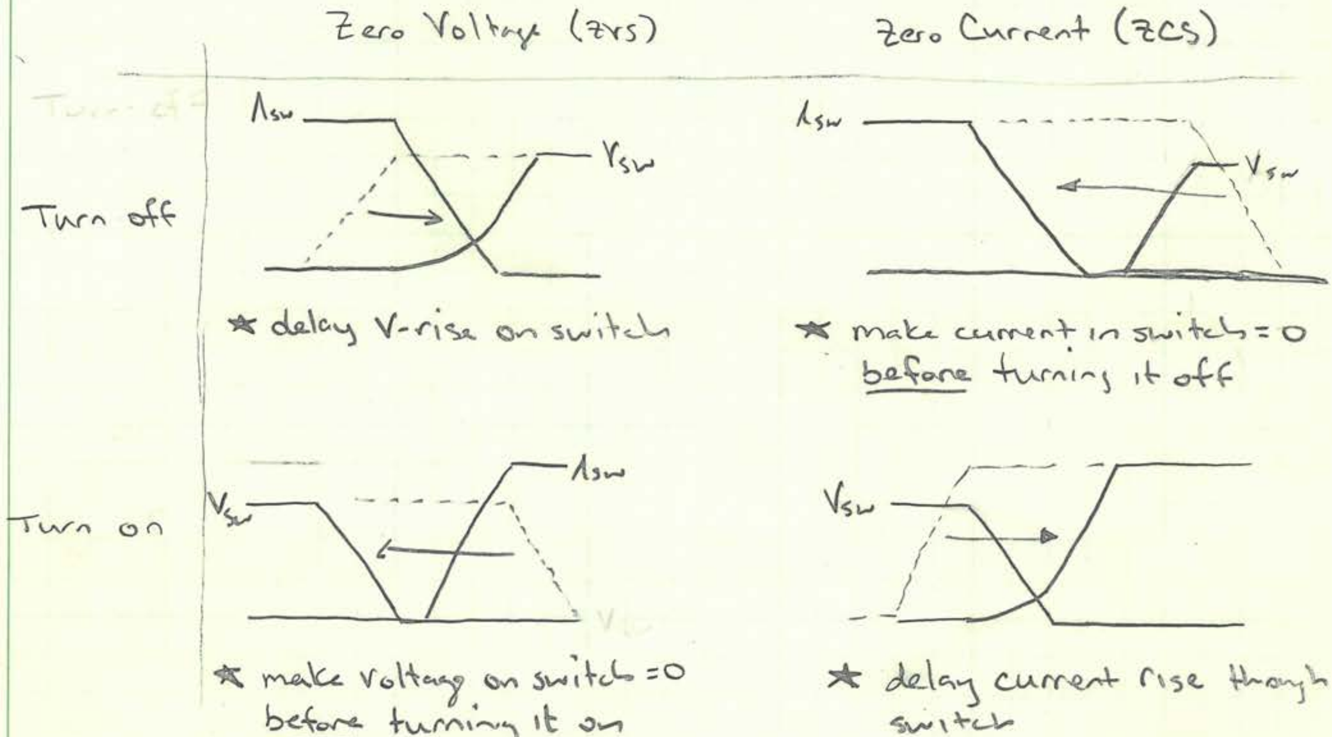
## ZCS / ZVS Techniques, Inverter Applications

Review:

Soft switching techniques reduce switching losses by reducing overlap of high voltage and current periods during switching.




Soft switching is achieved through the use of additional circuitry and control action. Usually this is at the expense of other aspects of the converter (e.g. complexity, cost, etc.), but the trade can be worthwhile.

Last time, we looked at soft-switching approaches for dc-dc converters

Example #1: ZCS Quasi-Resonant Buck Converter

- Each cycle, the converter generates a soft resonant "pulse" of current to the output
- devices turn on and off softly ZCS
- requires frequency-based control, not duty ratio.

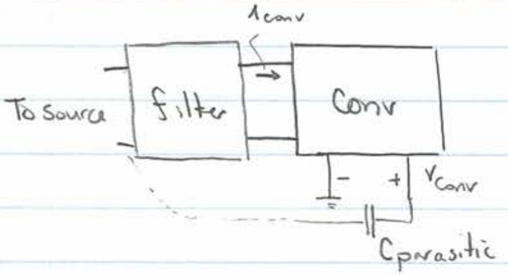
Example #2: ZVT PWM Boost Converter

- duty ratio control is achieved w/ ZVS for main devices
- but, several extra components for "baby boost", not fully soft switched

Today: Soft switching for inverters. RPI, ARCP, (RDCL?)

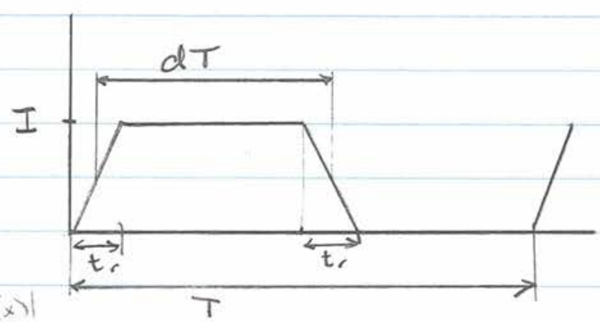
6.334 Lecture Notes — Soft switching, Cont'd

Snubbing and soft switching serve to slow the transitions of voltage and/or current at the switching transitions. How does this affect filter design and EMI emissions?




filtering is often driven by "square wave" voltage & current transitions in the converter. Snubbing and soft switching control the rise & fall times (for a trapezoid)

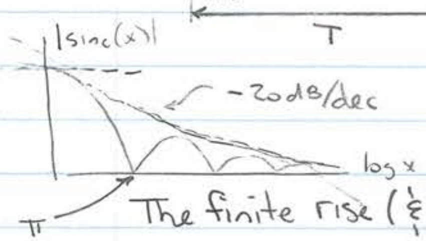
For a <u>trapezoid</u> in current (or voltage)




The fourier series is:

$$|I_n| = 2Id\left[\frac{\sin(n\pi d)}{\pi dn}\right]\left[\frac{\sin\left(\frac{n\pi t_r}{T}\right)}{\left(\frac{n\pi t_r}{T}\right)}\right]$$

This factor controls the high-frequency content.




The finite rise (& fall) time applies a sinc function factor to the harmonic amplitudes (which would simply be a factor of "1" for a square wave / zero rise time)

$\text{sinc}(x) = \frac{\sin(x)}{x}$ has magnitude peaks @ $x = (2k+1)\frac{\pi}{2}$ $k \in I$

$|\text{value}| = \frac{1}{(2k+1)\pi/2} = \frac{2/\pi}{2k+1} \sim \frac{1}{k}$

$$\therefore \frac{\sin(n\pi t_r f_1)}{n\pi t_r f_1} \quad ; \; n = \frac{f}{f_1}$$

$$\therefore \frac{\sin(\pi f t_r)}{\pi f t_r} \text{ has an envelope } = \begin{cases} \frac{1}{\pi f t_r} & f > \frac{1}{\pi t_r} \\ 1 & f < \frac{1}{\pi t_r} \end{cases}$$

the nonzero rise time provides an added 20 dB/dec attenuation for $f > 1/\pi t_r$

6.334 Lecture Notes Soft switching cont'd

Suppose we have a switching frequency f and a rise time that is:

$t_r = \frac{0.01}{f_1}$ (1% rise/fall) $f_c = \frac{1}{\pi t_r} = 31.8 f_1$

$t_r = \frac{0.02}{f_1}$ (2% rise/fall) $f_c = \frac{1}{\pi t_r} = 15.9 f_1$

$t_r = \frac{0.05}{f_1}$ (5%) $f_c = \frac{1}{\pi t_r} = 6.3 f_1$

$t_r = \frac{0.1}{f_1}$ (10%) $f_c = \frac{1}{\pi t_r} = 3.18 f_1$

So @ f = 1MHz (for example) a 2% rise time can help for frequencies below 30MHz (conducted EMI band) and a 10% rise time can provide ~ 1 order of magnitude attenuation by 30MHz!

Ott, Electromagnetic Compatibility Engineering

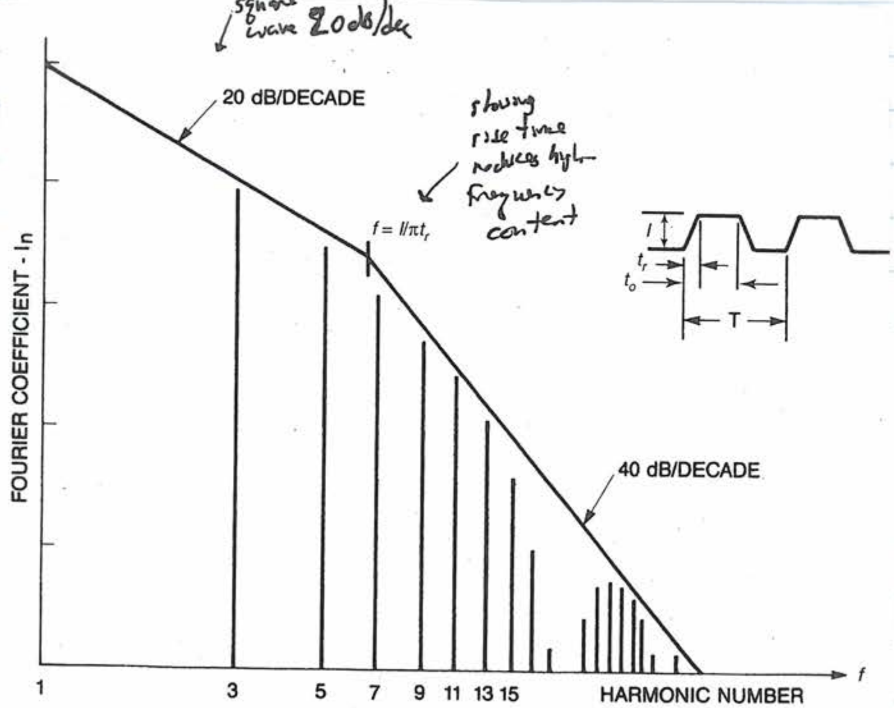


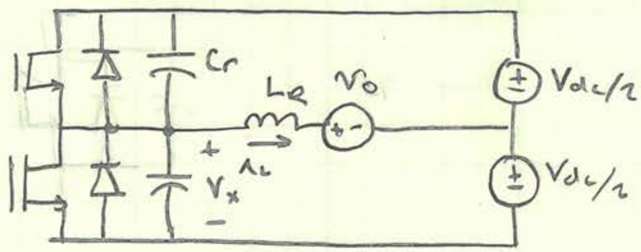

**FIGURE 12-4.** Envelope of Fourier spectrum of a 50% duty cycle trapezoidal wave.

$$I_n = 2Id\left[\frac{\sin(n\pi d)}{n\pi d}\right]\left[\frac{\sin\left(\frac{n\pi t_r}{T}\right)}{\frac{n\pi t_r}{T}}\right], \quad (12\text{-}5)$$

## RESONANT POLE INVERTER

ZERO VOLTAGE TURN ON AND TURN OFF OF DEVICES

⇒ First, consider switching cycle (overhead/handout)




e.g. if $i_{REF} > 0$
$i_{p+} = 2i_{REF} + i_{min}$
$i_{p-} = -i_{min}$

⇒ overall operation: $\langle i_L \rangle \approx \frac{i_{p+} + i_{p-}}{2}$

control $i_{p+}$, $i_{p-}$ to achieve desired $\langle i_L \rangle$ in a switching cycle.

also, there are requirements on $i_{p+}$, $i_{p-}$ to achieve soft sw.

$i_{p+}$ must be pos. enough to ring $V_x$ from $V_{dc}$ to 0.

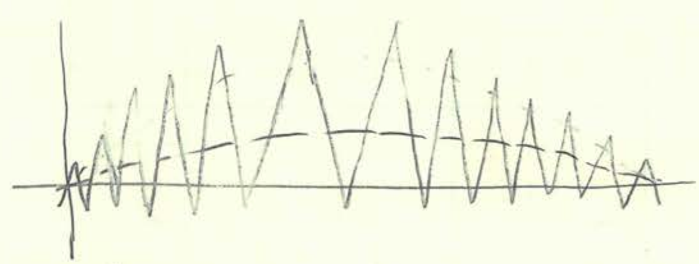
$i_{p-}$ must be neg. enough to ring $V_x$ from 0 to $V_{dc}$.

⇒ derived conditions: define $i_{min} = 2\sqrt{\frac{C_r V_{dc} |V_{cf}|}{L_r}}$

If $V_o > 0$ $|i_{p+}| > i_{min}$, $|i_{p-}| > 0$

$V_o < 0$ $|i_{p+}| > 0$, $|i_{p-}| > i_{min}$

Pick $i_{p+}$, $i_{p-}$ to satisfy these constraints and to yield desired $\langle i_L \rangle$



$$f_{sw} = \frac{\frac{1}{4}V_{dc}^2 - V_{cf}^2}{V_{dc} L_r (i_{p+} + i_{p-})} \sim \frac{1}{\langle i_L \rangle}$$

so to control $\langle i_L \rangle$ we get widely varying switching freq.

So: RPI gives us : ZVS soft switching
small resonant components
simple control

But : Requires Variable f control
yields high output current ripple

Another approach which eliminates these requirements at the expense of high complexity:

Auxiliary Resonant Commutated Pole Inverter (ARCP)

→ uses additional switches & res components (aux circuit) to allow the switch state to be changed whenever desired

→ many operational modes, depending on state.

⇒ go through example commutation sequence (if time)

ARCP gives us : Total control of bridge leg at ZVS
(aux circuit is ZCS)

BUT : Very high control & sensing complexity.

→ suitable for very high power converters

Final notes : Many issues w/ soft switching we have ignored.

→ device physics & switching characteristics
(not all devices operate well w/ ZVS, ZCS)

→ control complexity, implementation
(dead times, etc.)