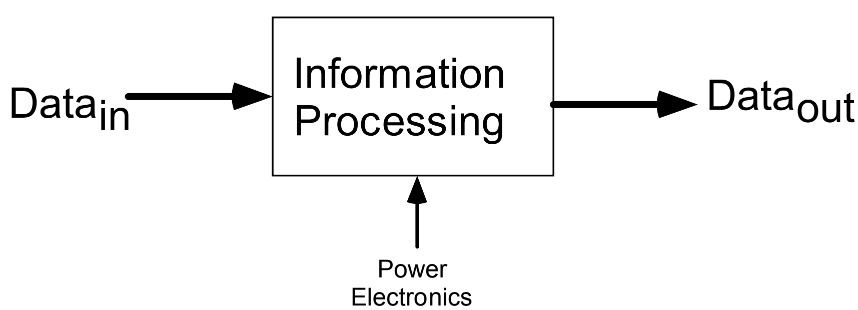
- We will start with chapters 1 and 2 in Mohan, Undeland and Robbins
- Then move on to Chapter 7.

Power Converters



- Take unregulated input power and produced processed (regulated) output power.
- Could have different freqency (or even dc) than input
- Regulated voltage magnitude, current, etc.
- Information electronics used to control power processing

Information Electronics



- Require power to work on the information

Fundamental Rules of Power Electronics

1. Kirchhoff's Laws (KCL and KVL) still apply

2. Energy (and Power) are conserved. Pin = Pout

3. You can't change the current through an inductor instantaneously

$$v = L \cdot \left(\frac{d}{dt} i \right)$$

We will view this as:

$$\Delta v = L \cdot \frac{\Delta i}{\Delta t}$$ where Δt is often the time it takes a switch to open and interrupt current

We can rewrite this as:

$$\Delta v \cdot \Delta t = L \cdot \Delta i$$ volt-second balance

As a result we will treat an inductor as a current source when it is in a circuit.

4. You can't change the voltage across a capacitor instantaneously

$$i = C \cdot \left(\frac{d}{dt} v \right)$$

We will view this as:

$$\Delta i = C \cdot \frac{\Delta v}{\Delta t}$$

We can rewrite this as:

$$\Delta i \cdot \Delta t = C \cdot \Delta v$$ charge balance

As a result we will treat a capacitor as a voltage source when it is in a circuit.

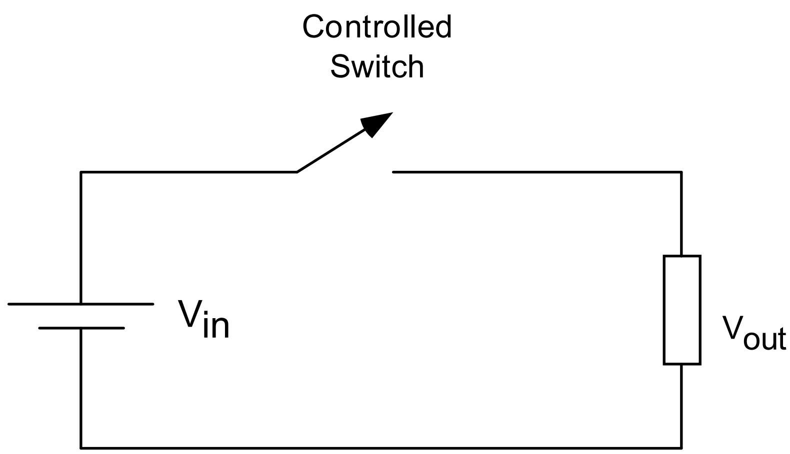
- We always need to be careful about interrupting current through an inductor, or connecting tw voltage sources (capacitors) in parallel by closing a switch.
- Circuit will operate in a cyclic steady-state between switching transients.

Basic Idea

Suppose Want to produce a regulated dc output voltage. We have a variable dc input voltage, and we want a lower output voltage.

- Options include:
  1. Voltage divider (poor efficiency)
  2. Using a dc generator (high cost and bulky)
  3. Linear regulator (again, poor efficiency since drop the difference between input and output voltage across a transistor)
  4. But we can take that linear regulator circuit and push in into non-linear region where device carries high current, but has a low voltage drop. Repeated turn device on and off to synthesize a waveform with desired average characteristics

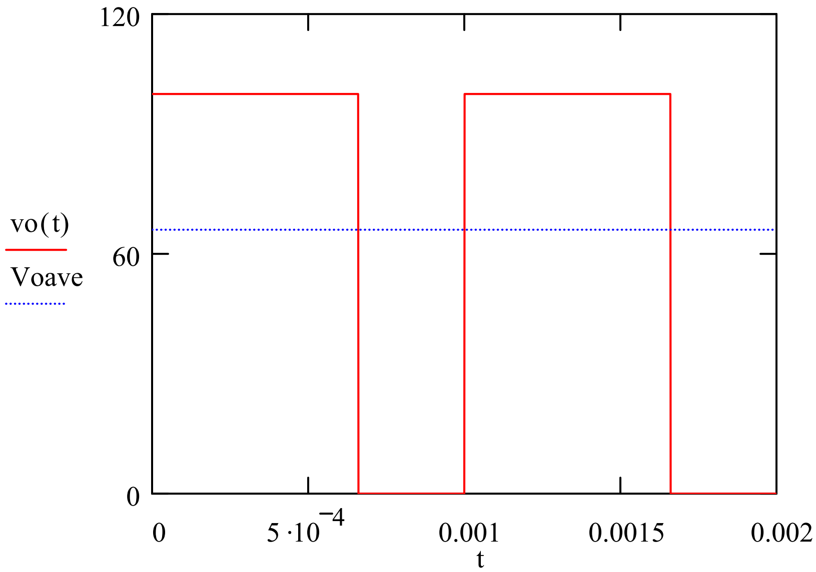
Lets pursue option 4 further



- When the switch closed, Vout = Vin, when its open, Vout = 0.
- The waveform looks like the one below.
- The total period for one switching cycle is T_s
- The switch period (1 over switching frequency, could be a few Hertz to hundeds of kHz
- The switch is on for a period T_{on}, which is $D*T_s$

$$Vd := 100V \qquad D := 0.66 \qquad Ts := 0.001sec$$

$$t := 0sec, 0.000001sec .. 2Ts \qquad vo(t) := \begin{cases} Vd & \text{if } 0 \le t \le D \cdot Ts \\ 0 & \text{if } D \cdot Ts < t < Ts \\ Vd & \text{if } Ts < t \le Ts + D \cdot Ts \\ 0 & \text{otherwise} \end{cases}$$



The blue line is the average output voltage.

Use upper case V for average value, and lower case v for instantaneous value. Same holds for current

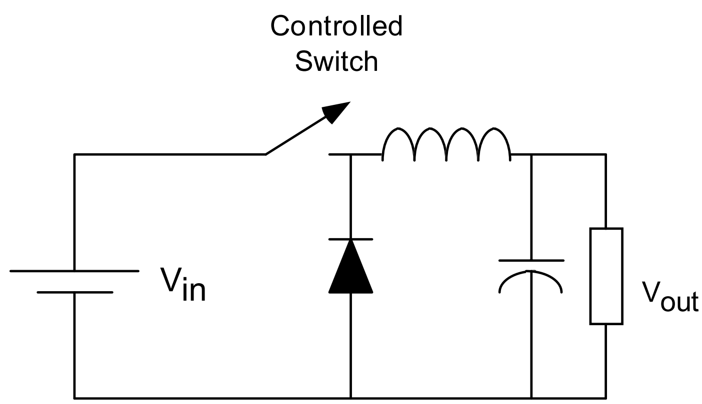
$$Vo = Vd = Vin$$

$$Io = \frac{Vo}{R}$$

$$V_o = \frac{1}{T_s}\cdot\int_0^{T_s} v(t)_o\,dt = \frac{1}{T_s}\cdot\left(\int_0^{D\,T_s} V_d\,dt + \int_{D\cdot T_s}^{T_s} 0\,dt\right) = \frac{t_{on}}{T_s}\cdot V_d = D\cdot V_d$$

$$V_o = D\cdot V_d$$ Average value of v_o

- Where: $0 \le D \le 1$
- By varying D, one is able to vary the average voltage. This will be more efficient than the o options. There will be some losses when switch opens and closes, and while the switch conducts (there is some internal "resistance")
- We will call this a buck converter.
- Most loads won't tolerate so much variaton in the output voltage.
- Add a capacitor across the load to filter the output voltage (store energy)
- Now we will be connecting two voltage sources together when the switch closes. To keep from violating one of the fundamental rules, we need to add an inductor between the capacit and the switch.
- Now we also need an alternate current path for the inductor current when the switch is open add the diode shown in the figure. Will be forced to turn on (commutate on) when the switc turns off (commutates off).



- Now look at the current through the inductor.
- The average current through the inductor is the average load current (the average current ir capacitor is zero.
- When the switch is closed, the inductor will see a voltage:

$$\Delta v = \frac{(Vd - Voave)}{L}$$ The current will ramp up linearly.

- When the switch is open:

$$\Delta v = \frac{(0 - Voave)}{L}$$ The current will ramp down linearly.

- In steady-state end of one switch period is initial condition for the next one.

$Ls := 10mH$ $\quad Rload := 10ohm$ $\quad Ts := 0.001sec$

$Vd := 100V$ $\quad D := 0.6$ $\quad fs := \frac{1}{Ts}$

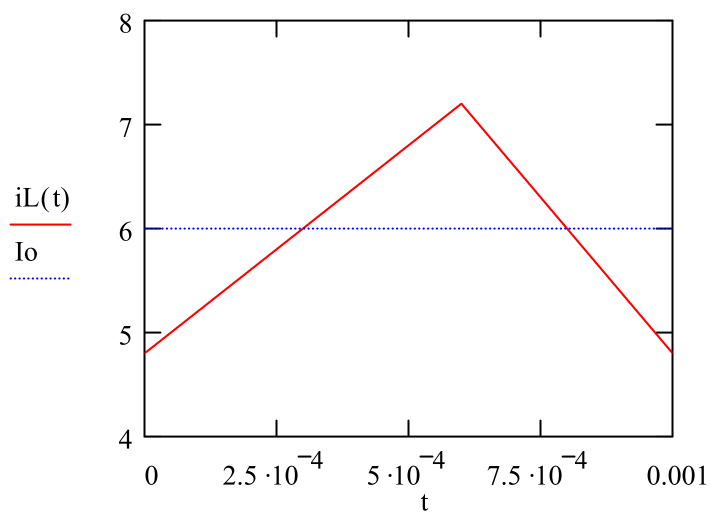
$Vo := D \cdot Vd$ $\quad Vo = 60V$ $\quad fs = 1000Hz$

$Io := \frac{Vo}{Rload}$ $\quad Io = 6A$

- Peak to peak current ripple (change during the time the switch closed)

$$\Delta IL := \frac{Vo \cdot (1 - D)}{Ls \cdot fs} \qquad \Delta IL = 2.4A$$

$$iL(t) := \begin{cases} \dfrac{-\Delta IL}{2} + \left(\dfrac{Vd - Vo}{Ls}\right)\cdot t + Io & \text{if } 0 \le t < D\cdot Ts \\ \dfrac{\Delta IL}{2} + \left(\dfrac{-Vo}{Ls}\right)\cdot(t - D\cdot Ts) + Io & \text{if } D\cdot Ts \le t \le Ts \end{cases}$$



- This will repeat for each cycle.
- The rising part of the current flows through the switch
- The falling part through the diode.

$$is(t) := \begin{cases} \dfrac{-\Delta IL}{2} + \left(\dfrac{Vd - Vo}{Ls}\right)\cdot t + Io & \text{if } 0 \le t < D\cdot Ts \\ 0 & \text{if } D\cdot Ts \le t \le Ts \end{cases}$$

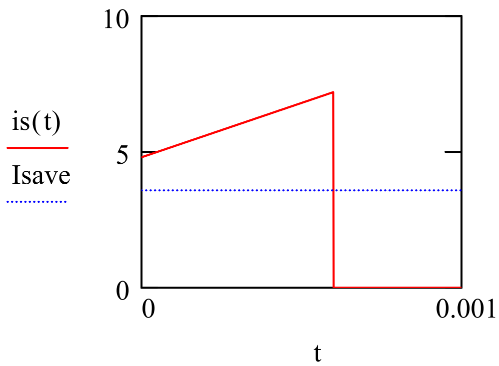
$$idiode(t) := \begin{cases} 0A & \text{if } 0 \le t < D\cdot Ts \\ \dfrac{\Delta IL}{2} + \left(\dfrac{-Vo}{Ls}\right)\cdot(t - D\cdot Ts) + Io & \text{if } D\cdot Ts \le t \le Ts \end{cases}$$

$$Isave := \frac{1}{Ts}\cdot\int_0^{Ts} is(t)\,dt \qquad Idave := \frac{1}{Ts}\cdot\int_0^{Ts} idiode(t)\,dt$$

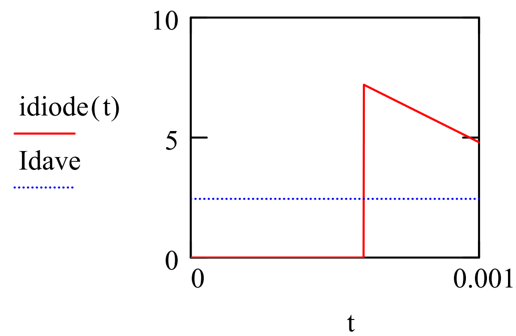
$\text{Isave} = 3.6\,\text{A}$ $\text{Idave} = 2.4\,\text{A}$

$\text{Isave} + \text{Idave} = 6\,\text{A}$ which is the average output current

Switch current



Diode Current



- The average of the switch current is the average input current.
- We can also find the average input current from the conversvation of power.

$$\text{Pd} = \text{Po}$$

$$V_d \cdot I_d = V_o \cdot I_o$$

- Which can be rewritten as:

$$\frac{I_o}{I_d} = \frac{V_d}{V_o} = \frac{1}{D}$$

I_o is the average current

For out example:

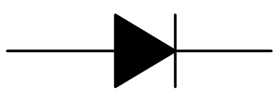
$\text{Id} := \text{D} \cdot \text{Io}$ $\text{Id} = 3.6\,\text{A}$ which matches the average switch current

Parts of a power converter:

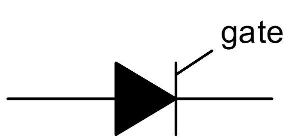
- Converter usually needs a current source on one side and voltage source on the other side. In dc-dc buck converter above, Vd is a stiff voltage source, and the inductor is added to create a current source
- Most converters have passive components (L and C) to help create better voltage or current sources

Switching Devices

- Power Diode: p-n junction. Allows current to flow in one direction. For more detail see Chapte 20 in Mohan, Undeland and Robbins.
  * Turns on when a forward voltage across it and a forward current tries to flow through it.
  * Turns off when the current tries to reverse.
  * When on there will be a small voltage drop (approximately 0.7V-1V for a Silicon based power diode
  * Circuit symbol (current flows in the direction of the "arrow" in the symbol:



- Power Thyristor: p-n-p-n layers. Allows current to flow in one direction. For more informatic see Chapter 23 in Mohan, Undeland and Robbins. Also called a Silicon controlled rectifier (SCR)
  * Turns on when a forward voltage across it and a forward current tries to flow through it and a gate pulse is applied to overcome the n-p junction.
  * Turns off when the current tries to reverse. Gate pulse does not turn it off.
  * When on there will be a small voltage drop (approximately 1.5-2 V for a Silicon based power thrysitor
  * Circuit symbol (current flows in the direction of the "arrow" in the symbol:



- Power Bipolar Junction Transistor (BJT). See chapter 21 in Mohan, Undeland and Robbins
  * NPN or PNP like regular BJT. Will have a low value of β and so it requires a large curre to allow it to open and interrupt current. Operate in non-linear region when on so has relatively low voltage drop.
  * Due to slow turn-off time and large current needed to turn on or off they are no longer us