LLC Converter Design Using Scaling Laws

Nicola Rosano

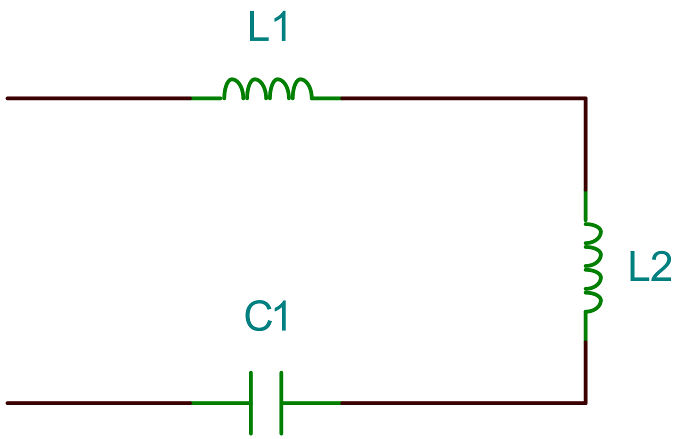
Power Supply Design Center Group Member

Webinar starts at:
7 pm Italian hours

Agenda

What is the meaning of LLC and why choose LLC topology?

- «LLC» string identifies a circuit combination of two inductors and one capacitor placed somewhere in your power stage.



Agenda

- **Intro**
- ZVS & ZCS
- LC combo
- LC series is the right way
- From Series LC to LLC
- LLC Design
- Inverter Input Stage
- Output rectifier Stage
- The Rac concept
- The transformer
- Scaling laws
- Results
- Graphical Approach
- Related Topics

What is the meaning of LLC and why choose LLC topology?

- «LLC» string identifies a circuit combination of two inductors and one capacitor placed somewhere in your power stage.
- LLC belongs to the resonant converter family. Resonant conversion is not something new.

A comparison of half-bridge resonant converter topologies

Publisher: IEEE | Cite This | PDF

Metrics

Published in: IEEE Transactions on Power Electronics (Volume: 3, Issue: 2, April 1988)

Page(s): 174 - 182

INSPEC Accession Number: 3193047

Date of Publication: April 1988

DOI: 10.1109/63.4347

ISSN Information:

Publisher: IEEE

Authors

R.L. Steigerwald

Corporate Research and Development, General Electric Company Limited, Schenectady, NY, USA

What is the meaning of LLC and why choose LLC topology?

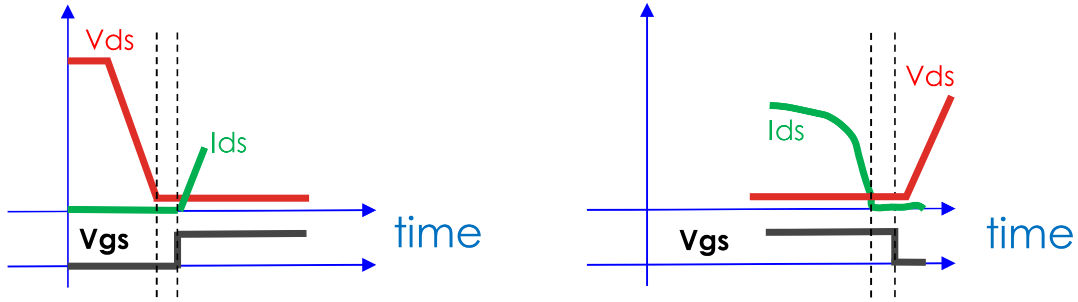
- «LLC» string identifies a circuit combination of two inductors and one capacitor placed somewhere in your power stage.
- LLC belongs to the resonant converter family. Resonant conversion is not something new.
- Related Literature is not always efficient: too much math (sometimes wrong) and too many circuit diagrams
- Its analysis is still considered complex and sometimes poorly understood.
- If **correctly** designed it assures **zero-voltage switching** AND **zero current switching** somewhere in your power stage.

RN1

Agenda

How to get ZVS and ZCS? Three rules and you're safe!

- ZVS @ turn on → Turn on the FET after its Vds becomes low allowing then, and only then, the current to pass through the switch.
- ZCS @ turn off → Turn off the FET after its current becomes low allowing then, and only then, its Vds to increase



How can we do that?

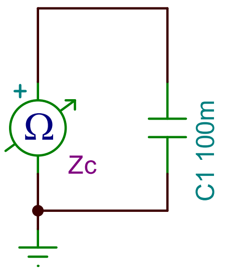
- We need the current to run back and forth into the power stage.
- The input impedance must appear inductive to the input voltage source
- The dead time between two consecutives FETs turn on is critical.

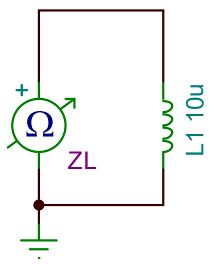
Diapositiva 5

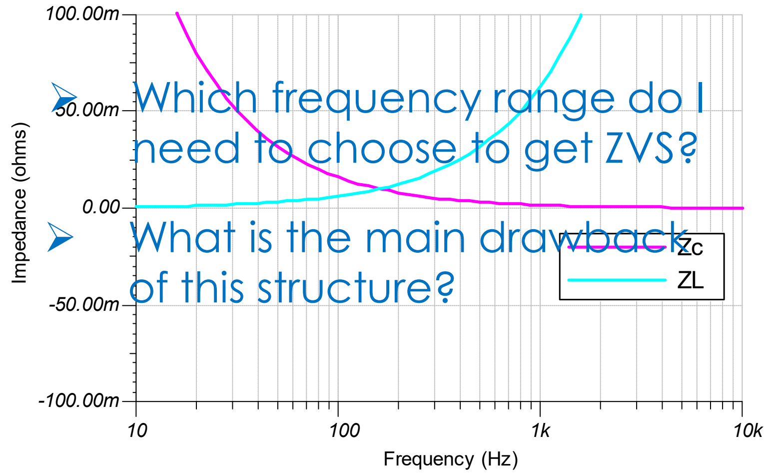
RN1 ROSANO Nicola; 03/12/2020

Back to basics: why the LC combo is not good enough?

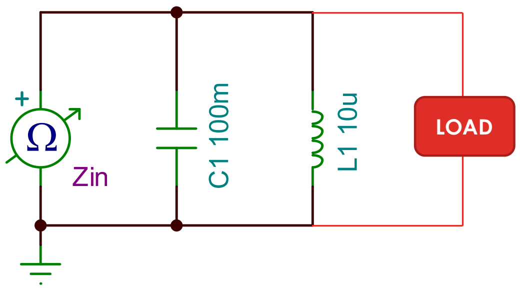
- LC parallel

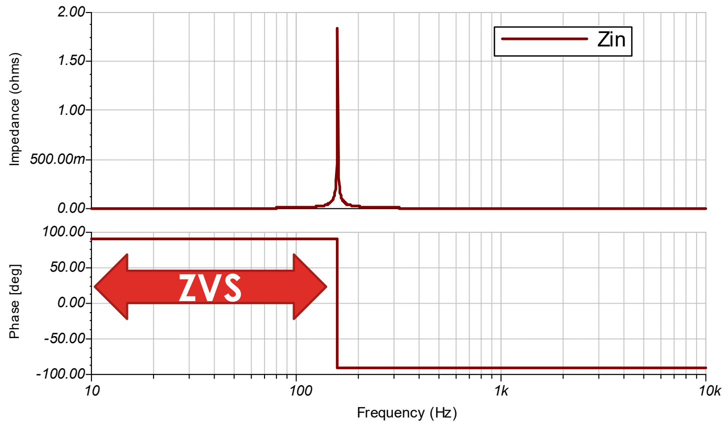






- Which frequency range do I need to choose to get ZVS?
- What is the main drawback of this structure?





Agenda

- Intro
- ZVS & ZCS
- **LC combo**
- LC series is the right way
- From Series LC to LLC
- LLC Design
- Inverter Input Stage
- Output rectifier Stage
- The Rac concept
- The transformer
- Scaling laws
- Results
- Graphical Approach
- Related Topics

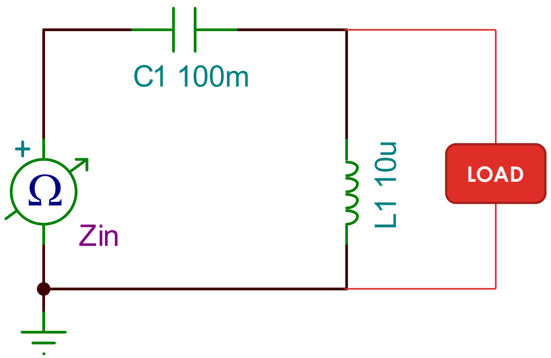
Back to basics: why the LC combo is not good enough?

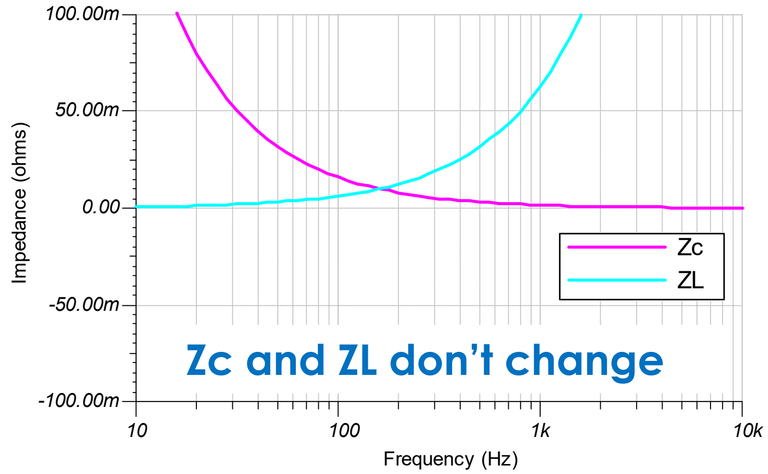
- LC series

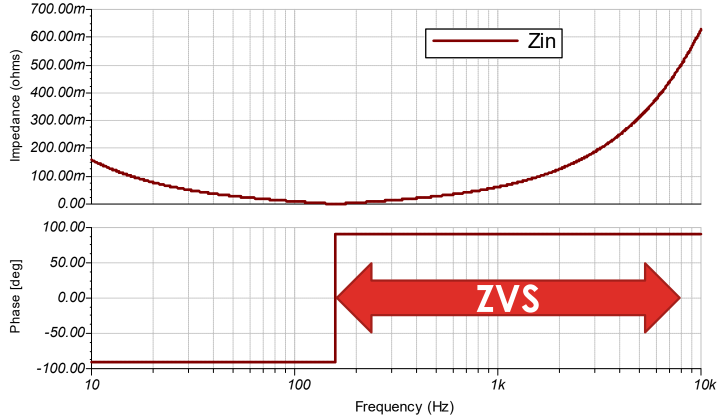
➤ Which frequency range do I need to choose to get ZVS?

➤ Why it is better than LC parallel structure?

➤ What are the drawbacks of this structure?



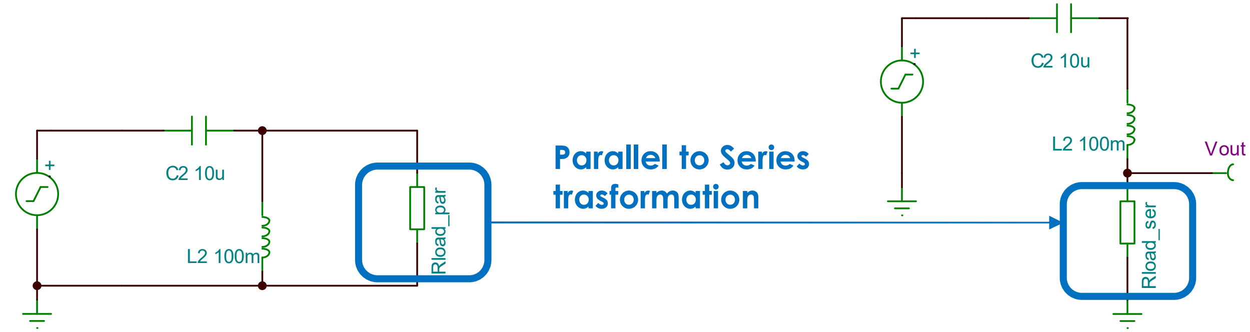


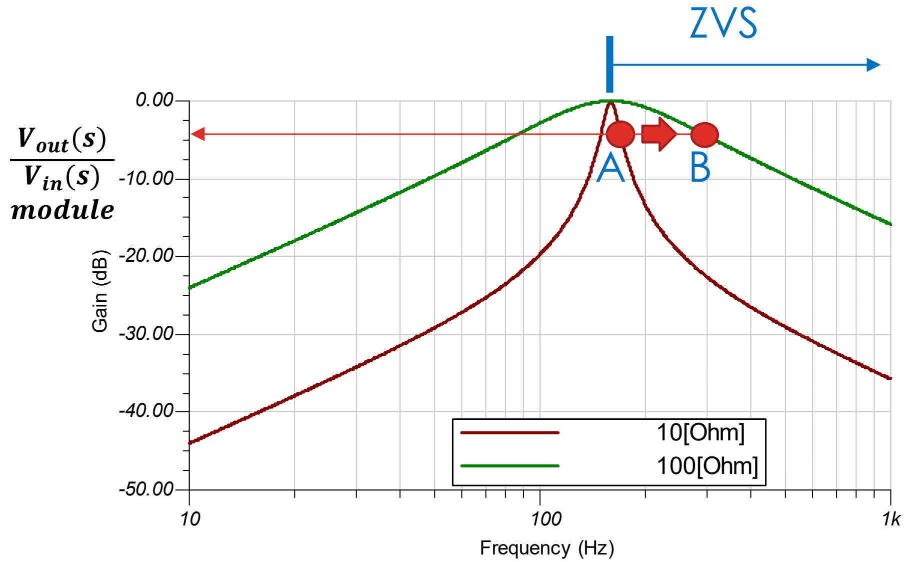


Agenda

- Intro
- ZVS & ZCS
- LC combo
- **LC series is the right way**
- From Series LC to LLC
- LLC Design
- Inverter Input Stage
- Output rectifier Stage
- The Rac concept
- The transformer
- Scaling laws
- Results
- Graphical Approach
- Related Topics

LC series configuration: Load Regulation





Point A is at Rload = 10 Ohm (example: heavy load)

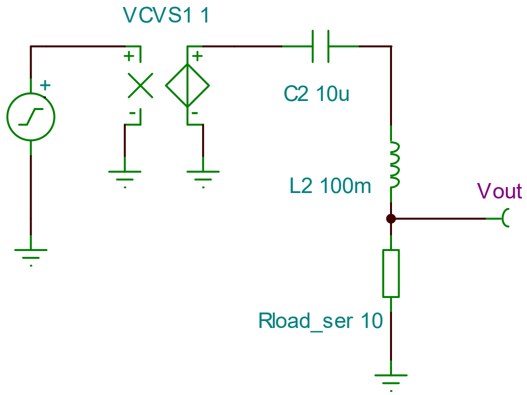
Point B is at Rload = 100 Ohm (example: light load)

How to get LOAD regulation?

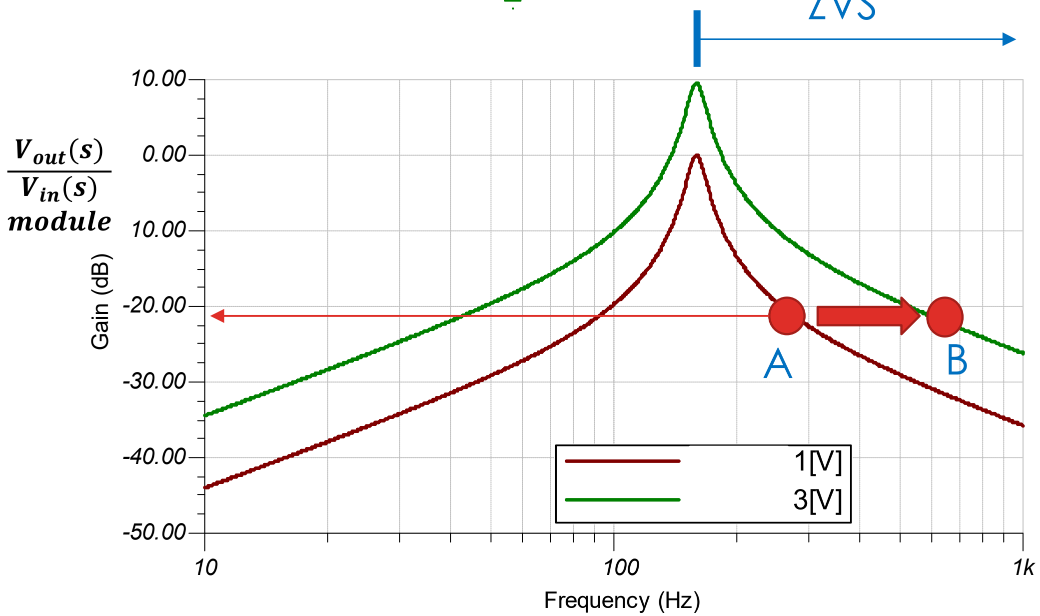
If $Iload \uparrow$ $then\ f \downarrow$ or if $Iload \downarrow$ $then\ f \uparrow$

Agenda

LC series configuration: Input Voltage Regulation



- The VCVS mimics a x3 Vin in the loop.



Point A is at Vin = 1V (example: bus min)

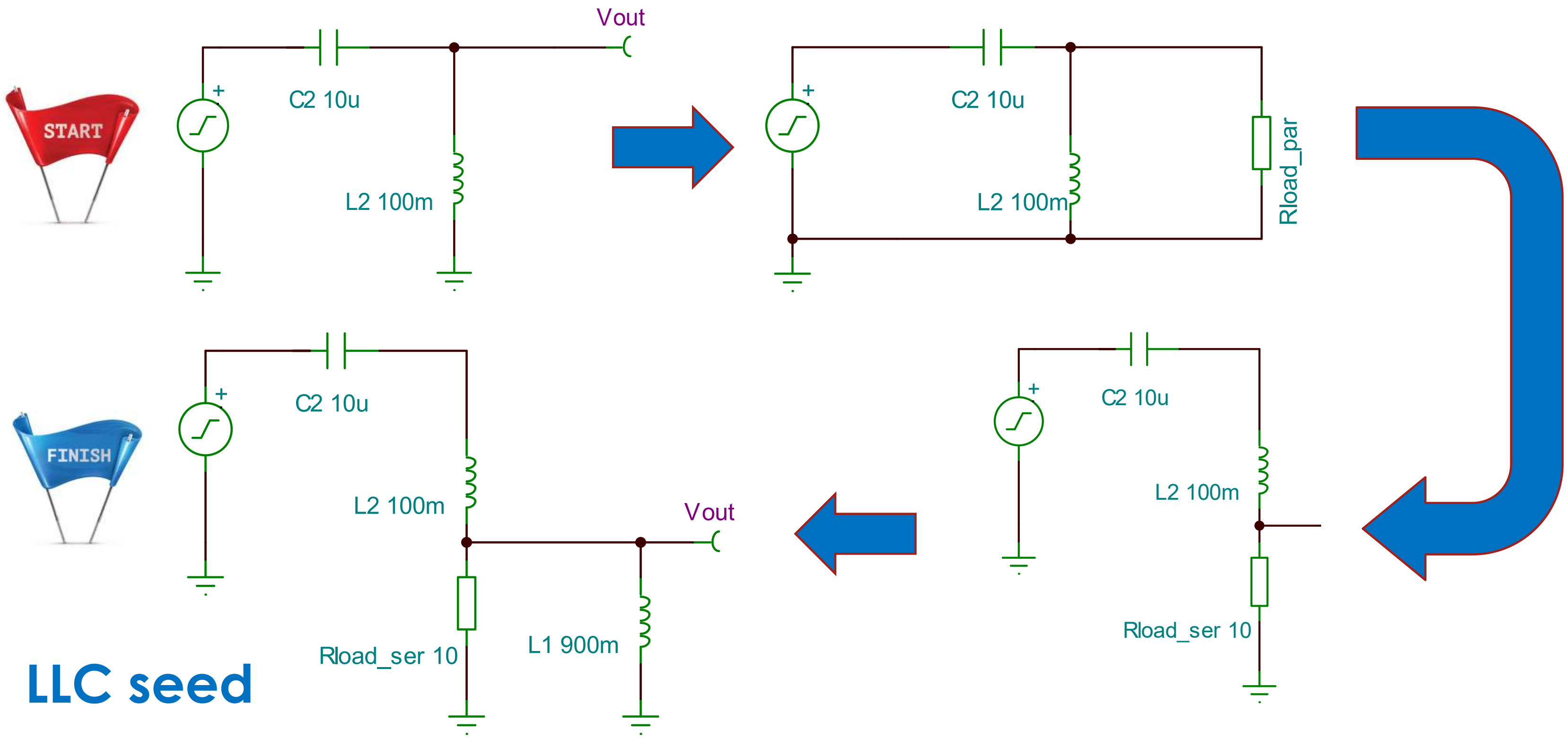
Point B is at Vin = 3 V (example: bus max)

How to get BUS regulation?

$$\text{if } Vin \uparrow then\ f \uparrow \text{ or if } Vin \downarrow then\ f \downarrow$$

Agenda

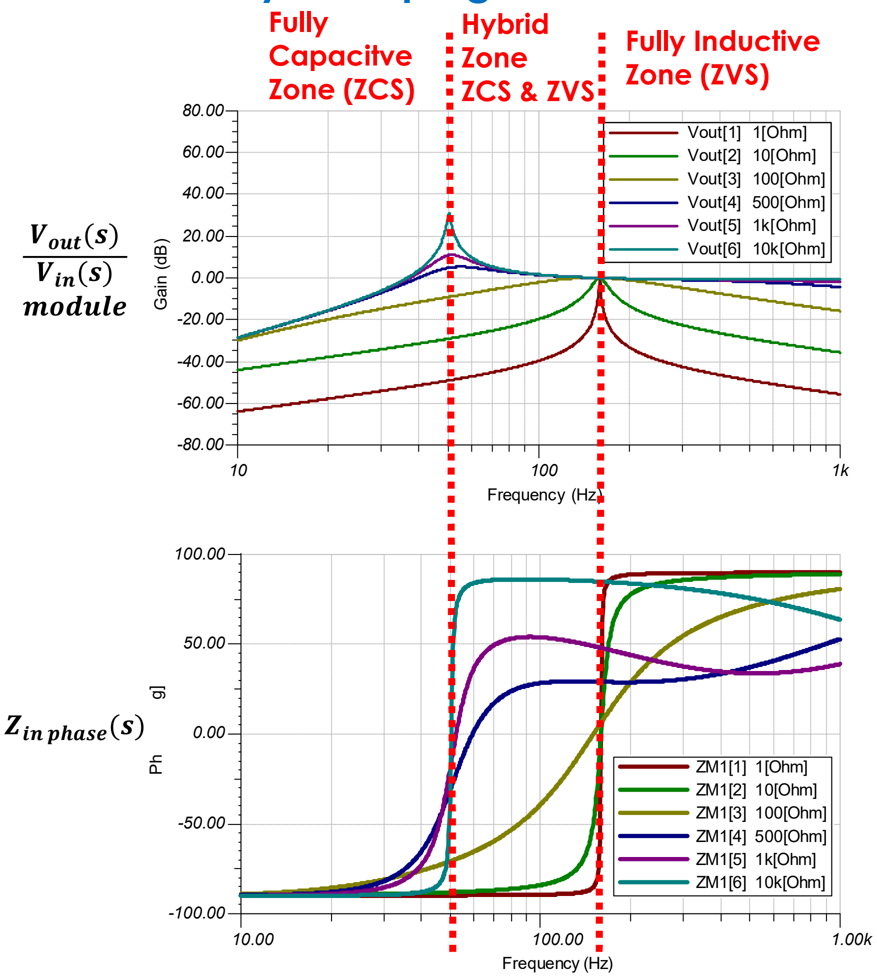
Switching from series LC to LLC

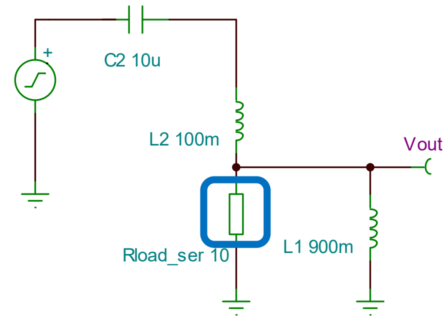


LLC seed

Switching from series LC to LLC
Indentifying the right working frequency range

- **Let's start by sweeping the Load resistor**





Where do I get ZVS or ZCS?

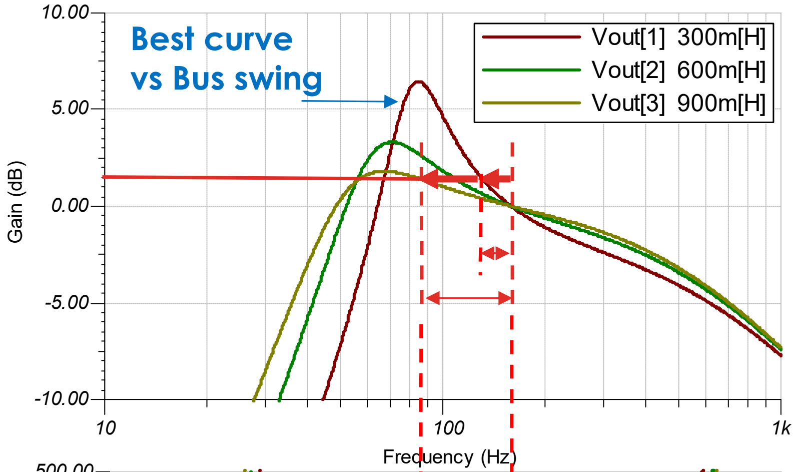
Look at the input impedance phase!

Agenda

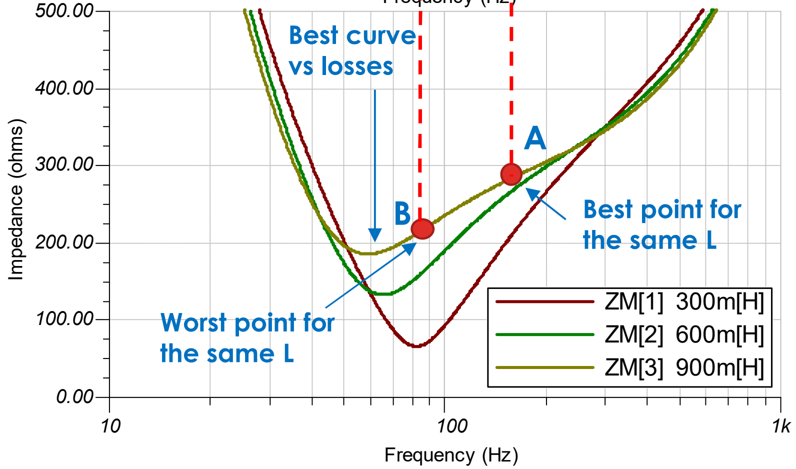
Switching from series LC to LLC
Indentifying the right ratio of inductances

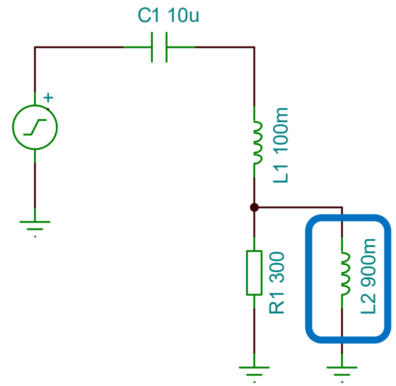
- **What if I sweep the greater inductance?**

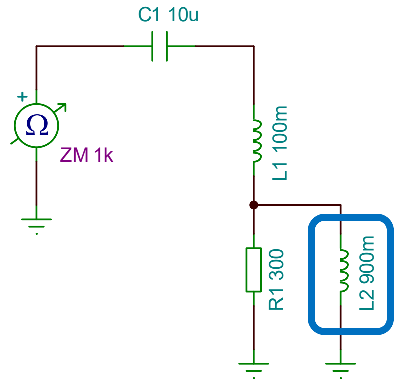
$\frac{V_{out}(s)}{V_{in}(s)}$ *module*



$Z_{in\,module}(s)$







LLC design procedure

Requirements: Vin=52-32V; Vout=12V; Pout=25W; fmax=140kHz

- Choose the Ratio of inductances

➢ Keep L2 between 4 to 11 times L1 in any practical LLC converter.

➢ Higher inductance ratio means lower circulating currents (higher efficiency)

➢ Lower inductance ratio means lower frequency span to get the same gain.

➢ Let's start by selecting **L1 = 100mH** as initial starting point!

➢ **For this design let's choose: m = L2 / L1=9. So L2 = 900mH**

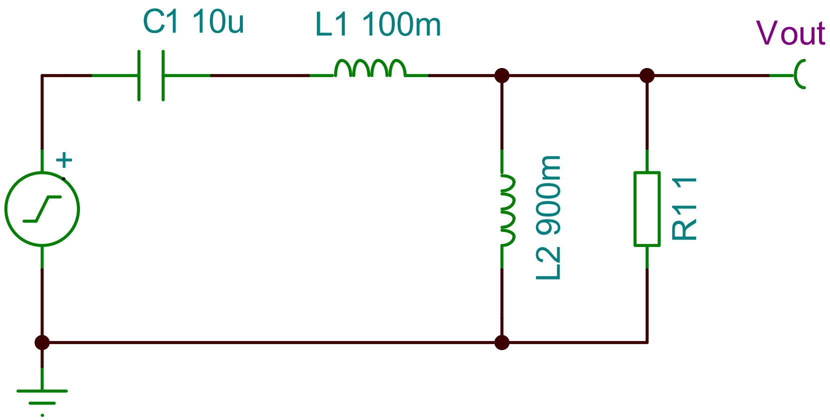
…independently from the requirements… 

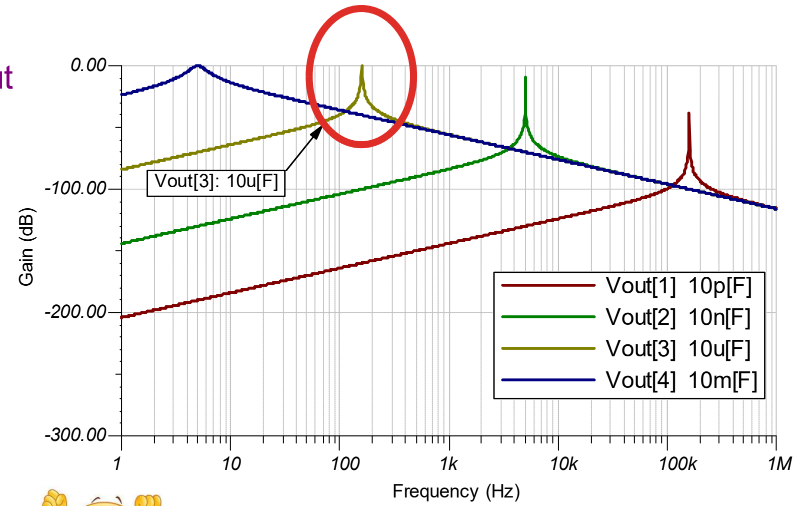
LLC design procedure

Requirements: Vin=52-32V; Vout=12V; Pout=25W; fmax=140kHz

- Choose the Resonant Capacitor

➢ Resonant Capacitor choice, as well as L1, is arbitrary (at the beginning)
➢ Let's place a low tank resistor (1Ohm for example) to select whatever capacitor value you want in the range 1Hz – 1MHz
➢ **Let's choose 10µF for example**





…independently from the requirements…

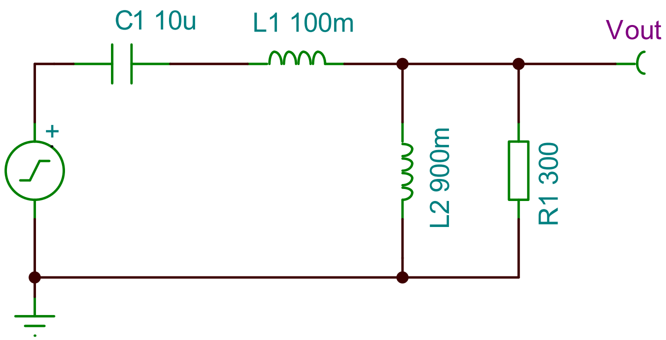
Agenda

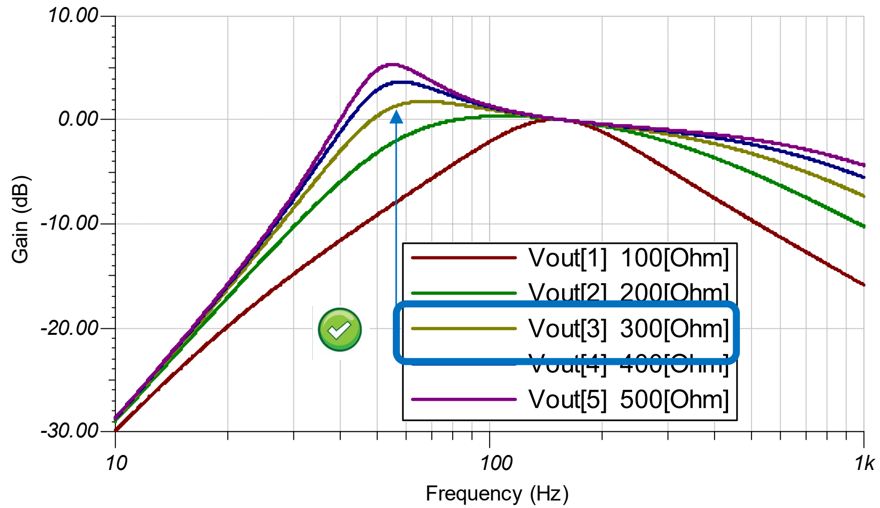
LLC design procedure

Requirements: Vin=52-32V; Vout=12V; Pout=25W; fmax=140kHz

- Choose the minimum tank resistor to get ZVS

➢ Assuming L1=100m, C1=10u, L2=900m the minimum acceptable value for Rtank is around 300 Ohm. **It identifies the max load current condition.**



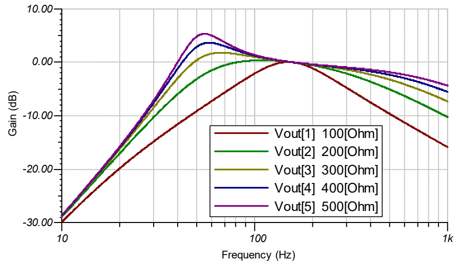


Agenda

LLC design procedure

Requirements: Vin=52-32V; Vout=12V; Pout=25W; fmax=140kHz

- Quality factor



➢ What exactly is Q here?

➢ Quality factor and tank resistor are linked by the following:

$$Q = \frac{1}{R} \cdot \sqrt{\frac{L_1 + L_2}{C_1}} \rightarrow \frac{1}{300} \cdot \sqrt{\frac{100m + 900m}{10u}} = 1.054$$

➢ **Recommended Quality factor for our LLC tank is 1.054 @ Iload max, Vmax**

…independently from the requirements…

Agenda

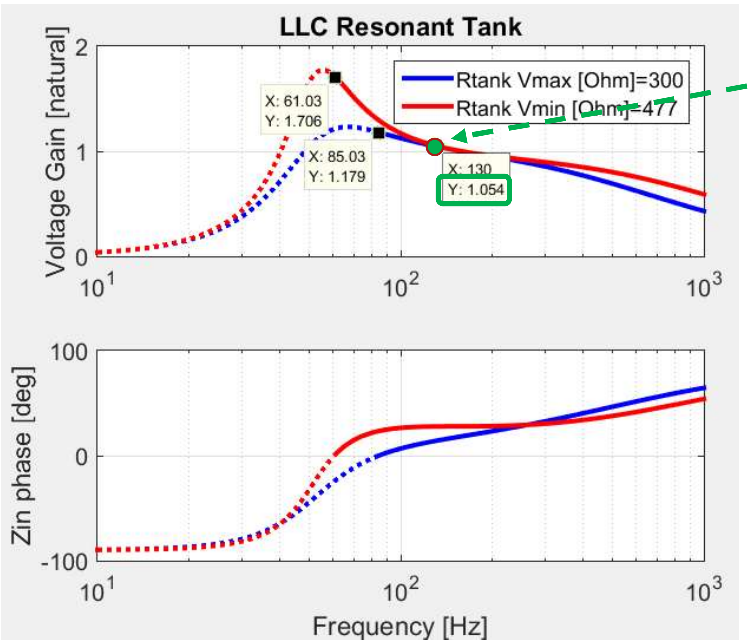
- Intro
- ZVS & ZCS
- LC combo
- LC series is the right way
- From Series LC to LLC
- **LLC Design**
- Inverter Input Stage
- Output rectifier Stage
- The Rac concept
- The transformer
- Scaling laws
- Results
- Graphical Approach
- Related Topics

LLC design procedure

Requirements: Vin=52-32V; Vout=12V; Pout=25W; fmax=140kHz

- Choose the best design entry point

➢ The best design gain entry point @Vinmax, Iloadmax is identified at a frequency slightly lower than the HI. Res one targeting a gain slightly higher than 1. For this case 5% margin has been selected.



Best design Entry Point (BEP)
Gain = 1.05
@Vinmax, Iloadmax.

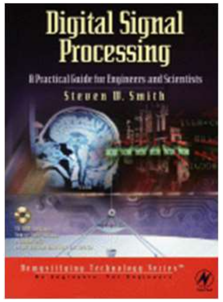
L1=100mH
L2=900mH
C1=10uF

Blue curve Rtank = 300 Ohm
Frequency [85 – **130**] Hz.
Gain [1.05 – **1.18**]

LLC design procedure

Requirements: Vin=52-32V; Vout=12V; Pout=25W; fmax=140kHz

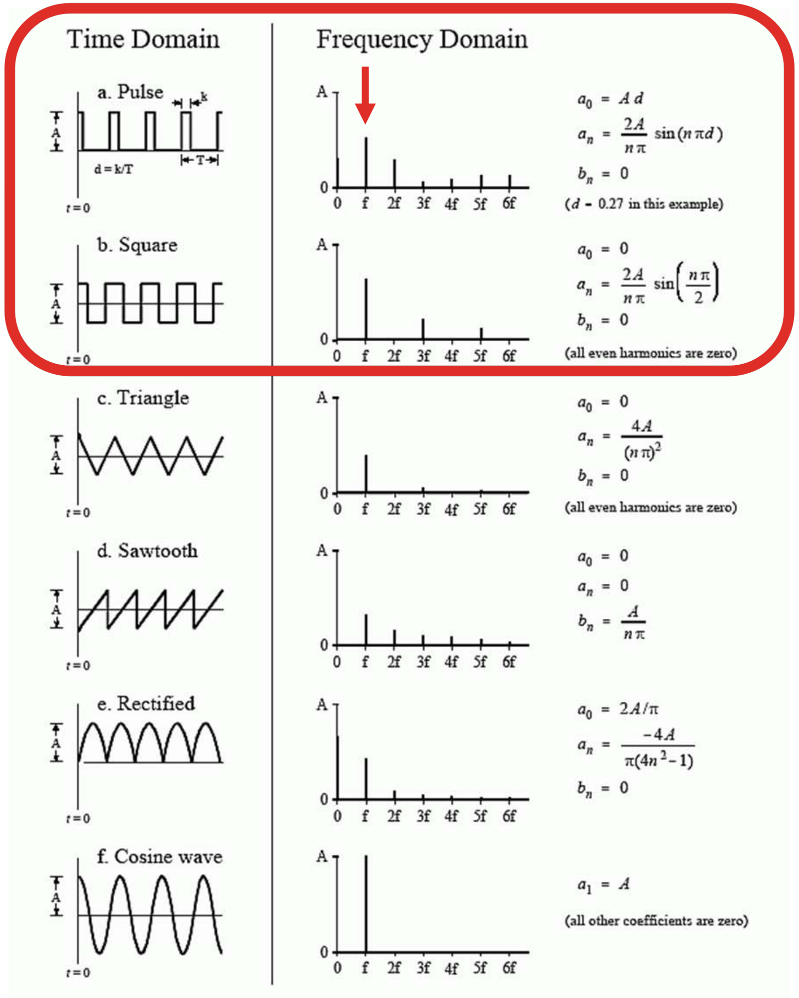
- First Harmonic Approximation



Digital Signal Processing
A Practical Guide for Engineers and Scientists
Chap 13

By Steven W. Smith

LLC uses first two waveforms only



Agenda

LLC design procedure

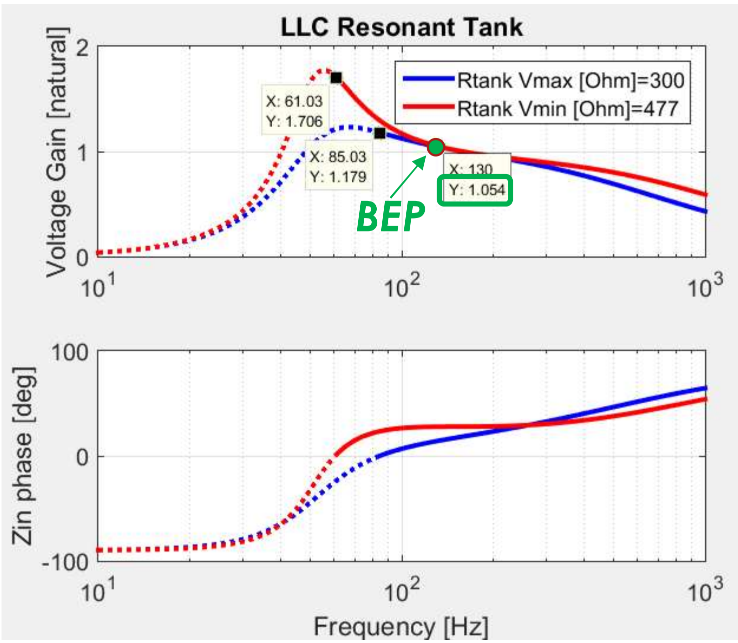
Requirements: Vin=52-32V; Vout=12V; Pout=25W; fmax=140kHz

HB input stage

- Fixing Issues at minimum bus

HB FHA Best entry gain

- ➢ If Vin = 52V than Vout tank = 52/2 x 4/pi x 1.05 = 34,76 V
- ➢ To work at min input we need a max gain of 34,76/(32/2 x 4/pi) = 1,7
- ➢ The maximum gain provided by Rtank equal to 300 Ohm is approx. 1.18



Rtank shall be increased!

To fix issues at minimum bus Rtank shall be increased from 300 Ohm to something around **477 Ohm** to get the needed gain of 1.7 !

Rtank =477 Ohm
L1=100mH
L2=900mH
C1=10uF
Frequency [**60** – 130] Hz.
Gain [1.05 – **1,7**]

Agenda

- Intro
- ZVS & ZCS
- LC combo
- LC series is the right way
- From Series LC to LLC
- **LLC Design**
- Inverter Input Stage
- Output rectifier Stage
- The Rac concept
- The transformer
- Scaling laws
- Results
- Graphical Approach
- Related Topics

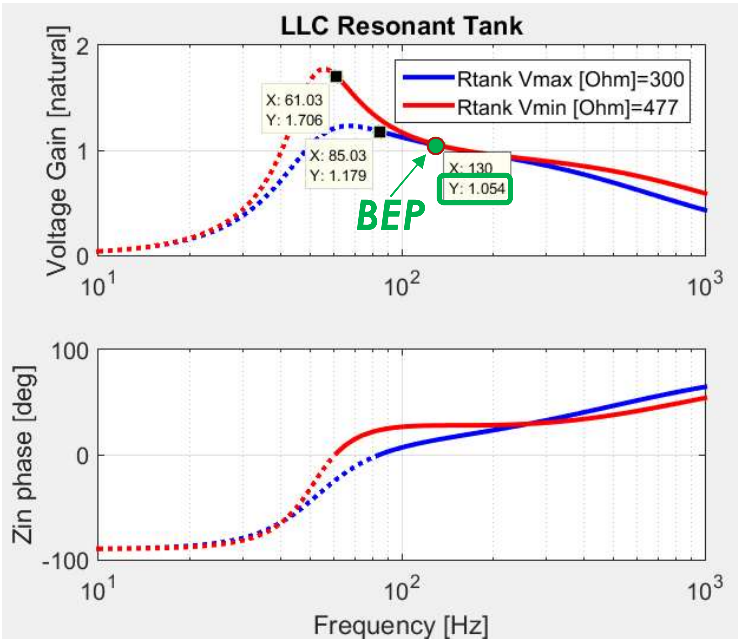
LLC design procedure

Requirements: Vin=52-32V; Vout=12V; Pout=25W; fmax=140kHz

HB input stage

- How much "peak" power does the tank source?

- ➢ If Vin = 52V than Vout tank = 52/2 x 4/pi x 1.05 = 34,76 V
- ➢ With Rtank = 300 → Pmax = Vout tank^2/ Rtank = 4 W **@ Vin max**
- ➢ With Rtank = 477→ Pmin = Vout tank^2/ Rtank = 2,53 W **@ Vin min**



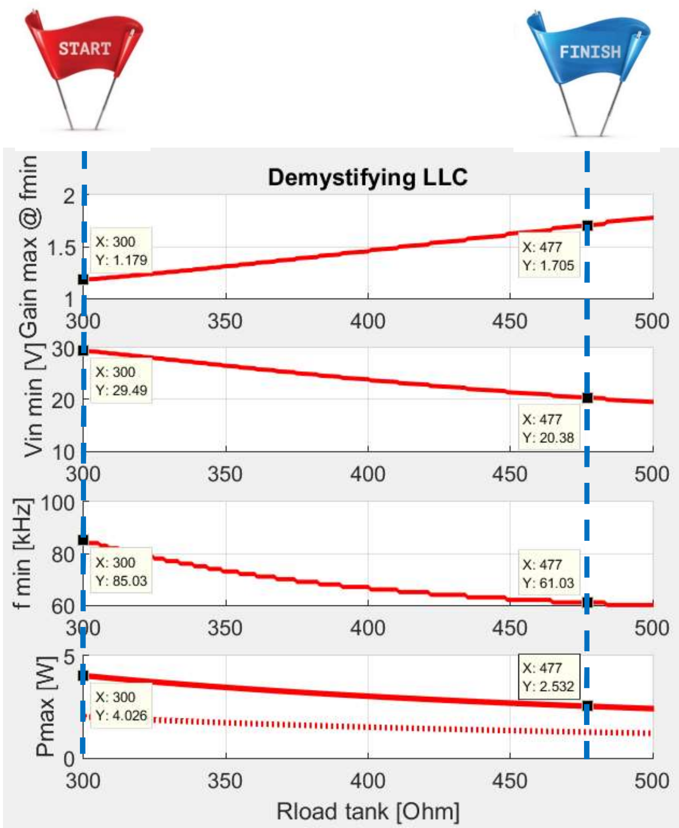
➢ **In which bus condition does the power requirement refer to?**

LLC design procedure

Requirements: Vin=52-32V; Vout=12V; Pout=25W; fmax=140kHz

- I like graphical solutions

➢ Previous calculations are confirmed by the plots below



Summarizing swinging from Bus max to Bus min we get:

Rtank:	[300 - 477] Ohm
Gain max	[1.18 – 1.7]
Vinmin FHA:	[29,5 – 20,4] V
fmin:	[85 – 61] Hz
Ppeak:	[4 – 2,5] W

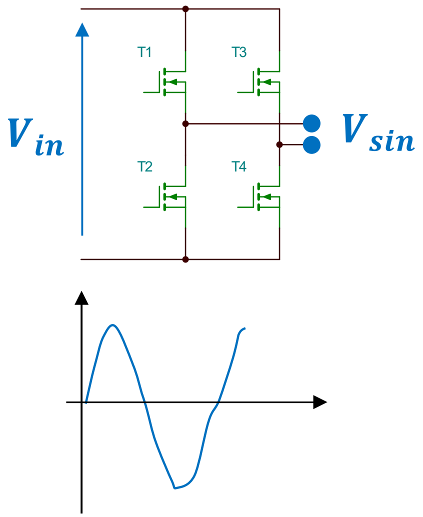
Agenda

- Intro
- ZVS & ZCS
- LC combo
- LC series is the right way
- From Series LC to LLC
- LLC Design
- **Inverter Input Stage**
- Output rectifier Stage
- The Rac concept
- The transformer
- Scaling laws
- Results
- Graphical Approach
- Related Topics

LLC design procedure

Requirements: Vin=52-32V; Vout=12V; Pout=25W; fmax=140kHz

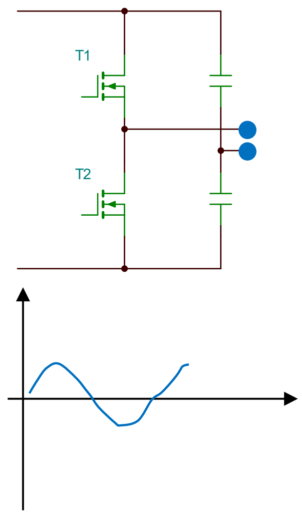
- Inverter Input stage can be divided in two main categories: HB or FB
- Whatever topology you pick be careful to correctly match the input stage with the LLC tank designed previously **(this affect the turn ratio!)**



FHA:

$$V_{sin\ AMPL} = \frac{4}{\pi} \cdot V_{in}$$

FULL BRIDGE

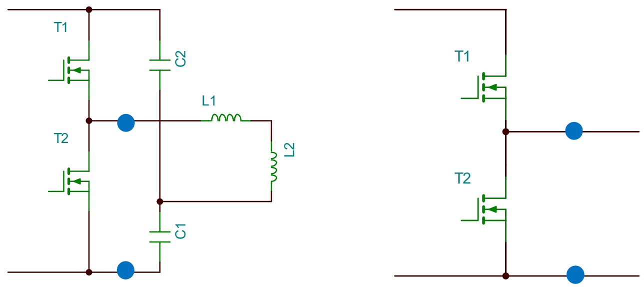


FHA:

$$V_{sin\ AMPL} = \frac{4}{\pi} \cdot \frac{V_{in}}{2}$$

HALF BRIDGE

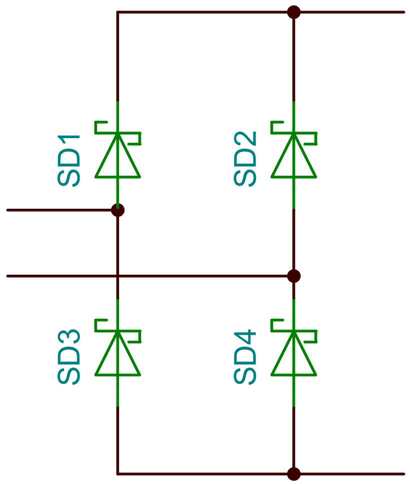
HB Variants



LLC design procedure

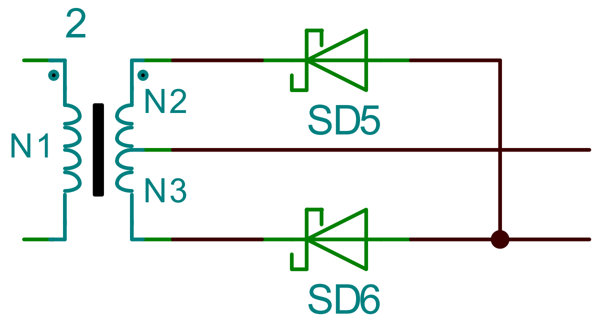
Requirements: Vin=52-32V; Vout=12V; Pout=25W; fmax=140kHz

- The output rectifier, as well as the input stage, exists in different ways



- **Full-Bridge Rectifier**
- Easier Magnetic

Use it for:
- High voltage
- Low Currents



- **Half-Bridge Rectifier**
- Harder Magnetic (Center tap)

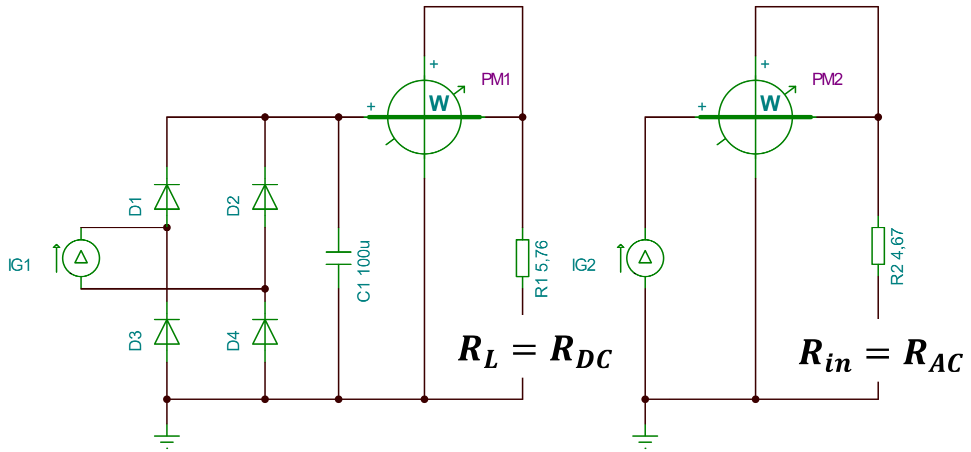
Use it for:
- High Currents
- Low Voltage

Agenda

LLC design procedure

Requirements: Vin=52-32V; Vout=12V; Pout=25W; fmax=140kHz

- The Rac Concept



$$P_{in\,bridge} = P_{out\,bridge}$$

$$R_{in} \cdot I_{rms}^2 = R_L \cdot I_{out\,DC}^2$$

$$R_{in} \cdot I_{rms}^2 = R_L \cdot \left(\frac{2}{\pi} \cdot I_{in\,peak}\right)^2$$

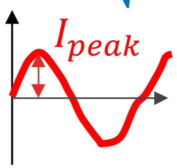
$$R_{in} \cdot I_{rms}^2 = R_L \cdot \left(\frac{2}{\pi} \cdot \sqrt{2} \cdot I_{rms}\right)^2$$

$$R_{in} = \frac{8}{\pi^2} \cdot R_L$$

➢ By keeping the same current excitation how much does the load resistor differ between the two circuits to get the same output DC power?

$$P_{dc} = R_{in} \cdot I_{rms}^2 = R_{in} \cdot \left(\frac{I_{peak}}{\sqrt{2}}\right)^2 \rightarrow I_{peak} = \sqrt{\frac{2P_{dc}}{R_{in}}} = \sqrt{\frac{2P_{dc}}{\frac{8}{\pi^2} \cdot R_L}} = \sqrt{\frac{\pi^2 \cdot P_{dc}}{4 \cdot R_L}} = \frac{\pi}{2}\sqrt{\frac{P_{dc}}{R_L}} = \frac{\pi}{2} \cdot \frac{P_{dc}}{V_{out}}$$

$$I_{peak} = \frac{\pi}{2} \cdot \frac{P_{dc}}{V_{out}} = \frac{\pi}{2} \cdot \frac{25}{12} = 3.27$$

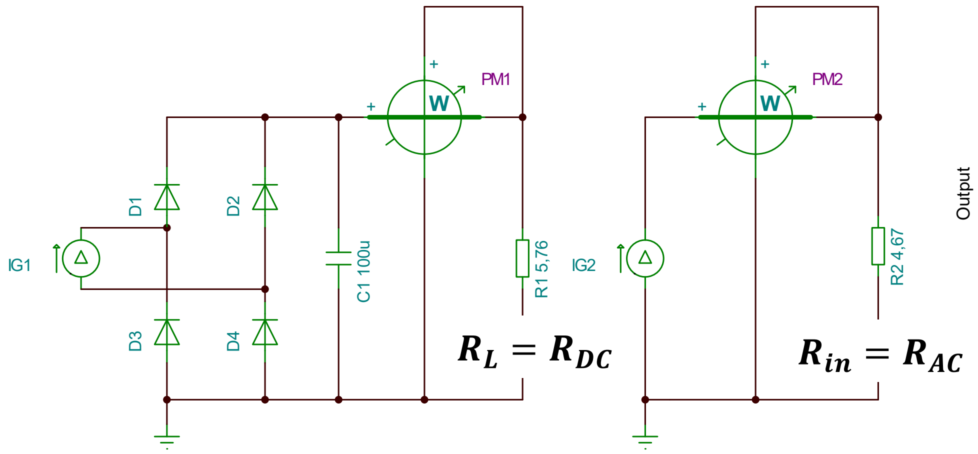


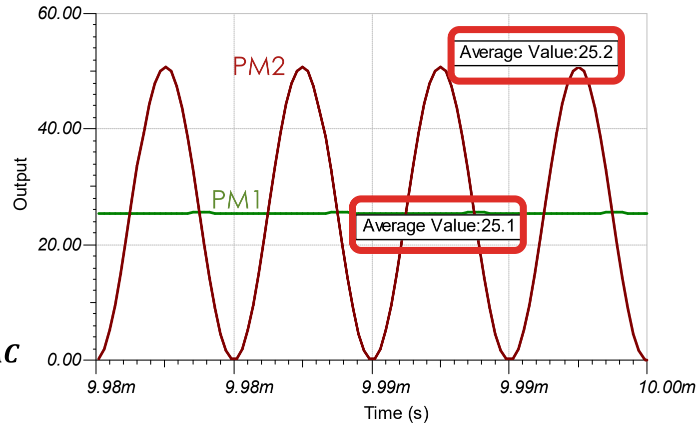
Valid for both circuits!

LLC design procedure

Requirements: Vin=52-32V; Vout=12V; Pout=25W; fmax=140kHz

- The Rac Concept





➢ Peak Power target at the bridge input is then 50W. **In which condition?**

➢ **What is the peak power we need to target at Vbus max?**
Back to basics

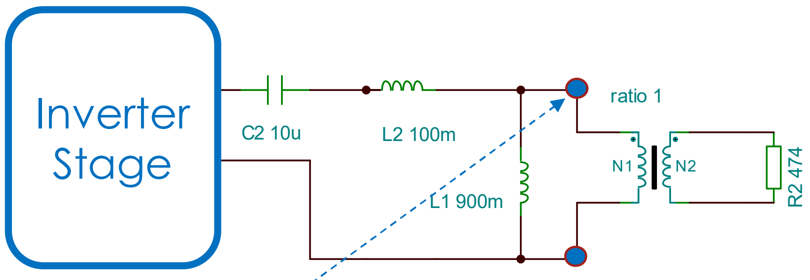
$$P_{max\,Vbus\,min} : P_{tank\,Vbus\,min} = X : P_{tank\,Vbus\,max}$$

50W : 2.53W = x : 4W → Peak power at Vbus max is : 50 x 4 / 2.53 = **80W! @Vmax**

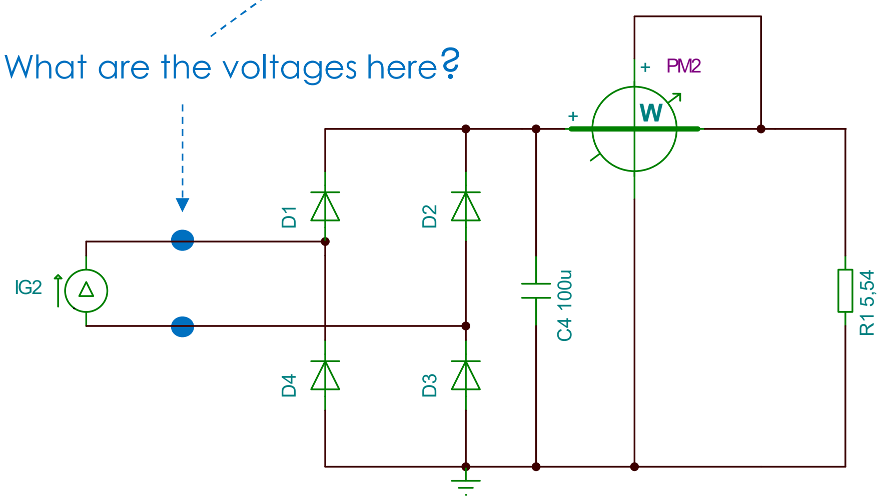
LLC design procedure

Requirements: Vin=52-32V; Vout=12V; Pout=25W; fmax=140kHz

- Inserting the output rectifier



What are the voltages here?



How to link them?
The transformer

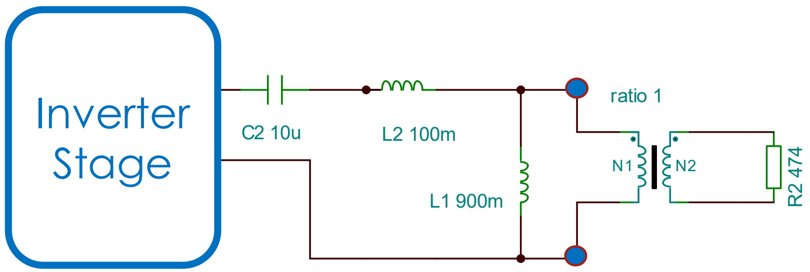
Agenda

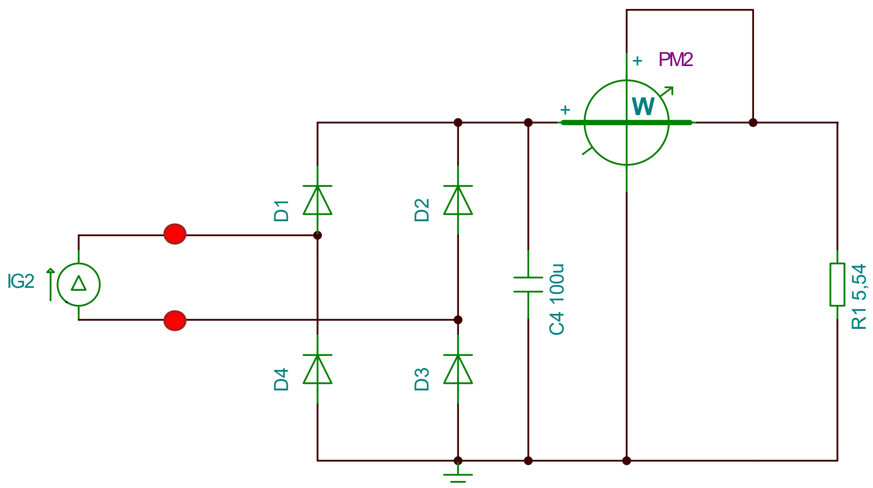
- Intro
- ZVS & ZCS
- LC combo
- LC series is the right way
- From Series LC to LLC
- LLC Design
- Inverter Input Stage
- Output rectifier Stage
- The Rac concept
- **The transformer**
- Scaling laws
- Results
- Graphical Approach
- Related Topics

LLC design procedure

Requirements: Vin=52-32V; Vout=12V; Pout=25W; fmax=140kHz

- Calculating the transformer turn ratio





Half Bridge + FHA on the primary

$V_{tank\ peak} = 34.75V$

Ohm's law on the secondary:

$V_{sec\ peak} = R_{in\ bridge} \cdot I_{peak\ sec} =$

$= R_{in\ bridge} \cdot \frac{\pi}{2} \cdot \frac{P_{dc}}{V_{out}} = \frac{8}{\pi^2} \cdot R_L \cdot \frac{\pi}{2} \cdot \frac{P_{dc}}{V_{out}} =$

$= \frac{8}{\pi^2} \cdot \frac{V_{out}^2}{P_{dc}} \cdot \frac{\pi}{2} \cdot \frac{P_{dc}}{V_{out}} = \frac{4}{\pi} \cdot V_{out} = 15.3$

$$\frac{V_{tank\ peak}}{V_{sec\ peak}} = \frac{N_1}{N_2} = \frac{34.75}{15.3} = 2.27$$

Or equivalently :

$$\boldsymbol{Turn\ ratio} = \frac{\boldsymbol{V_{in\ tank\ DC\ max} \cdot Gain_{best}}}{\boldsymbol{V_{out} + V_d}}$$

$$= \frac{\frac{52}{2} \cdot 1.05}{12} = 2.27$$

Agenda

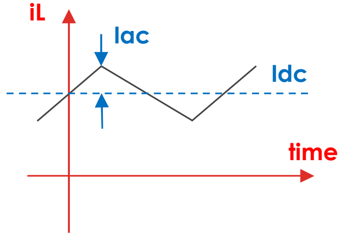
- Intro
- ZVS & ZCS
- LC combo
- LC series is the right way
- From Series LC to LLC
- LLC Design
- Inverter Input Stage
- Output rectifier Stage
- The Rac concept
- The transformer
- **Scaling laws**
- Results
- Graphical Approach
- Related Topics

LLC design procedure

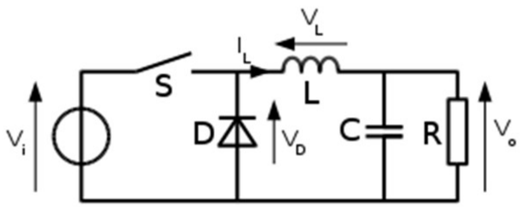
Requirements: Vin=52-32V; Vout=12V; Pout=25W; fmax=140kHz

- **Scaling Laws**

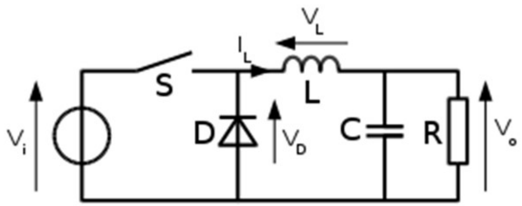
$$L = \frac{V_{out} \cdot (1-D)}{r \cdot f_{sw} \cdot I_{out}} \qquad C = \frac{I_{out} \cdot r}{8 \cdot f_{sw} \cdot \Delta V} \qquad r = \frac{2 \cdot I_{ac}}{I_{dc}}$$



Pointed out by S. Maniktala



$$P, \; L, \quad C, \quad E_1 = \frac{1}{2} \cdot L \cdot I^2$$



$$2 \cdot P, \; \frac{L}{2}, 2 \cdot C, \quad E_2 = \frac{1}{2} \cdot \frac{L}{2} \cdot (2I)^2 = L \cdot I^2 \rightarrow E_2 = 2 \cdot E_1$$

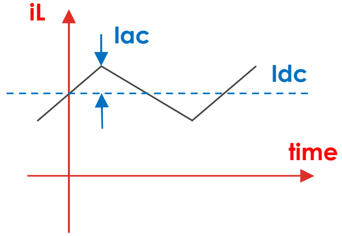
x2 Power means:
L value /2
L size x2

LLC design procedure

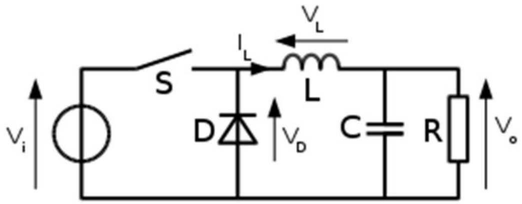
Requirements: Vin=52-32V; Vout=12V; Pout=25W; fmax=140kHz

- **Scaling Laws**

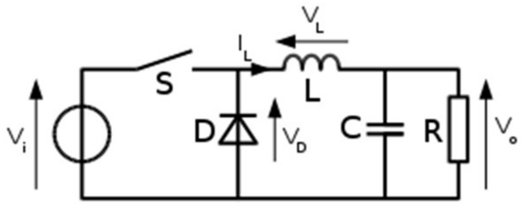
$$L = \frac{V_{out} \cdot (1-D)}{r \cdot f_{sw} \cdot I_{out}} \qquad C = \frac{I_{out} \cdot r}{8 \cdot f_{sw} \cdot \Delta V} \qquad r = \frac{2 \cdot I_{ac}}{I_{dc}}$$



Pointed out by S. Maniktala



$$f, \; L, \quad C, \quad \boxed{E_1 = \frac{1}{2} \cdot L \cdot I^2}$$



$$2 \cdot f, \; \frac{L}{2}, \; \frac{C}{2}, \quad E_2 = \frac{1}{2} \cdot \frac{L}{2} \cdot I^2 \rightarrow \boxed{E_2 = \frac{E_1}{2}}$$

What happens to the L size if I double both power and frequency?

x2 frequency means:
L value /2
L size /2

LLC design procedure

Requirements: Vin=52-32V; Vout=12V; Pout=25W; fmax=140kHz

- Calculating the frequency scaling factor

Does kf change?

Scaling Mirror		
	L	C
Frequency x k_f	L/k_f	C/k_f
Power x k_p	L/k_p	C $\cdot$ k_p

$$k_{f\ scaling} = \frac{f_{max\ design}}{f_{res\ HI}} = \frac{f_{max\ design}}{\frac{1}{2\pi\sqrt{L_1 \cdot C_1}}} = \frac{f_{max\ design}}{\frac{1}{2\pi\sqrt{100m \cdot 10u}}} = \frac{140k}{159.155} = \mathbf{880}$$

or

$$k_{f\ scaling} = \frac{f_{min\ design}}{f_{res\ LOW}} = \frac{\left(f_{max\ design}/\sqrt{1+\frac{L_2}{L_1}}\right)}{\frac{1}{2\pi \cdot \sqrt{(L_1+L_2)C_1}}} \overset{m=\frac{L_2}{L_1}}{\Longrightarrow} \frac{f_{max\ design}}{\sqrt{1+m}} \cdot 2\pi \cdot \sqrt{(L_1 + m \cdot L_1)C_1} =$$

$$f_{max\ design} \cdot 2\pi \cdot \sqrt{L_1 \cdot C_1} = f_{max\ design} \cdot \frac{1}{f_{res\ HI}} = \mathbf{880} \rightarrow \textbf{\textit{same as above}}!$$

Agenda

- Intro
- ZVS & ZCS
- LC combo
- LC series is the right way
- From Series LC to LLC
- LLC Design
- Inverter Input Stage
- Output rectifier Stage
- The Rac concept
- The transformer
- **Scaling laws**
- Results
- Graphical Approach
- Related Topics

LLC design procedure

Requirements: Vin=52-32V; Vout=12V; Pout=25W; fmax=140kHz

- Calculating the power scaling factor:

Does kp change?

Scaling Mirror		
	L	C
Frequency x k_f	L/k_f	C/k_f
Power x k_p	L/k_p	C $\cdot$ k_p

$$k_{p\ scaling} = \frac{P_{peak\ max\ design}}{P_{max\ tank}} = \frac{80}{4} = \mathbf{20}$$

or

$$k_{p\ scaling} = \frac{P_{peak\ min\ design}}{P_{mix\ tank}} = \frac{50}{2.5} = \mathbf{20}!$$

Agenda

LLC design procedure

Requirements: Vin=52-32V; Vout=12V; Pout=25W; fmax=140kHz

- Calculating effective values:

Scaling Mirror		
	L	C
Frequency x k_f	L/k_f	C/k_f
Power x k_p	L/k_p	C $\cdot$ k_p

$$L_{1\,real} = \frac{L1}{k_f \cdot k_p} = \frac{100m}{880 \cdot 20} = 5.7\ uH$$

$$L_{2\,real} = \frac{L2}{k_f \cdot k_p} = \frac{900m}{880 \cdot 20} = 51.5\ uH$$

$$C_{1\,real} = \frac{C1}{k_f} \cdot k_p = \frac{10u \cdot 20}{880} = 225\ nF$$

Resonances scale accordingly:

$$f_{low} = \frac{1}{2\pi\sqrt{(L_1 + L_2) \cdot C1}} = 44.2\ kHz$$

$$f_{high} = \frac{1}{2\pi\sqrt{L_1 \cdot C1}} = 140\ kHz$$

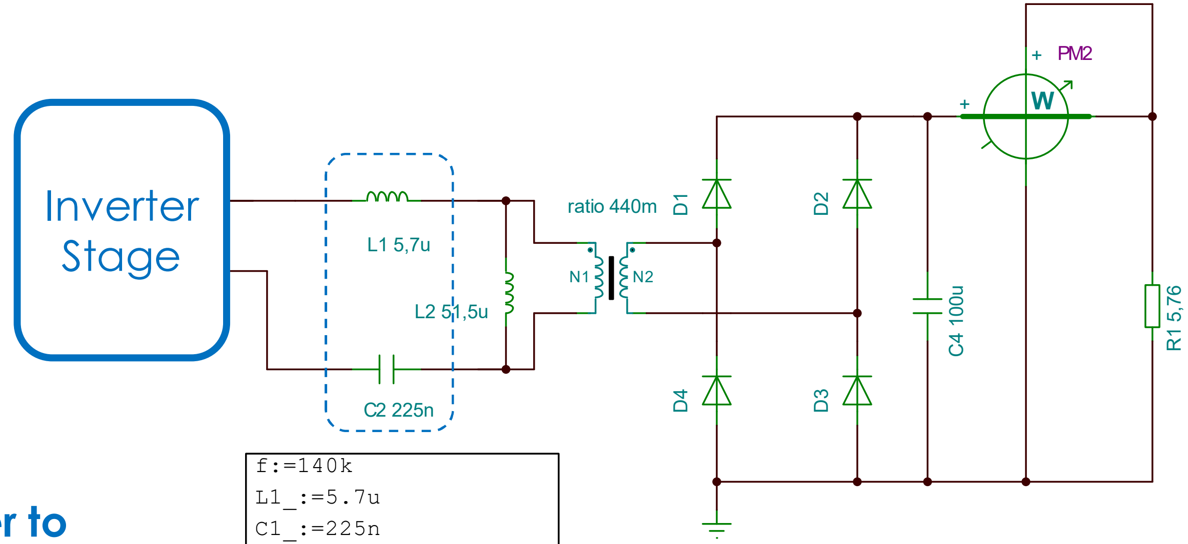
Agenda

- Intro
- ZVS & ZCS
- LC combo
- LC series is the right way
- From Series LC to LLC
- LLC Design
- Inverter Input Stage
- Output rectifier Stage
- The Rac concept
- The transformer
- **Scaling laws**
- Results
- Graphical Approach
- Related Topics

LLC design procedure

Requirements: Vin=52-32V; Vout=12V; Pout=25W; fmax=140kHz

- Assembling all stages balancing transformer terminals



Remember to balance transformer terminals
Layout Critical!

```
f:=140k
L1_:=5.7u
C1_:=225n
Cbridge:=500u

Zc:=1/(2.pi.f.C1_)
Zl:=2.pi.f.L1_
ZcB:=1/(2.pi.f.Cbridge)

Zc=[5.0525]
Zl=[5.014]
ZcB=[2.2736m]
```

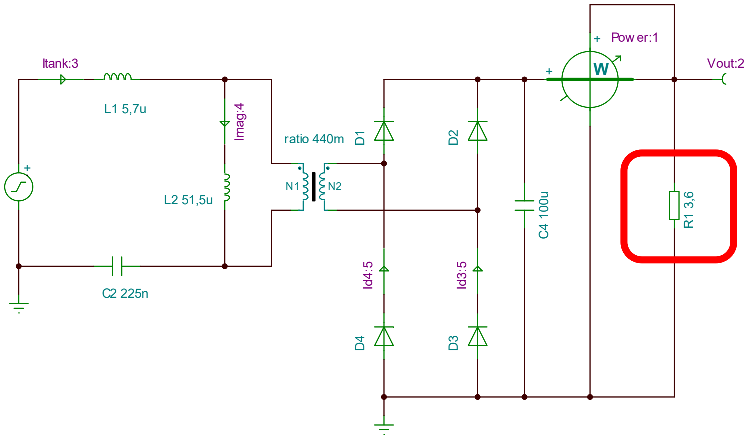
Agenda

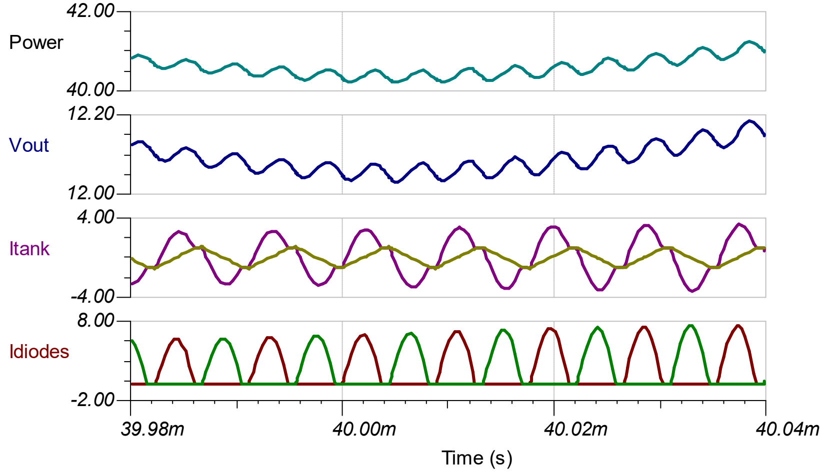
- Intro
- ZVS & ZCS
- LC combo
- LC series is the right way
- From Series LC to LLC
- LLC Design
- Inverter Input Stage
- Output rectifier Stage
- The Rac concept
- The transformer
- Scaling laws
- **Results**
- Graphical Approach
- Related Topics

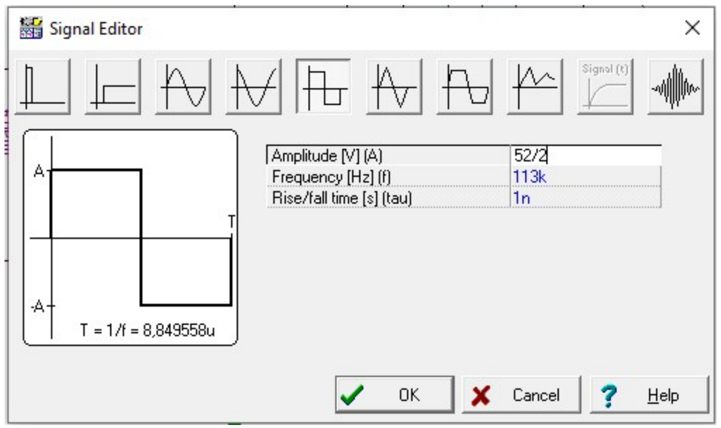
LLC design procedure

Requirements: Vin=52-32V; Vout=12V; Pout=25W; fmax=140kHz

- Waveforms: Max Bus @ 40 W DC Power







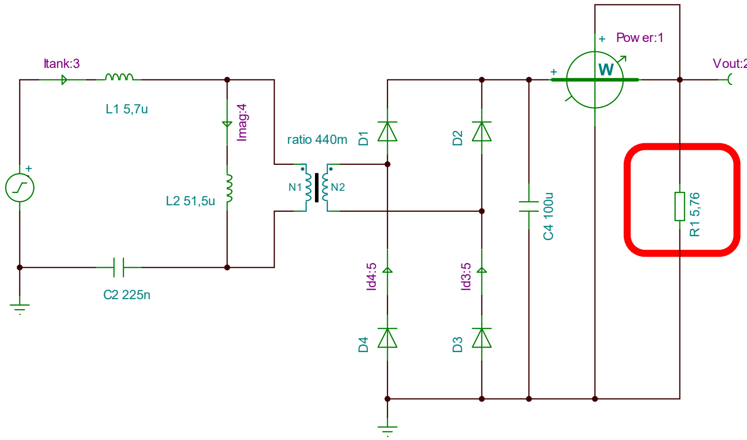
Agenda

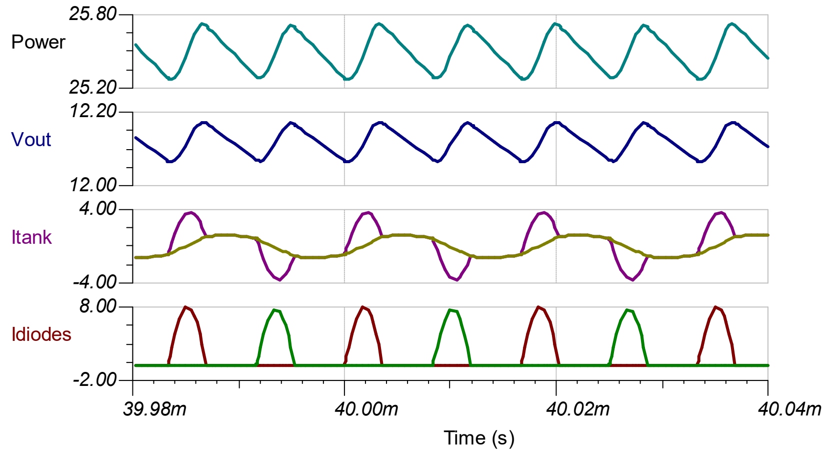
- Intro
- ZVS & ZCS
- LC combo
- LC series is the right way
- From Series LC to LLC
- LLC Design
- Inverter Input Stage
- Output rectifier Stage
- The Rac concept
- The transformer
- Scaling laws
- **Results**
- Graphical Approach
- Related Topics

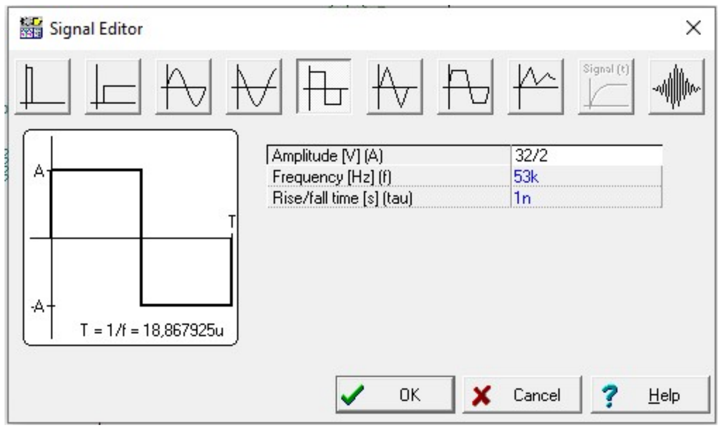
LLC design procedure

Requirements: Vin=52-32V; Vout=12V; Pout=25W; fmax=140kHz

- Waveforms: Min Bus @ 25 W DC Power







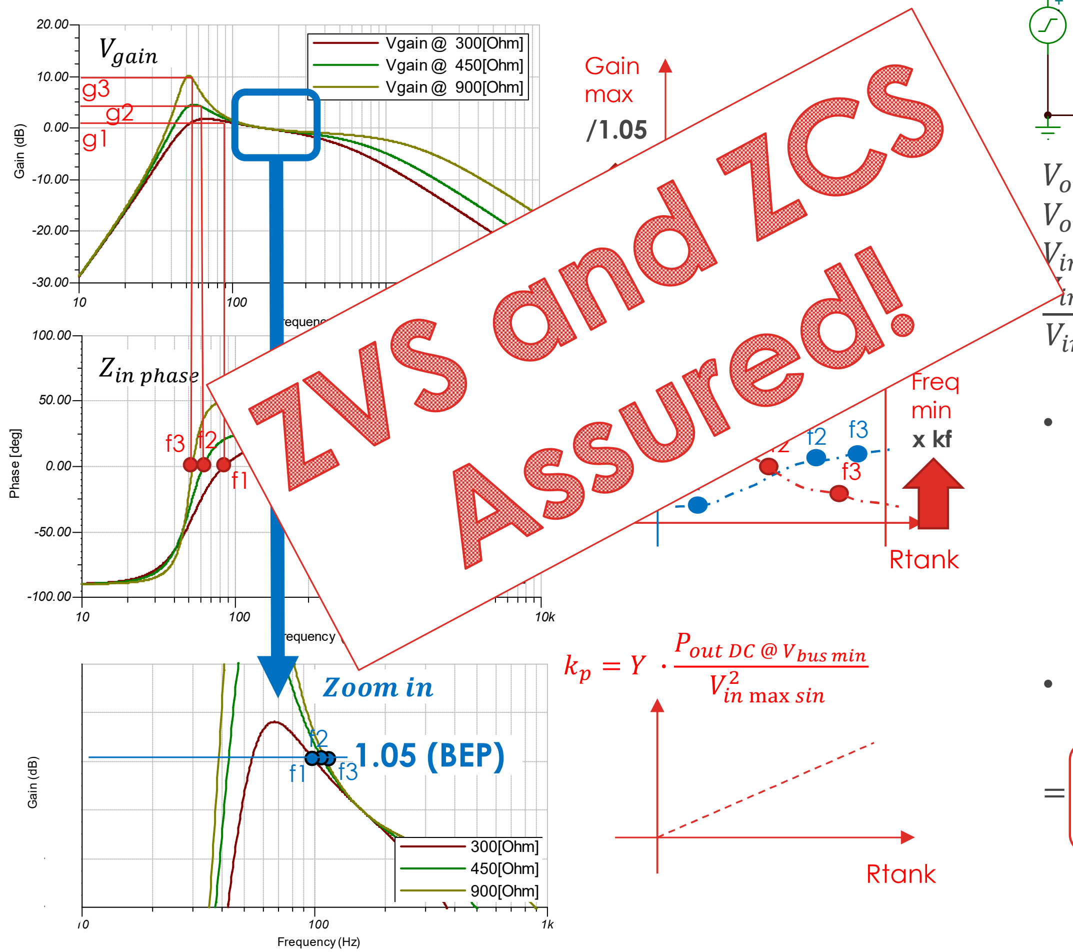
- FHA is not precise @ Vbus min.
- **Vout@53kHz was high! The controller corrected the frequency at 60kHz to lower the tank gain!**

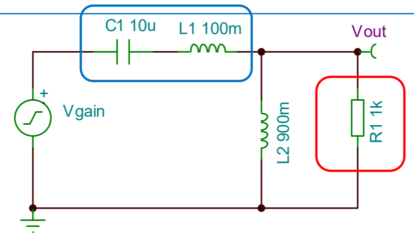
LLC design procedure
Graphical Approach

Let's try with a real example!

Agenda

- Graphical approach: **Kill the design in 1minute**





$$V_{out\ tank} = V_{in\ max} \cdot 1.05$$
$$V_{out\ tank} = V_{in\ min} \cdot Gain_{max}$$
$$V_{in\ max} \cdot Gain_{best} = V_{in\ min} \cdot Gain_{max}$$
$$\frac{V_{in\ max}}{V_{in\ min}} = \frac{Gain_{max}}{1.05}$$

- $k_f = \frac{f_{max\ requirement}}{f_{res\ HI\ LLC\ seed}}$

- $k_p = \frac{P_{in\ peak\ bridge\ @\ V_{bus\ min}}}{P_{out\ peak\ tank}} = \frac{2 \cdot P_{out\ DC\ @\ V_{bus\ min}}}{\frac{\left(V_{in\ max} \frac{4}{\pi} \cdot 1.05\right)^2}{R_{tank\ max}}}$

$$= R_{tank} \cdot \frac{2}{(1.05)^2} \cdot \frac{P_{out\ DC\ @\ V_{bus\ min}}}{V^2_{in\ max\ sin}}$$

Y

Pointed out By me

Agenda

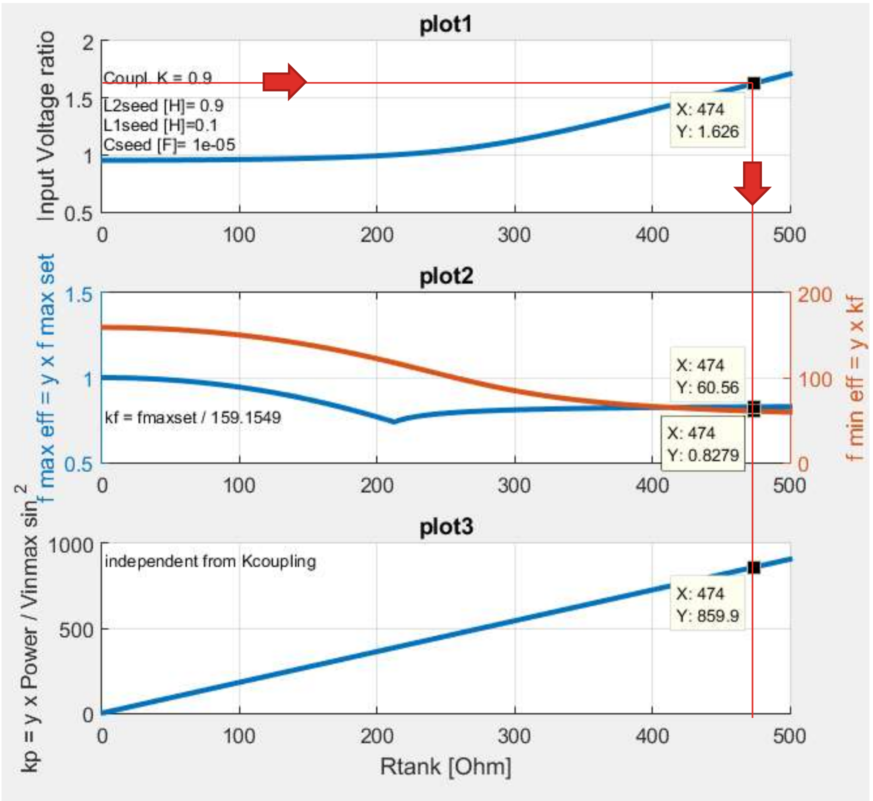
- Intro
- ZVS & ZCS
- LC combo
- LC series is the right way
- From Series LC to LLC
- LLC Design
- Inverter Input Stage
- Output rectifier Stage
- The Rac concept
- The transformer
- Scaling laws
- Results
- **Graphical Approach**
- Related Topics

Pointed out By me

LLC design procedure

Requirements: Vin=52-32V; Vout=12V; Pout=25W; fmax=140kHz

- I like graphical solutions
- **Example 1 : Same requirements**



- $\frac{V_{in\,max}}{V_{in\,min}} = \frac{52}{32} = 1.625 \rightarrow$ From plot 1 Rtank = 474 Ohm.
- From plot 2, setting Rtank = 474 Ohm, we get three info:

  a) $k_{f\,scaling} = \frac{140k}{159.155} = 879.64 \approx 880$

  b) (blue graph) fmax eff = y · fmax set = 0.828 · 140k = 116 kHz. Frequency at which the gain module is 1.05 (Iload max, Vin max) – best entry point!

  c) (red graph) fmin eff = $k_{f\,scaling}$ · y = 880 · 60.56 = 53.7 kHz. Frequency at which the tank gain is max at required Vin min. Here the gain is (bullet 1) · 1.05 = $\frac{V_{in\,max}}{V_{in\,min}} \cdot 1.05 = 1.625 \cdot 1.05 = 1.7$

- From plot 3 we get : $k_{p\,scaling} = 860 \cdot \frac{P}{(V_{in\,max\,tank\,sin})^2} = 860 \cdot \frac{25}{(33.1)^2} \approx 20$. Applying scaling laws:

  $L1 = \frac{L1_{seed}}{k_f \cdot k_p} = 5.7uH$; $L2 = \frac{L2_{seed}}{k_f \cdot k_p} = 51.32uH$;

  $C = \frac{C_{seed}}{k_f} \cdot k_p = 226nF;$

- $Turn\ ratio = \frac{V_{in\,tank\,DC} \cdot Gain_{best}}{V_{out}} = \frac{N_1}{N_2} = \frac{\frac{52}{2}}{12} \cdot 1.05 = 2.275$
- $R_{load\,max} = \frac{V_{out}^2}{P_{out}} = \frac{144}{25} = 5.76;$
- $C_{out\,max} = \frac{V_{out}}{R_{load} \cdot f_{sw\,min} \cdot \Delta V_{ripple}} = 395u$

Same results as the previous 36 slides !

Agenda

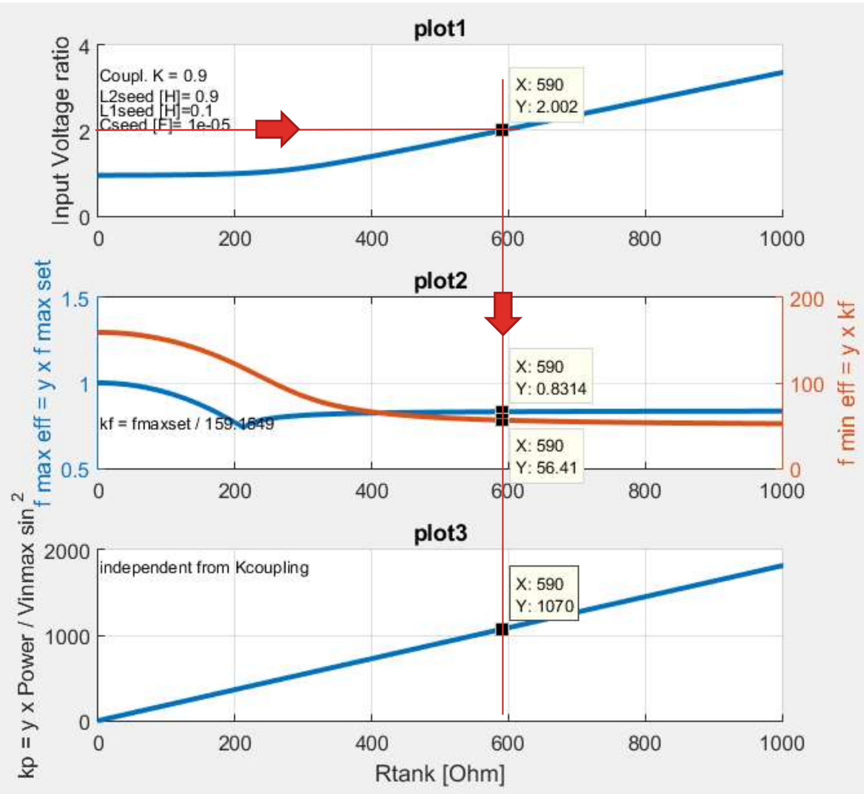
- Intro
- ZVS & ZCS
- LC combo
- LC series is the right way
- From Series LC to LLC
- LLC Design
- Inverter Input Stage
- Output rectifier Stage
- The Rac concept
- The transformer
- Scaling laws
- Results
- **Graphical Approach**
- Related Topics

Pointed out By me

LLC design procedure

Requirements: Vin=200-400V; Vout=800V; Pout 14kW; fmax=50kHz

- **Example 2: requirements by Илия Хаджиев (Iliya Hadjiev)**



- $\frac{V_{in\,max}}{V_{in\,min}} = \frac{400}{200} = 2 \rightarrow$ From plot 1 Rtank = 590 Ohm.
- From plot 2, setting Rtank = 590 Ohm, we get three info:

  a) $k_{f\ scaling} = \frac{50}{159.155} \approx 314.16$

  b) (blue graph) fmax eff = y · fmax set = 0.83 · 50k = 41.5kHz. Frequency at which the gain module is 1.05 (Iload max, Vin max)

  c) (red graph) fmin eff = $k_{f\ scaling}$ · y = 56.1 · 314.16= 17.6 kHz. Frequency at which the tank gain is max at required Vin min. Here the gain is (bullet 1) · 1.05 = $\frac{V_{in\,max}}{V_{in\,min}} \cdot 1.05 = 2 \cdot 1.05 = 2.1$

- From plot 3 we get : $k_{p\ scaling} = 1070 \cdot \frac{P}{(V_{in\ max\ tank\ sin})^2} = 1070 \cdot \frac{14k}{(254.64)^2} \approx 231$. Applying scaling laws:

  $L1 = \frac{L1_{seed}}{k_f \cdot k_p} = 1.4uH$; $L2 = \frac{L2_{seed}}{k_f \cdot k_p} = 12.4uH$;

  $C = \frac{C_{seed}}{k_f} \cdot k_p = 7.35uF$;

- $Turn\ ratio = \frac{V_{in\ tank\ DC} \cdot Gain_{best}}{V_{out}} = \frac{N_1}{N_2} = \frac{\frac{400}{2}}{800} \cdot 1.05 = 0.262$
- $R_{load\ max} = \frac{V_{out}^2}{P_{out}} = \frac{800^2}{14k} = 45.7$;
- $C_{out\ max} = \frac{V_{out}}{R_{load} \cdot f_{sw\ min} \cdot \Delta V_{ripple\ (1V)}} = 1mF$

… going directly with 3 plots…

Agenda

- Intro
- ZVS & ZCS
- LC combo
- LC series is the right way
- From Series LC to LLC
- LLC Design
- Inverter Input Stage
- Output rectifier Stage
- The Rac concept
- The transformer
- Scaling laws
- Results
- **Graphical Approach**
- Related Topics

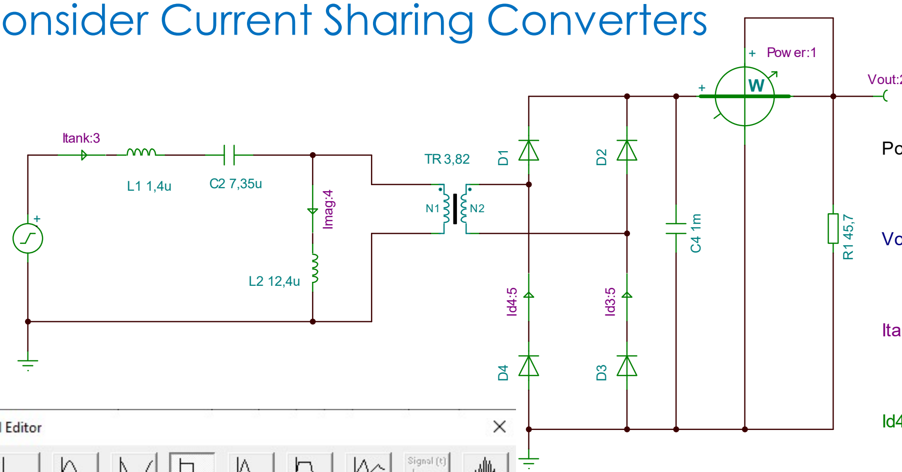
LLC design procedure

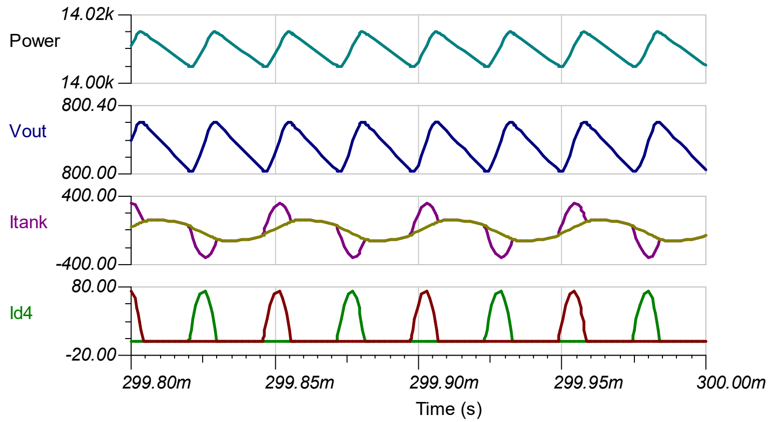
Requirements: Vin=200-400V; Vout=800V; Pout=14kW; fmax=50kHz

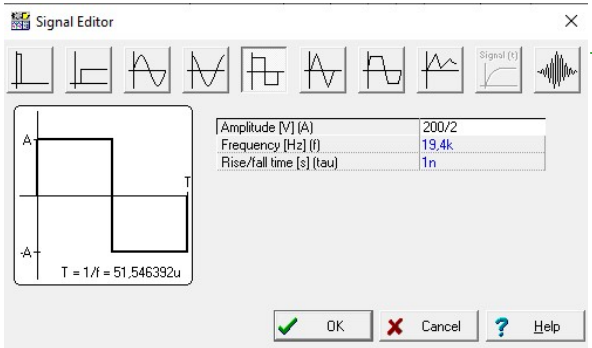
- Waveforms: Min Bus @ 14 kW DC Power

Notes:

- ➢ You're boosting the voltage! Reversing ZVS to sec AND ZCS to pri. could help.
- ➢ Careful to the controller direction of correction
- ➢ Consider Current Sharing Converters







LLC design procedure

Requirements: Vin=40-56V; Vout=48V; Pout=200W; fmin=200kHz

- **Example 3: requirements by Ray Ridley**

➢ Both resonances are related by the following formula:

$$\frac{f_{res\ HI}}{f_{res\ LOW}} = \frac{\frac{1}{2\pi\sqrt{L_1 \cdot C_1}}}{\frac{1}{2\pi\sqrt{(L_1 + L2)\cdot C_1}}} = \frac{\frac{1}{\sqrt{L_1}}}{\frac{1}{\sqrt{L_1 + L2}}} = \frac{\sqrt{L_1 + L2}}{\sqrt{L_1}} \rightarrow \frac{f_{res\ HI}}{f_{res\ low}} = \sqrt{1 + \frac{L_2}{L_1}}$$

➢ Targeting fmin = 200kHz means $f_{max} = f_{min} \cdot \sqrt{1 + \frac{L2}{L_1}}$ whatever inductance ratio you pick.

➢ Here $\boldsymbol{m} = \frac{\boldsymbol{L_2}}{\boldsymbol{L_1}} = \boldsymbol{6} \rightarrow f_{max} = 200k \cdot \sqrt{1+6} \approx 530kHz$

➢ **Resonances will be at 200kHz and 530kHz. Our working frequency range will fall inside these extrema.**

➢ Low inductance ratio means lower frequency working range but higher circulating currents and viceversa!

Agenda

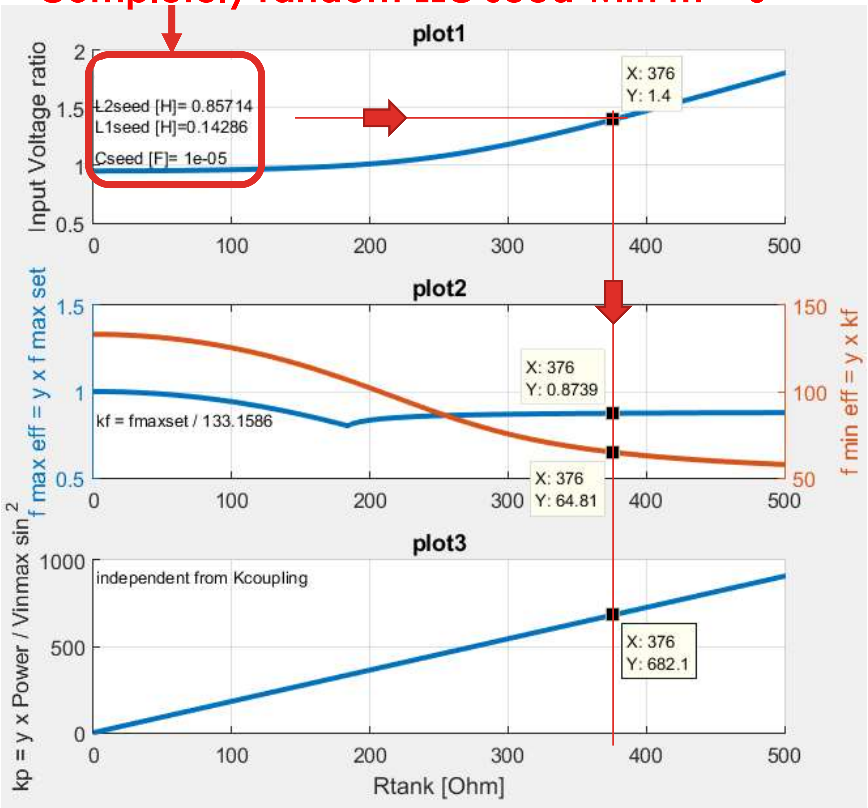
- Intro
- ZVS & ZCS
- LC combo
- LC series is the right way
- From Series LC to LLC
- LLC Design
- Inverter Input Stage
- Output rectifier Stage
- The Rac concept
- The transformer
- Scaling laws
- Results
- **Graphical Approach**
- Related Topics

LLC design procedure

Requirements: Vin=40-56V; Vout=48V; Pout=200W; fmax=530kHz

- **Example 3: requirements by Ray Ridley**

Completely random LLC seed with m = 6



- $\frac{V_{in\,max}}{V_{in\,min}} = \frac{56}{40} = 1.4 \rightarrow$ From plot 1 Rtank = 376 Ohm.
- From plot 2, setting Rtank = 376 Ohm, we get three info:

  a) $k_{f\,scaling} = \frac{530}{133.16} \approx 3980.2$

  b) (blue graph) fmax eff = y · fmax set = 0.874 · 530k = 463 kHz. Frequency at which the gain module is 1.05 (Iload max, Vin max)

  c) (red graph) fmin eff = $k_{f\,scaling} \cdot$ y = 3980.2 · 64.81 = 258 kHz. Frequency at which the tank gain is max at required Vin min. Here the gain is (bullet 1) · 1.05 = $\frac{V_{in\,max}}{V_{in\,min}} \cdot 1.05 = 1.4 \cdot 1.05 = 1.47$
- From plot 3 we get : $k_{p\,scaling} = 682 \cdot \frac{P}{(V_{in\,max\,tank\,sin})^2} = 682 \cdot \frac{200}{\left(\frac{56}{2} \cdot \frac{4}{\pi}\right)^2} \approx 107.32$. Applying scaling laws:

  $L1 = \frac{L1_{seed}}{k_f \cdot k_p} = 334.44\,nH\,;\; L2 = \frac{L2_{seed}}{k_f \cdot k_p} = 2\,uH\,;$

  $C = \frac{C_{seed}}{k_f} \cdot k_p = 270\,nF;$

- $Turn\ ratio = \frac{V_{in\,tank\,DC} \cdot Gain_{best}}{V_{out}} = \frac{N_1}{N_2} = \frac{\frac{56}{2}}{48} \cdot 1.05 = 0.6125$
- $R_{load\,max} = \frac{V_{out}^2}{P_{out}} = \frac{48^2}{200} = 11.52;$
- $C_{out\,max} = \frac{V_{out}}{R_{load} \cdot f_{sw\,min} \cdot \Delta V_{ripple}} \approx 200\,uF$

… going directly with 3 plots…

Agenda

- Intro
- ZVS & ZCS
- LC combo
- LC series is the right way
- From Series LC to LLC
- LLC Design
- Inverter Input Stage
- Output rectifier Stage
- The Rac concept
- The transformer
- Scaling laws
- Results
- **Graphical Approach**
- Related Topics

LLC design procedure

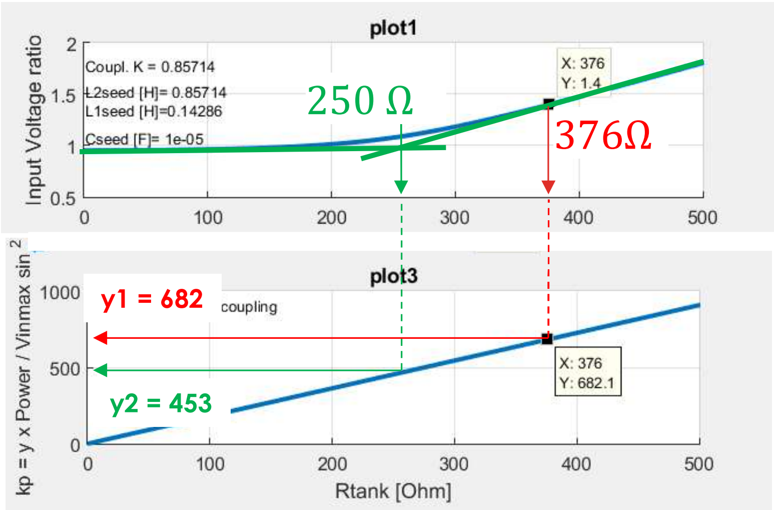
Requirements: Vin=40-56V; Vout=48V; Pout=200W; fmax=530kHz

- Example 3: requirements by Ray Ridley

➢ DC power @ Vmin is 200W

➢ What is the power we can source @ Vmax ?

kp cannot Change!



$$k_{p\ scaling} = 682 \cdot \frac{P}{(V_{in\ max\ tank\ sin})^2} = 107.32$$

$$k_p = y_2 \cdot \frac{P_{out\ DC\ @\ V_{bus\ max}}}{\left(V_{in\ max\ DC} \cdot \frac{4}{\pi}\right)^2}$$

$$\rightarrow P_{max} = \frac{k_p}{y_2} \cdot V^2_{in\ max\ sin} = \frac{107.32}{453.5} \cdot \left(\frac{56}{2} \cdot \frac{4}{\pi}\right)^2 = 300\ W$$

$$k_p = y_1 \cdot \frac{P_{out\ DC\ @\ V_{bus\ min}}}{\left(V_{in\ max\ DC} \cdot \frac{4}{\pi}\right)^2}$$

$$\rightarrow P_{min} = \frac{k_p}{y_1} \cdot V^2_{in\ max\ sin} = \frac{107.32}{682.1} \cdot \left(\frac{56}{2} \cdot \frac{4}{\pi}\right)^2 = 200W$$

Output DC power range is: [200W – 300W] !

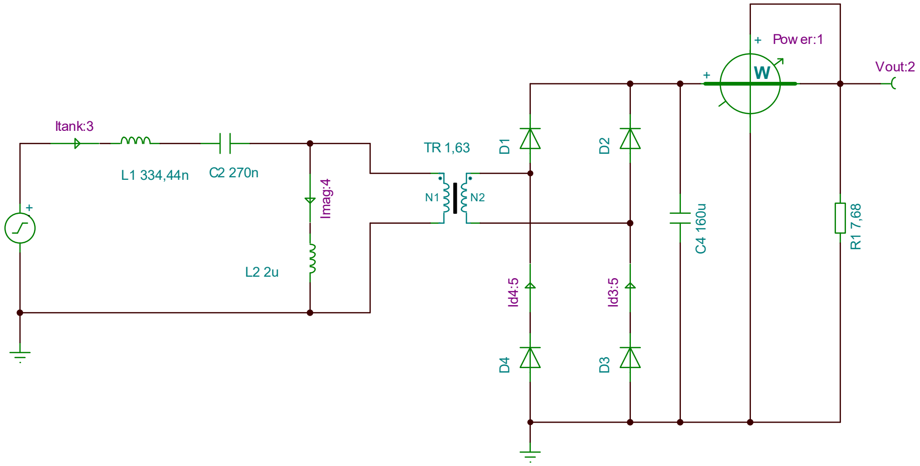
Agenda

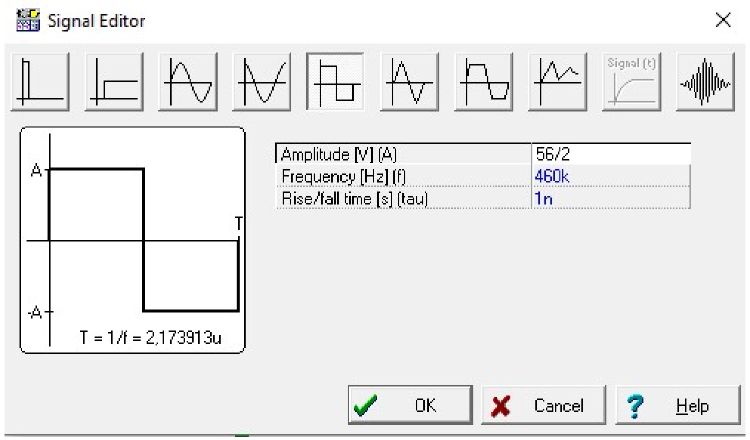
- Intro
- ZVS & ZCS
- LC combo
- LC series is the right way
- From Series LC to LLC
- LLC Design
- Inverter Input Stage
- Output rectifier Stage
- The Rac concept
- The transformer
- Scaling laws
- Results
- **Graphical Approach**
- Related Topics

LLC design procedure

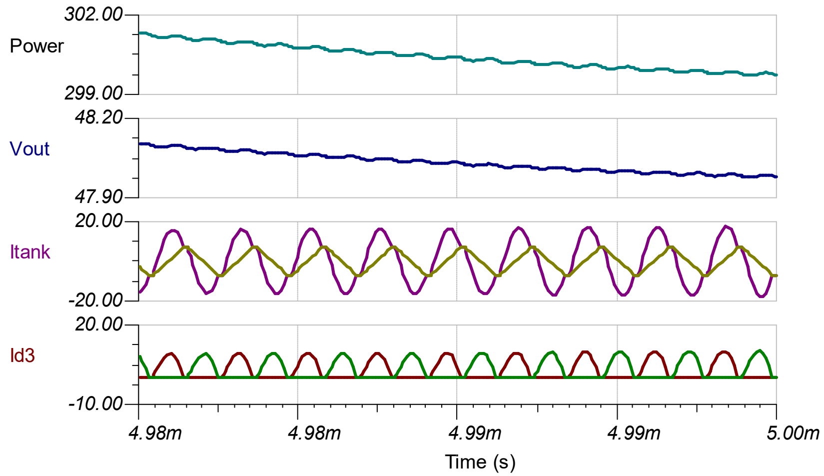
Requirements: Vin=40-56V; Vout=48V; Pout=200W; fmax=530kHz

- Example 3: requirements by Ray Ridley





- Max bus, Max Power



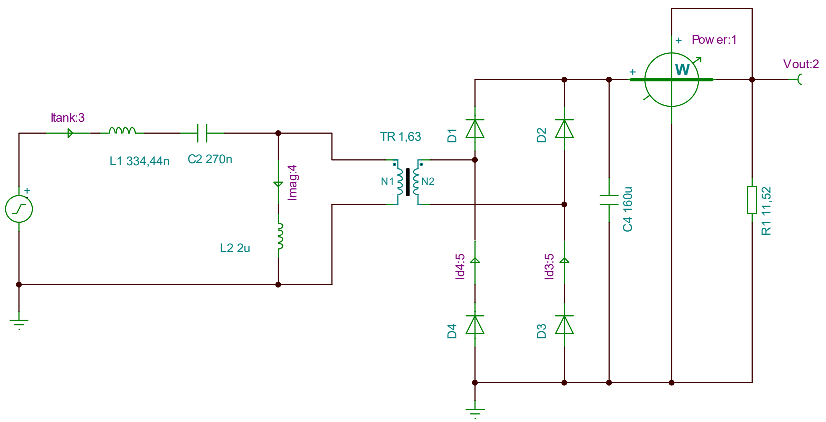
Agenda

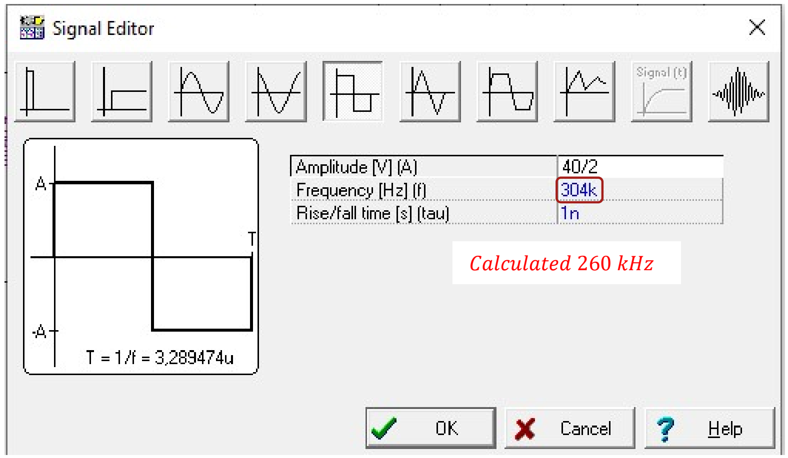
- Intro
- ZVS & ZCS
- LC combo
- LC series is the right way
- From Series LC to LLC
- LLC Design
- Inverter Input Stage
- Output rectifier Stage
- The Rac concept
- The transformer
- Scaling laws
- Results
- **Graphical Approach**
- Related Topics

LLC design procedure

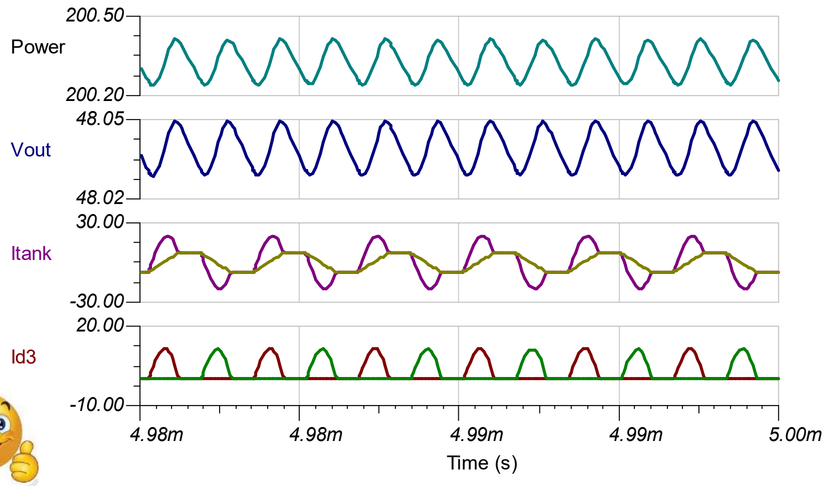
Requirements: Vin=40-56V; Vout=48V; Pout=200W; fmax=530kHz

- Example 3: requirements by Ray Ridley





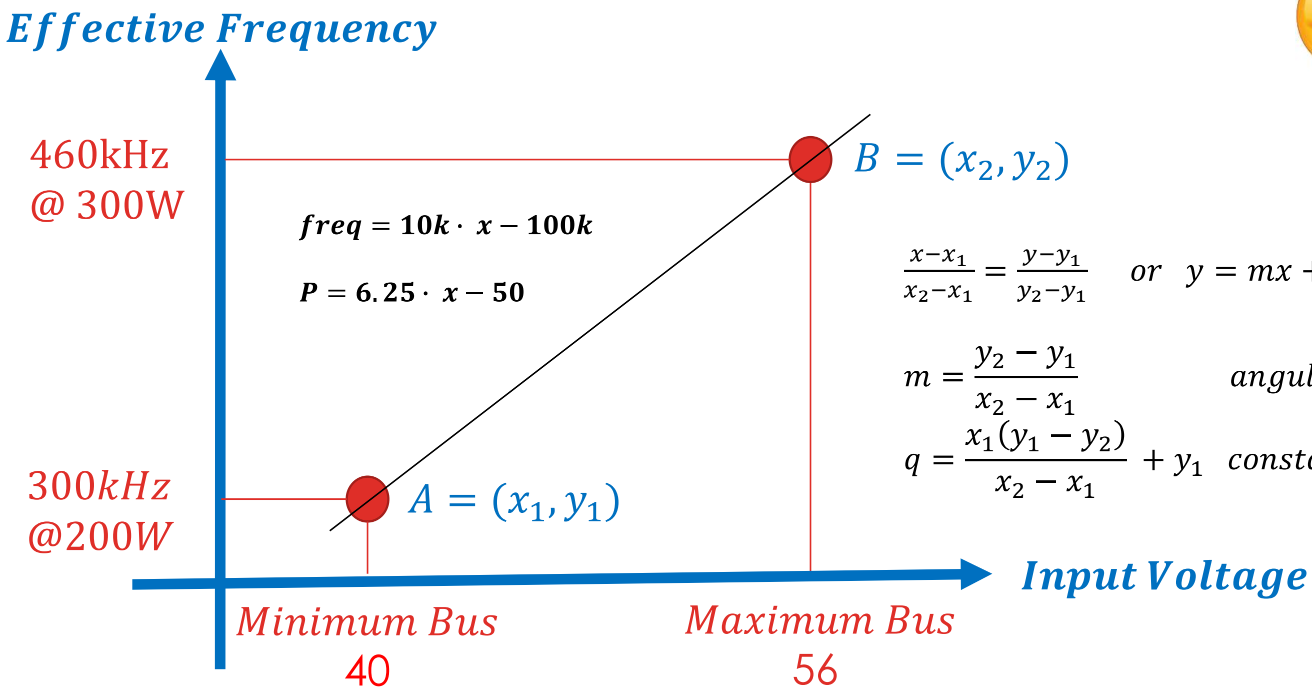
- Min bus, Min Power
- FHA not precise @Vbus min. Vout@258kHz was high! The controller corrected the frequency at 300kHz (40kHz more) to lower the tank gain!
- The tank current drifts from being purely sinusoidal once we move far away the higher resonance point. The reason why tons of designs are tuned around the higher resonance, **without mentioning that working "beyond" means: no ZCS + very high frequency + higher frequency span to get the same delta gain + higher core losses**



LLC design procedure

Requirements: Vin=40-56V; Vout=48V; Pout=200W; fmax=530kHz

- Example 3: requirements by Ray Ridley
- **What is the effective frequency AND the available power at 52V input bus voltage?**



$$\frac{x-x_1}{x_2-x_1} = \frac{y-y_1}{y_2-y_1} \quad or \quad y = mx + q \quad with:$$

$$m = \frac{y_2 - y_1}{x_2 - x_1} \qquad angular\ coefficient$$

$$q = \frac{x_1(y_1 - y_2)}{x_2 - x_1} + y_1 \qquad constant\ term$$

$$If\ V_{in} = 52, the\ effective\ frequency\ is\ 420kHz\ @\ 275W$$

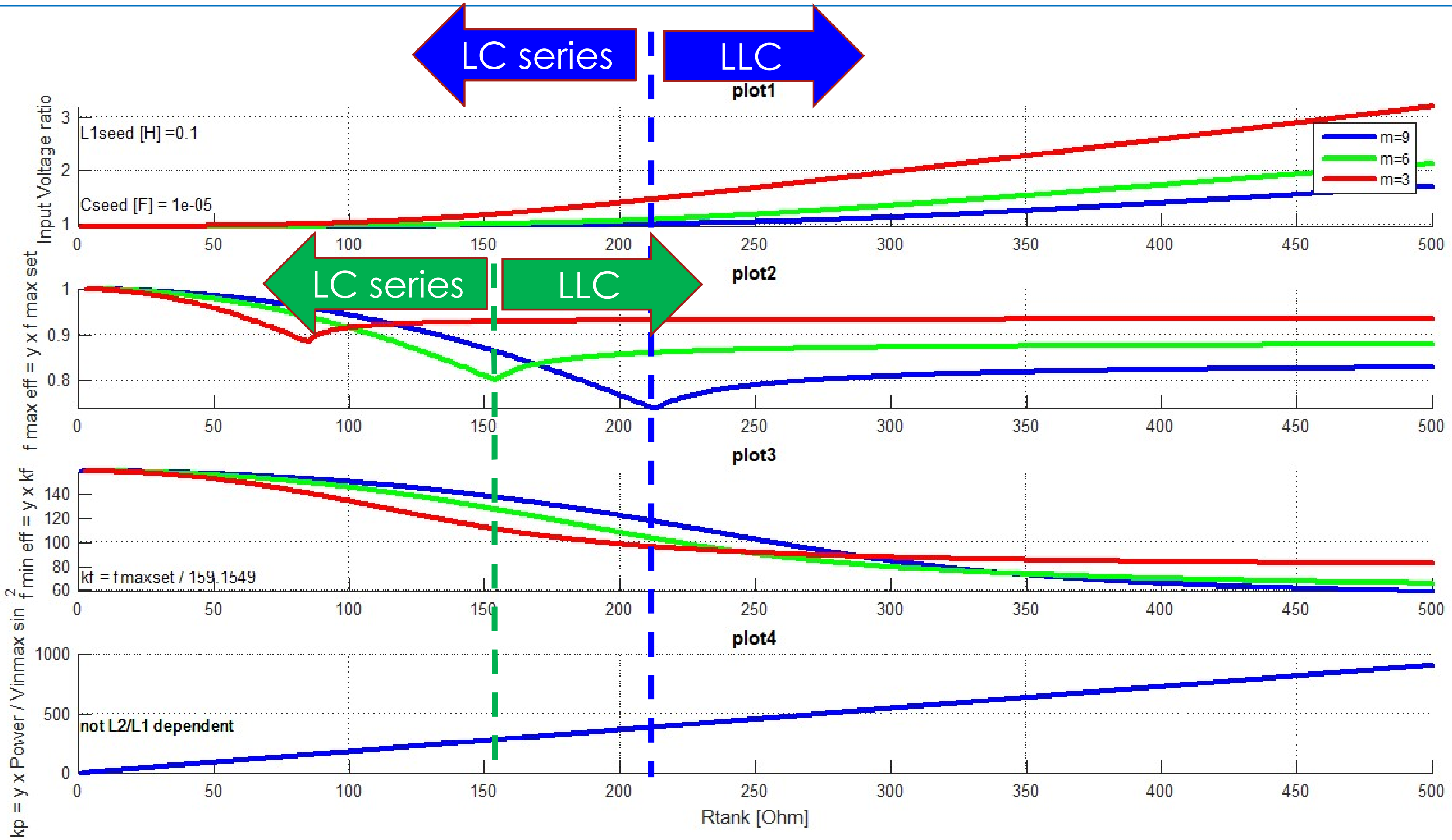
Agenda

- Intro
- ZVS & ZCS
- LC combo
- LC series is the right way
- From Series LC to LLC
- LLC Design
- Inverter Input Stage
- Output rectifier Stage
- The Rac concept
- The transformer
- Scaling laws
- Results
- **Graphical Approach**
- Related Topics

Push it to the limit

LLC design procedure

Universal Curves (m=L2/L1) : best entry gain > 1

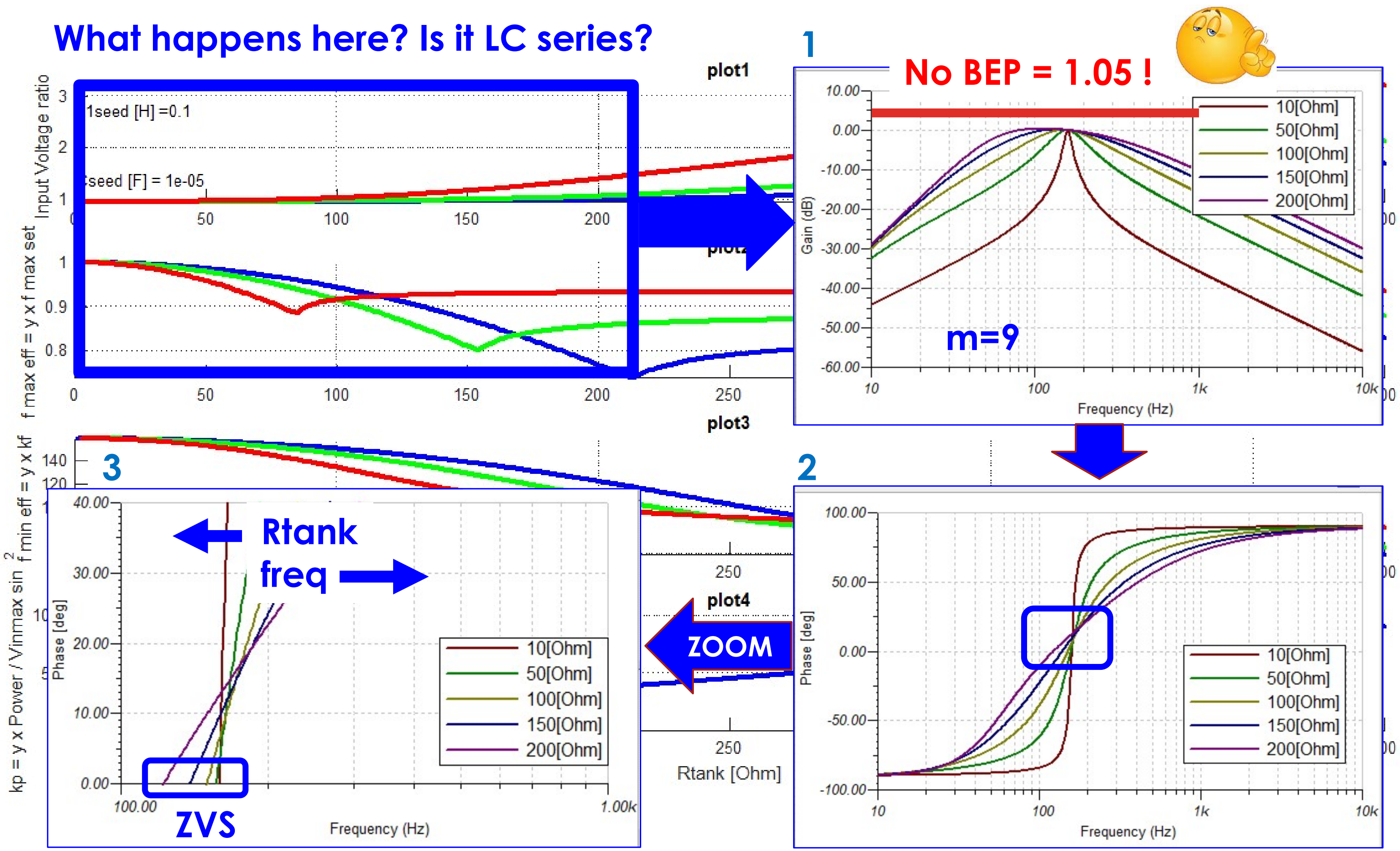


Agenda

- Intro
- ZVS & ZCS
- LC combo
- LC series is the right way
- From Series LC to LLC
- LLC Design
- Inverter Input Stage
- Output rectifier Stage
- The Rac concept
- The transformer
- Scaling laws
- Results
- **Graphical Approach**
- Related Topics

LLC design procedure

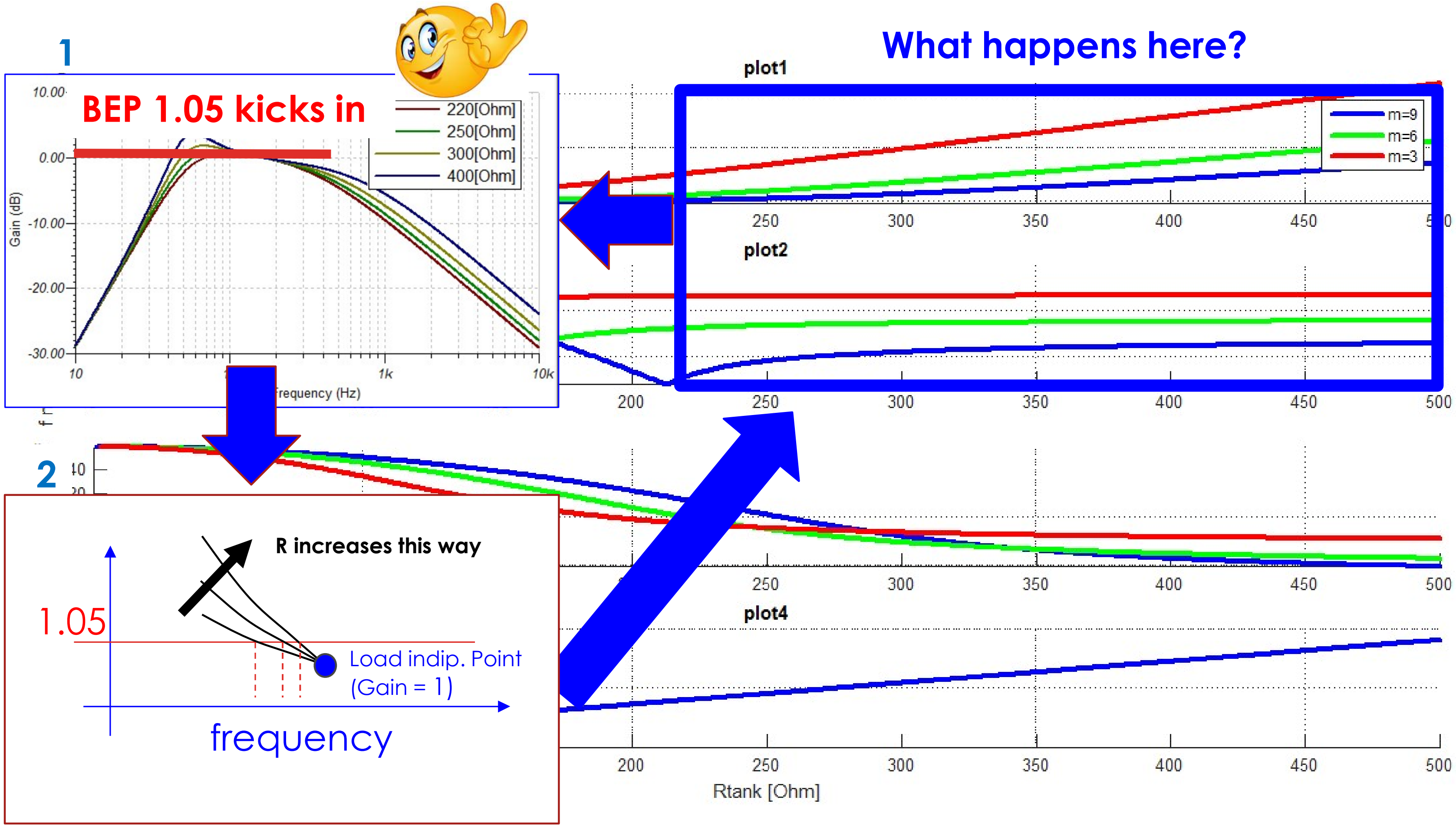
Universal Curves (m=L2/L1) : best entry gain > 1



Push it to the limit

LLC design procedure
Universal Curves (m=L2/L1)

Agenda



R and f increase in the same direction! OR:
If R increases, to get 1.05, than f increases.

Push it to the limit

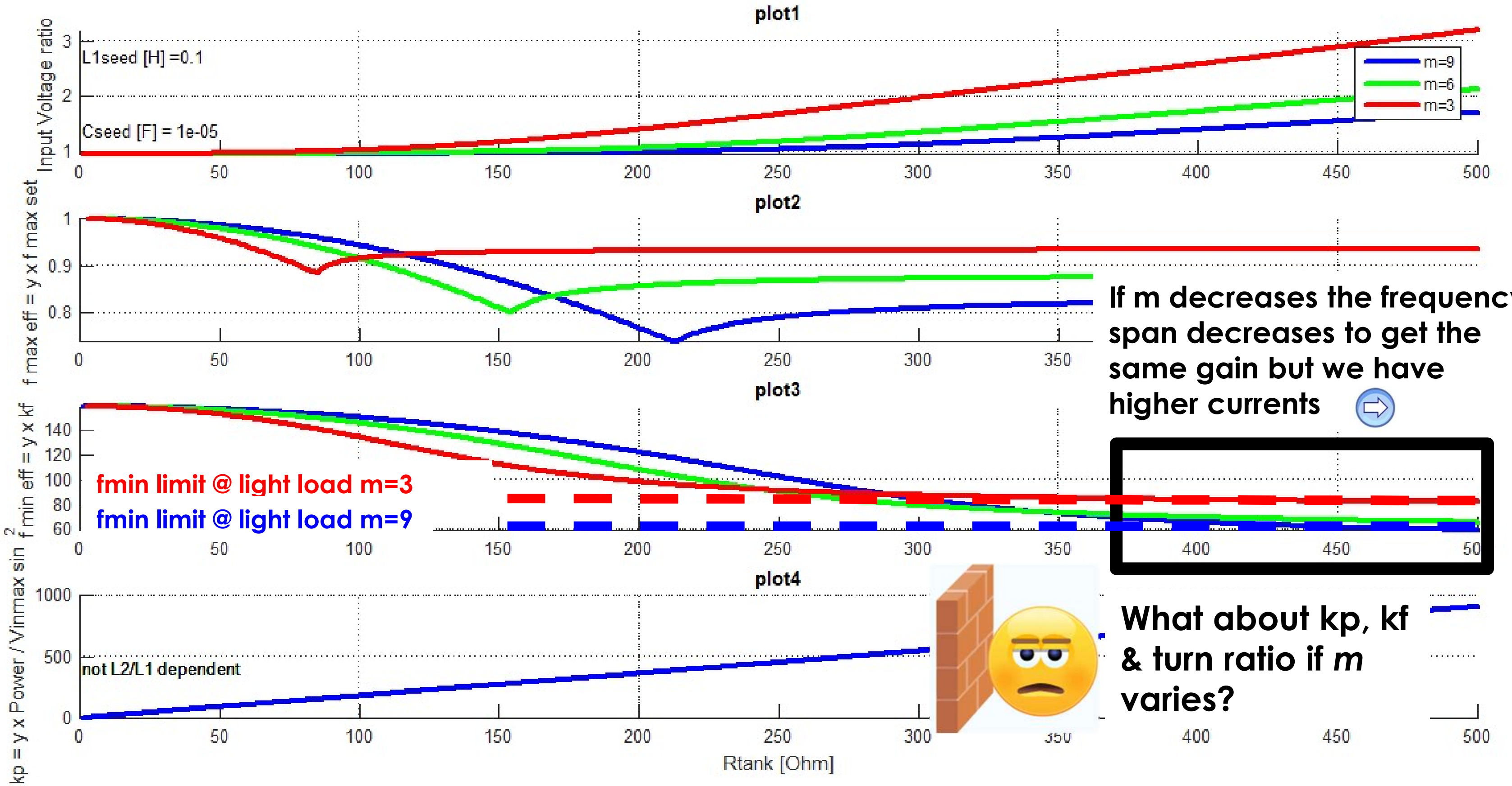
Agenda

- Intro
- ZVS & ZCS
- LC combo
- LC series is the right way
- From Series LC to LLC
- LLC Design
- Inverter Input Stage
- Output rectifier Stage
- The Rac concept
- The transformer
- Scaling laws
- Results
- **Graphical Approach**
- Related Topics

Push it to the limit

LLC design procedure

Universal Curves (m=L2/L1) : best entry gain > 1



If m decreases the frequency span decreases to get the same gain but we have higher currents

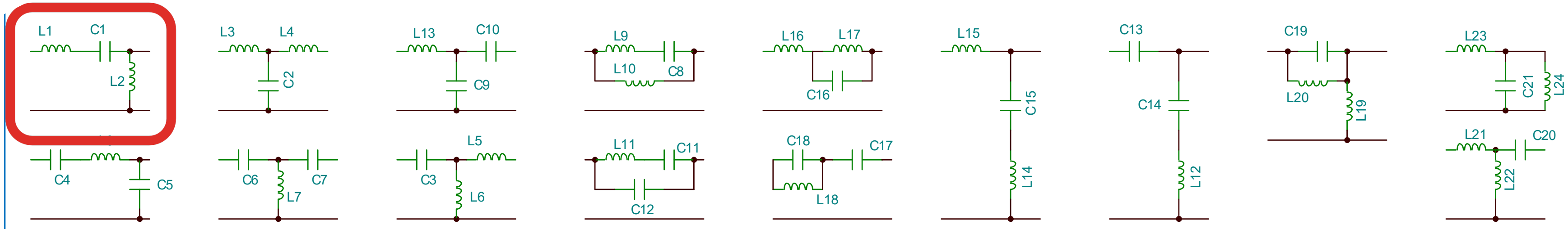
What about kp, kf & turn ratio if *m* varies?

Agenda

Questions?

- How to close the LLC loop? *We need another webinar.*
- Is LLC always better? *Always is nothing.*
- What happens if I want to work beyond the higher resonance?
- Is this approach valid anyway working beyond the HI res.?
Sure! Respin the universal curves for a lower gain entry point: 0.8, 0.9 … , whatever gain entry point you want.
- What about the other resonant topologies L*C* combo?
Intutively I would plot the universal curves for the topology you need.

We discussed this !



Agenda

- Intro
- ZVS & ZCS
- LC combo
- LC series is the right way
- From Series LC to LLC
- LLC Design
- Inverter Input Stage
- Output rectifier Stage
- The Rac concept
- The transformer
- Scaling laws
- Results
- Graphical Approach
- **Related Topics**

LLC design procedure 2

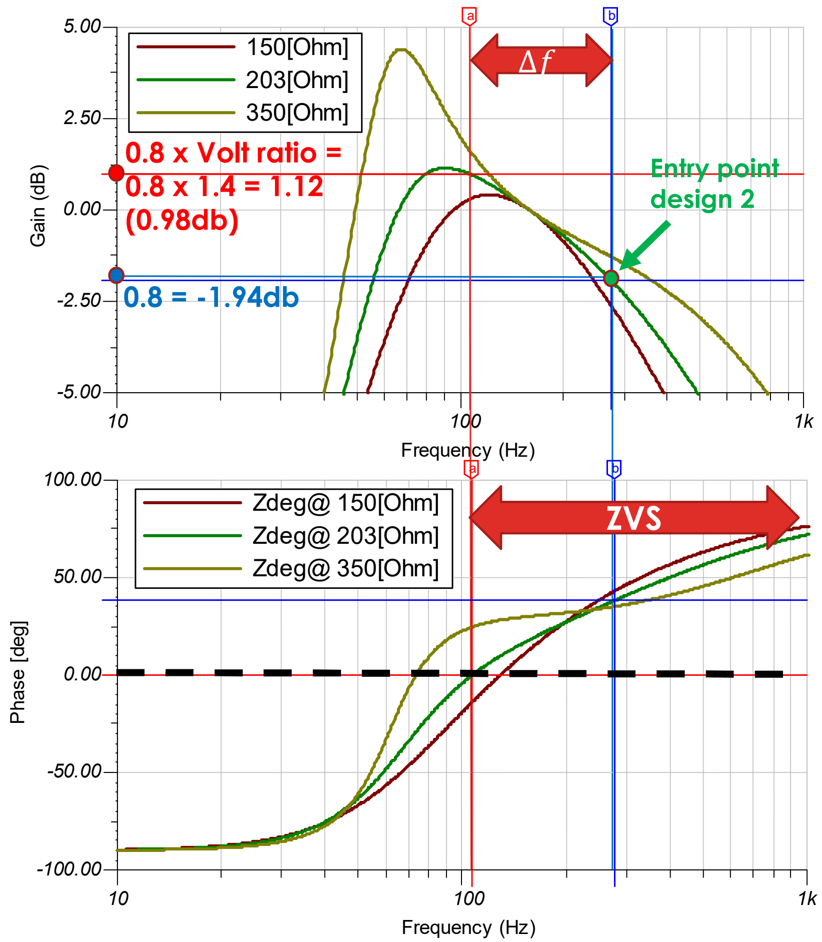
Universal Curves (m=L2/L1) : best entry gain < 1

LLC design procedure 2

Universal Curves (m=L2/L1) : best entry gain < 1

- In this case (entry point equal to 0,8) the Universal Curves suggest the tank resistor able to guarantee:

➢ Full bus swing
➢ Minimum Frequency Span for the required delta Gain
➢ ZVS and ZCS below the higher res.
➢ ZVS beyond the higher res. Currents here will be Hard Switched!



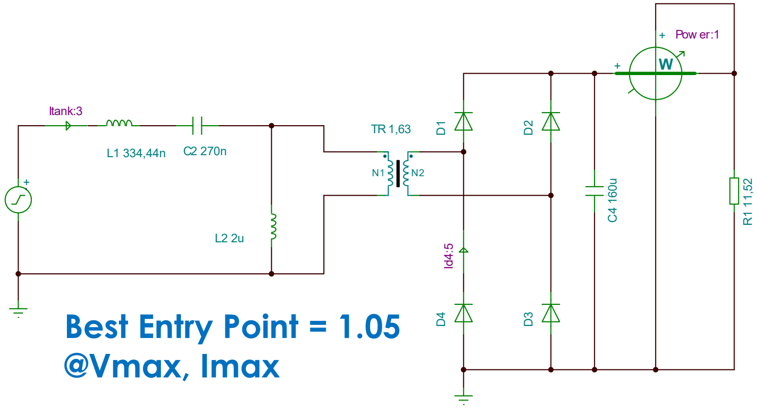
Agenda

- Intro
- ZVS & ZCS
- LC combo
- LC series is the right way
- From Series LC to LLC
- LLC Design
- Inverter Input Stage
- Output rectifier Stage
- The Rac concept
- The transformer
- Scaling laws
- Results
- Graphical Approach
- **Related Topics**

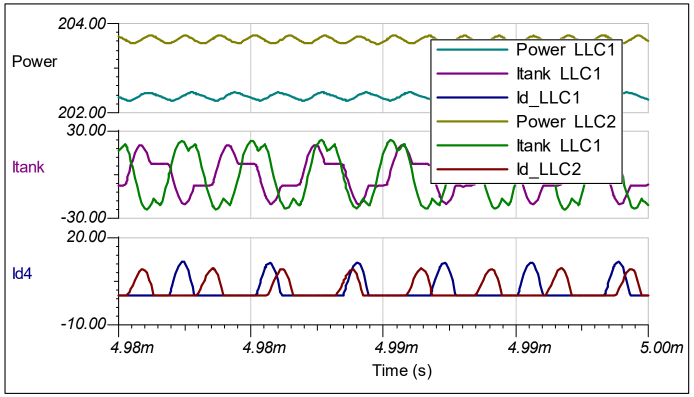
LLC design procedures

Which one do you prefer?

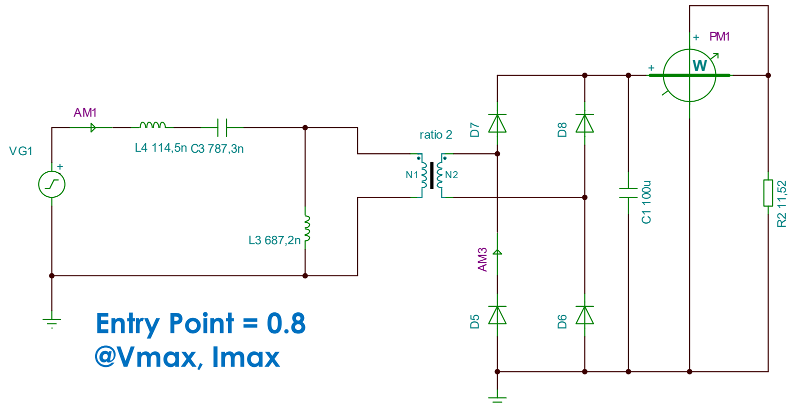
- ***LLC1 designed working between resonances***
- ***LLC2 designed by working around the higher resonance***



Best Entry Point = 1.05 @Vmax, Imax



-Both of them w orks in ZVS and ZCS at Vbusmin AND they reciprocal fmin: (differs)
-The second LLC w ork at very high frequency (900kHz), very small components, but no ZCS on secondary



Entry Point = 0.8 @Vmax, Imax

With universal curves you need few minutes to compare them and select the one suitable for you.

Both @ Vin min

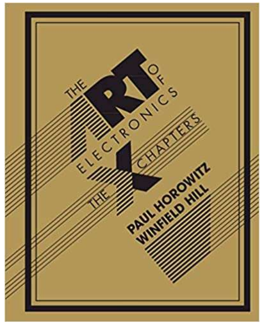
Agenda

Ending notes

- Check always ZVS & ZCS → look at the waveforms

- No particular math needed: Ohm's law only.

"It's easy to be dazzled by the apparent power of mathematics but please resist to the temptation to take refuge in complex equations to understand how the circuit really works".
[Horowitz – Hill. The Art of Electronics - Chap 4]



- Sweeping Rtank gives much more info!

- Combine these plots with Scaling Laws

Acknowledgements

- Ray Ridley, for hosting me and his massive contribution to our world as well as his infinite patience to give technical support to all power electronics engineers.
- Power Supply Design FaceBook Goup
- Ridley Engineering Power Supply Design Center

SMPS A-Z 3rd is coming

(DAB, PSFB, LLC, Graphical Tricks, Universal Curves, Linear Modeling etc)

Mission : make power conversion EASY.
Complex math forbidden!

Sanjaya Maniktala
Nicola Rosano

View Our Entire Webinar Series

MAGNETICS CORE LOSS WEBINAR

In this groundbreaking webinar, Dr. Ridley demonstrates circuit models for core loss that provide loss estimations regardless of waveform. The models provide better worst-case analysis than the original data.

HAPPY HOUR WITH DR. RIDLEY - WEBINAR

This is an open discussion without any formal presentation from Dr. Ridley. Ask any questions you like about power electronics, history, frequency response, topologies, technology, people, or the past and future of our field.

DESIGN, BUILD AND TEST A FLYBACK TRANSFORMER - WEBINAR

In this webinar Dr. Ridley shows you how to Design, Build, and Test a Flyback Transformer. We had the ambitious plan to actually build the transformer live during the webinar.

MAGNETICS PROXIMITY LOSS - WEBINAR

Dr. Ridley tackles the advanced topic of magnetics winding losses. He shows how to reduce complex analytical expressions to straightforward circuit models.

BUILD A CURRENT MODE CONTROLLER IN ONE HOUR - WEBINAR

Design and Build a Current Mode Controller in One Hour and learn the 7 secrets of current-mode control

DESIGNING AND MEASURING CONVERTER CONTROL LOOPS - WEBINAR

In this webinar, we will do live demonstration in hardware of measuring a power stage, designing the compensator, and measuring the resulting loop gain and closed-loop responses.

VOLTAGE-MODE OR CURRENT-MODE CONTROL? - WEBINAR

Watch Dr. Ridley's webinar on voltage and current mode control. Get the definitive answer on which you should be using.

POWER SUPPLY DESIGN ESSENTIALS - WEBINAR

In this webinar we will go deep into the design of a converter and many of the aspects that need to be considered.

MAGNETICS ESSENTIALS - WEBINAR

In This video Dr. Ray Ridley talks about Magnetics Essentials

LINK FROM RIDLEYWORKS TO PSIM - WEBINAR

In This video Dr. Ray Ridley talks about the link between RidleyWorks and PSIM

POWER SUPPLY DESIGN CENTER FACEBOOK ARCHIVES

In this article, we have all of the Power Supply Design Center posts from Facebook, archived by Bob Gudgel.

[112] THE POWER OF DOWELL'S EQUATIONS AND CURVES

The standardized curves of Dowell's equations are a superb tool for designing better high-frequency magnetics. A careful balance of layer count and wire or foil count is needed to reach an optimum design.