Design of Integrated Magnetics using Artificial Intelligence

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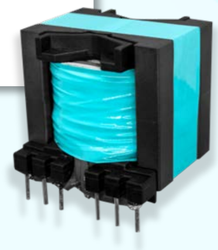
Introduction

This presentation will be focused on the integration of inductances and transformers in bridge topologies.

TABLE OF CONTENTS

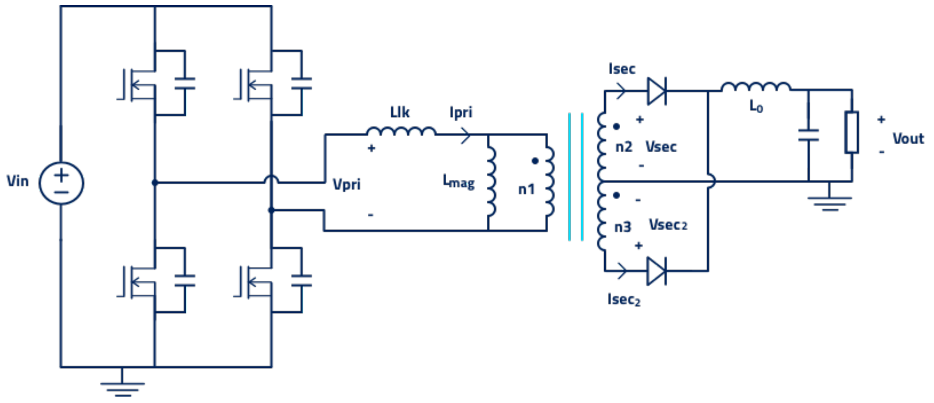
1. Magnetic Components in PSFB and LLC Topologies
2. Options of integration
3. Elements of the magnetics
4. Function and examples



Integrated Magnetics in PSFB and LLC

Transformers in Bridge topologies are the key components to achieve high power density.

PSFB

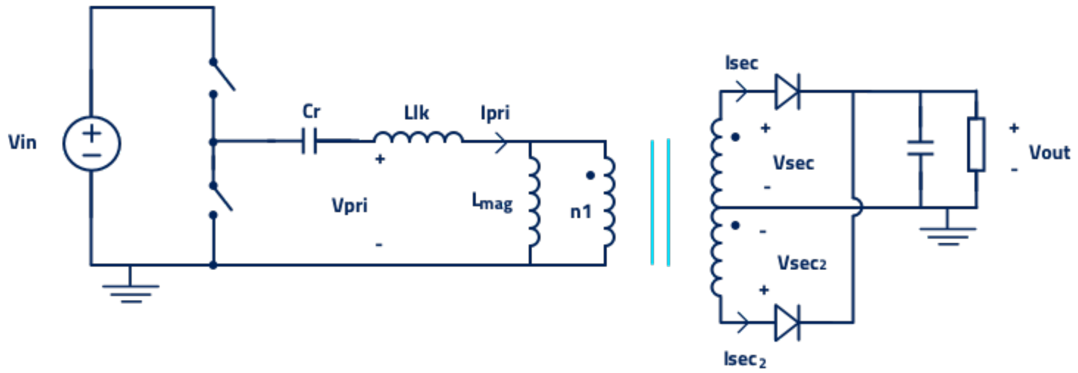


Trafo

L_o

L_{lk}

LLC



Trafo

L_r

L_{lk}

PSFB and LLC: Magnetics in each case

PSFB	LLC
It includes an **output inductor (L_o)** to store the energy.	LLC stores the energy in the **resonant inductor (L_{Lk}).**
It requires L_{lk} to achieve ZVS. The value depends on the parasitic capacitance of the Mosfets.	It works with the resonance between L_r and C_r.
The typical values in 3.6 kW automotive applications are below 5 uH.	In automotive OBC of 3.6 kW, the most popular designs require an Lr in the range of 10-40 uH.

Transformer and Inductance Options in PSFB

PSFB

OPTION I

External Inductance for achieving ZVS

2 components

OPTION II

Design the transformer with L_{lk} equal to the Lzvs

1 component

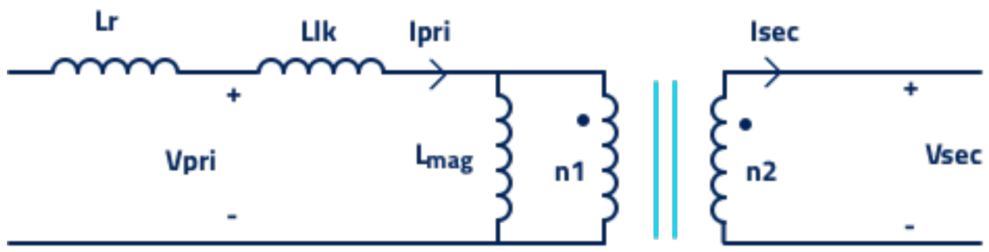
OPTION III

Use both, an external L and an internal L.

Mergence

Transformer and Inductance Options in LLC

LLC



OPTION I

L_r is an independet component

2 components

OPTION II

Design the transformer with L_{lk} equal to the L_r

1 component

OPTION III

Use both, an external L and an internal L.

Mergence

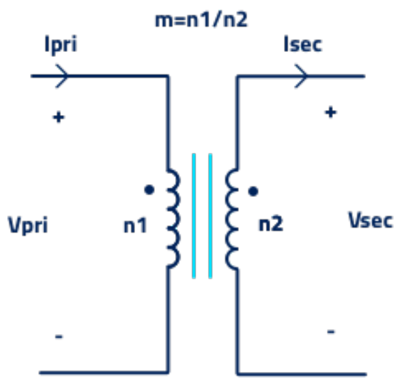
Ideal Transformer

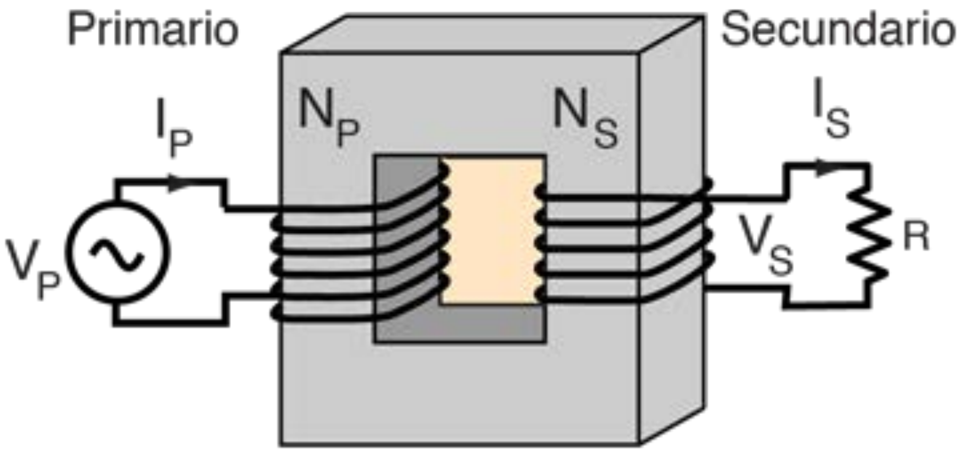
The ideal transformer is a component with the following features:

The Voltage applied to primary is reflected in secondary with the turn ratio relation, independently of the frequency

It does not store energy

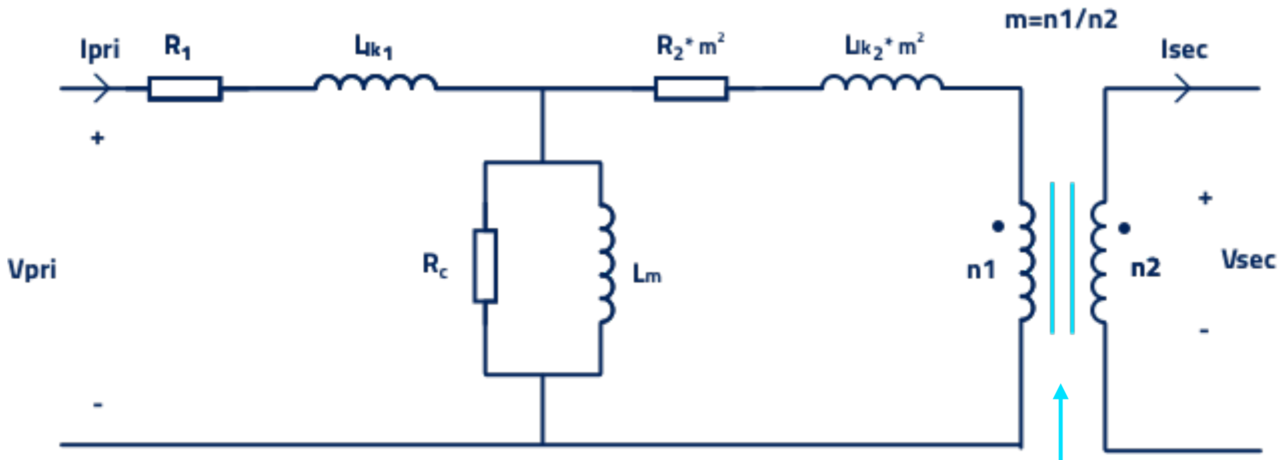
Perfect Coupling

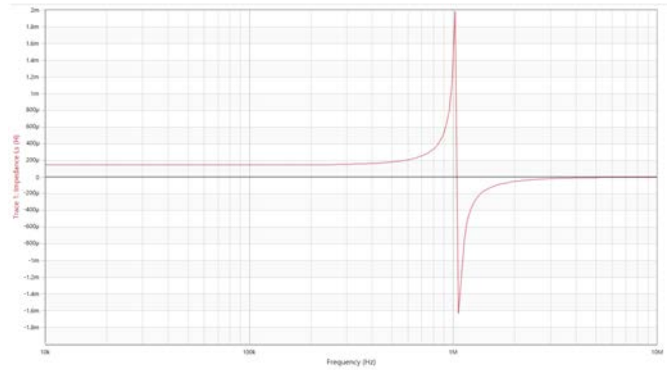




Real Transformer

The real transformer includes parasitic components like the L_{lk}, C_{par} and Impedance Frequency dependence.





The turn ratio has a big impact on the L_{lk} value

AC Inductance

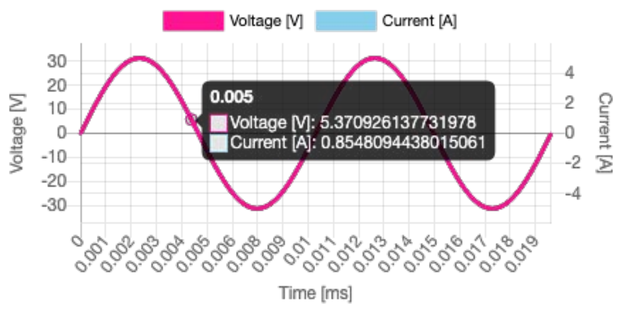
The Resonant Inductor is a pure AC current component. This is translated into the storage of lots of energy.

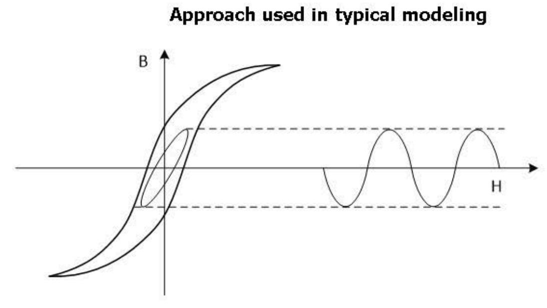
Losses mechanisms are different, depending on the material selected. The hysteresis loop is larger than DC indutors.

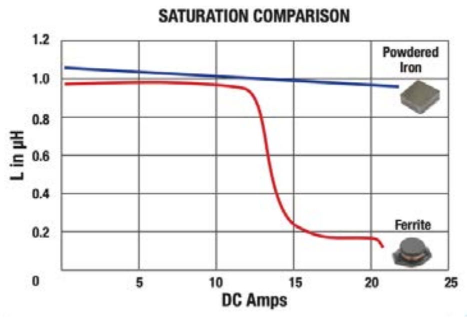
Powder materials are common due to their distrubuted gap and saturation limits.

Powder is limited in shapes, permeability and sizes.

In powder materials, the Inductance depends on temperature and current.







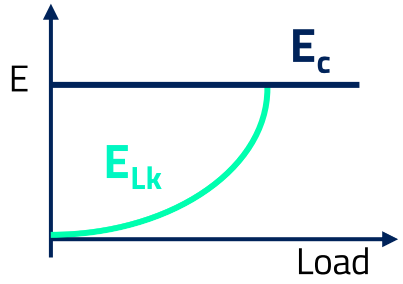
Source: https://www.vishay.com/docs/48155/_did-you-know_ihlp_saturation_vmn-ms7373.pdf

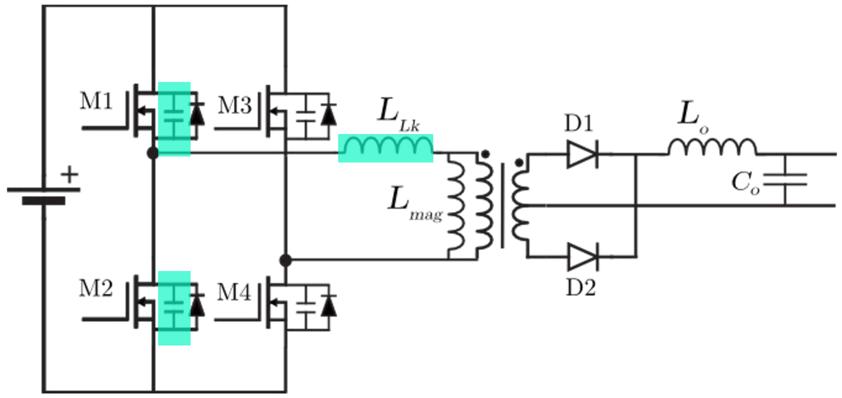
ZVS Review – The function of L_{LK} as L_{ZVS}

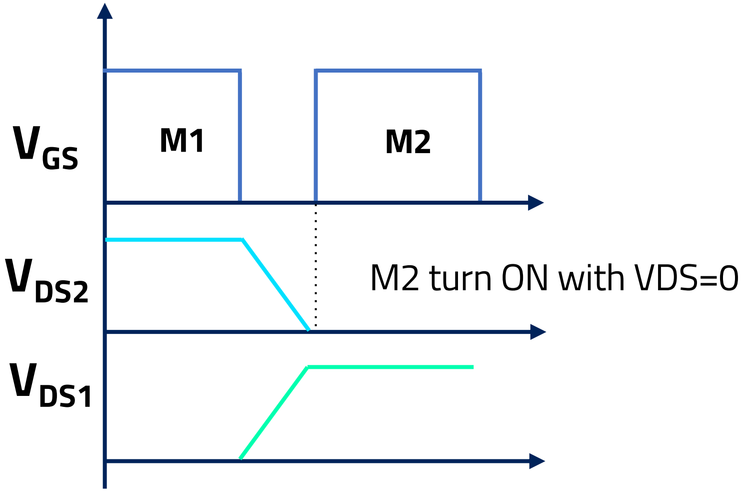
In the phenomenon for discharging the parasitic capacitances, and switch the ON the Mosfet without switching losses, the L_{Lk} is key as explained by [Sabate'90]. If the energy in the L_{Lk} is sufficient during the dead time for discharging the capacitor, ZVS can be achieved.

$$E_c < E_{lk}$$

$$E_{lk} = \frac{1}{2} {I_p}^2 L_{lk} \qquad E_c = \frac{1}{2} V^2 C_{eq}$$

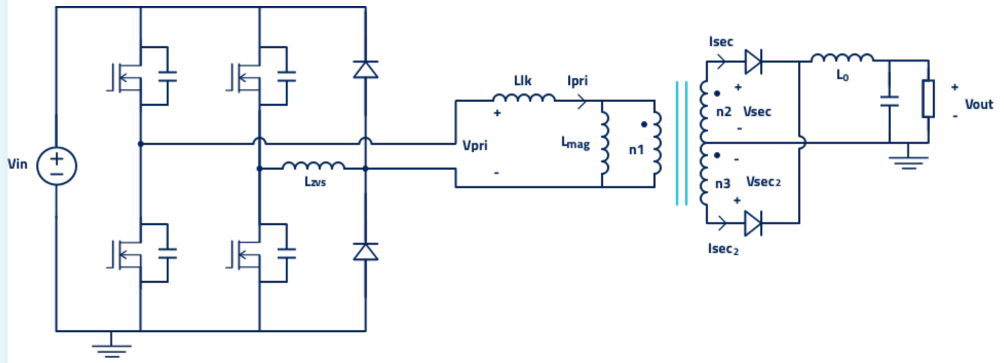






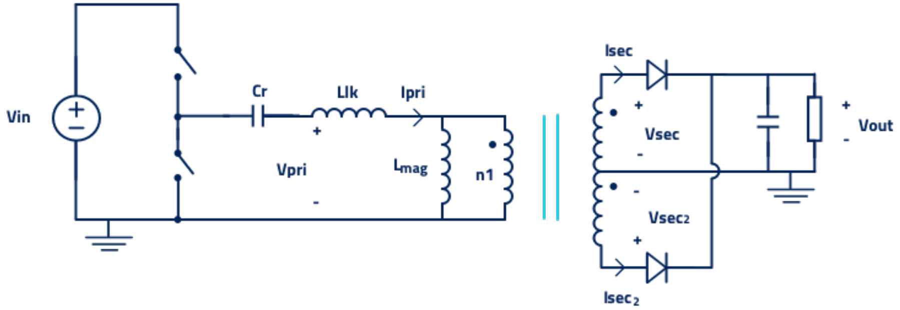
External series inductance

ZVS function in PSFB



The external inductance helps to achieve ZVS. In the publication by Richard Redl ['90], he introduces an additional "commutating" inductor which extends the ZVS range. This solution includes additional diodes.

Resonant function in LLC



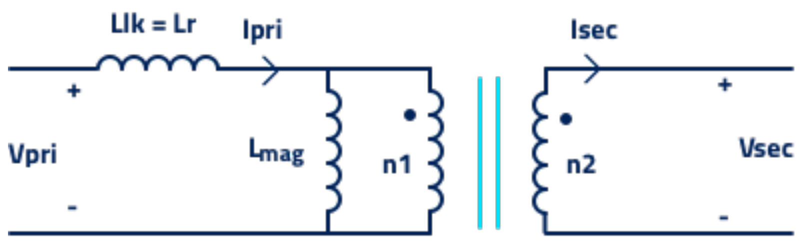
The LLC resonance is obtained with the values of the series inductance plus the leakage inductance and the resonant capacitor. The inductor function is creating the resonance.

Integrated inductance

In both cases, the integration of the serial inductance consists of designing the transformer, with the goal of achieving a specific value of L_{lk}.

ADVANTAGES

- The L_{Lk} cannot saturate
- Less components
- Cost and Volume



DISADVANTAGES

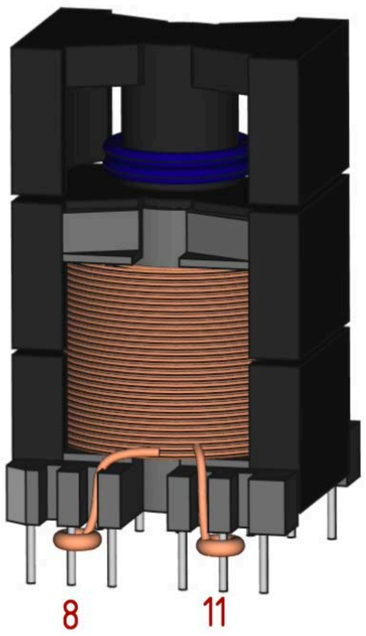
- Coupling decrease
- Manufacturing complexity
- EMI noise

Merging the ZVS Inductance and the Transformer

The third option is to achieve the desired inductance adding a half core to the transformer structure and using the same wire.

ADVANTAGES

- Flux cancellation decrease losses
- Compact solution



DISADVANTAGES

- Customization coil former
- Manufacturing complexity

Example of an integrated magnetic design in PSFB

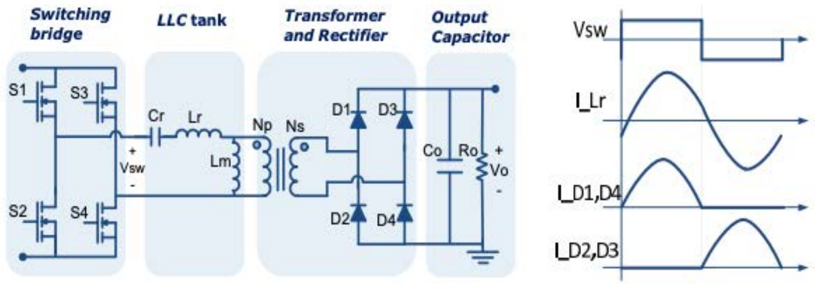
Resonant LLC Converter: 250 W

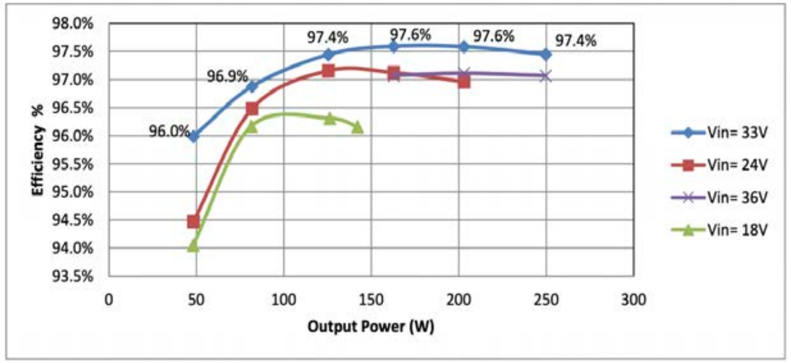
Vin=33V Vo=400 V

f_{sw}= 50 kHz

N=1:12

L_{zvs}=2,2 uH





Source: Infineon web
(https://www.infineon.com/dgdl/Application_Note_Resonant+LLC+Converter+Operation+and+Design_Infineon.pdf?fileId=db3a30433a047ba0013a4a60e3be64a1)

Example of external ZVS inductance in PSFB

Resonant LLC Converter: 2000 W

V_{in}=385V V_o=48 V

f_{sw}= 100 kHz

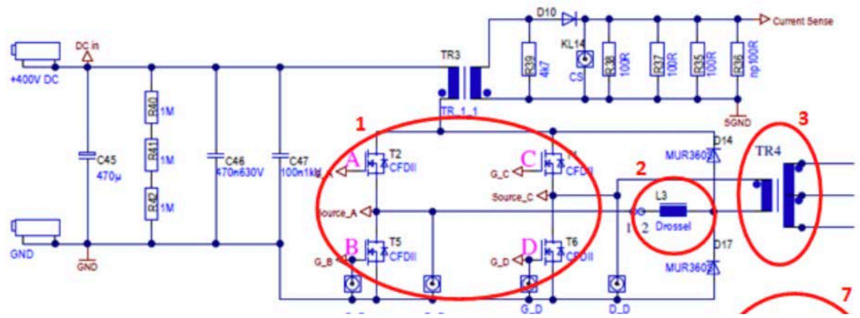
Tr PQ40/40

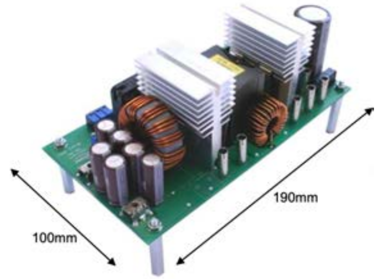
N=20:4:4

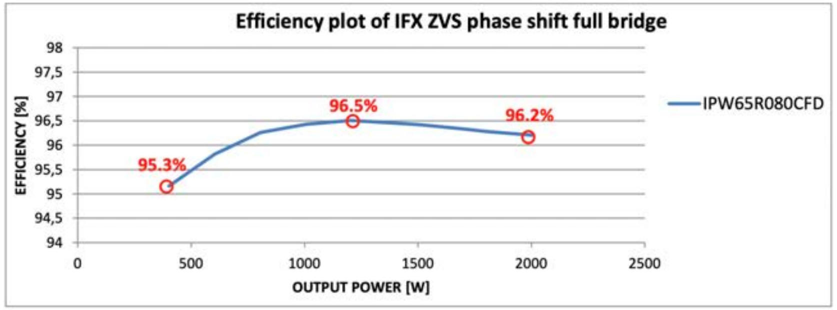
Toroidal inductor Kool-Mu Material

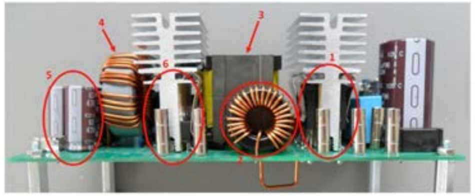
L_{zvs}=30-52 uH

Lo=18 uH Molypermalloy material









Source: Infineon web
(https://www.infineon.com/dgdl/Infineon-ApplicationNote_EvaluationBoard_EVAL_2KW_ZVS_FB_CFD2+ZVS-AN-v01_00-EN.pdf?fileId=db3a30433f9a93b7013f9f582ddb1fd9)

Example of external resonant inductance in LLC

Resonant LLC Converter: 600 W

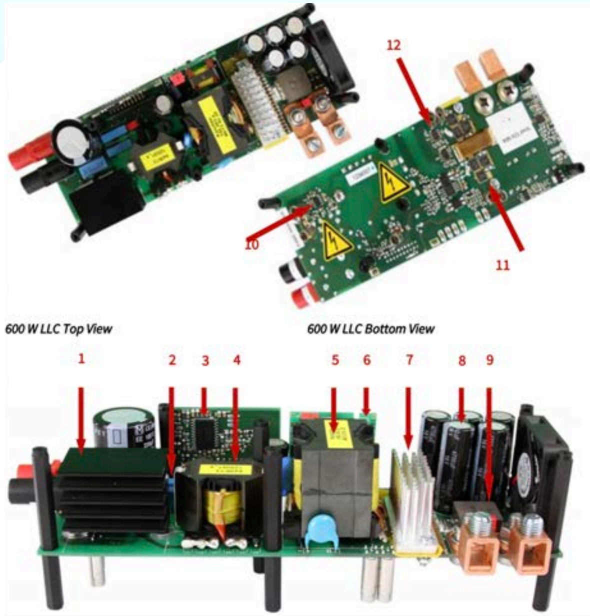
V_{in}=380V V_o=12 V

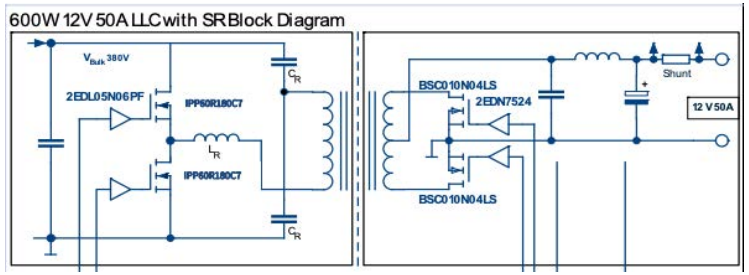
f_{sw}= 150 kHz

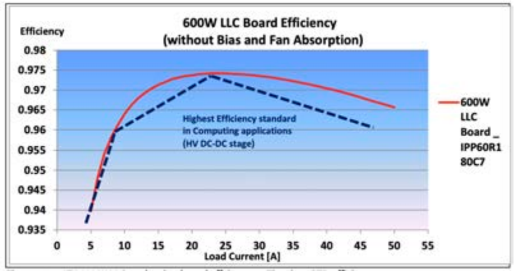
N=16:1

L_r=13 uH (RM-12)

Tr – PQ35/35







Source: Infineon web
(https://www.infineon.com/dgdl/Infineon-ApplicationNote_EVAL_600W_12V_LLC_C7_with_600V_C7_XMC-ApplicationNotes-v01_00-EN.pdf?fileId=5546d46253f6505701544cc1d15c20d7)

Example of design with a Mergence magnetic in LLC

Resonant LLC Converter: 3300 W

V_{in}=400V V_o=51 V

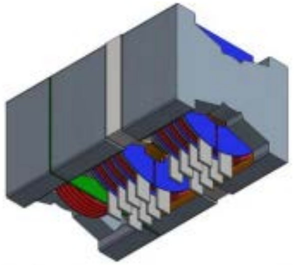
f_{sw}= 50 kHz

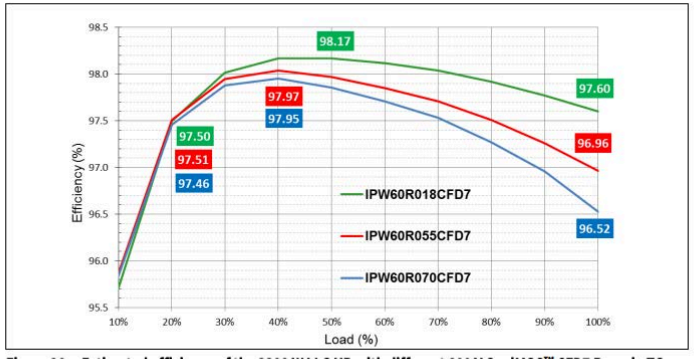
PQ35/28

N=15:4

L_{mag}=100 uH (2 transformers in parallel)

L_r=10 uH (half PQ35/28)

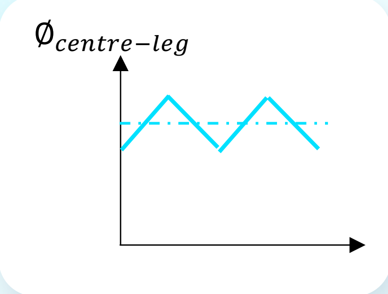


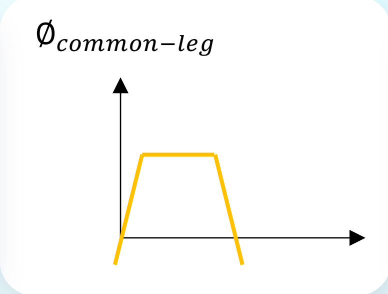


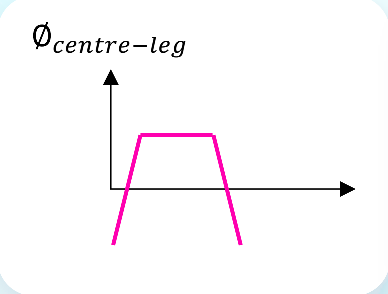
Note: *The main transformer structure actually comprises two parallel transformers integrated with the external resonant inductance. This enables realization of the required low L_m with several small gaps instead of a single large one.*

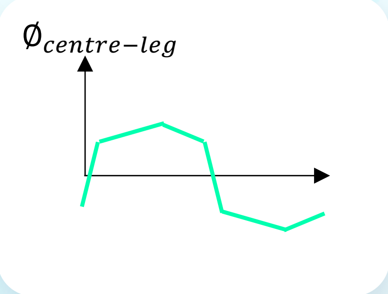
Source: Infineon web
(https://www.infineon.com/dgdl/Application_Note_Resonant+LLC+Converter+Operation+and+Design_Infineon.pdf?fileId=db3a30433a047ba0013a4a60e3be64a1)

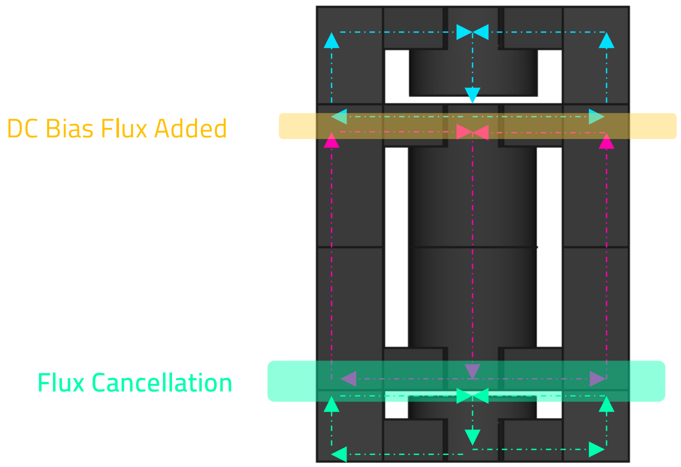
Example of Full Integrated Magnetic in PSFB





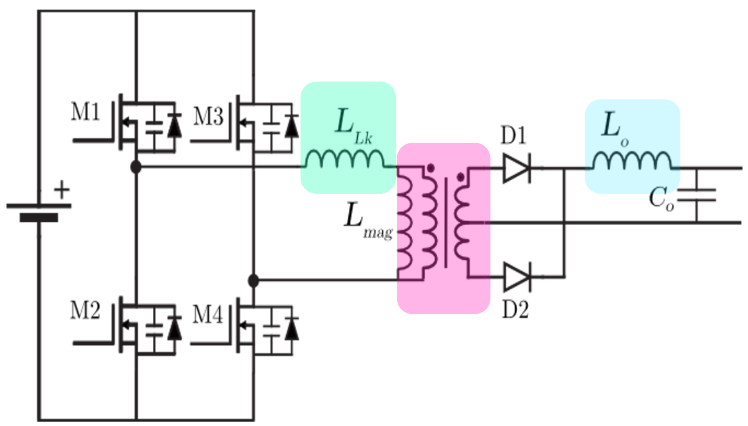






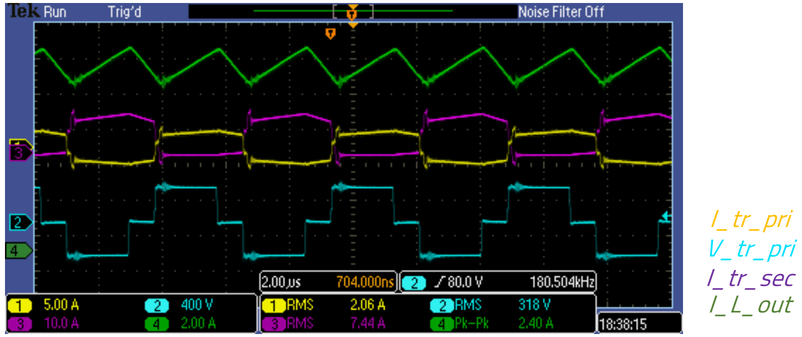
- The three magnetics could be integrated on a single structure.
- Special attention needs to be taken care to avoid Lout saturation.
- Extra core loss would appear in the core leg shared by the transformer and the output inductor.
- Customized core shape needed to maximize the performance **(Patent Pending)**

Application number	EP20382513.8

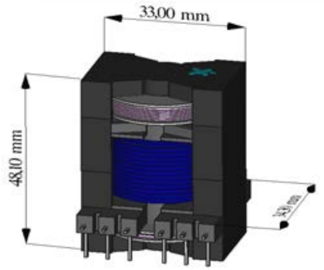


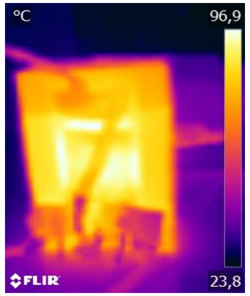
Example of Full Integrated Magnetic in PSFB

- A sample was built and tested in Frenetic's Lab.
- Transformer core exhibit a loss increase of 0,13 W.
- Overall magnetics efficiency decreased a 0,04%
- The integrated magnetic reached a steady state temperature of 96 °C
- Compact solution – 34,3 x 48,1 x 33 mm (including coil former)



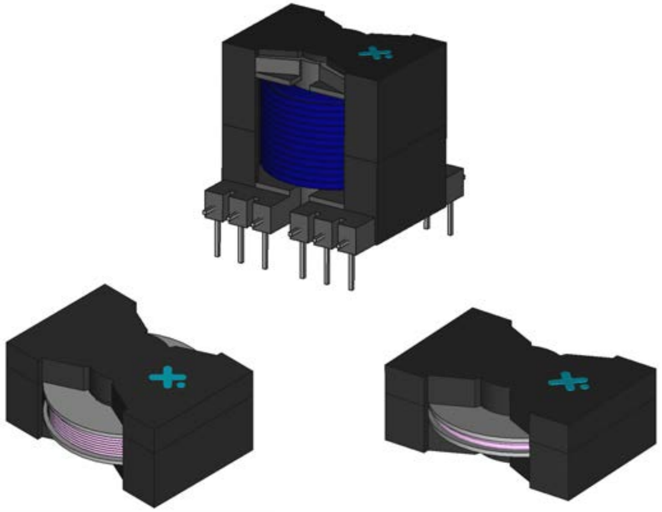
- 400 V – 48 V
- P_o=500 W
- L_{mag} = 3.8 mH
- Lr = 11.5 μH
- L_{lk} = 3 μH
- L_o = 22 μH
- Ploss Max 3 magnetics = 5,81 W



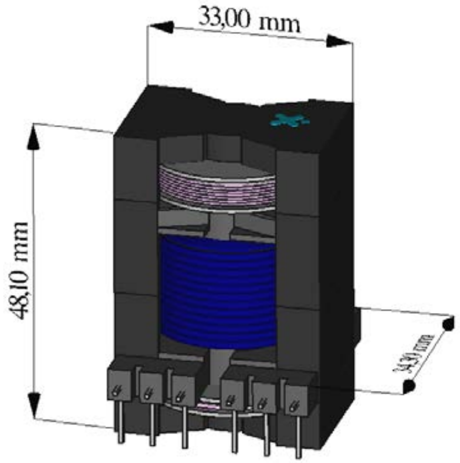


Comparison between fully integrated and PSFB

CLASSIC



PROPOSED



	CLASSIC	PROPOSED
Losses	5.68 W	5,81 W
Volume	40.13 cm3	33.4 cm3

16% reduction

Integration Impact on the Design Stage

Integrating the L_{lk} in the transformer is a great solution, but it can be a nightmare during the design phase, due to the numbered of iterations needed.

ADVANTAGES

- The L_{Lk} cannot saturate
- Less components
- Cost and Volume

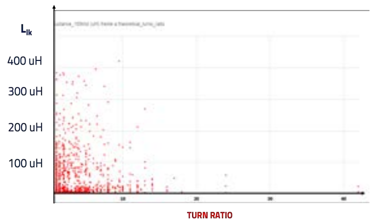
DISADVANTAGES

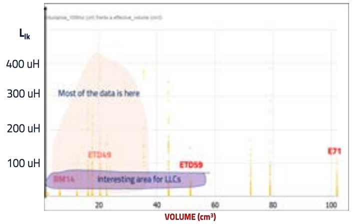
- L_{lk} need to be simulated
- Samples need to be build
- Iterations are really slow

AI for the L_{lk} estimation

Integrating the L_{lk} in the transformer is a great solution, but it can be a nightmare during the design phase, due to the number of iterations needed.

DATA FROM THE LAB





PAGE 31

AI ALGORYTHMS

FAST AND ACCURATE MODELS

With the data from the lab, applying AI, we can have **fast models to provide accurate L_{lk} values.**

L_{lk} can be simulated in seconds with high accuracy

You can see the impact on the design instantaneuosly

The number of iteration is eliminated

References

[1] J. A. Sabate, V. Vlatkovic, R. B. Ridley and F. C. Lee, "High-voltage, high-power, ZVS, full-bridge PWM converter employing an active snubber," [Proceedings] APEC '91: Sixth Annual Applied Power Electronics Conference and Exhibition, Dallas, TX, USA, 1991, pp. 158-163,

[2] R. Redl, N. O. Sokal and L. Balogh, "A novel soft-switching full-bridge DC/DC converter: Analysis, design considerations, and experimental results at 1.5 kW, 100 kHz," 21st Annual IEEE Conference on Power Electronics Specialists, San Antonio, TX, USA, 1990, pp. 162-172.

[3] Javier Torres “PROTOTIPADO Y CONTROL DE UN CONVERTIDOR CC-CC PARA ALIMENTAR UN RADAR ELECTRÓNICO”.

[4] José María Molina Thesis, 2017, “Three Phase Buck type rectifier integrated with current fed full bridge”.

[5] O'Loughlin, M. (2010). UCC28950 600-W, phase-shifted, full-bridge application report. TI Lit. No. SLUA560B, 1-30.

[6] https://www.psma.com/sites/default/files/uploads/tech-forums-magnetics/presentations/is015-transformerdesignconsiderationforfullbridgephaseshift.pdf

Thank you for your attention

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