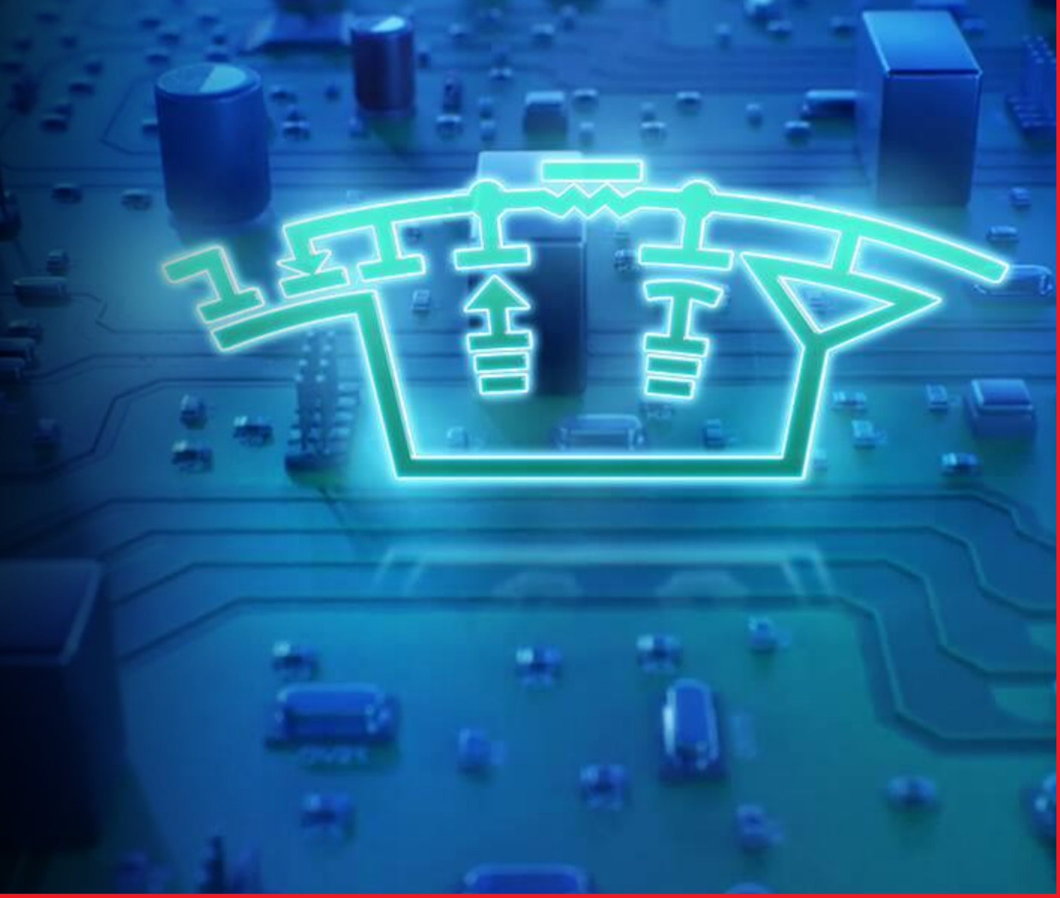
Power Supply Design Seminar

Survey of Resonant Converter Topologies



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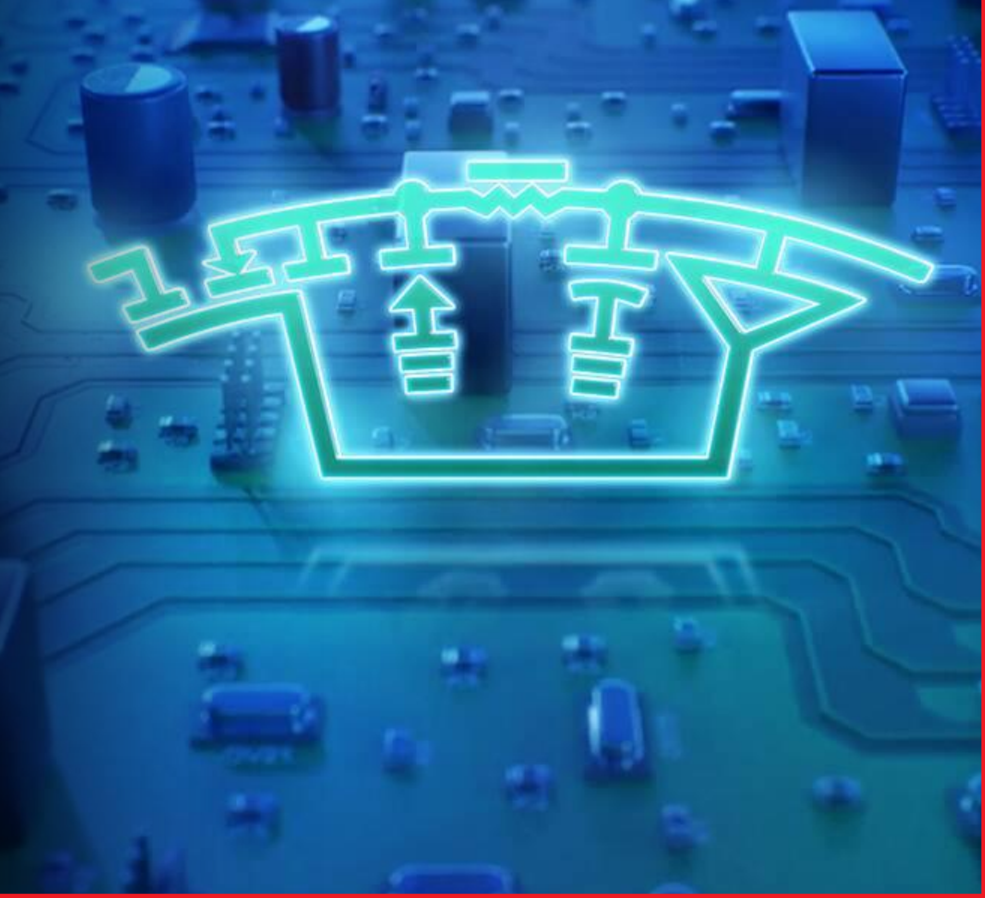
Agenda

Introduction

Feature presentation

Live Q&A session

Enter questions into chat at any time



2025 Power Supply Design Seminar

Texas Instruments

Webinar Series

April 30	Common mistakes in DC/DC converters and how to fix them
May 28	Survey of resonant converter topologies
June 25	Power Factor Correction (PFC) circuit basics
July 30	Power-conversion techniques for complying with automotive emissions requirements
August 27	Switch-mode power converter compensation made easy
September 24	Constructing your power supply – layout considerations

Last Wednesday of every month
8:00AM & 8:00PM (US Central Time Zone)

Welcome to the PSDS 2025 webinar series!

Texas Instruments

The history of Power Supply Design Seminar

- In 1977 Bob Mammano, the "Father of PWM Industry," started the seminar
- 47+ years
- 26+ seminars
- 100+ technical topics
- 50,000+ customers
- A comprehensive archive of white papers, presentations and videos

Power supply industry legends associated with PSDS:
Bob Mammano, Lloyd Dixon, Bill Andreycak, Robert Kollman, Laszlo Balogh

WWW.TI.COM/PSDS for all prior content

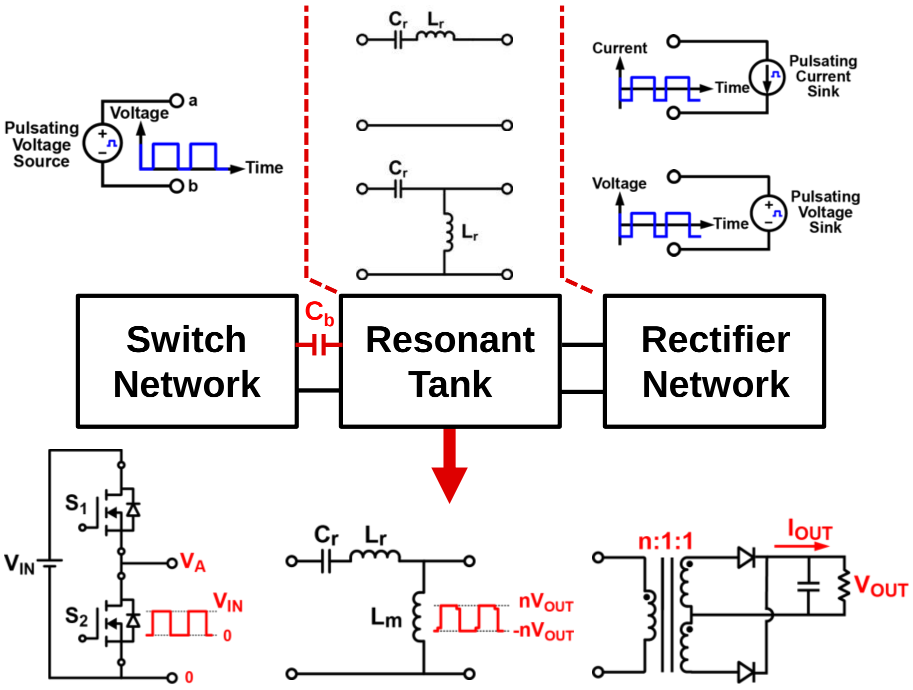
Agenda

- 2- and 3-element resonant topologies fundamentals
- LLC series resonant converter (LLC-SRC) introduction and design example
- Resonant converters for wide input/output voltage range
- Resonant converter variations
- Resonant converter design challenges
- Effects of real life parasitics/parameters
- Resonant converter selection guide – rule of thumb

2- and 3-Element Resonant Topologies Fundamentals

Classical Resonant Topology Structure

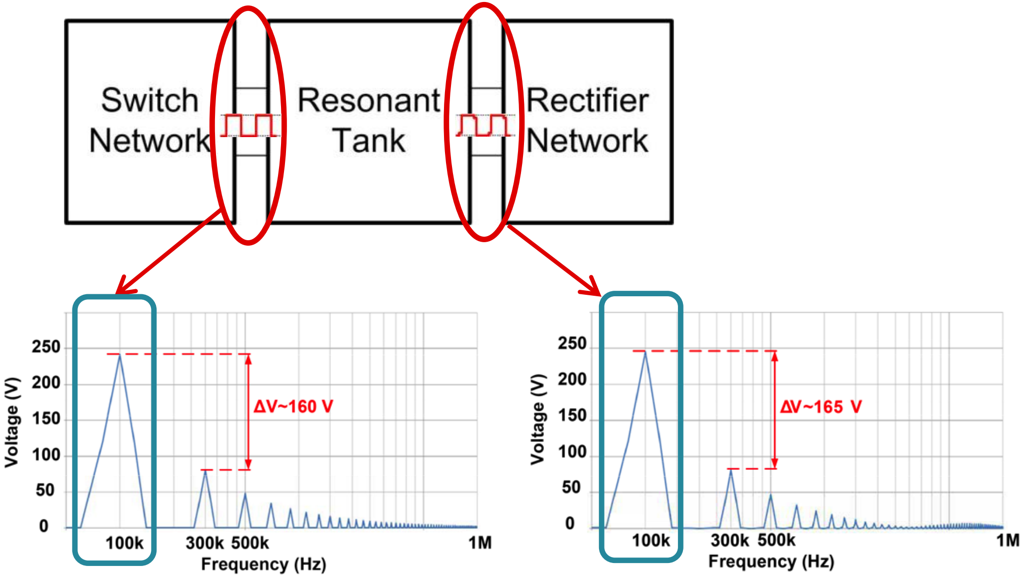
- Why?
  - Possible soft-switching over entire load range
- Structure
  - Switch network
  - Resonant tank
  - Rectifier network
- Assumptions
  - Variable frequency control (VFC)
  - Consider only switch network with **pulsating voltage output**



LLC Series Resonant Converter

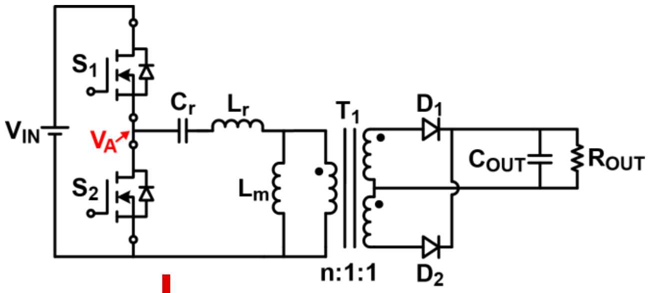
Resonant Topology Analysis

Fundamental harmonic analysis (FHA)
(or so called sinusoidal approximation)

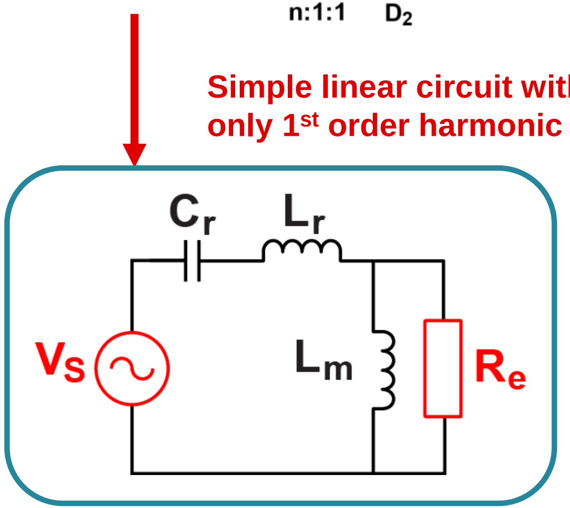


FFT of a Square Wave

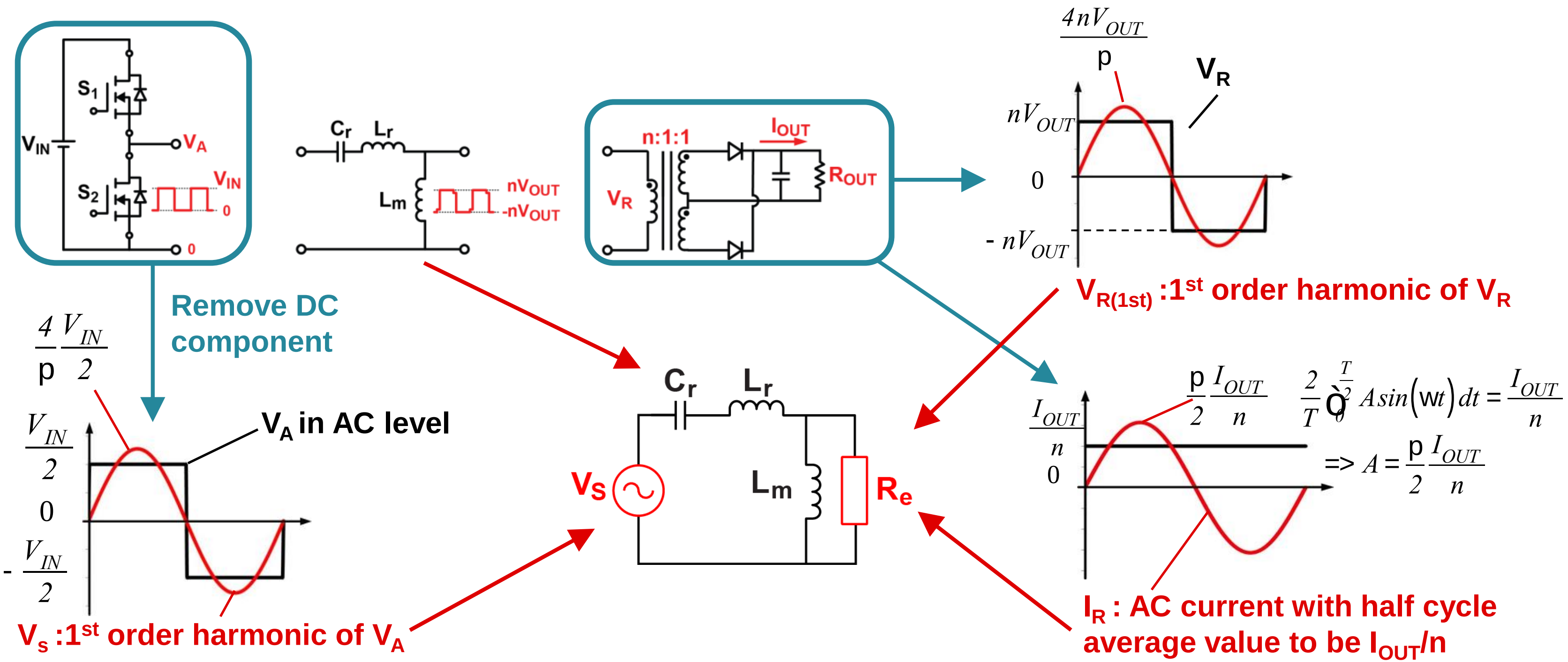
FFT of Resonant Tank Response



Simple linear circuit with only 1st order harmonic



Circuit Linearization Example: LLC–SRC

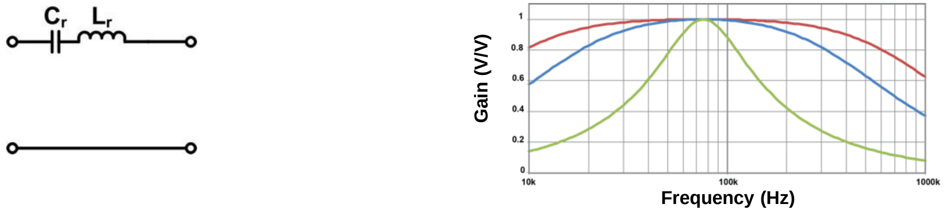


$$V_s(t) = \frac{4(V_{IN}/2)}{\pi} \sin(\omega_s t)$$

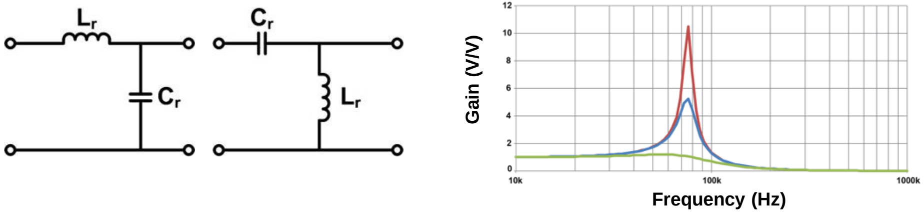
$$R_e = \frac{V_{R(1st)}(t)}{I_R(t)} = \frac{8n^2}{\pi^2}\frac{V_{OUT}}{I_{OUT}} = \frac{8n^2}{\pi^2} R_{OUT}$$

Fundamental Resonant Elements

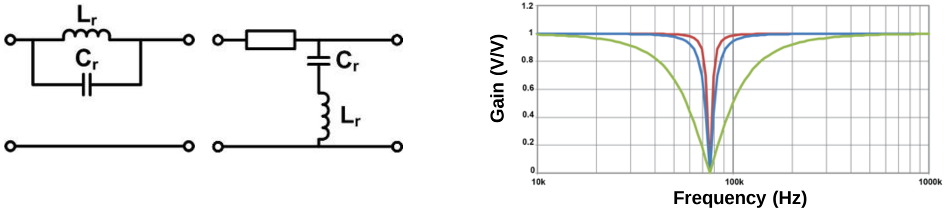
Series Resonance (SR) – Provides "Buck" Function

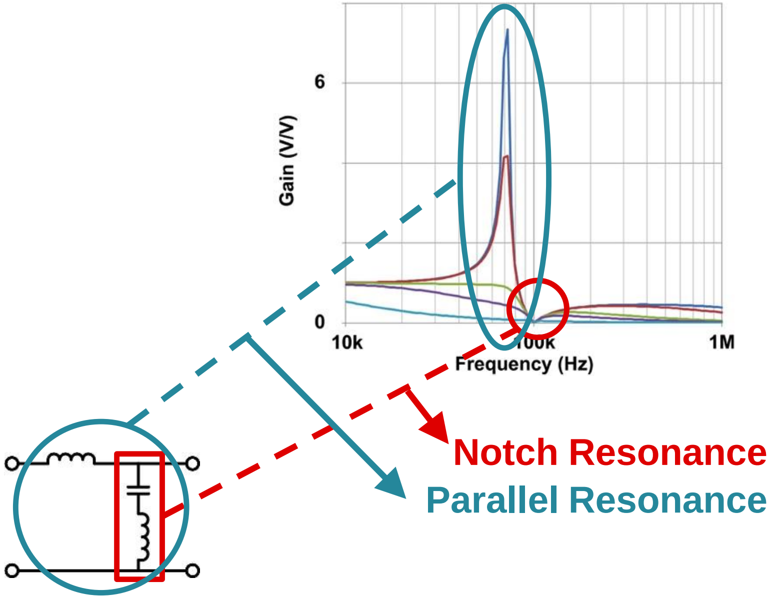


Parallel Resonance (PR) – Provides "Boost" Function



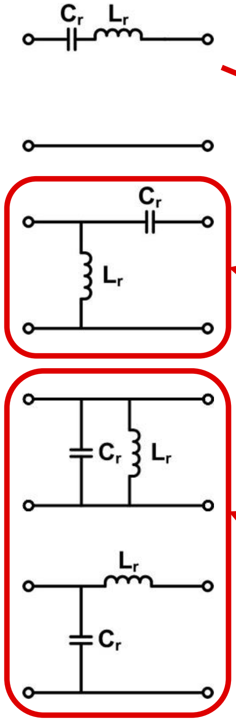
Notch Resonance (NR) – Zero Gain at f_r

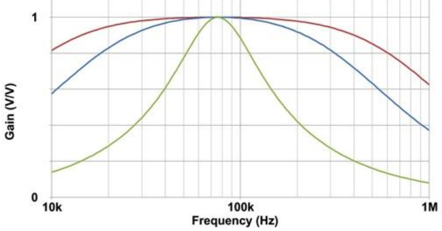




2-Element Soft-Switching Resonant Topologies

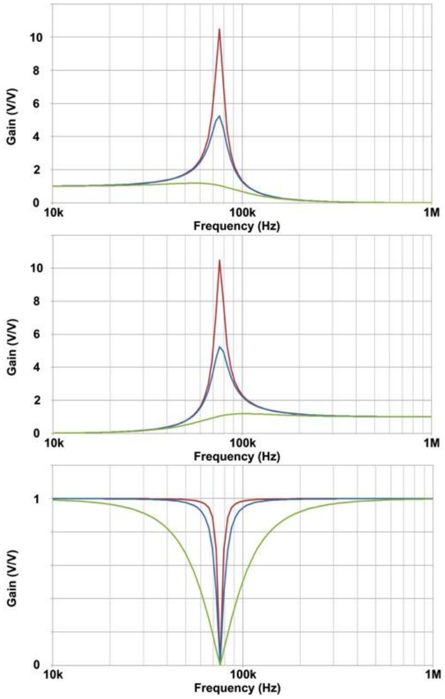
Input/output voltage gain (w/ sinusoidal voltage input)

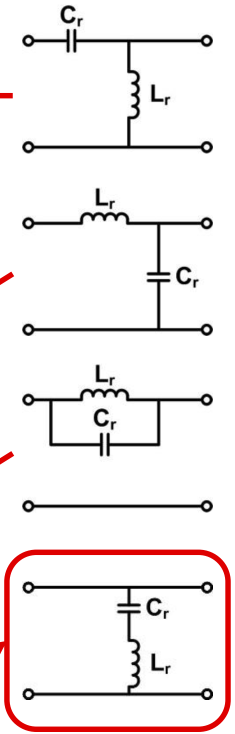




Inductor voltage clamped
- not resonant

Requires current source

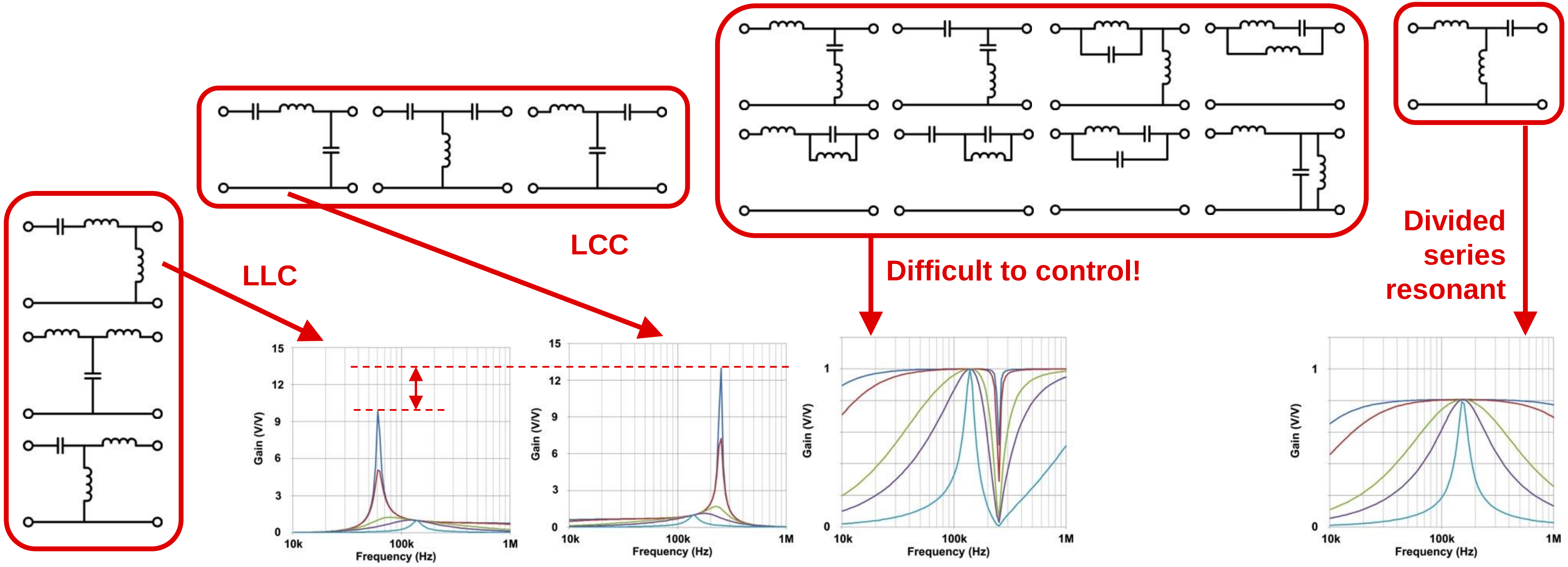




Lack of voltage regulation capability

3-Element Soft-Switching Resonant Topologies

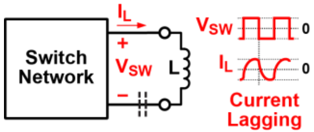
- 36 possible resonant tanks, 23 could be used with voltage source
- **15** of the 23 have all resonant elements participate in output voltage/current regulation

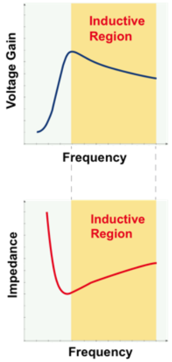


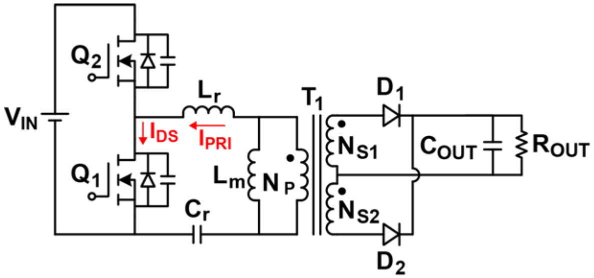
How to Achieve Soft-Switching?

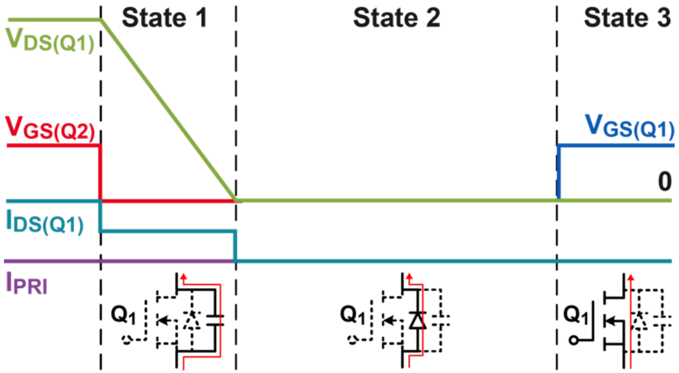
Necessary and sufficient soft-switching conditions:

1. Inductive input impedance
2. Sufficient energy inside resonant tank for discharging/charging output capacitor of switches in switching network $$LI_L^2 > C_{TOTAL}V_{SW}^2 = 2C_{OSS}V_{SW}^2$$
3. Enough dead-time between switches inside switch network







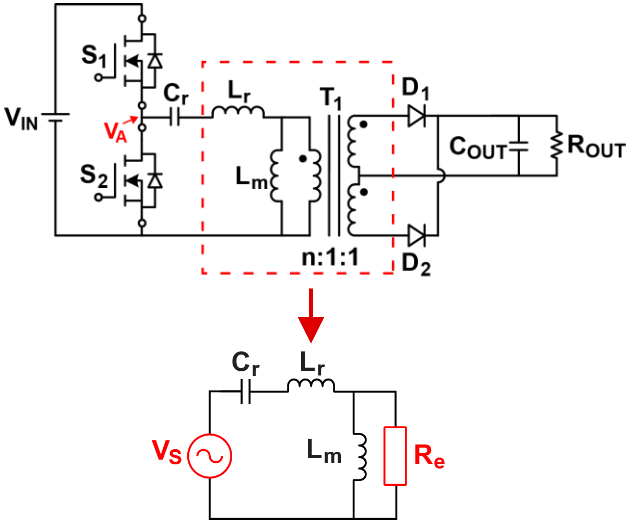


LLC Series Resonant Converter (LLC–SRC)

LLC–SRC Key Features

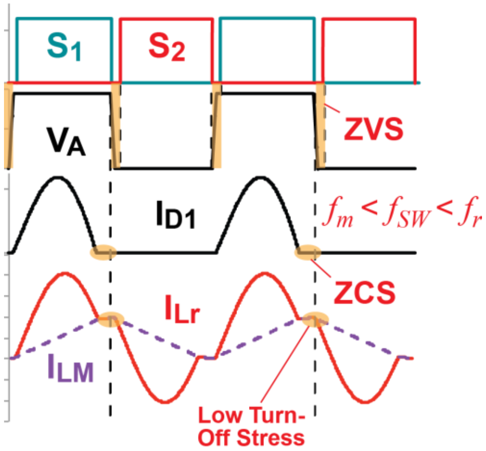
Benefits

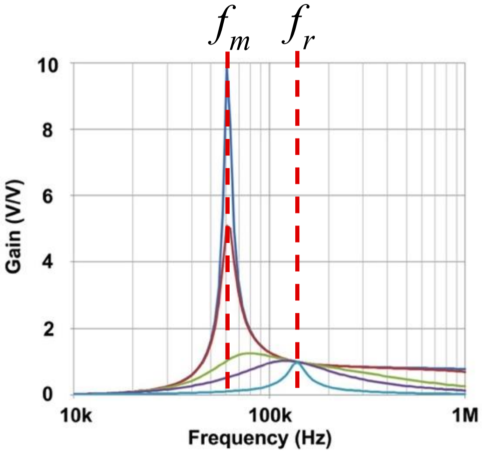
- Easy magnetic integration
- Achieve soft-switching over entire load range
  - Possible for high frequency operation
- Optimized efficiency around f_r



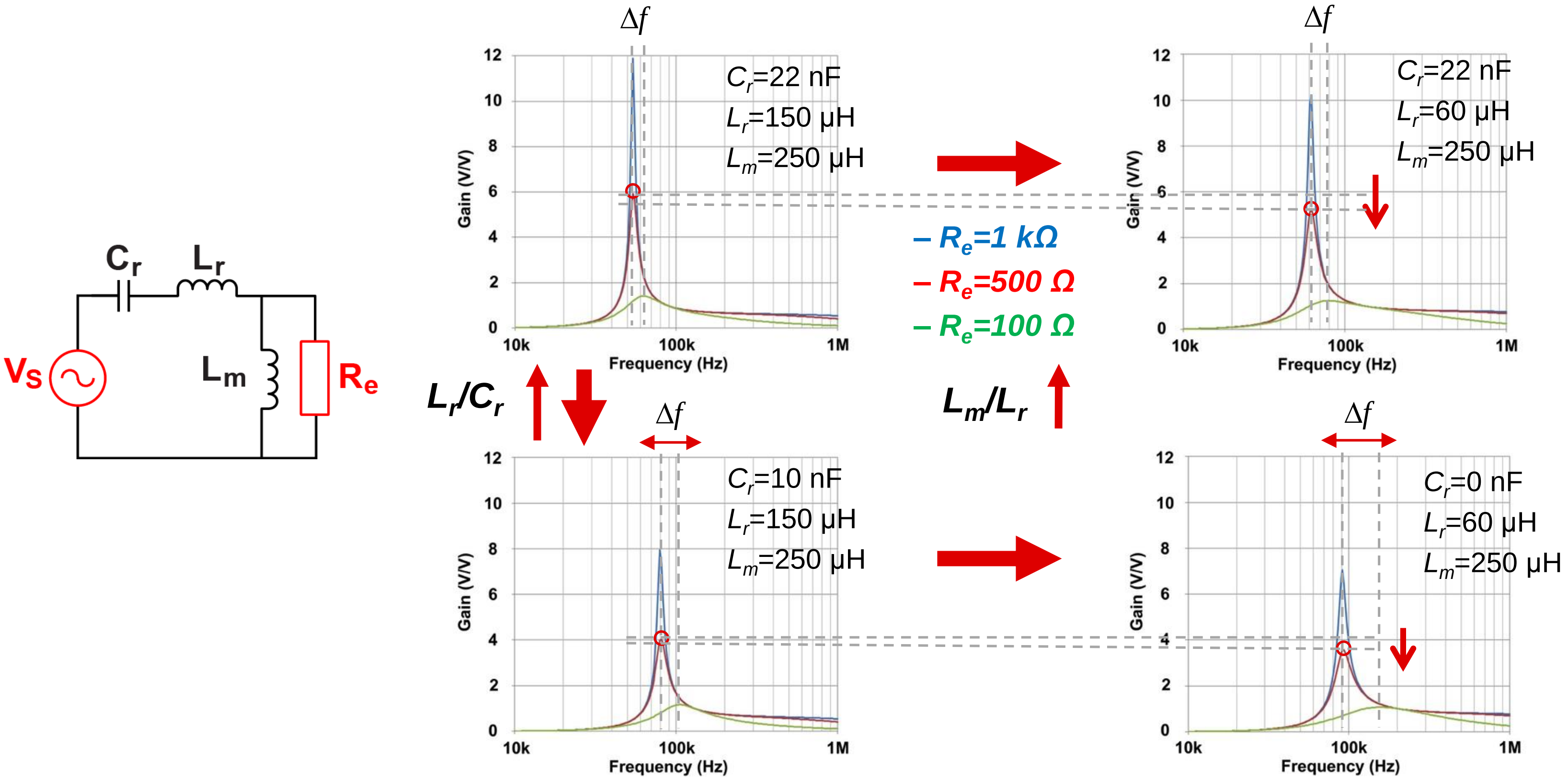
$$\frac{nV_{OUT}}{V_{IN}/2} = \frac{1}{\sqrt{\left(\frac{1}{w^2 L_m C_r}\right)^2 \left(\frac{w^2}{w_m^2} - 1\right)^2 + \left(\frac{1}{wC_r n^2 R_{OUT}}\right)^2 \left(1 - \frac{w^2}{w_r^2}\right)^2}}$$

$$\omega_r = 2\pi f_r = \frac{1}{\sqrt{L_r C_r}} \qquad \omega_m = 2\pi f_m = \frac{1}{\sqrt{(L_r + L_m) C_r}}$$





Effect of Resonant Parameter Variations

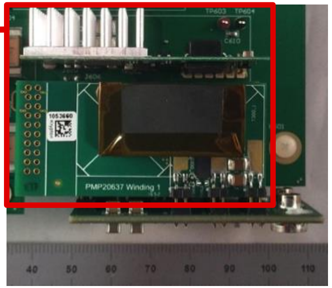


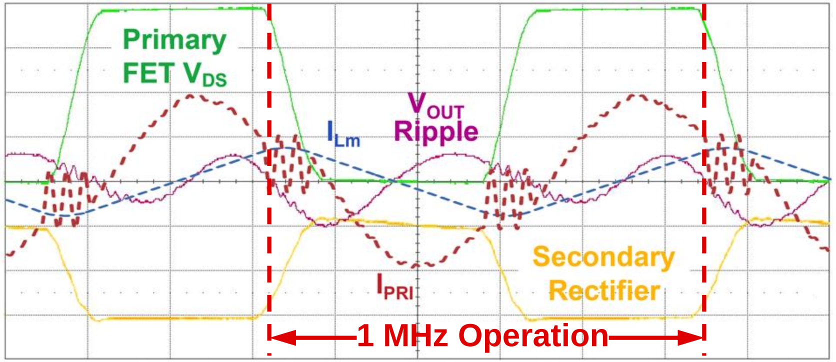
LLC–SRC Design Example

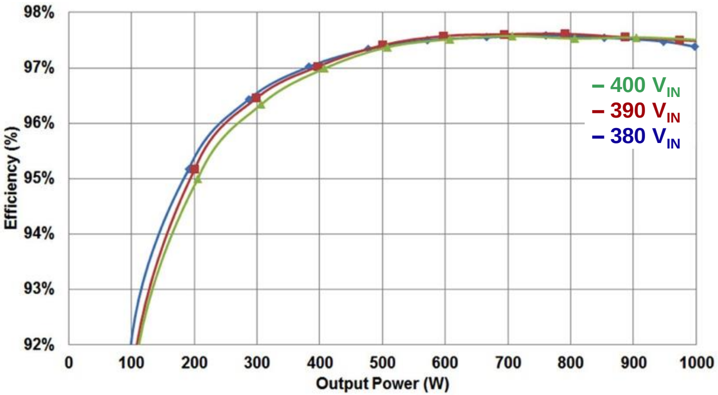
Operate right on resonant frequency

- 385 V_{IN} to 48 V_{OUT}, 1 MHz operation
- Peak efficiency: 97.6%
- Weight< 210 g

Power stage
55 mm(L) x
45 mm(W) x
40 mm(H)
>165 W/in^3



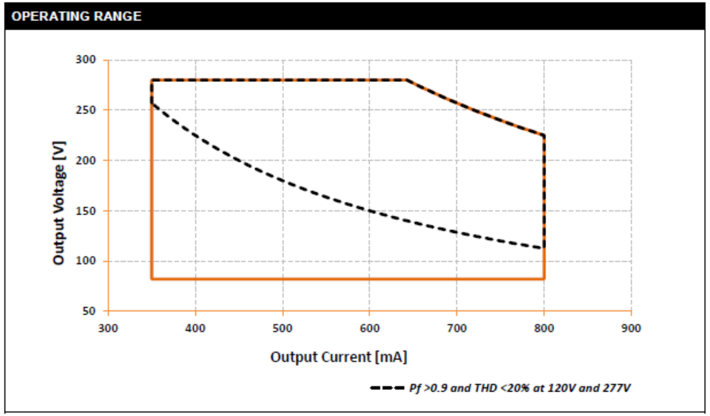




Resonant Converters For Wide Input/Output Voltage Range

The Need for Wide Input/Output Voltage Range

- AC/DC applications without need for PFC
- Battery charger
- Lighting



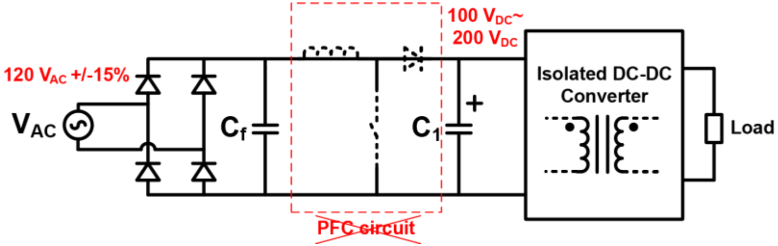
LED PSU spec

EN61000–3–2 harmonic requirements

Harmonic Order N	75 W < P < 600 W Maximum Permissible Harmonic Current (mA/W)
3	3.4
5	1.9
7	1.0
9	0.5
11	0.35
13	0.269
15 < n < 39	3.85/n

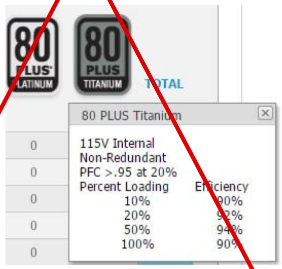
Title 22

Deep dimming: down to 0.1% load dimming (dim to dark)



80PLUS

ENERGY STAR

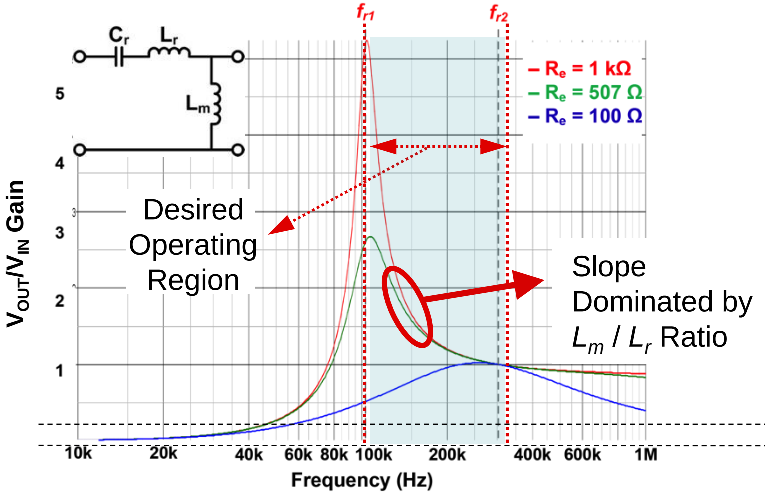


Candidates' Comparison – LLC vs LCC

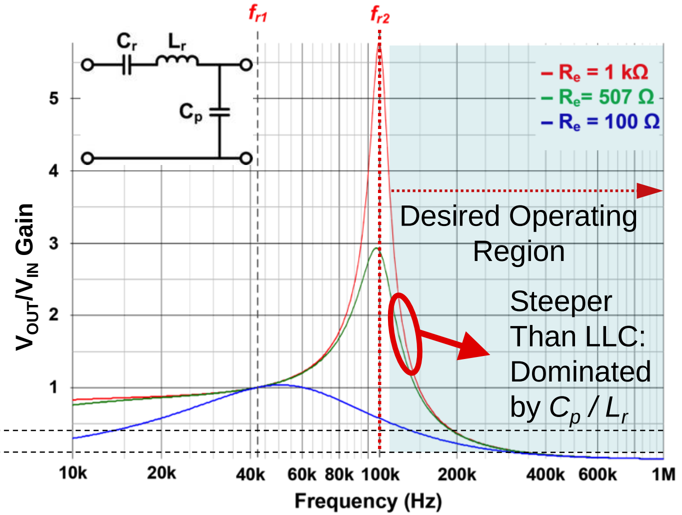
Voltage gain

- LCC can achieve zero gain at high frequency

	LLC	LCC
f_{r1}	$\frac{1}{2\pi\sqrt{(L_r+L_m)C_r}}$	$1/(2\pi\sqrt{L_r\frac{C_rC_p}{C_r+C_p}})$
f_{r2}	$\frac{1}{2\pi\sqrt{L_rC_r}}$	$\frac{1}{2\pi\sqrt{L_rC_r}}$



LLC Voltage Gain



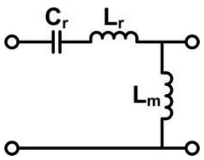
LCC Voltage Gain

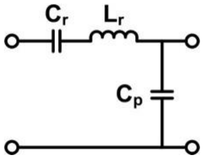
Resonant Converter Designs for Lighting

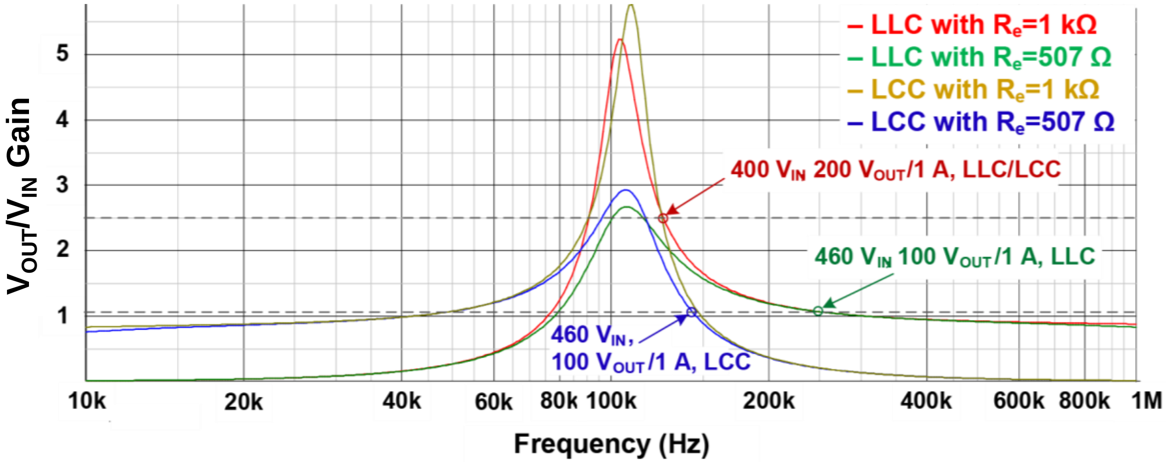
- LLC resonant tank parameters: L_r=40 µH, L_m=300 µH, C_r=7 nF
- LCC resonant tank parameters: L_r=300 µH, C_r=0.047 µF, C_p=8.2 nF

Target spec:

- V_{IN} range: 400-460 V
- V_{OUT} range: 100-200 V
- I_{OUT}: 1 A, P_{OUT} = 200 W



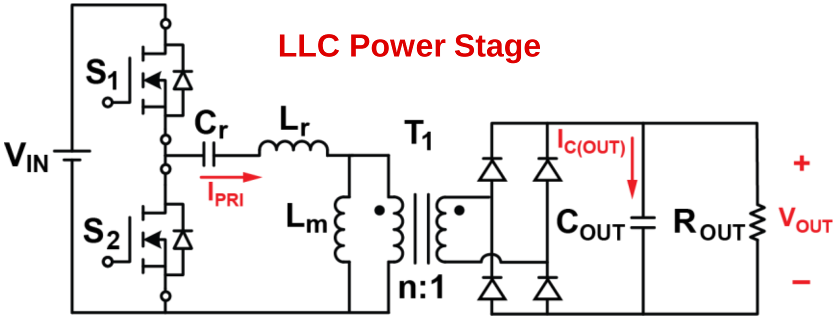


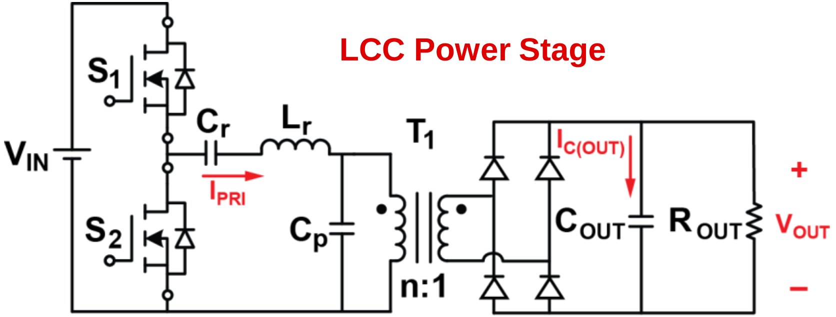


Simulation Results (LLC & LCC for Lighting)

V_{IN} (V)	V_{OUT} (V)	I_{OUT} (A)	LLC I_{PRI} (A_{RMS})	LCC I_{PRI} (A_{RMS})	LLC f_{SW} (kHz)	LCC f_{SW} (kHz)	LLC $I_{C(OUT)}$ (A_{RMS})	LCC $I_{C(OUT)}$ (A_{RMS})
400	200	1	1.73	2.69	131	122	1.37	1.97
460	200	1	1.69	2.76	138	125	1.32	1.98
400	100	1	0.775	1.65	196	130	0.904	1.66
460	100	1	0.709	1.7	245	135	0.722	1.67

$\Delta F_{LLC} > \Delta F_{LCC}$





LLC has lower RMS current than LCC

– Implies better efficiency on LLC

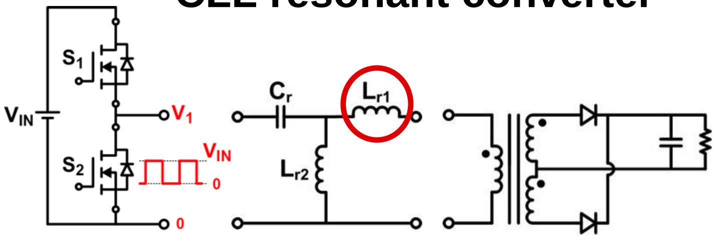
LCC has narrower frequency variation

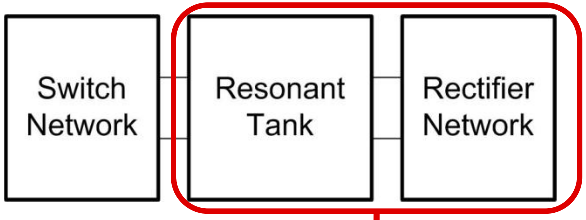
– May not need bursting at light load

Resonant Converter Variations

Integrate Resonant Tank and Rectifier Network

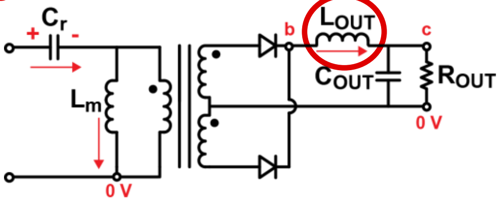
CLL resonant converter



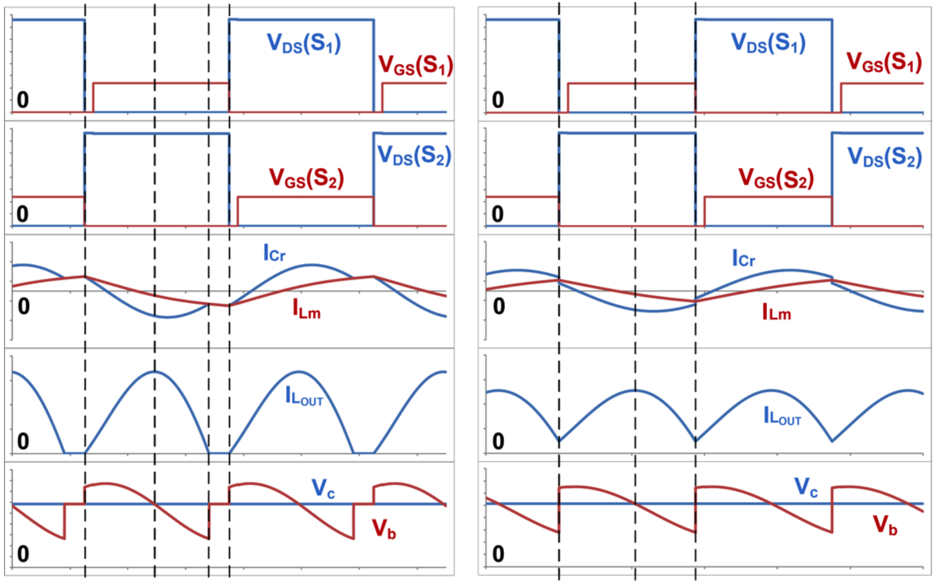


Combine resonant and rectifier stage

$$L_{r1} = n^2 L_{OUT}$$



$f_{sw} < f_{r1}$ $\quad$ $f_{sw} > f_{r1}$

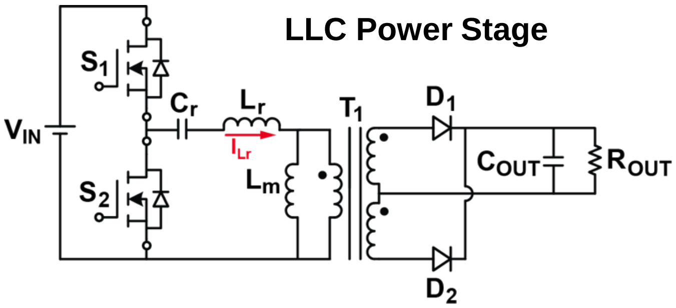


Possible size reduction and efficiency improvement!

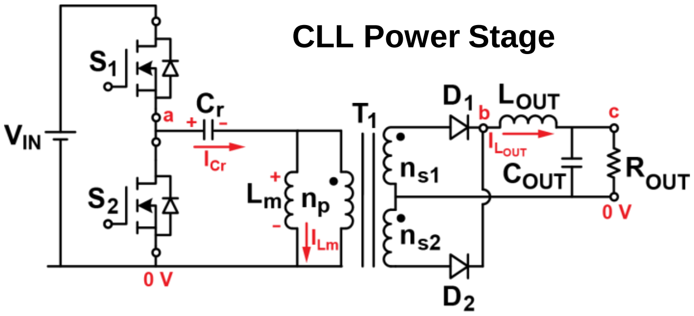
$$f_{r1} = \frac{1}{2\pi\sqrt{C_r\left(L_{r1} // L_{r2}\right)}}$$

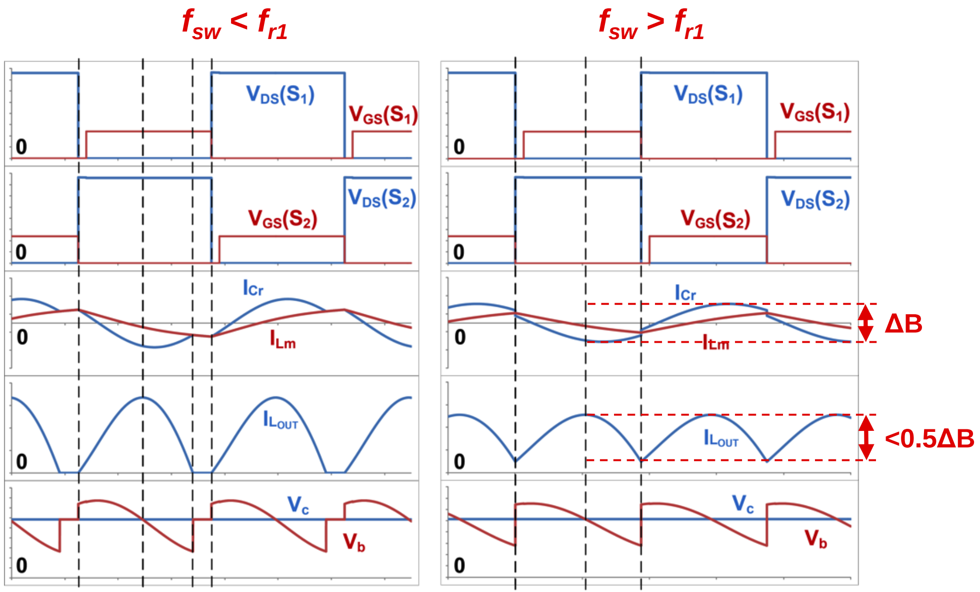
$$f_{r2} = \frac{1}{2\pi\sqrt{C_r L_{r2}}}$$

LLC & CLL Resonant Inductor Loss Comparison



LLC I_{Lr} is equivalent to CLL I_{Cr} !



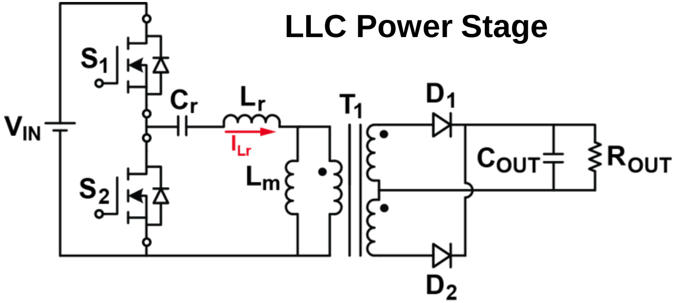


LLC L_r to CLL L_{OUT} => less than half ΔB, frequency doubled

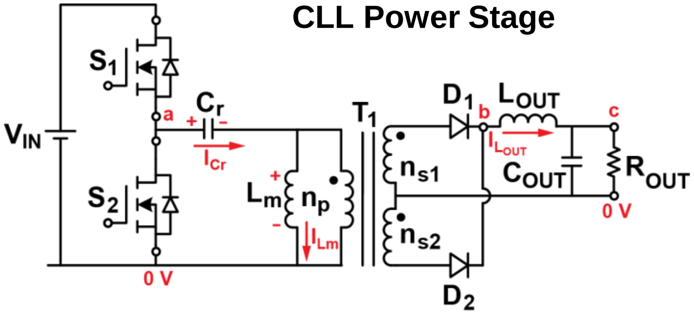
$$P_{CORE} = kDB^{a} f^{b}$$

LLC & CLL Resonant Inductor Loss Comparison

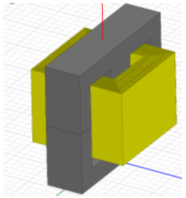
LLC Power Stage



CLL Power Stage



FEA simulation setting and results:

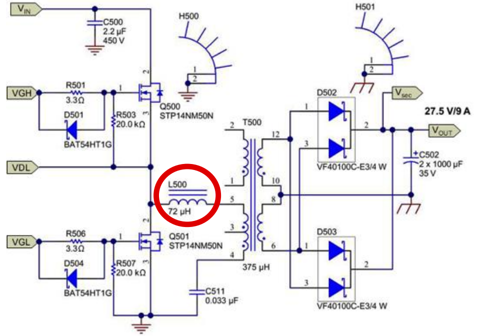


Core: EE19 (3C95)
Copper sheet —
Width: 10 mm
Thickness: 0.05 mm

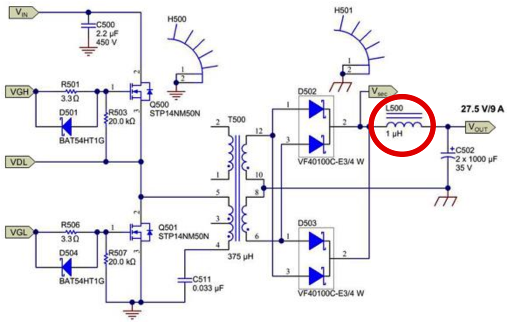
	LLC	CLL
Inductance	73 µH	1.2 µH
Turns	24	3
Parallel winding	1	8
R_{DC}	31.5 mΩ	0.48 mΩ

	$f_{SW}=f_{r1}$	$f_{SW}>f_{r1}$	$f_{SW}<f_{r1}$
LLC L_r loss (winding/core)	0.87 W (0.4 W/0.47 W)	1.11 W (0.38 W/0.73 W)	0.69 W (0.35 W/0.34 W)
CLL L_r loss (winding/core)	0.43 W (0.12 W/0.31 W)	0.23 W (0.07 W/0.15 W)	0.53 W (0.14 W/0.39 W)

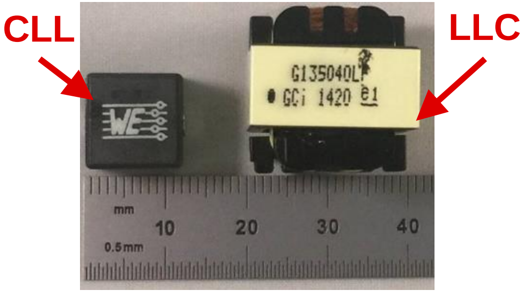
LLC & CLL Prototypes and Comparison



LLC-SRC



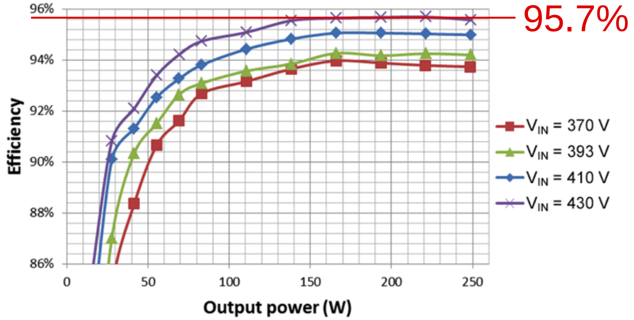
CLL



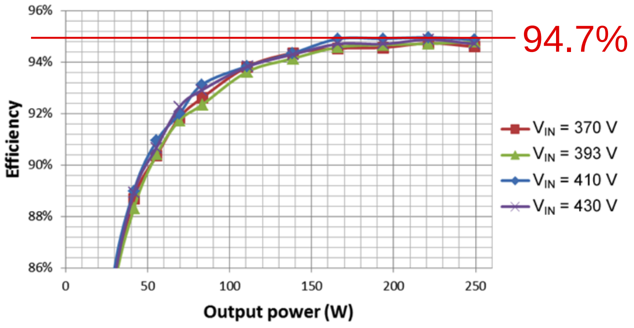
Resonant Inductors

Smaller size and 1% better efficiency!

CLL Efficiency @ 27.5 V_{OUT}



LLC Efficiency @ 27.5 V_{OUT}

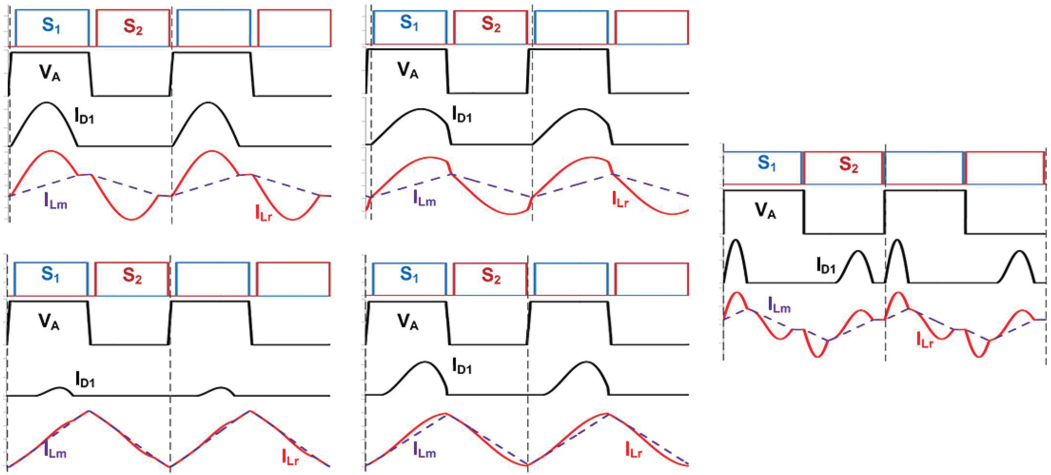


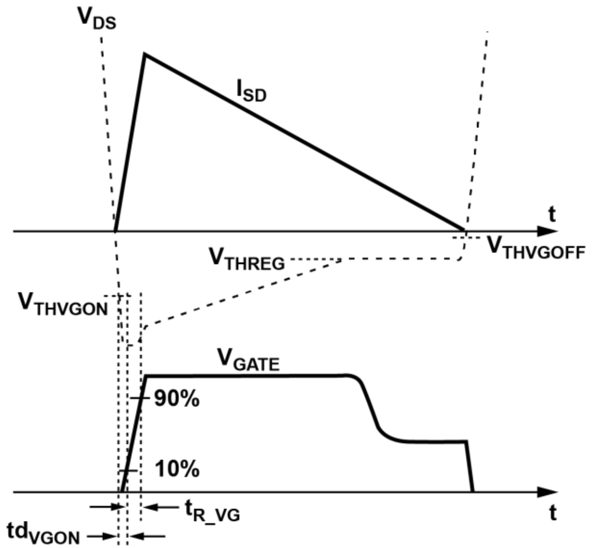
Resonant Converter Design Challenges

States of Operation

- **Lots of states – not just DCM and CCM in PWM converter**
  - LLC-SRC: more than 5 possible states
  - Output rectifier does not always conduct current when corresponding primary switch turns off →

Can't just turn SR on when primary switch off!

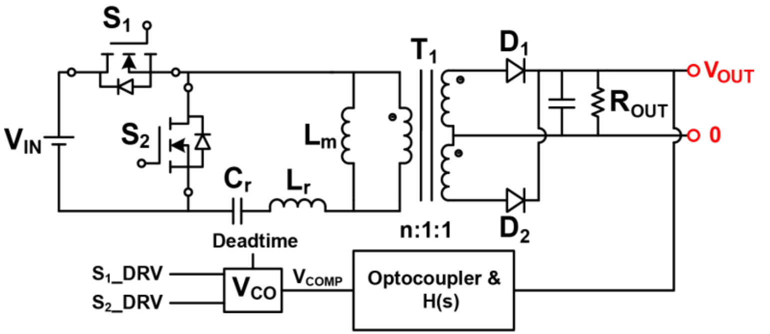


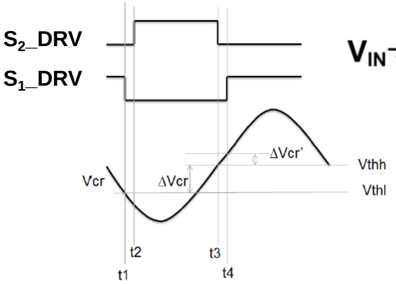


V_{DS} Sensing for SR Control

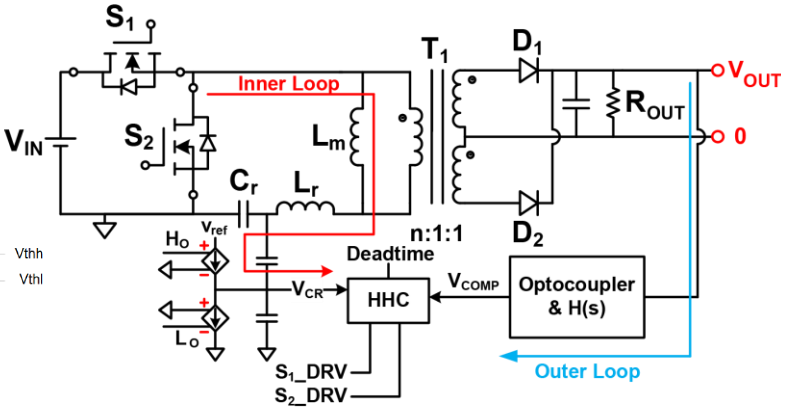
Resonant Converter Transient Response

- **Variable frequency control (VFC)**
  - Analogous to voltage mode control
    - Slow transient response
    - Higher order plant transfer function
    - Poor input voltage rejection
- **Hybrid hysteresis control (HHC)**
  - Analogous to current mode control
    - Fast transient response
    - ~1st order plant gain
    - Inherent line rejection





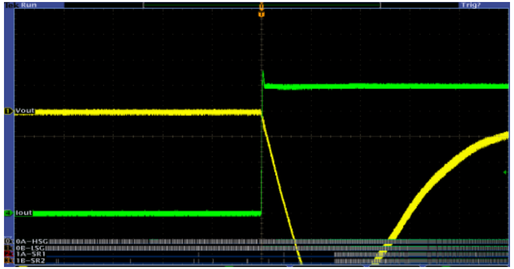
V_{thh} = DC + V_{COMP}*0.5
V_{thl} = DC – V_{COMP}*0.5
Where DC is common mode voltage reference



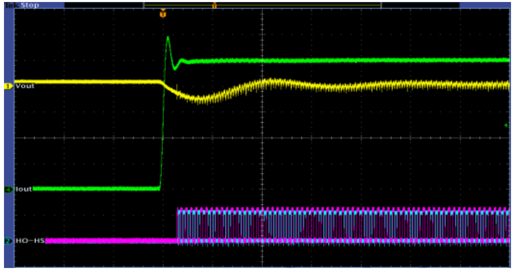
Transient Response Comparison: VFC vs HHC

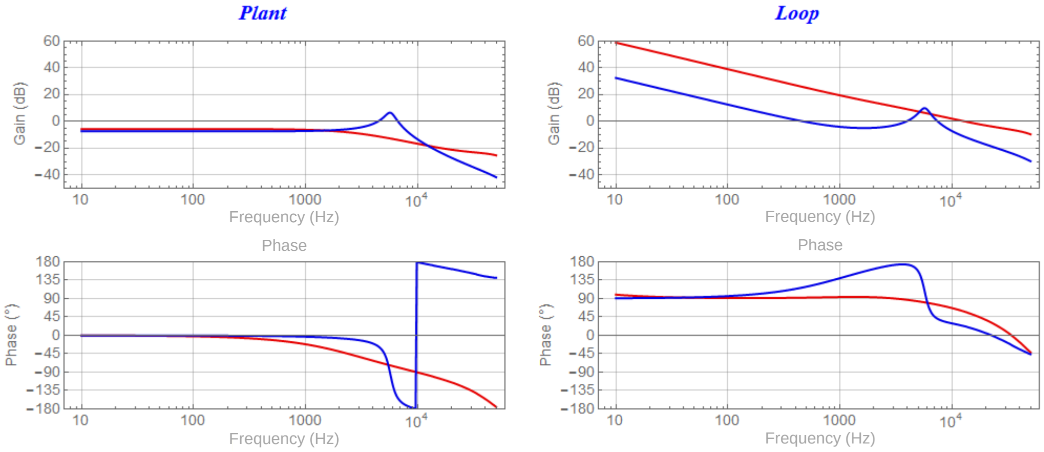
No load to full load transient

– VFC: >20% V_{OUT} deviation



– HHC: 1.25% V_{OUT} deviation





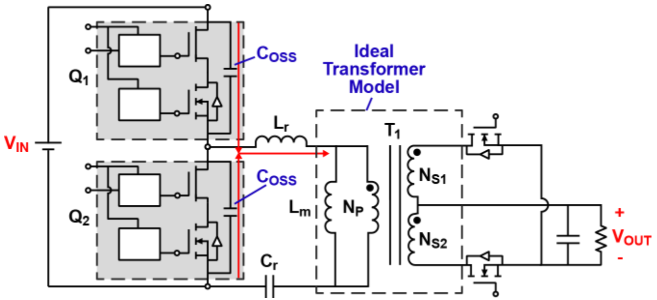
– *VFC*

– *HHC (with 25% C_{OUT} reduction)*

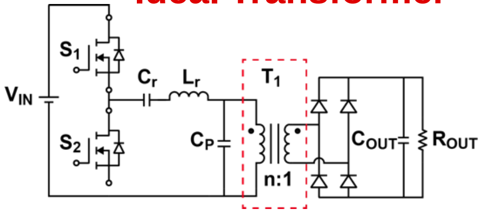
Effects Of Real Life Parasitics/Parameters

Non-Ideal Transformer

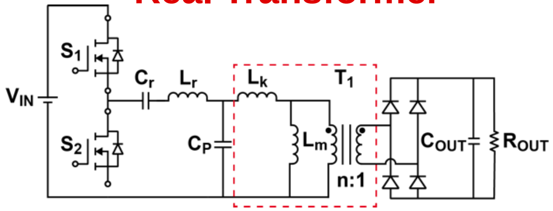
- Magnetizing inductance
- Transformer winding capacitance

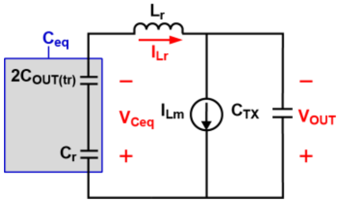


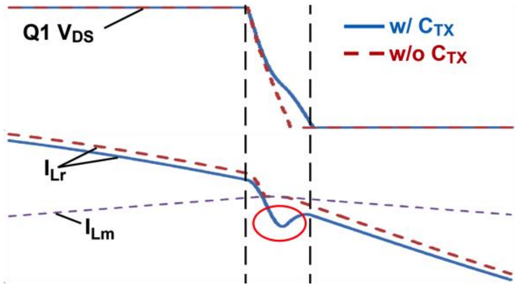
Ideal Transformer

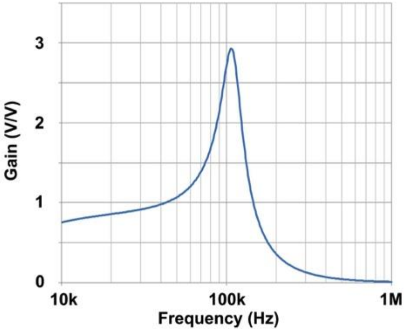


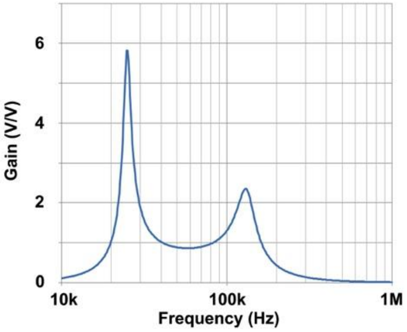
Real Transformer





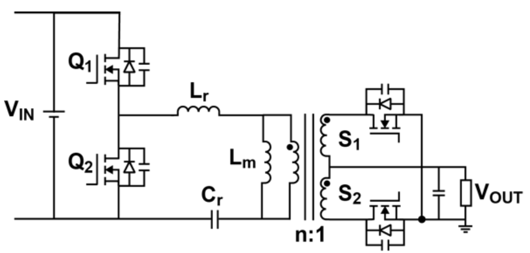


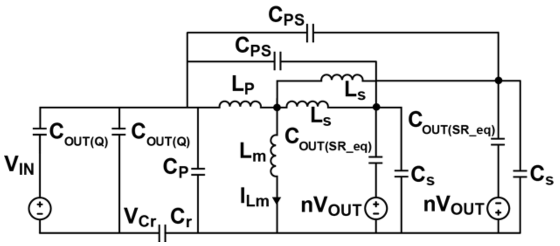




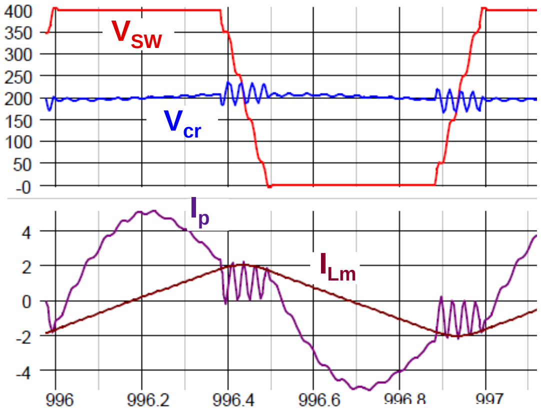
Component Parasitics

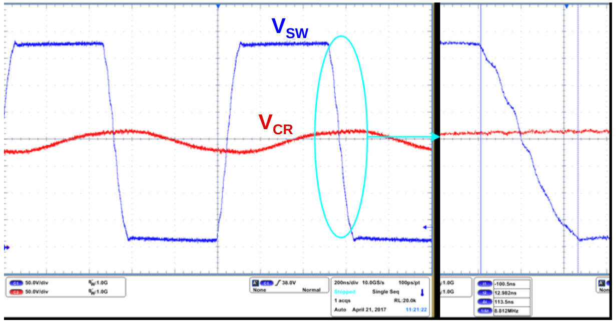
- More parasitics – 1 MHz LLC as an example
  - C_{oss} (primary FET and SR FET), winding capacitances





Deadtime Transient Model



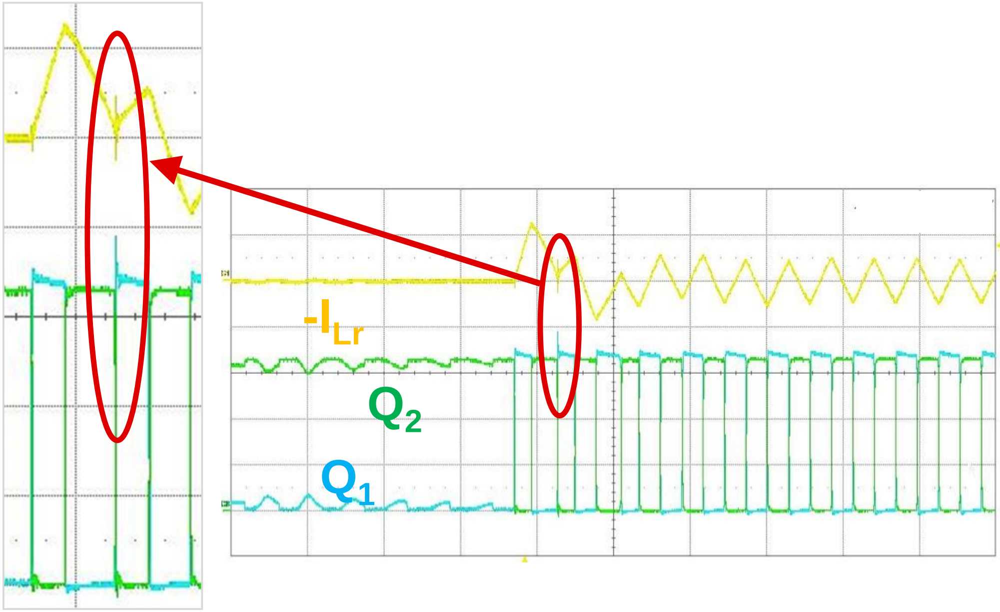


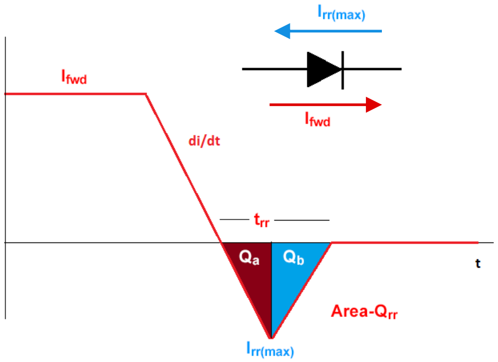
$$C_{eq} = 2C_{ps} + \cfrac{1}{\cfrac{1}{2C_{O\_SR\_eq} + C_s} + \cfrac{1}{2C_{O\_Q} + C_p}}$$

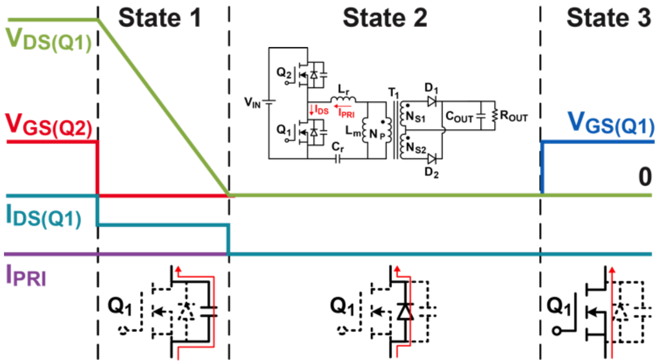
Both winding capacitance and MOSFET C_{OSS} dominate the ringing

Non-Ideal Switches

MOSFET body diode reverse recovery charge



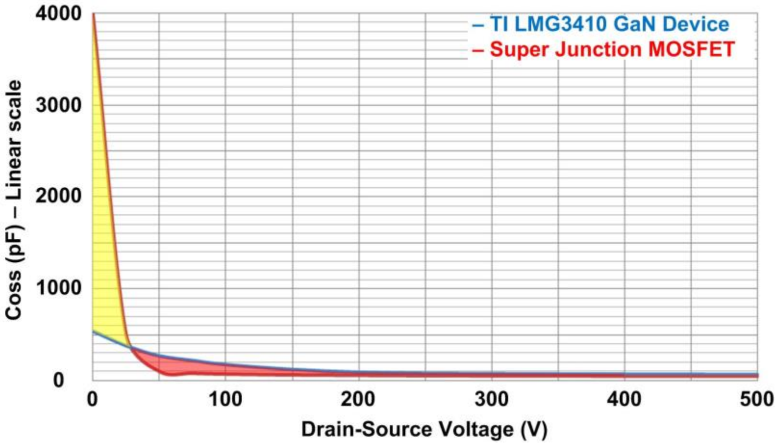


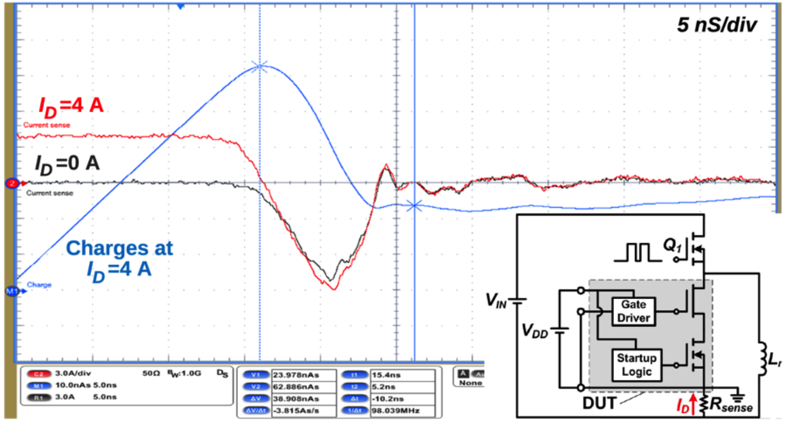


Wide Bandgap Devices for Resonant Converter

- Benefits of wide bandgap devices (SiC & GaN)
  - Zero or minimum Q_{rr}
    - No body diode reverse recovery concern
  - Linear output capacitance
    - Minimize the duration of dead-time

$$t_{DT} = \frac{2\int_{0}^{V_{DS}} C_{oss}\left(V_{DS}\right) V_{DS}}{I}$$



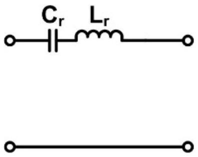
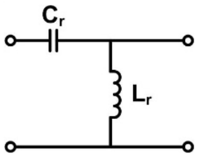
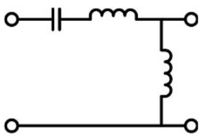
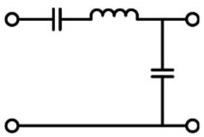
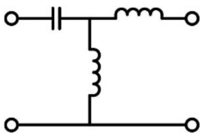


Dual-Pulse Test Results of TI LMG3410 GaN Device

Resonant Converter Selection Guide

Rule of Thumb on Resonant Converter Selection

- More resonant elements ⟶ less efficient
- More capacitors ⟶ higher gain & narrower frequency variation
- Avoid notch resonance

	LC Series	LC Parallel	LLC	LCC	CLL
					
Frequency variation	Wide	Wide	Moderate	Narrow	Moderate
Component voltage/current stresses	Lowest	High	Low	Highest	High
ZVS(input)/ ZCS(output)	ZVS	ZVS	ZVS & ZCS	ZVS	ZVS & ZCS

Primary Switches ← ZVS(input)

Secondary Rectifiers ← ZCS(output)

Summary

- Fundamentals of resonant converter: structure and analysis method
- Soft-switching conditions of resonant converters
- Design examples and comparison of three resonant converters:
  - LLC, LCC, CLL
- Common issues and design challenges

References

- B. Yang, “Topology Investigation for Front End DC–DC Power Conversion for Distributed Power System,” Ph.D dissertation, VPI&SU, Sept. 2003.
- Daocheng Huang et al, “Classification and Selection Methodology for Multi-Element Resonant Converters,” 2011 IEEE APEC.
- R. Yu, G. K. Y. Ho, B. M. H. Pong, B. W. K. Ling and J. Lam, "Computer-Aided Design and Optimization of High-Efficiency LLC Series Resonant Converter," in *IEEE Transactions on Power Electronics*, vol. 27, no. 7, pp. 3243-3256, July 2012.
- High Efficiency and High Power Density 1 kW Resonant Converter Reference Design with TI HV GaN FET: http://www.ti.com/tool/PMP20637
- 400 VDC Input to 28 V/9 A Output Compact, High Efficiency CLL Resonant Converter Reference Design: http://www.ti.com/tool/PMP9750

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