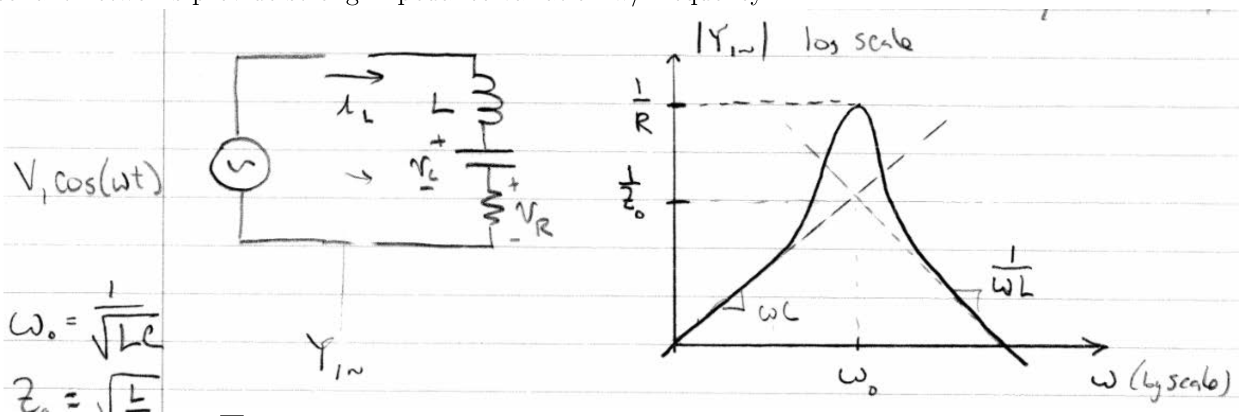
6.622 Power Electronics | *Prof. David Perreault*

Lecture 36 - Resonant Power Conversion Continued

1 Review:

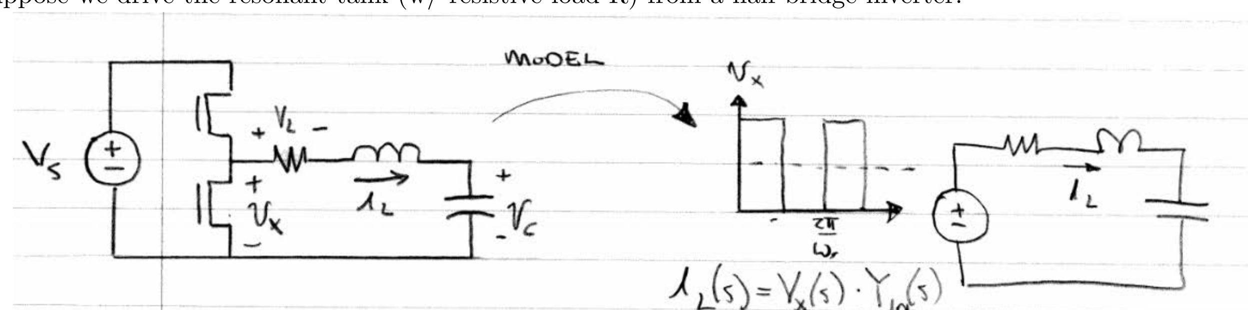
Resonant networks provide strong impedance variation w/ frequency



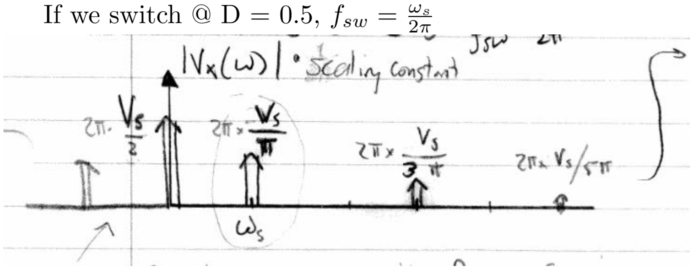
$\omega_0 = \frac{1}{\sqrt{LC}}, z_0 = \sqrt{\frac{L}{C}}, Q@\omega_0 = \frac{z_0}{R} \Rightarrow$ we can control power to load R by varying frequency!

2 "Class D" amplifier in "series resonant" converter

Suppose we drive the resonant tank (w/ resistive load R) from a half-bridge inverter:



If we switch @ D = 0.5, $f_{sw} = \frac{\omega_s}{2\pi}$



@ high Q ($R << \sqrt{\frac{L}{C}}$)
ω_s near ω_0
i_L sinusoidal

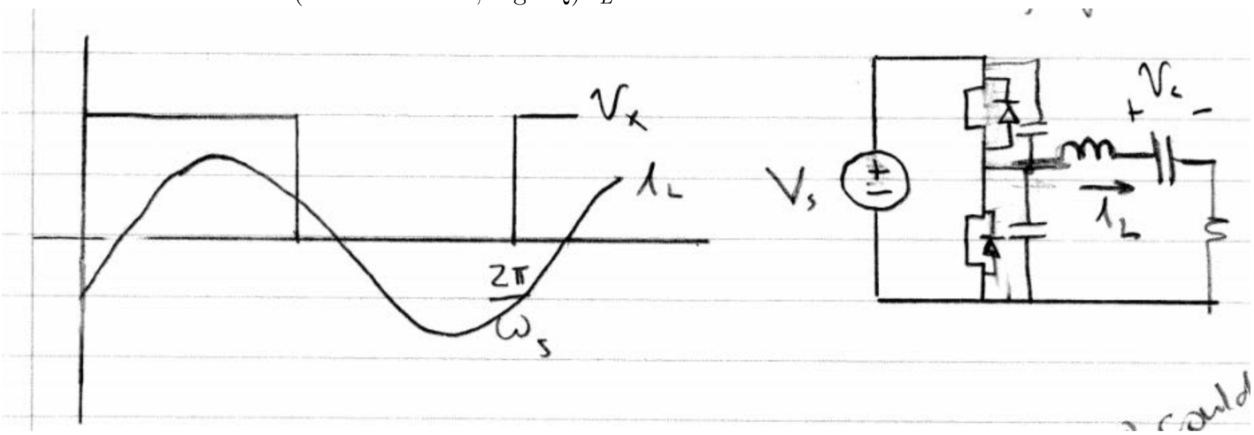
Fourier transform based on exponential form of series, + has scaling on it (-2π)

To control i_L, power to R, we might vary switching frequency above or below resonance.
$|i_L(j\omega_s)| = |V_x(j\omega_s) \cdot Y_{in}(j\omega_s)|$

- $\Rightarrow$ Above resonance $f_{sw} > \frac{\omega_0}{2\pi}$ network looks inductive
- $\Rightarrow$ Below resonance $f_{sw} < \frac{\omega_0}{2\pi}$ network looks capacitive (keep $3f_{sw} >> \omega_0$ to avoid amplifying harmonic voltage)

3 Fundamental Harmonic Approximation (FHA)

$\Rightarrow$ if harmonics well filtered (near resonance, high Q) i_L sinusoidal



Above resonance i_L <u>lags</u> $v_{x,1}$

$\Rightarrow$ If we add capacitors across the switch (could be junction capacitor) we can always get 2VS turn on and turn off!

0. A <u>"nice"</u> characteristic is that device + component currents change proportional to load current (good for efficiency vs load)

1. Note: Device voltages are clamped @ V_s, but i_L, v_c can have <u>large</u> peak values. <u>At</u> resonance:

$$\frac{\text{CAP voltage fundamental}}{\text{Drive fundamental}} = |\frac{V_c}{V_{x,1}}||_{\omega=\omega_0} = \frac{\sqrt{\frac{L}{C}}}{R} = Q! \text{ can be ¿¿ } 1$$

2. challenge: as <u>Resistor varies</u>
   (a) If R too small, $v's, i's \uparrow$ or must move away from resonance
   (b) If R too large, tank $Q \downarrow$, low selectivity (wide f var), nonsinusoidal waveforms, can lose soft switching

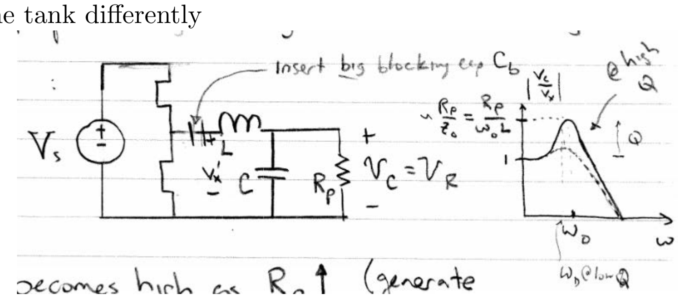
With the series circuit there are concerns w/ load resistor variation (The load may vary naturally w/ system (e.g. induction cooking). <u>Rectifiers</u> provide loads having equivalent resistance that vary w/ power + output power)

1. If $R \rightarrow$ too small we must move away from resonance or peak V's, i's become large
2. If $R \rightarrow$ too big selectivity of the tank becomes poor
   - Current not sinusoidal
   - "soft" switching lost

We can get different properties by loading the tank differently

e.g. parallel loading:
Neglecting c_b (or from other side of c_b):

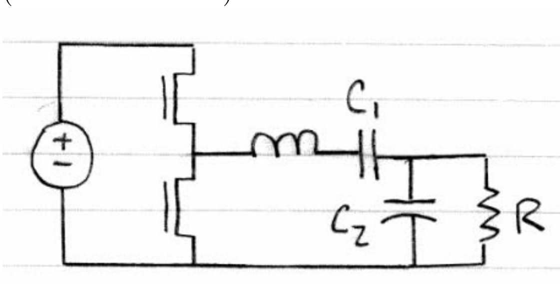
$$\frac{v_c}{v'_\alpha} = \frac{1}{s^2LC + s\frac{L}{R_p} + 1}$$



In this case, tank Q becomes high as $R_p \uparrow$ (generate big $V's$ and $I's$ in tank when $R_p \to \infty$), and tank $Q \downarrow$ as $R_p \downarrow$.
A further impact of this is that well as power decreases R $\uparrow$. Efficiency a light load may be a challenge
This is used to good effect in fluorescent lamp ballasts:

- Lamp $R \uparrow$ until a big voltage is applied and lamp "strikes"
- Once lamp is struck, $R_p \downarrow$ and tank becomes more loaded, delivering appropriate power at lower voltages.

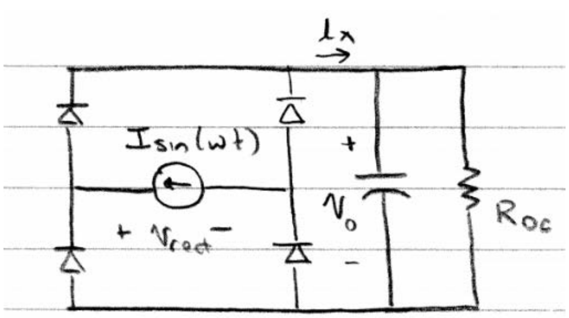
To get a balance between series and parallel behavior, the "series parallel" approach is sometimes used (also called "LCC").

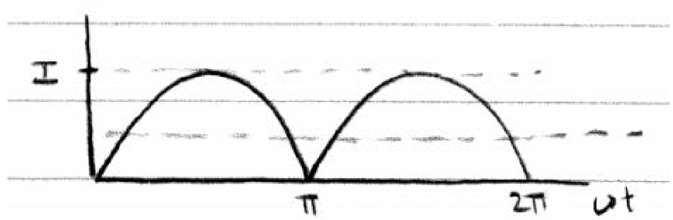


- @ low "R" values R "shorts out" C_2 and design acts "like" a series res control
- @ high "R" values the equivalent resonant characteristics change [C_{eq} goes from C_1 to $C_1||C_2$]

If we increase f_{sw}, we get behavior "like" parallel res.

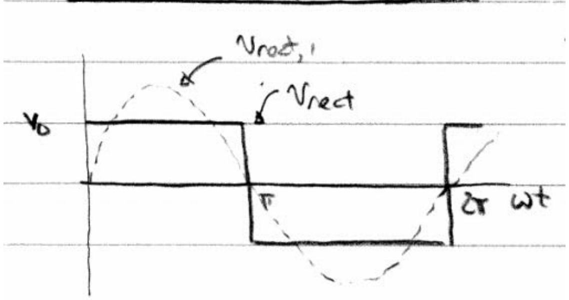
What about dc-dc conversion? $\Rightarrow$ model the rectifier!
We can also use the "Fundamental Harmonic Approximation" to model rectifiers





$$< i_x >= \frac{1}{\pi}\int_0^\pi I sin(\phi) d\phi = \frac{2}{\pi} I$$

$$\therefore \boxed{V_0 = \frac{2}{pi} I R_{DC}}$$



If V_0 is determined by a dc load resistor

fundamental component of V_{rect} is

$$\boxed{v_{rect,1} = \frac{4}{\pi} V_0 sin(\omega t)}$$

Cases:

1. For a <u>fixed</u> output voltage V_0 (not determined by a dc resistor). $P_{av} =< i_x > \cdot V_0 = \frac{2}{\pi} I V_0$ or $I = \frac{\pi}{2} \frac{P_{av}}{V_0}$
   So the FHA ac impedance posed by the rectifier is:

$$R_{ac,eff} = \frac{V_{rect,1}}{I sin(\omega t)} = \frac{4}{\pi} \frac{V_0}{I} = \frac{4}{\pi} \frac{V_0}{\pi} \frac{2 \cdot V_0}{P_{av}}$$

$$\boxed{R_{ac,eff} = \frac{8}{\pi^2} \frac{V_0^2}{P_{av}}} \text{General form for other rectifiers} K \frac{V_0^2}{P_{av}}$$

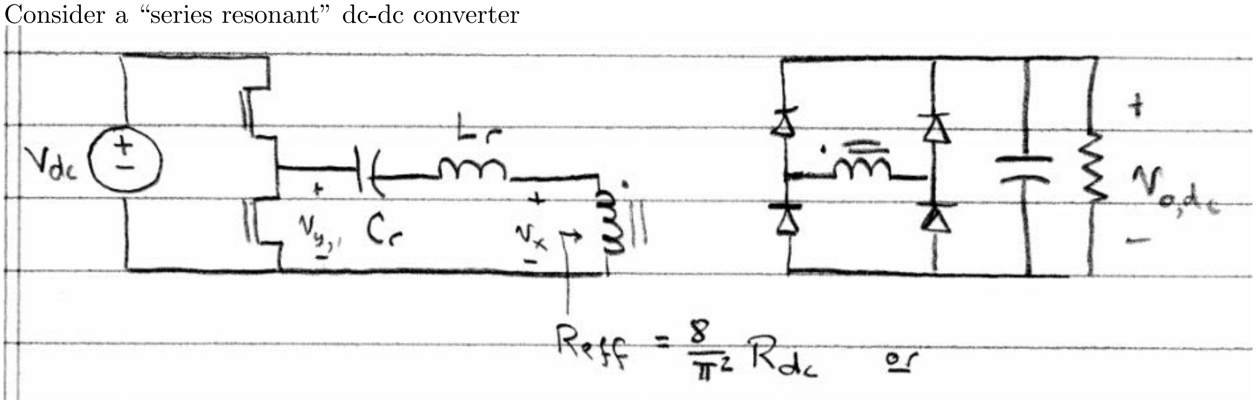
2. If the rectifier is loaded with a dc resistor R_{DC}:

$$R_{ac,eff} = \frac{V_{rect,1}}{I sin(\omega t)} = \frac{4V_0}{\pi I} = \frac{4}{\pi I} \cdot \frac{2IR_{DC}}{\pi}$$

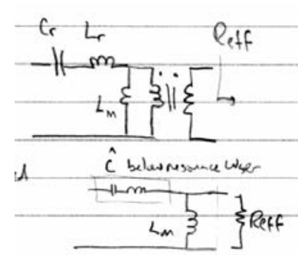
$$\boxed{R_{ac,eff} = \frac{8}{\pi^2} \cdot R_{DC}} \text{ General form for other rectifiers } K' \cdot R_{DC}$$

   Similar expressions may be found for other rectifiers

Consider a "series resonant" dc-dc converter

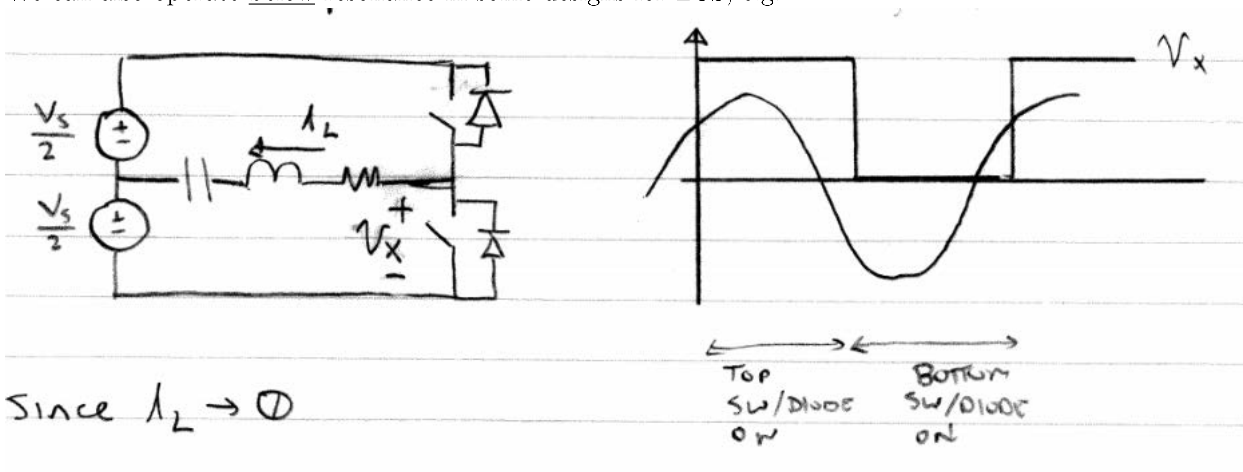


- Operate above $\omega_0 = \frac{1}{L_r C_r}$ to get ZVS soft switching.
- This works for a "dc gain" such that $|V_{x,1}| \leq |V_{y,1}|$.
  - We can change inverter and/or rectifier topology (full-bridge, half-bridge) to adjust the gain, as well as transformer turns ratio.
  - For very "light" loads (R_{dc} big) tank selectivity/frequency range becomes a problem.
    * Can "burst" converter on and off $\Rightarrow R_{eff} = \frac{8}{\pi^2} \frac{V_0^2}{P_{\text{on}}}$ (power when burst is "on").
    * Can use a different tank structure, such as parallel, LCC, LLC.
- We often pick a tank that meets requirements of an application and absorbs parasitics in a useful way (e.g., "series-parallel"/LCC or parallel resonant converter PRC can be used when a high-voltage secondary yields high transformer capacitance and/or rectifier capacitance)



- By gapping the transformer, we can get an "LLC" design:
  - Above $\omega_{\text{ser}} = \frac{1}{\sqrt{L_r C_r}}$, we get behavior a bit like a series-resonant converter, but L_m helps at low power and provides inductive ZVS current.
  - Below ω_{ser}, we can still be inductively loaded and get additional voltage gain by resonance between $\hat{C}$ and L_m, "matching" over some range.

We can also operate below resonance in some designs for ZCS, e.g.



Since $i_L > 0$ before top switch turns on, bottom diode conducts + bottom switch off @ ZCS. Same w/ top switch

A variation of this trick uses multiple resonances to provide ZCS turn on for the switches, also. Good for thyreistors.