Lecture 34 - Soft-Switching 2

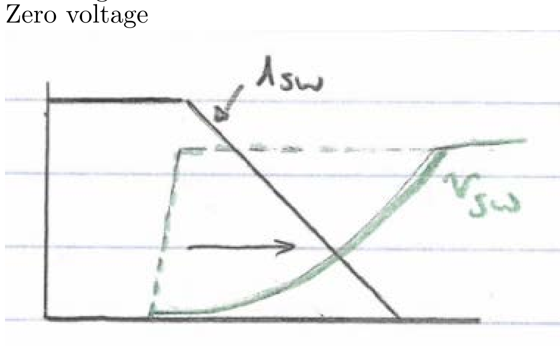
1 Review

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

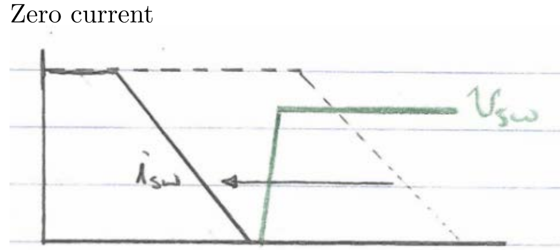
Zero voltage

Zero current

Turn off

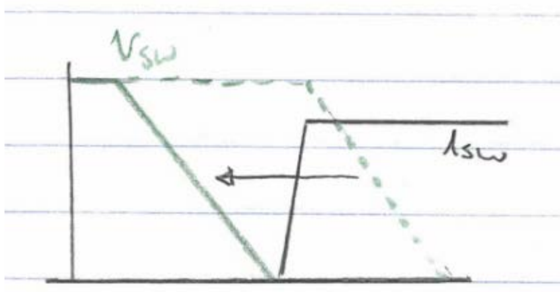


⋆ Delay V-rise on switch

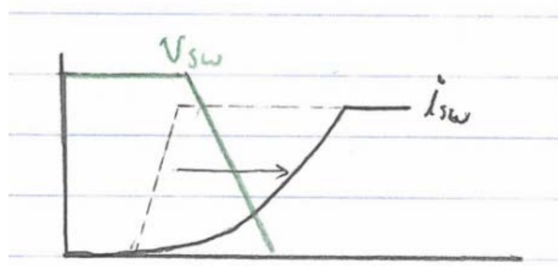


⋆ Make current in switch */rightarrow* 0 <u>BEFORE</u> turning off switch

Turn on



⋆ Make switch voltage go to zero <u>before</u> switch turn on



⋆ Delay current rise on switch

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.

<u>Last Time</u>, we looked at soft-switching approaches for dc-dc converters:

Example #1: ZCS Quasi-Resonant Buck Converter

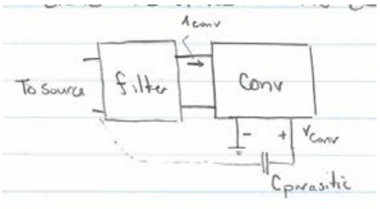
- Each cycle, the converter generates a soft resonant "pulse" of current to the output
- Devices turn on and off softly, ZCS
- Requires frequency-based control, not duty ratio

Example #2: ZVT PWM Boost Converter

- Duty ratio control is achieved with ZVS for <u>main</u> devices
- But, several extra components for "baby boost", not fully soft switched

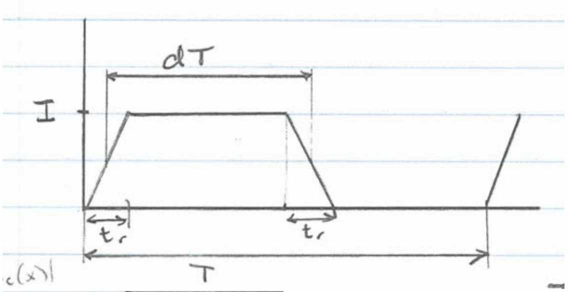
Today: Soft switching for inverters: RPI, ARCP, (RDCL?)

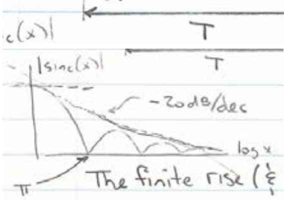
Snubbing and soft switching serve to slow the transitions of voltage and/or current at the switching transitions. How does this affect filter design and EMI emissions?



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

For a trapezoid in current (or voltage)





The fourier series is:

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

The rightmost term controls the high-frequency content.

The finite rise (and 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)

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

$|value| = \frac{1}{(2k+1)\frac{T}{2}} = \frac{\frac{2}{\pi}}{2k+1}$ ~ $\frac{1}{K}$

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

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

The nonzero rise time provides an added 20dB/dec attenuation for f¿$\frac{1}{\pi t_r}$

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

$t_r = \frac{0.01}{f_1}$	(1% rise/fall)	$f_c = \frac{1}{\pi t_r}$	$31.8f_1$
$t_r = \frac{0.02}{f_1}$	(2% rise/fall)	$f_c = \frac{1}{\pi t_r}$	$15.9f_1$
$t_r = \frac{0.05}{f_1}$	(5%)	$f_c = \frac{1}{\pi t_r}$	$6.3f_1$
$t_r = \frac{0.1}{f_1}$	(10%)	$f_c = \frac{1}{\pi t_r}$	$3.18f_1$

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 30 MHz!

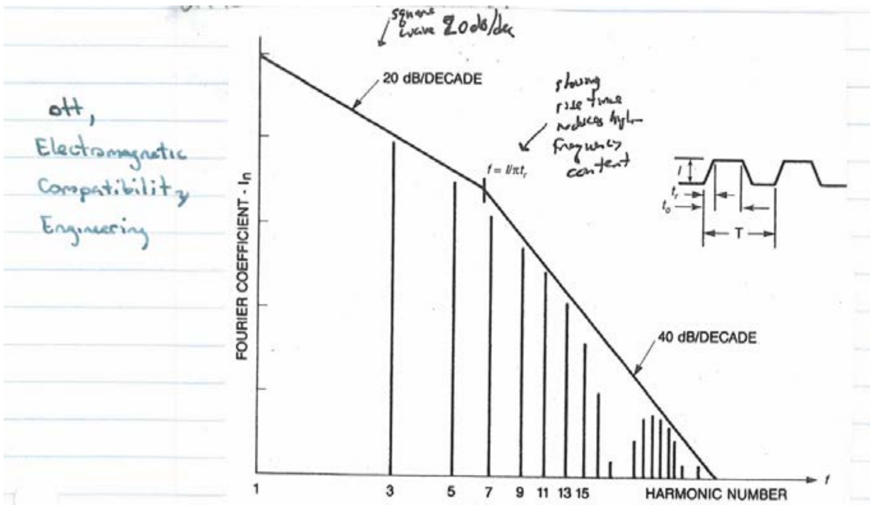


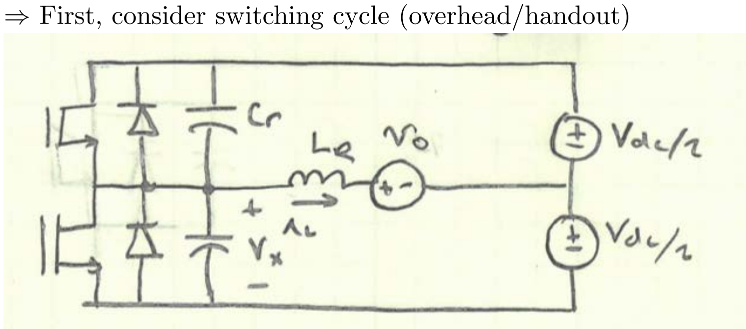
FIGURE 12-4. Envelope of Fourier spectrum of a 50% duty cycle trapezoidal wave.

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

2 Resonant Pole Inverter

Zero voltage turn on and turn off of devices

$\Rightarrow$ First, consider switching cycle (overhead/handout)



$\Rightarrow$ Overall operation: $\langle i_L \rangle \approx \frac{i_{p+}+i_{p-}}{2}$, e.g. $i_f i_{ref} > 0, i_{p+} = 2i_{ref} + i_{min}, i_{p-} = -i_{min}$

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.

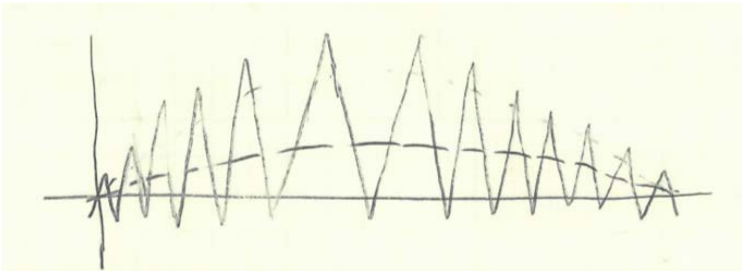
1. i_{p+} must be positive enough to ring v_x from v_{dc} to 0
2. i_{p-} must be negative enough to ring v_x from 0 to v_{dc}

$\Rightarrow$ Desired conditions: define $i_{min} = 2\sqrt{\frac{c_r v_{dc} |v_{cf}|}{L_r}}$

$$\text{if } v_0 > 0, |i_{p+}| > i_{min}, |i_{p-}| > 0$$

$$v_0 < 0, |i_{p+}| > 0, |i_{p-}| > i_{min}$$

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

Auxiliary Resonant Commutated Pole Inverter (ARCP)

- Uses additional switches & resonant components (auxiliary 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 (auxiliary circuit is ZCS)

But:

- Very high control & sensing complexity
- Suitable for very high power converters

Final Notes

Many issues with soft switching we have ignored:

- Device physics/switching characteristics (not all devices operate well with ZVS, ZCS)
- Control complexity & implementation (dead times, etc.)

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