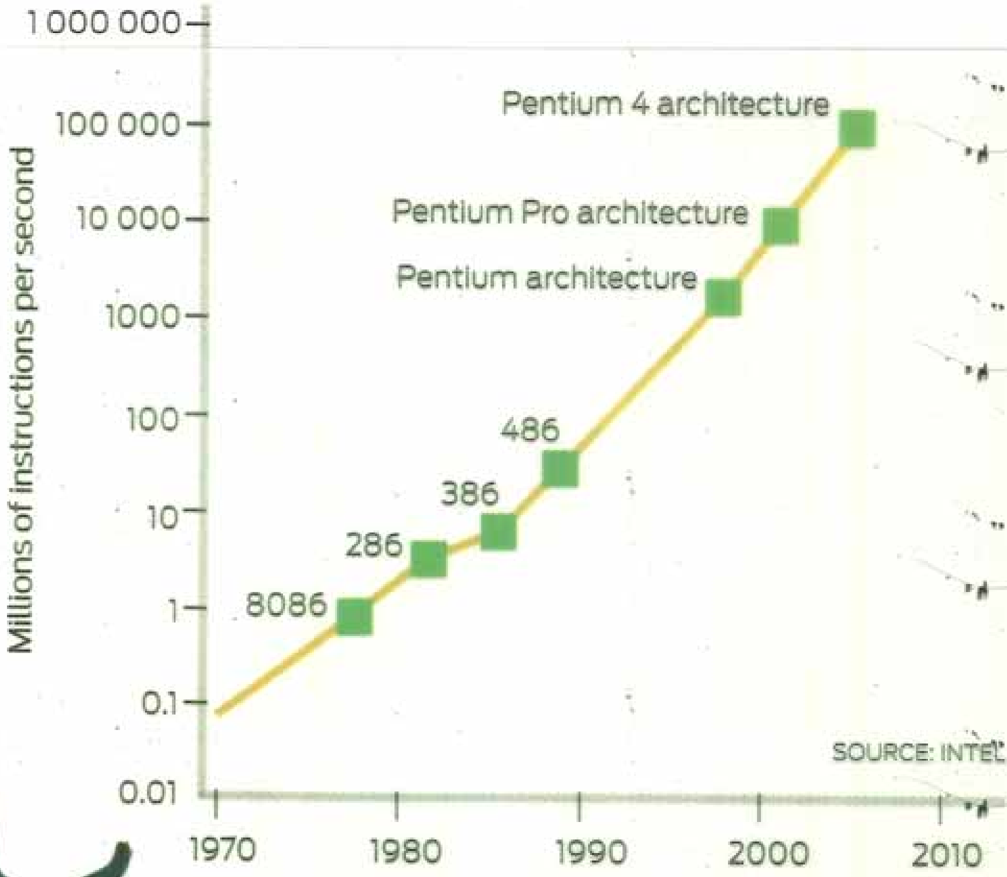
ECE 562

Week 11 Lecture 1

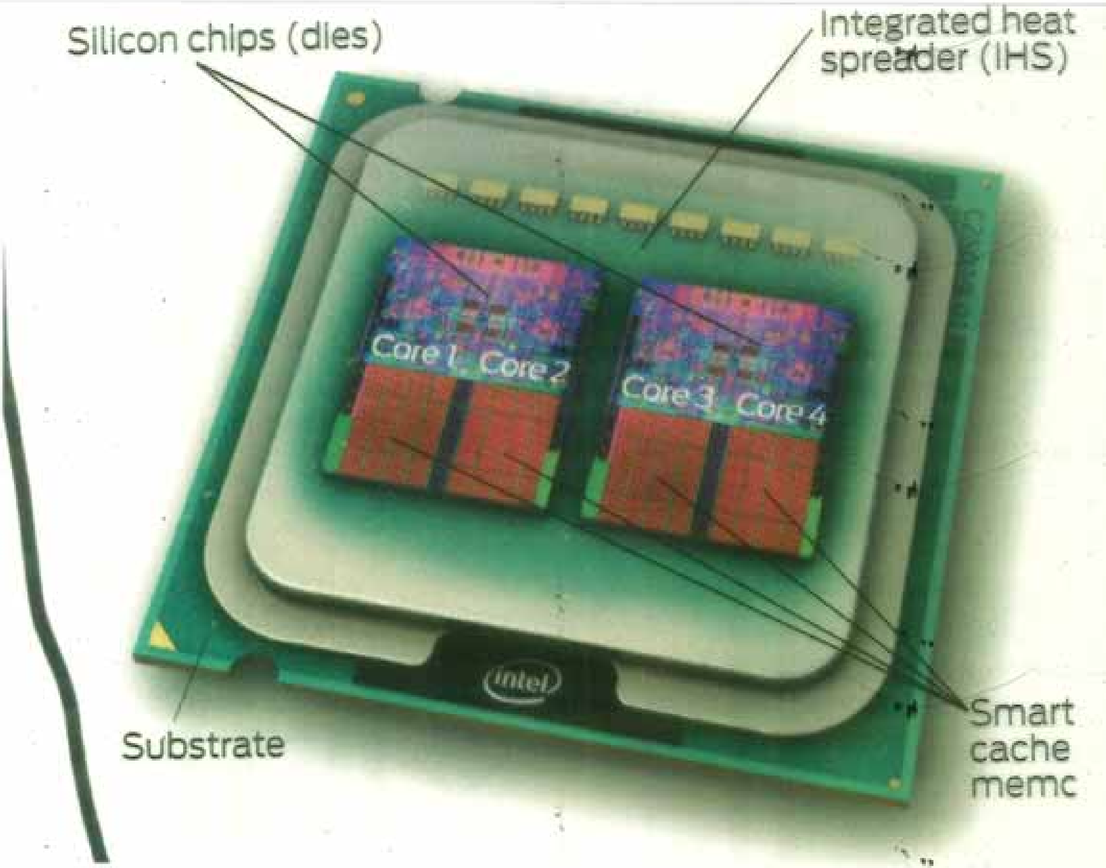
Fall 2008

Week 11 Lecture 1
Summary

Slides	Topic
3-6	Progress in microelectronics
7-11	Resonant converters
12-21	RLC impedance
22-29	Impedance in resonant converters
30-33	DC-DC resonant converters
34-40	Solving for resonant converter
41-45	Fluorescent lamp circuits



Millions of instructions per second
1 000 000
100 000
10 000
1000
100
10
1
0.1
0.01
1970
1980
1990
2000
2010
8086
286
386
486
Pentium architecture
Pentium Pro architecture
Pentium 4 architecture
SOURCE: INTEL



Silicon chips (dies)
Integrated heat spreader (IHS)
Core 1
Core 2
Core 3
Core 4
intel
Substrate
Smart cache memc

'r

s

to-
80
f a
ni-

y's
: a
to

Parallel Paths

Chips with multiple processors to speed computing chores

Supplier/chip	Processors	Typical use
Sun Microsystems/UltraSparc T1	8	Managing Web applications
IBM, Sony, Toshiba/Cell	9	PlayStation 3 game console
Cavium Networks/Octeon	16	Data storage networks
Azul Systems/Vega	48	Accelerating Java software
Intel/Teraflops chip	80	Research
Rapport/KC256	256	Image processing
PicoChip/PC102	302	Wireless communications

Sources: the companies

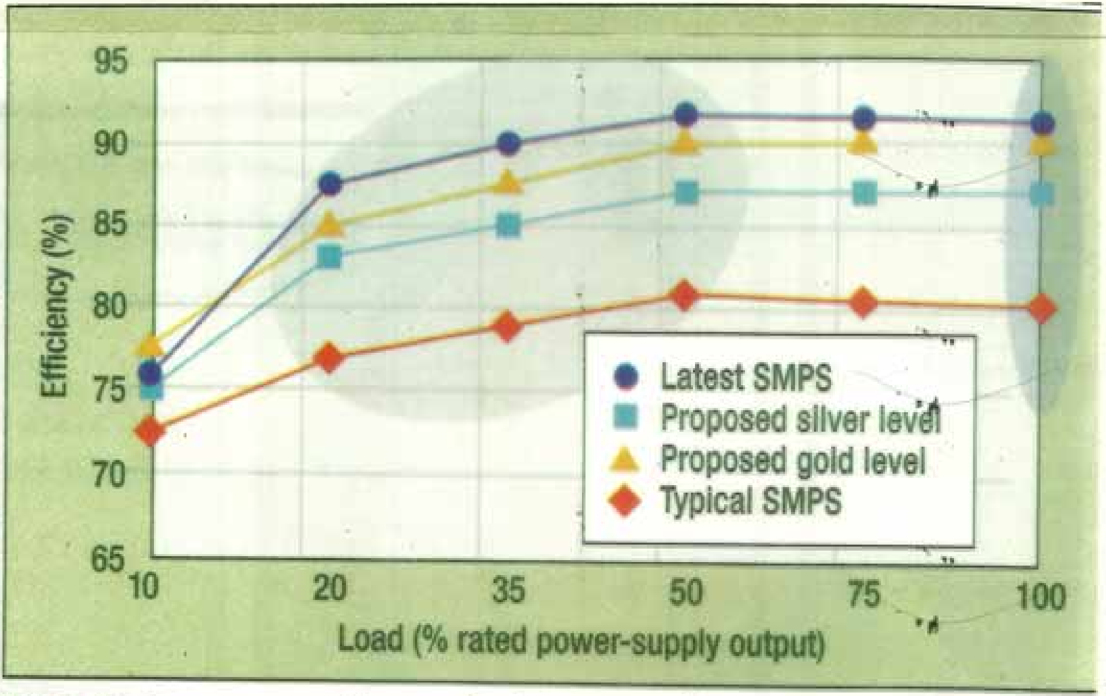


Fig. 1. *In some computing and telecom applications, power supplies are now expected to meet targets for efficiency in the 10% to 50% load range, while still achieving high efficiency at full load.*[1]

Why Resonant Converters?

PWM Converters are limited in efficiency as $f_{sw} \uparrow$ MHz

$$P_{loss} = \left[DC + \begin{matrix}\text{fixed}\\ \text{loss}\end{matrix} \right] + f_{sw} \underline{E_{sw}}$$

Can be trended to zero if:

① Employ ⓐ ZVS zero voltage switching

ⓑ $\begin{pmatrix} ZIS \\ ZCS \end{pmatrix}$ zero current switching

② ① requires changing from □-waves, △-waves, trapezoid-waves

to sinusoids

buck
boost
etc

> 96% efficient

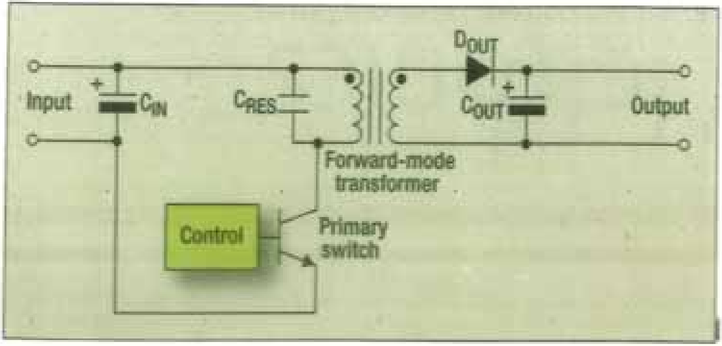


Fig. 1. *Key components of the RDFC resonant topology include a bipolar junction transistor as the primary switch and resonant capacitor (C_{RES}), which resonates with the transformer magnetizing inductance to achieve fully resonant switching.*

Subtle fix to PWM

use (quasi resonant) switching

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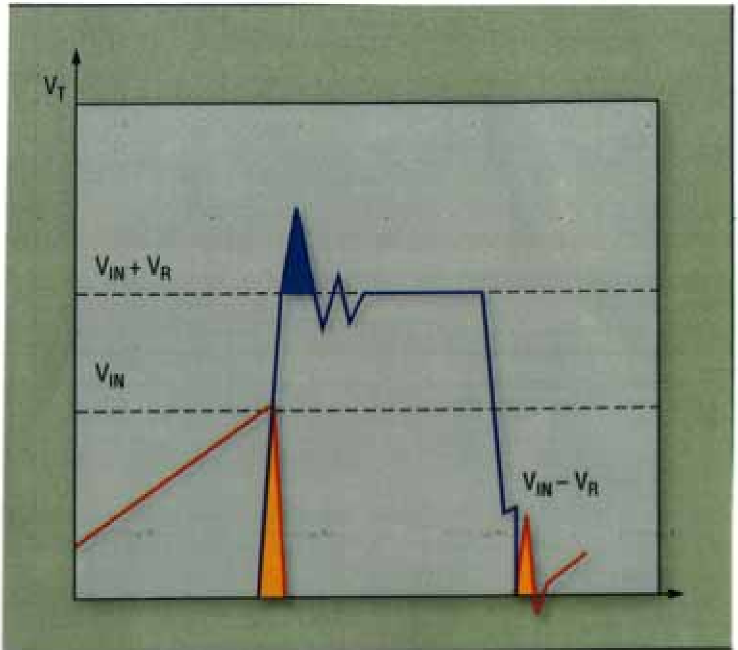


.2. *In a valley switching or quasi-resonant topology, the power tran-*
tor is turned on after leakage-inductance demagnetization, when
rcuit resonance causes a dip in the voltage across the transistor.

the meter's power requirements by up to 10 times, pushing consumption of the meter electronics as high as 20 W.

As mentioned previously, electric-energy metering

frequency	wavelength
60 Hz	5000 km (3107 mi)
3 kHz	100,000 m
30 kHz	10,000 m
300 kHz	1000 m
3 MHz	100 m
30 MHz	10 m
300 MHz	1 m
3 GHz	10 cm
30 GHz	1 cm
300 GHz	0.1 cm

PWM

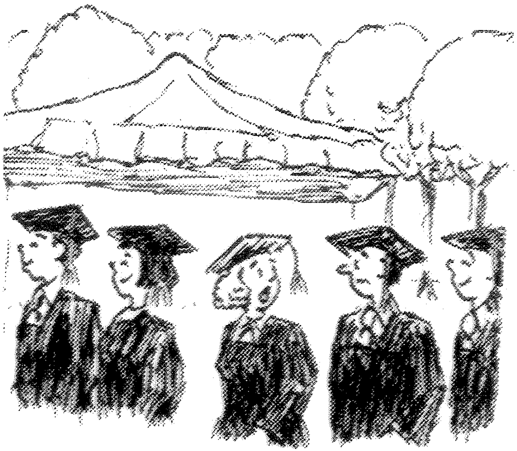
resonant

The electrical dimensions of a device or circuit are determined by comparing physical dimensions to wavelength. A device with length l has electrical dimensions (in wavelengths)

$$d_e = \frac{l}{\lambda},$$

Pepper . . . And Salt

THE WALL STREET JOURNAL



"Another hour and we'll be unemployed."

Graphical Guides: $Z(f)$

Semilog scale vs f

$$\underbrace{\log Z}_{\text{base or per unit employed}} \text{ vs } f \text{ (linear)}$$

$10\Omega \longrightarrow 20\text{ db}$

$\uparrow \times 10$

$1\Omega \longrightarrow 0\text{ db}$

$\downarrow \div 10$

$\frac{1}{10} \longrightarrow -20\text{ db}$

$20 \log \frac{Z}{1} \Rightarrow Z = 1$ is 0 db

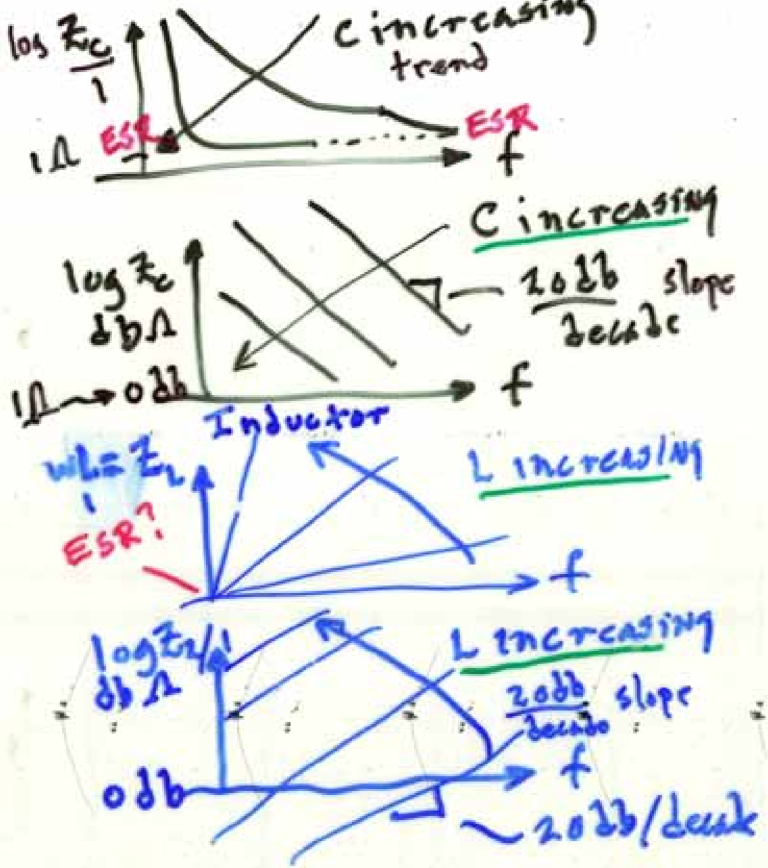
could be $Z = 50$ is 0 db

Recall also the

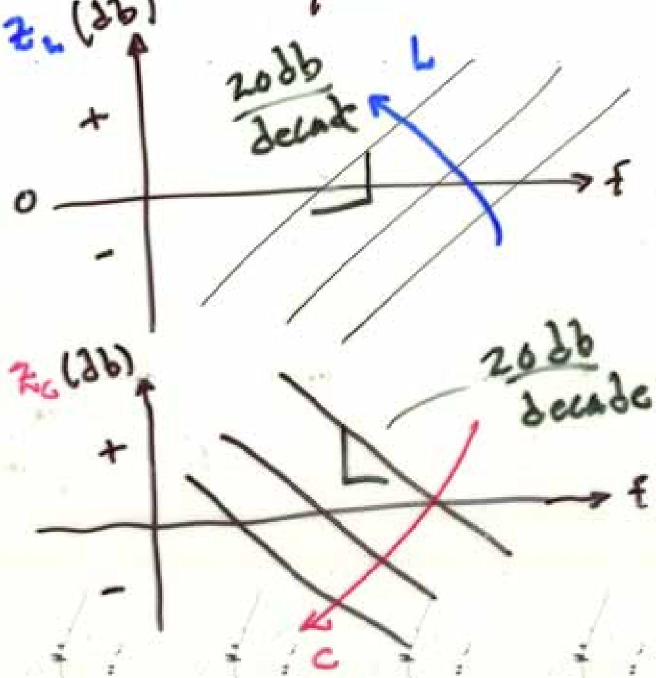
$\pm 3\text{db}$ $\begin{cases} -3\text{db} \longrightarrow .707 \text{ of base} \\ +3\text{db} \longrightarrow \times 1.414 \text{ or } \sqrt{2} \text{ of base} \end{cases}$

$\pm 6\text{db}$ $\begin{cases} -6\text{db} \longrightarrow \frac{1}{2} \text{ of base} \\ +6\text{db} \longrightarrow \times 2 \text{ of base} \end{cases}$

Ultra Basics: $Z_C = \frac{1}{\omega C}$



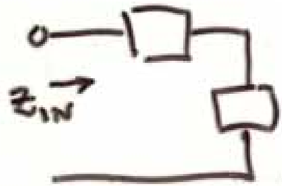
Base impedance could be 50 Ω in rf circuits
μwave



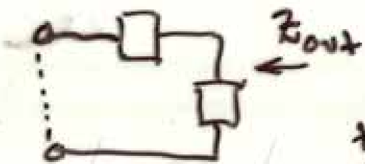
R-C and R-L Circuits

$\underline{Z_R}$ base $\underline{Z_C}$ base $\underline{Z_L}$ base

0 db when $|Z|$ = base



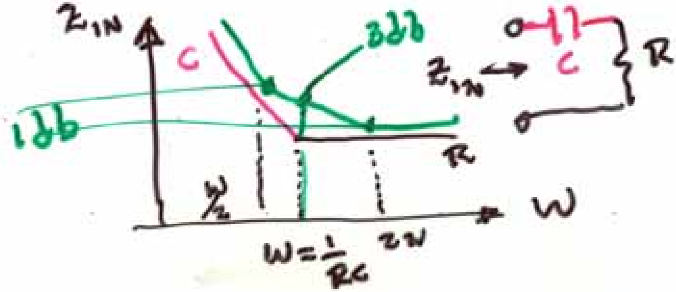
Series case always take the largest at any f



Parallel Case always take the smallest at any f

$Z_R = Z_C \rightarrow R = \frac{1}{WC} \rightarrow W_{RC} = \frac{1}{RC}$

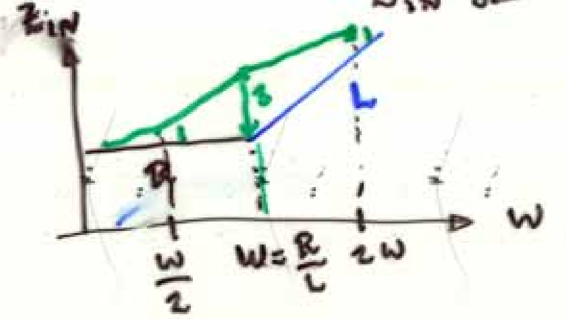
$Z_R = Z_L \rightarrow R = WL \rightarrow W_{RL} = \frac{R}{L}$

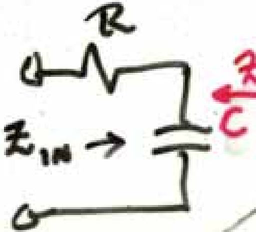


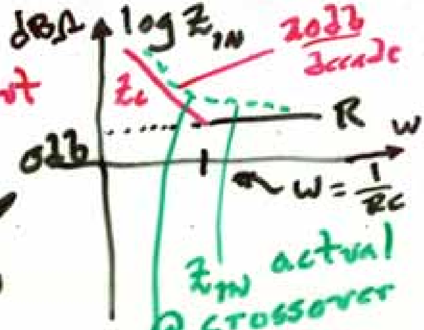
3db point @ w break

1db points @ $2w$, $\frac{w}{2}$

For the circuit







db $\quad Z_{IN}$

0 dbΩ ⟷ 1Ω

20dbΩ ⟷ 10Ω $\quad ω = \frac{1}{RC}$

-20dbΩ ⟷ $\frac{1}{10}$Ω

Series elements take the largest

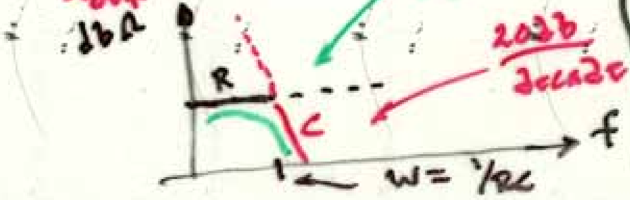
Z_{IN} actual @ crossover 3db higher

Recall from asymptotes

$f = \left.\begin{matrix} 2 f_{cross} \\ \frac{1}{2} f_{cross} \end{matrix}\right\}$ Z_{IN} + 3db from asymptotes

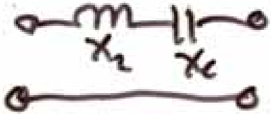
$Z_{out} = R \parallel C$

Z_{out} 3db lower



∥ elements take the smallest

Key Benchmark



Resonance occurs when

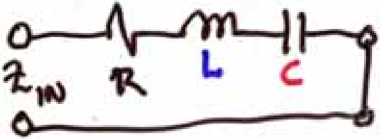
$$X_L = X_C$$

$$f_R = \frac{1}{2\pi\sqrt{LC}}$$

Characteristic Impedance: Z_0

$$Z_0 = X_L(f_R) = X_C(f_R)$$

$$Z_0 = \sqrt{\frac{L}{C}}$$

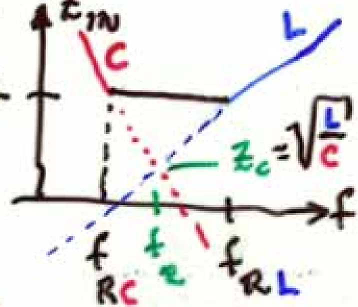


$$Z_{IN} = R + j\omega L - j\frac{1}{\omega C}$$

Always take in series the largest term

$\boxed{\#1 \;\; R > Z_c}$

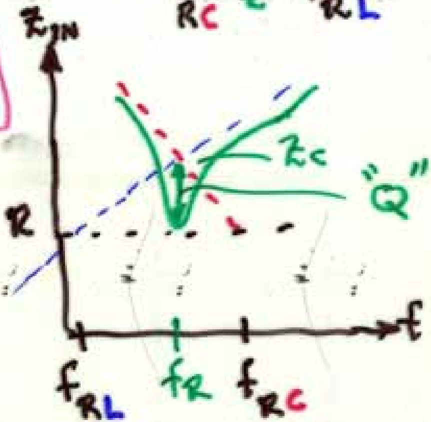
$$f_{RC} < f_R < f_{RL}$$



$\boxed{\#2 \;\; R < Z_c}$

$$f_{RL} < f_R < f_{RC}$$

$$Q \equiv \frac{Z_c}{R}$$



Q'ing Up of a circuit

depends on:

1) Circuit Topology

2) $|Z_C|$ vs R

3) $Q \sim \frac{Z_C}{R}$ Series L-R-C

$Q \sim \frac{R}{Z_C}$ Parallel R-L-C

Insight

$I_{IN} = \frac{V_{IN}}{Z_{IN}}$

Z_{IN} minimum @ f_R

$V_0 = I_{IN} X_C$

V_{out} maximum @ f_R

Chapter 19

Resonant Conversion

Introduction

crawling but insightful for "general trends"

19.1 Sinusoidal analysis of resonant converters

$\frac{V_{out}}{V_{in}}(f)$, sizing of L, C

range of V_{out}, i_{tank}

19.2 Examples

Series resonant converter

Parallel resonant converter

19.3 Exact characteristics of the series and parallel resonant converters

19.4 Soft switching

Zero current switching

Zero voltage switching

The zero voltage transition converter

19.5 Load-dependent properties of resonant converters

Suprise for Novice $R_L \rightarrow \infty$ $i_{sw} \uparrow$

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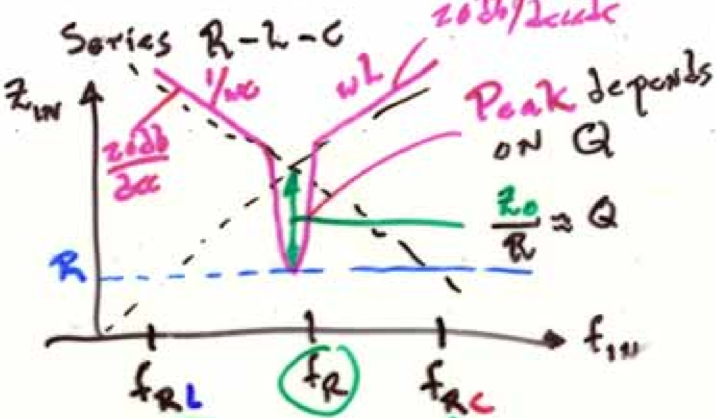
19.5 Load-dependent properties of resonant converters

Resonant circuits display $Q(R_L)$

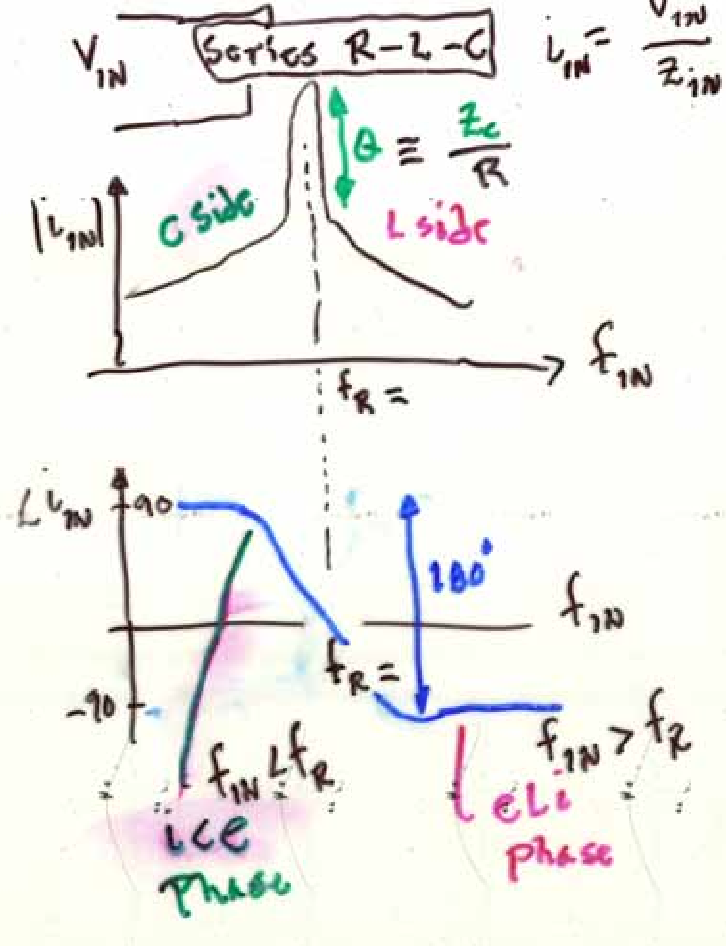


$Z_0 = \sqrt{\frac{L}{C}}$ Choices for L, C

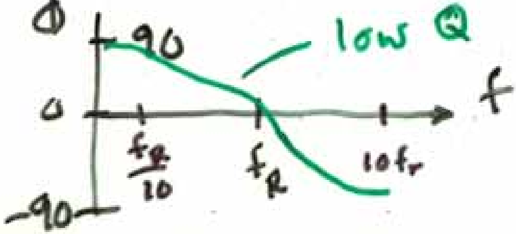
R is series resistance

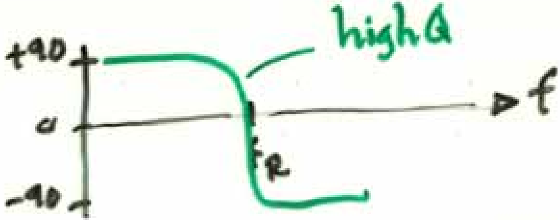
$$R = R_L + \underbrace{R_L(ESR) + R_C(ESR)}_{\text{limits } Q_{max}}$$

$Z_{in}(f_R) = R$



V_{IN}
Series R-L-C
$i_{IN} = \frac{V_{IN}}{Z_{IN}}$
$Q \equiv \frac{Z_c}{R}$
$|i_{IN}|$
C side
L side
f_{IN}
$f_R =$
$\angle i_{IN}$
90
-90
180°
f_{IN}
$f_R =$
$f_{IN} < f_R$
$f_{IN} > f_R$
ICE
Phase
ELI
Phase



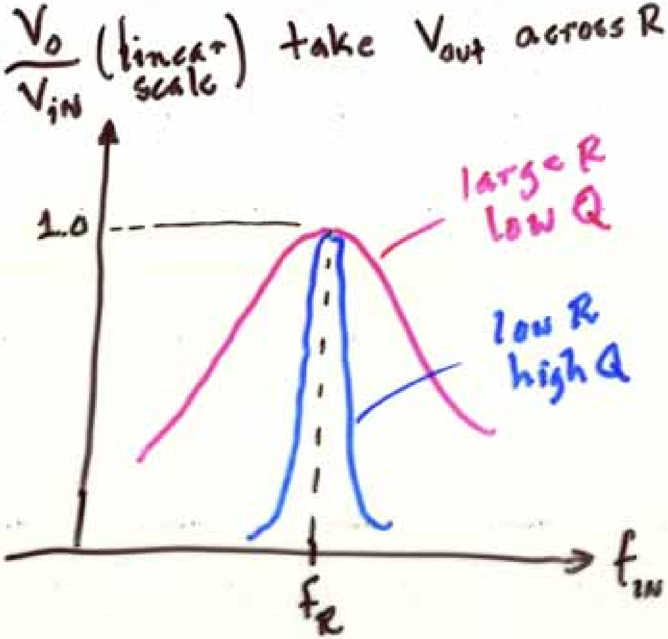


Slope of phase $\frac{-180^\circ Q}{\text{decade}}$

$Q = \frac{1}{2}$ $\frac{180^\circ \text{ change}}{\text{two decades}}$

$Q = 1$ $\frac{180^\circ \text{ change}}{\text{decade}}$

$Q = 5$ $\frac{180^\circ \text{ change}}{\text{octave}}$



$f_{IN} \neq f_R$ Buck Circuit

In resonant converters:

$\frac{V_o(f)}{V_{IN}(f)}$ set by f choice

VCO for feedback!

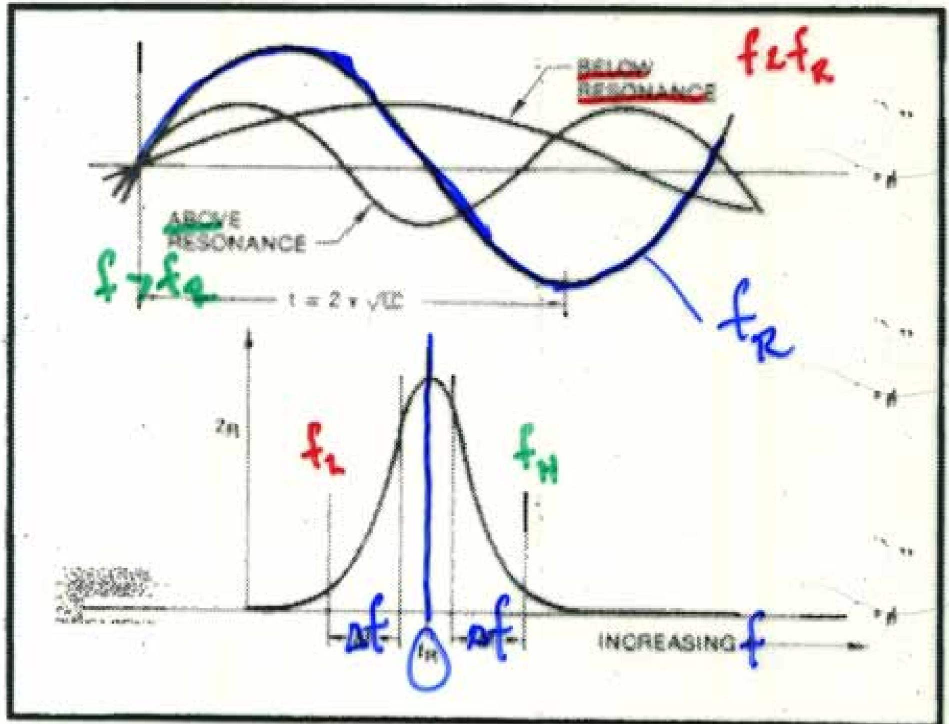
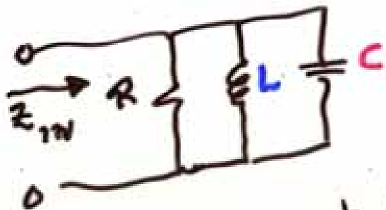


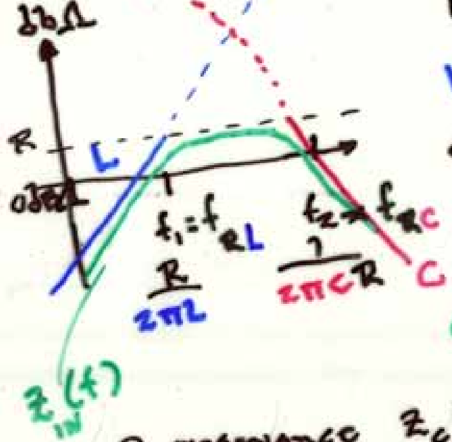
Fig. 11 - Variable Frequency Continuous Resonance

Parallel Resonant Circuit

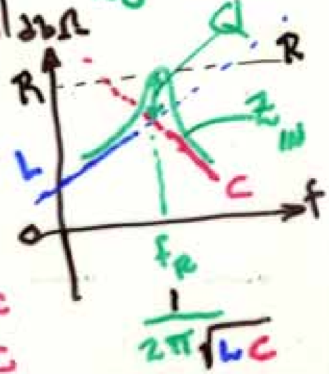


Two cases: R w.r.t. Z_c

$Z_c > R$



$Z_c < R$

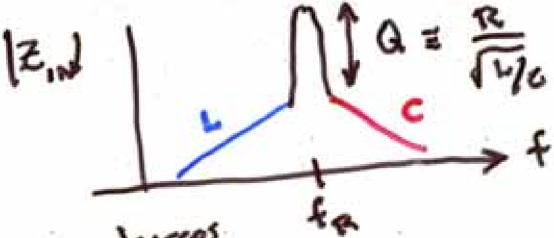


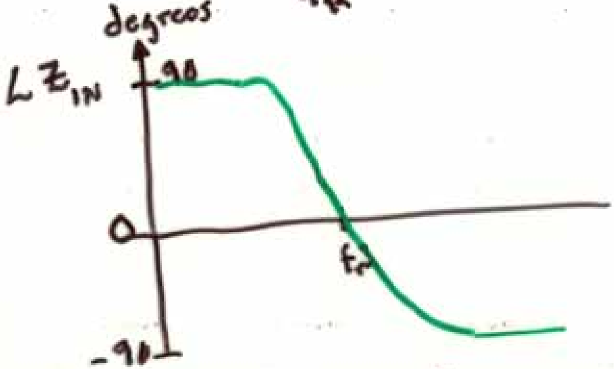
$Q = \frac{R}{Z_c}$

@ resonance $Z_c \parallel Z_L = \frac{Z_c Z_L}{Z_c - Z_L} \to \infty$

$\Rightarrow Z_{IN} = R \parallel \infty = R$

$V_{out} = V_{IN}$ for all f BUT

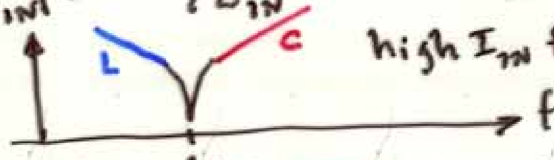


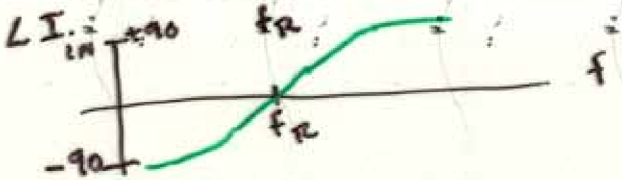


$|I_{IN}| = V_{IN}/Z_{IN}$

low I_{IN} @ f_R

high I_{IN} $f \neq f_R$



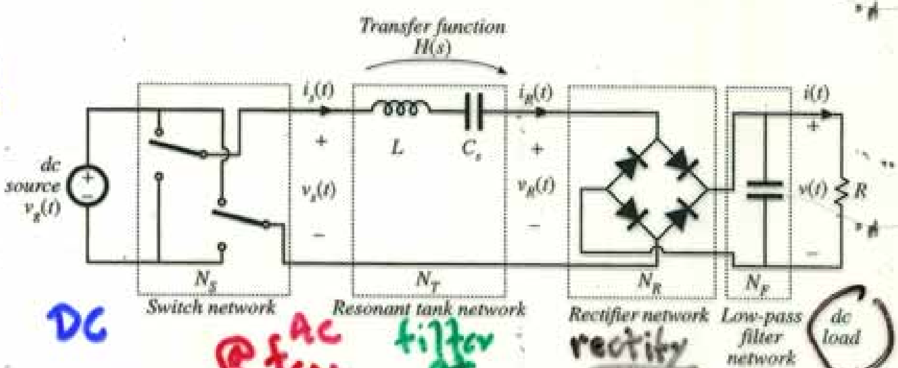


DC → DC

Derivation of a resonant dc-dc converter

Rectify and filter the output of a dc-high-frequency-ac inverter

rectified mains



DC

@ f_{sw} AC

filter at f_R

rectify AC to DC

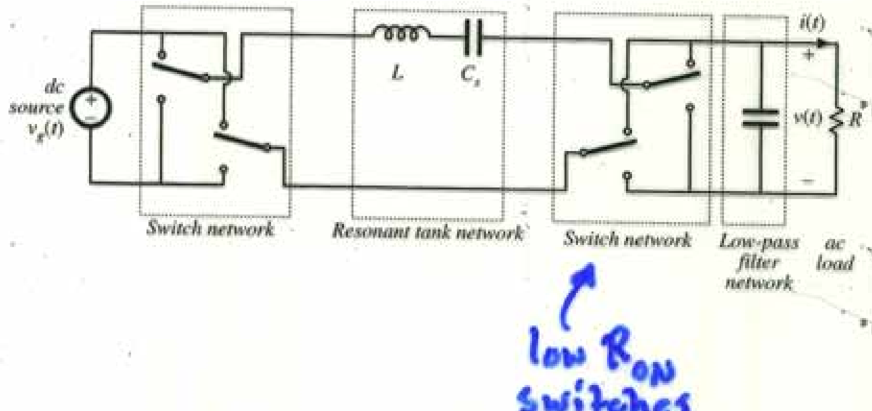
The series resonant dc-dc converter

if V_{out}^{DC} is low diodes.. ok?

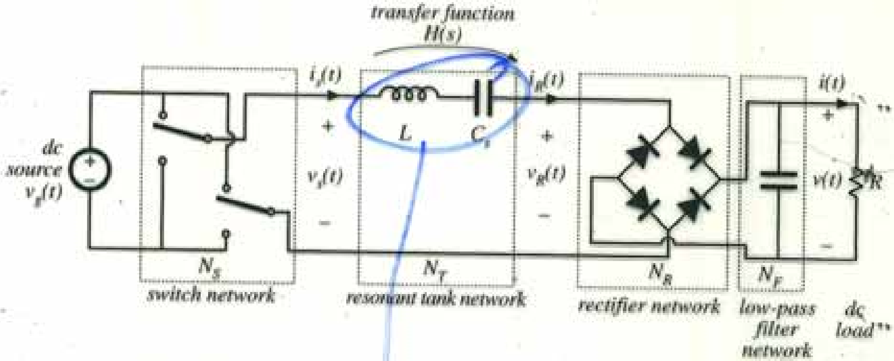
Solve diode loss for low V_{OUT}

A series resonant link inverter

Same as dc-dc series resonant converter, except output rectifiers are replaced with four-quadrant switches:



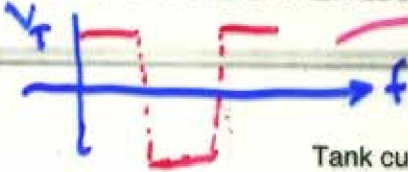
19.2 Examples
19.2.1 Series resonant converter

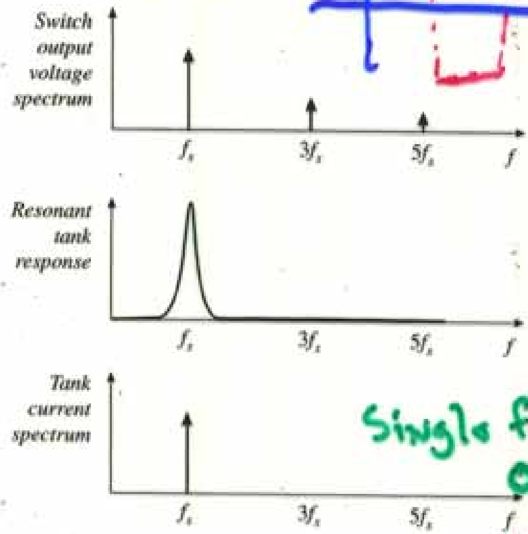


$$f_R = \frac{1}{2\pi\sqrt{LC}}$$

Tank network responds only to fundamental component of switched waveforms

□ - wave @ f_s





Tank current and output voltage are essentially sinusoids at the switching frequency f_s.

Output can be controlled by variation of switching frequency, closer to or away from the tank resonant frequency

Single frequency i @ f_R only if series R-L-C is high Q

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Power Electronics 3

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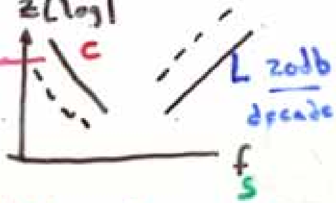
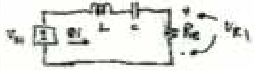


20db/decade

20db/decade

Up

Page 1



$H(s) = \frac{v_{R1}(s)}{v_{S1}(s)}$

Plot $|H|$

$Z_i(s) = sL + \frac{1}{sC} + R_e$

$H(s) = \frac{R_e}{Z_i(s)}$

$|Z_C| = \frac{1}{\omega C}$

$|Z_L| = \omega L$

$Z_C = Z_L$ @ $\omega_R = \frac{1}{\sqrt{LC}}$

$|Z_C| = |Z_L|$ @ ω_R

$= Z_0 = \sqrt{\frac{L}{C}}$

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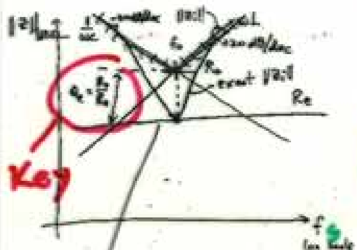

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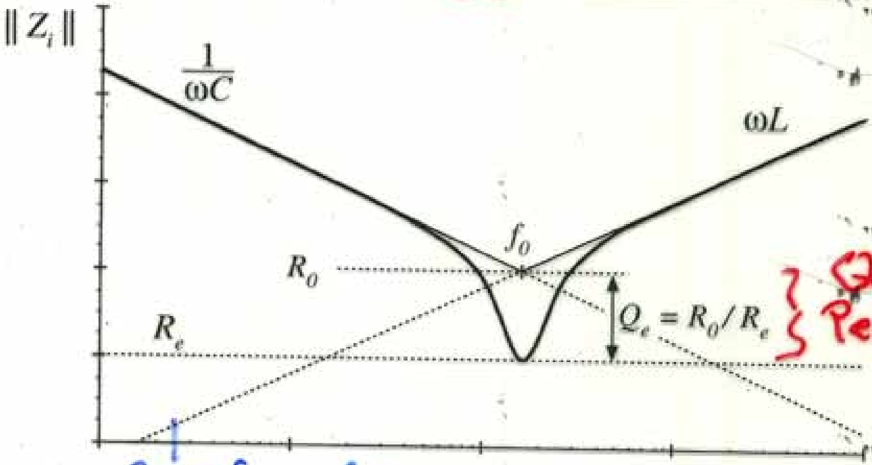
Case: $R_e < Z_0$

$Z_i(\omega_R) = ?$

$R_0 = \sqrt{L/C}$

Construction of Z_i

Series R-L-C: $Z_i = sL + \frac{1}{sC} + R_e$



Q Peaking

$f_{sw} = \frac{f_0}{3}$, $f_0/5$
resonance

both missing

In case of □-wave V_{IN} will appear

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at f_0: $\quad \omega_0 = 2\pi f_0$

$R_0 = \frac{1}{\omega_0 C} = \omega_0 L \Rightarrow \omega_0^2 = \frac{1}{LC}$

$= \sqrt{\frac{L}{C}} \qquad \Rightarrow \omega_0 = \frac{1}{\sqrt{LC}}$

Exact $\|Z_i\|$

at $\omega = \omega_0$

$Z_i(j\omega_0) = j\underbrace{\omega_0 L}_{=R_0} + \frac{1}{j\underbrace{\omega_0 C}_{\frac{1}{\omega_0 C} = R_0}} + R_e = \cancel{jR_0} + \frac{R_0 j}{j^2} + R_e$

$= R_e$

Z_C cancels Z_L

$V_R / V_{IN} = \frac{R_e}{Z_i} = M = \frac{V_{out}}{V_{sig}}$

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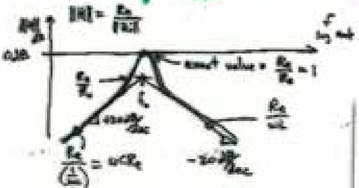

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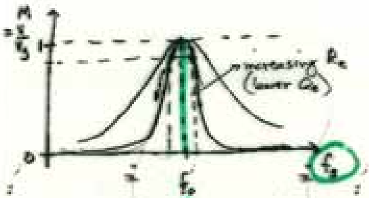

f_R

Z_L

$Q = \frac{Z_0}{R} = \frac{\sqrt{\frac{L}{C}}}{R}$

$Q = \frac{\frac{1}{\omega_R C}}{R} \qquad \frac{\sqrt{\frac{L}{C}}}{R}$

$= \frac{1}{\omega_R C R}$

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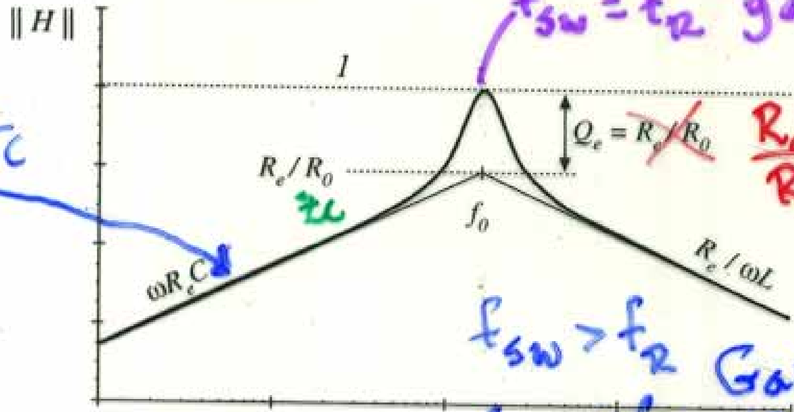
Define $\frac{f_s}{f_R} = F$

$H_{dB} = |R_e|_{dB} - |Z_i|_{dB}$

Construction of $H = \frac{R_e}{Z_i}$

$f_{sw} = f_R$ gain of 1

$\frac{R_e}{Z_c} \sim \frac{R_e}{1/\omega C}$



odd $\frac{R_0}{R_e} \leftarrow Z_c$

$f_{sw} > f_R$ Gain < 1

$f_{sw} < f_R$ Buck

$R_{load} \rightarrow \infty$ Gives DCM which is not predicted by simple sine analysis

$R_{load} \rightarrow \infty \Rightarrow$ low Q assumption violated need harmonics for validity

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Equation of M vs F

$M = \frac{V}{V_g}$ $F = \frac{f_s 2\pi}{f_o 2\pi} = \frac{\omega_s}{\omega_o}$

$M = \| H(j\omega_s) \|$ $\omega_s = 2\pi f_s$

$H(j\omega_s) = \frac{R_e}{j\omega_s L + \frac{1}{j\omega_s C} + R_e}$ $\omega_o = \frac{1}{\sqrt{LC}}$

$= \frac{V_o}{V_{signal}}$

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$= \frac{j\omega_s C R_e}{(j\omega_s L)(j\omega_s C) + 1 + j\omega_s C R_e}$

$= \frac{j\omega_s C R_e}{1 + \underbrace{j\omega_s C R_e}_{= j\frac{F}{Q_e}} - \underbrace{\omega_s^2 LC}_{\frac{\omega_s^2}{\omega_o^2} = F^2}}$

$\frac{V_o}{V_s} = f(F, Q)$

$\omega_0 = \omega_R$ $\frac{1}{\sqrt{LC}}$

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$Q_e = \frac{R_o}{R_e} = \frac{1}{\omega_o C R_e}$

$R_0 = \sqrt{L/C}$

$\omega_0 = \frac{1}{\sqrt{LC}}$

$Q = \frac{\omega_R \sqrt{L/C}}{\omega_R R} = \frac{1}{\omega_R C R}$

$\Rightarrow C = \frac{1}{\omega_o R_e Q_e}$

so $j\omega_s C R_e = \frac{j\omega_s R_e}{\omega_o R_e Q_e} = j\frac{\omega_s}{\omega_o}\frac{1}{Q_e}$

$= j\frac{F}{Q_e}$

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$j\frac{F}{Q}$

$$H(j\omega_s) = \frac{j\frac{F}{Q_e}}{1-F^2+j\frac{F}{Q_e}}$$

$$M = \|H(j\omega_s)\| = \frac{\|j\frac{F}{Q_e}\|}{\|1-F^2+j\frac{F}{Q_e}\|}$$

$$= \frac{\left(\frac{F}{Q_e}\right)}{\sqrt{(1-F^2)^2+\left(\frac{F}{Q_e}\right)^2}}$$

$\frac{V_{out}}{V_{IN}}$

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$$M = \frac{1}{\sqrt{1+\frac{Q_e^2}{F^2}(1-F^2)^2}}$$

$$M = \frac{1}{\sqrt{1+Q_e^2\left(\frac{1}{F}-F\right)^2}}$$

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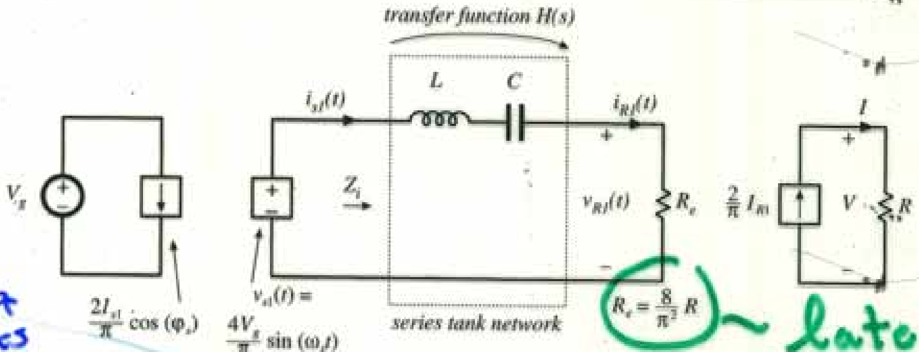
Model: series resonant converter



later rectifer effects

Circuit Element Changes

$$H(s) = \frac{R_e}{Z_i(s)} = \frac{R_e}{R_e + sL + \frac{1}{sC}}$$

Std. form

$$= \frac{\left(\frac{s}{Q_e \omega_0}\right)}{1 + \left(\frac{s}{Q_e \omega_0}\right) + \left(\frac{s}{\omega_0}\right)^2}$$

$$\omega_0 = \frac{1}{\sqrt{LC}} = 2\pi f_0$$

$$R_0 = \sqrt{\frac{L}{C}}$$

$$Q_e = \frac{R_0}{R_e}$$

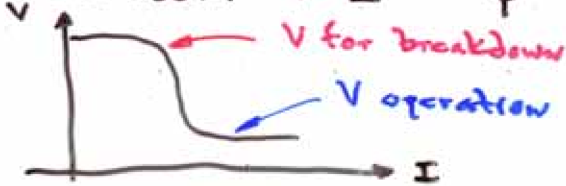
Series L-C only

$R\downarrow Q\uparrow$

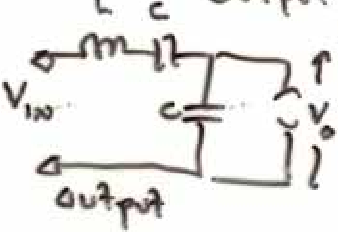
$$M = \left| H(j\omega_s) \right| = \frac{1}{\sqrt{1 + Q_e^2 \left(\frac{1}{F} - F\right)^2}}$$

$Q_e = \frac{\omega_0 L}{R_e} = \frac{1}{\omega_0 C R_e}$

Flouresent V-I



Big X_e works
How?
Why?

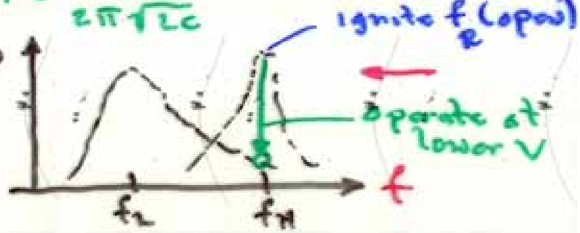


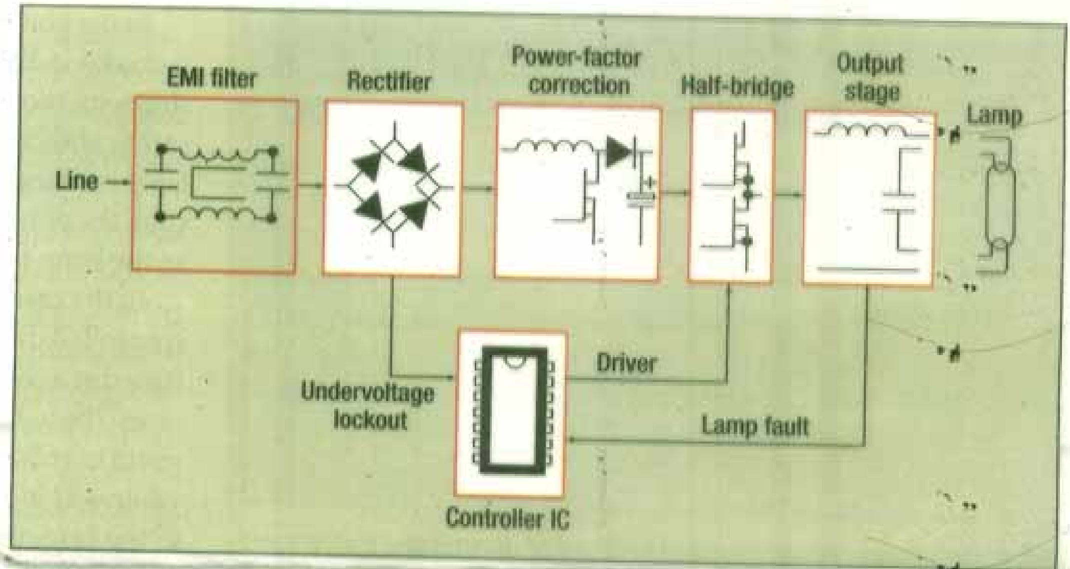
$$f_R(\text{open}) = \frac{1}{2\pi\sqrt{LC_{eff}}}$$

$$\frac{1}{C_{eff}} = \frac{1}{C} + \frac{1}{C}$$

$$C_{eff} \approx C/2$$

$$f(\text{short}) = \frac{1}{2\pi\sqrt{LC}}$$




EMI filter
Rectifier
Power-factor correction
Half-bridge
Output stage
Lamp
Line
Driver
Undervoltage lockout
Lamp fault
Controller IC

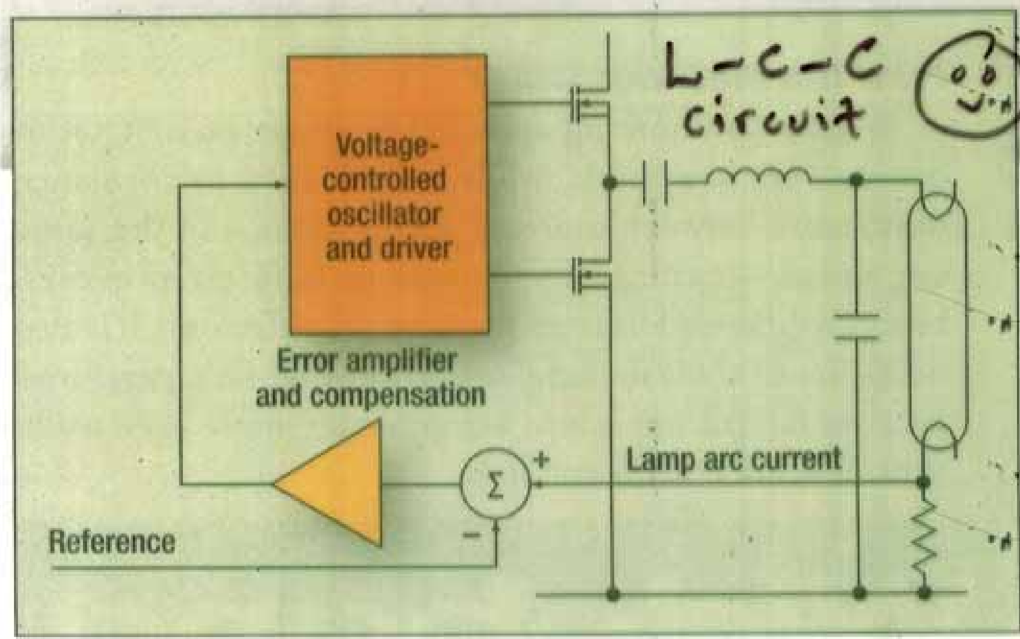
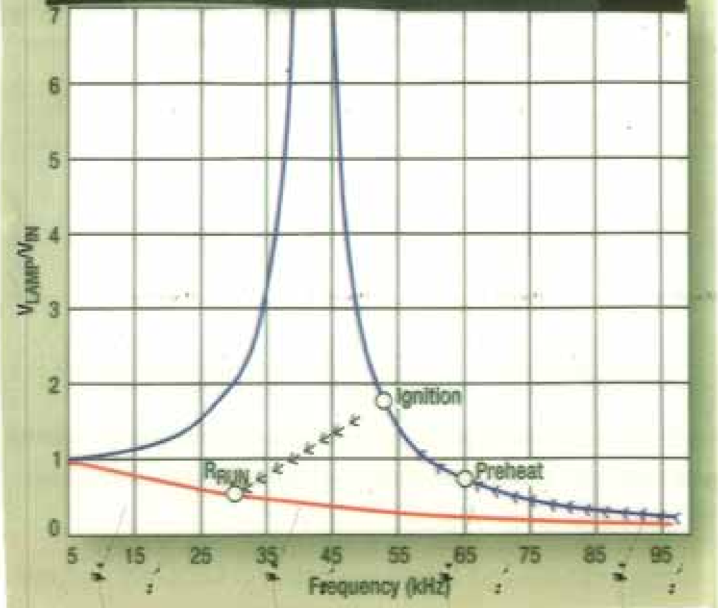


Fig. 3. *The analog arc-current control method of dimming a fluorescent lamp's ballast using frequency modulation is generally simpler than the digital approach.*

Fig. 1. Dimming fluorescent-lamp ballasts is commonly done by controlling the lamp power by modulating the frequency of the switched dc bus. Results shown here are for single-lamp voltage-mode heating, 90-Vac to 265-Vac input, 500-Vdc output, TC-T 32 W lamp, L = 4.30 mH and C = 3.3 nF.



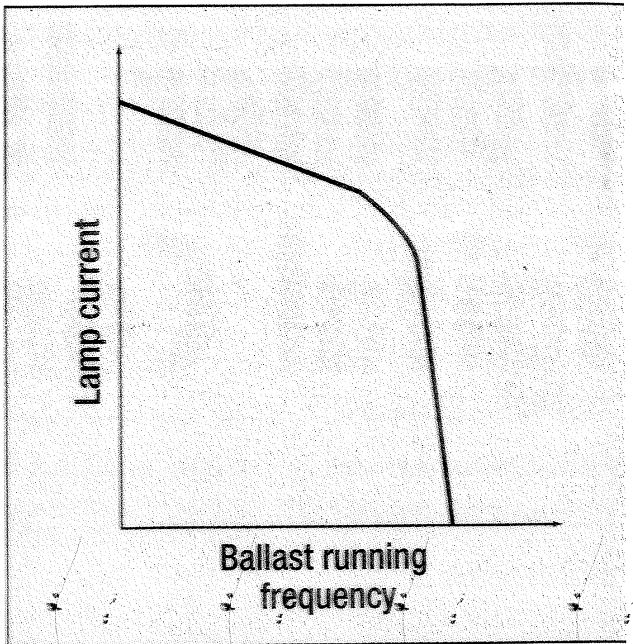


Fig. 7. *The increasing frequency of a fluorescent lamp's ballast sharply*