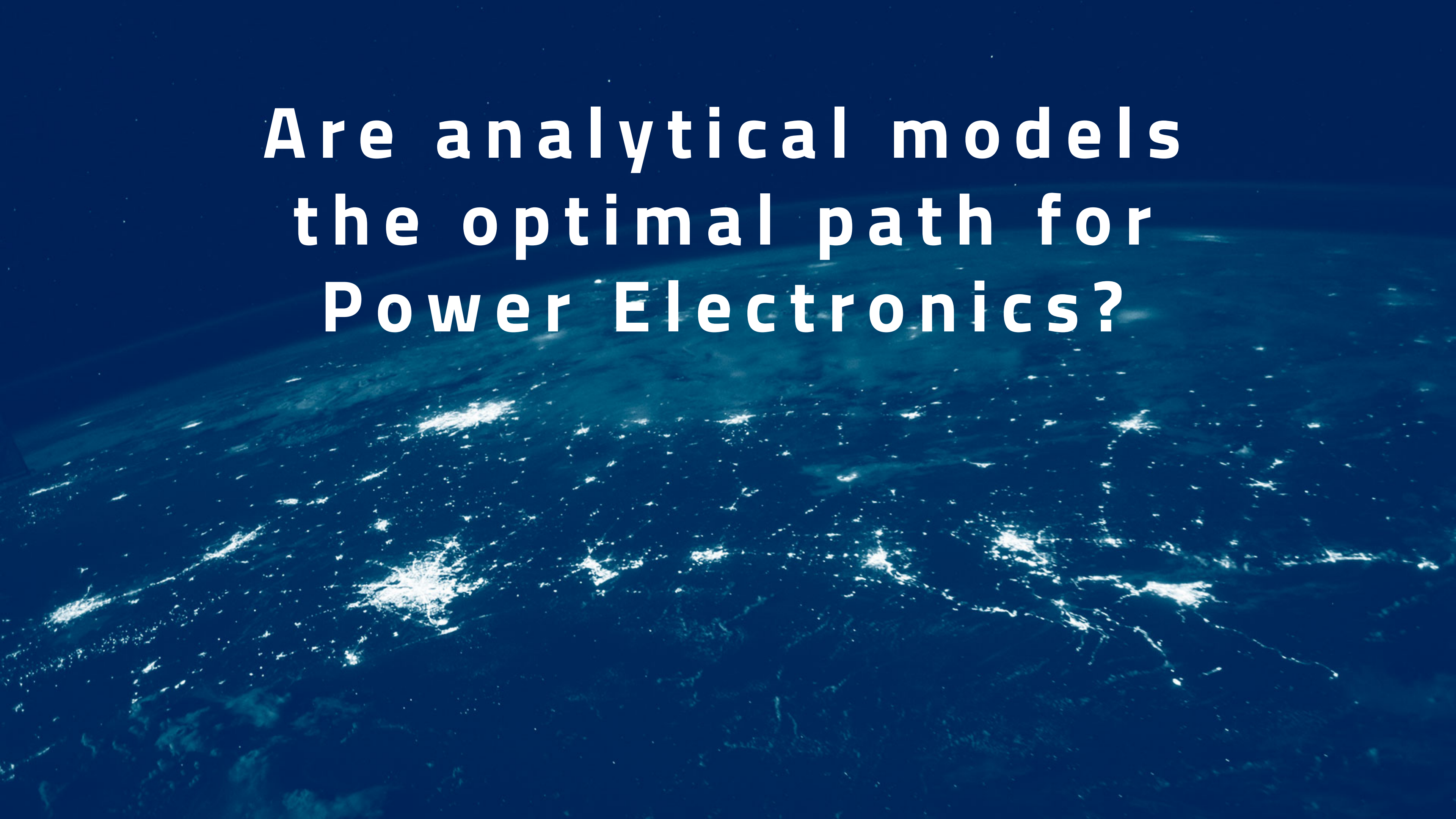
Transformer design consideration for Full Bridge Phase Shift

José M. Molina

IEEE APEC 2020: PSMA Industry Session
Design of Magnetics for Different Circuit Topologies
17 March 2020, New Orleans, USA

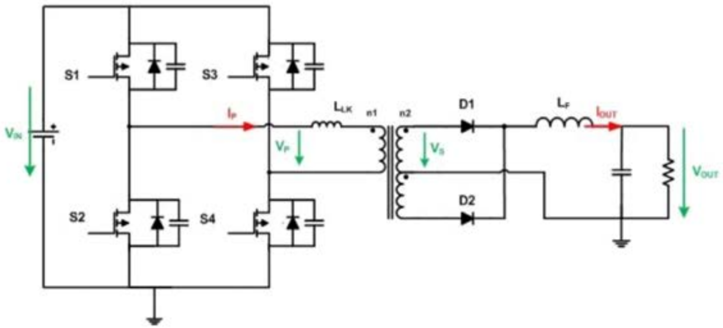
Are analytical models the optimal path for Power Electronics?



Full-Bridge Phase Shift (FBPS)

The main features of the FBPS power converter are:

- 4 switches + (2 or 4) diodes
- Galvanic Isolation
- Typical topology for power levels >300W
- High efficiency
- Suitable as a Voltage or current source

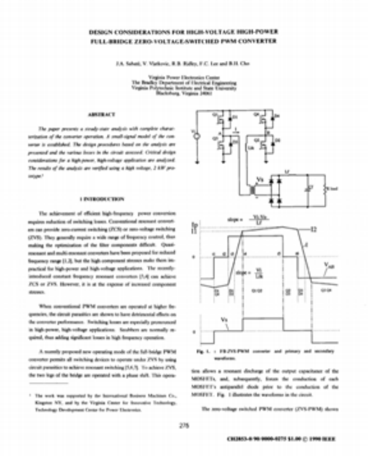


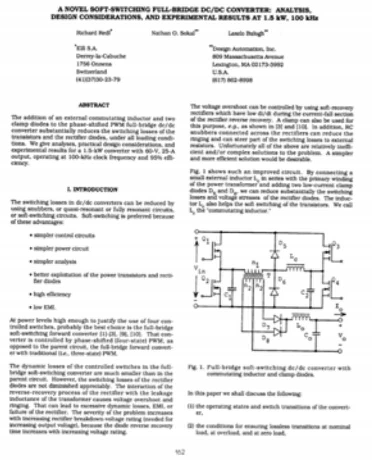
FBPS relevant publications

Some of the relevant publications in the literature related with this converter before becoming an industry standard

Sabate '90

- ZVS conditions
- Effective duty cycle


DESIGN CONSIDERATIONS FOR HIGH-VOLTAGE HIGH-POWER FULL-BRIDGE ZERO-VOLTAGE-SWITCHED PWM CONVERTER


A NOVEL SOFT-SWITCHING FULL-BRIDGE DC/DC CONVERTER: ANALYSIS, DESIGN CONSIDERATIONS, AND EXPERIMENTAL RESULTS AT 1.5 kW, 100 kHz

Redl '90

- Clamping Diode
- L_{ext}

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

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.

FBPS relevant publications

After the researchers have make their publications, industry started to create design guidelines.

Semiconductor industry has leathered the publication of app notes for Phase Shift Full Bridge converter using their chips.

TEXAS INSTRUMENTS

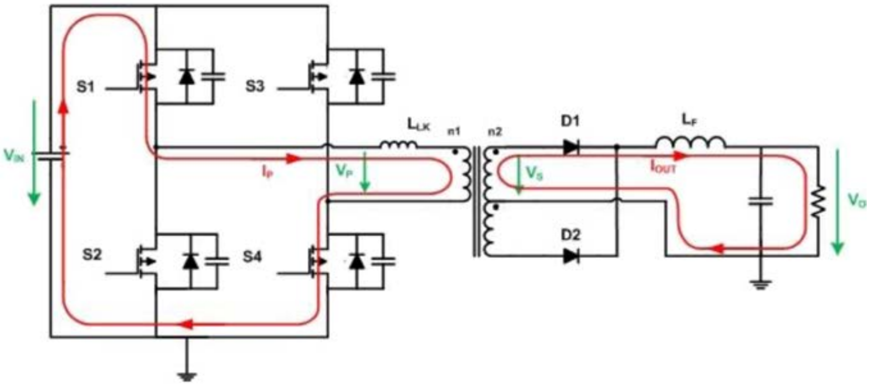
Application Report

SLUA560C–September 2010–Revised June 2011

UCC28950 600-W, Phase-Shifted, Full-Bridge Application Report

FBPS intervals

1



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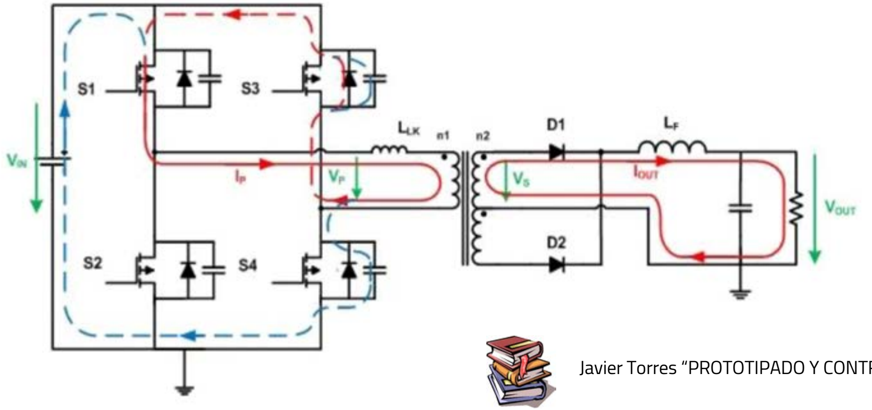

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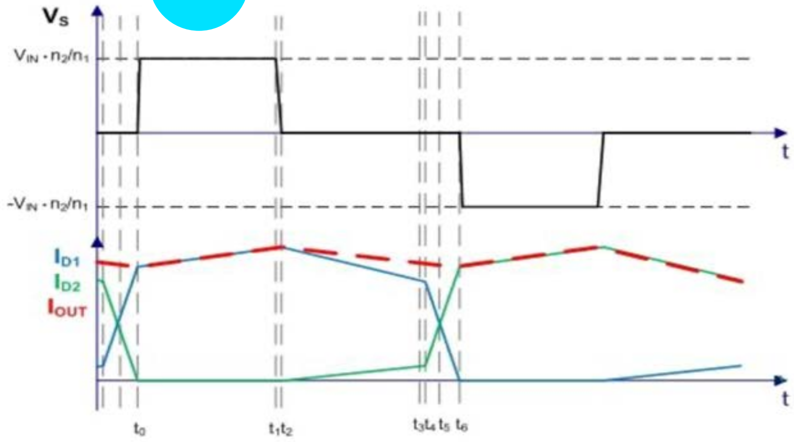
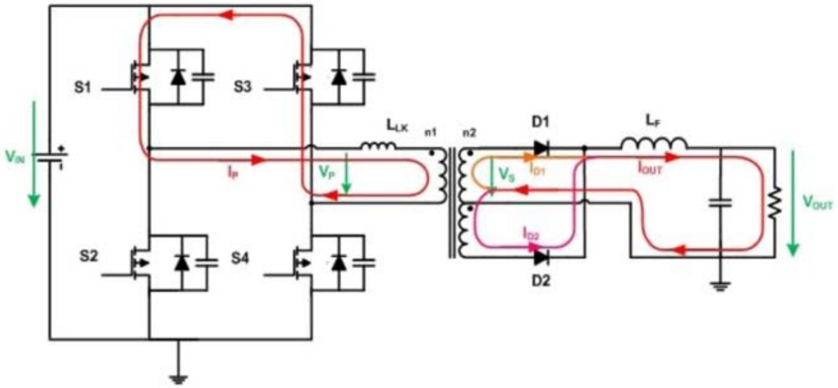


2

Javier Torres "PROTOTIPADO Y CONTROL DE UN CONVERTIDOR CC-CC PARA ALIMENTAR UN RADAR ELECTRÓNICO"

FBPS intervals

3



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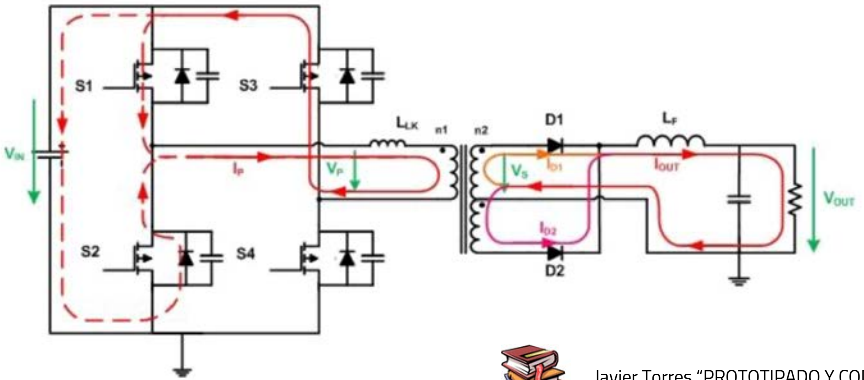
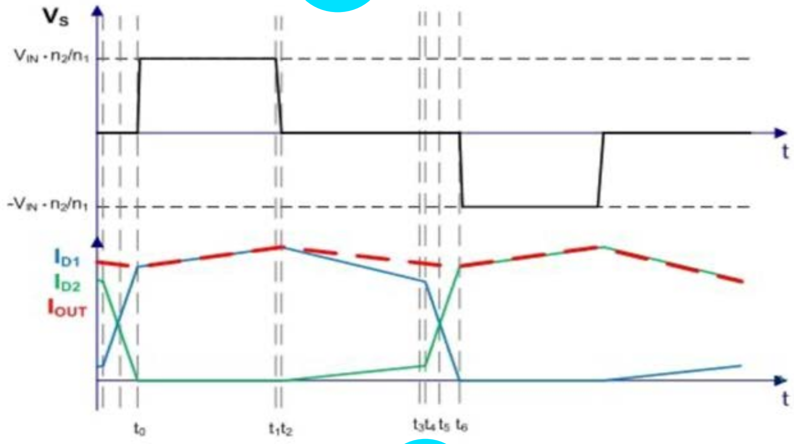
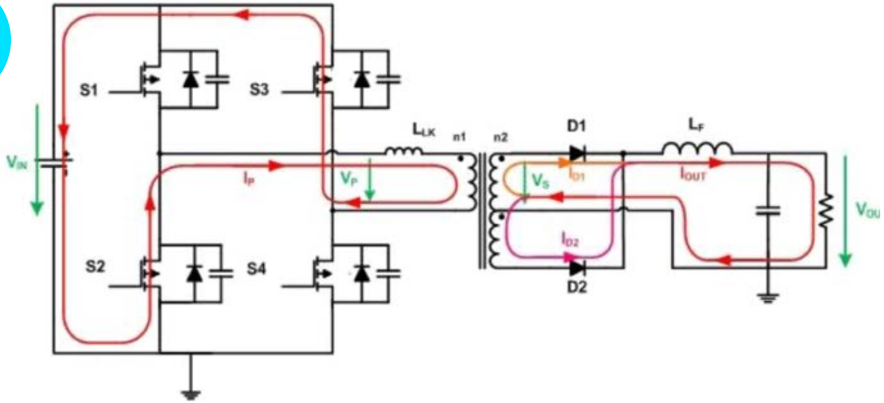




Javier Torres "PROTOTIPADO Y CONTROL DE UN CONVERTIDOR CC-CC PARA ALIMENTAR UN RADAR ELECTRÓNICO"

FBPS intervals

5



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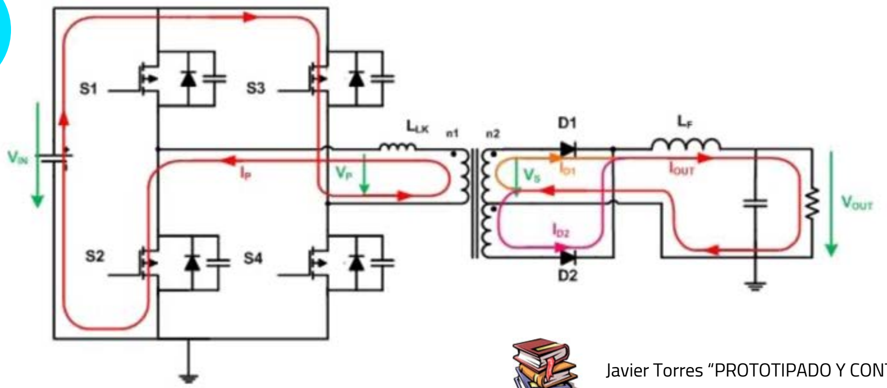

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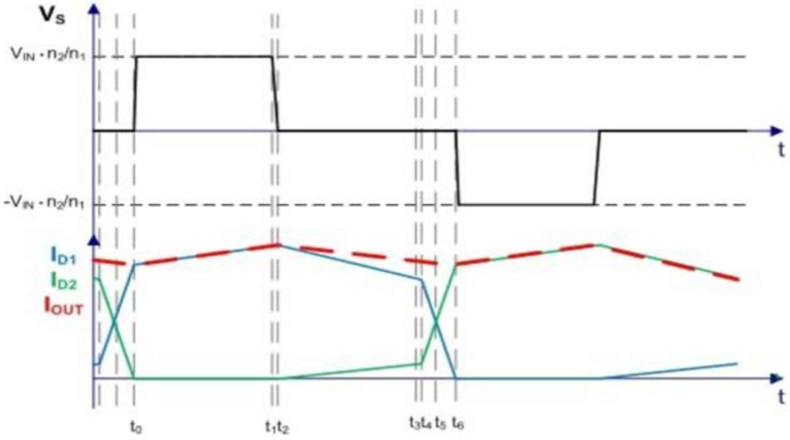


6

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

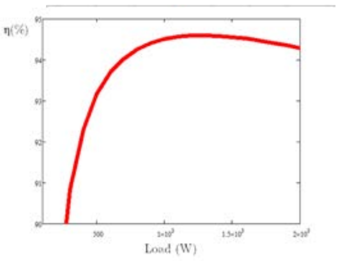
Design goals

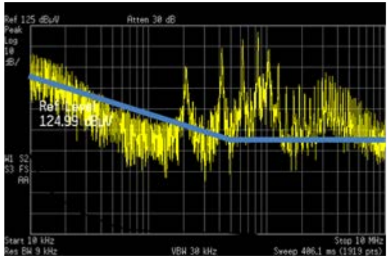
EFFICIENCY

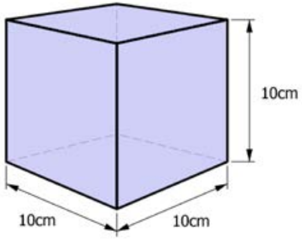
LOW EMI

LOW VOLUME

LOW COST

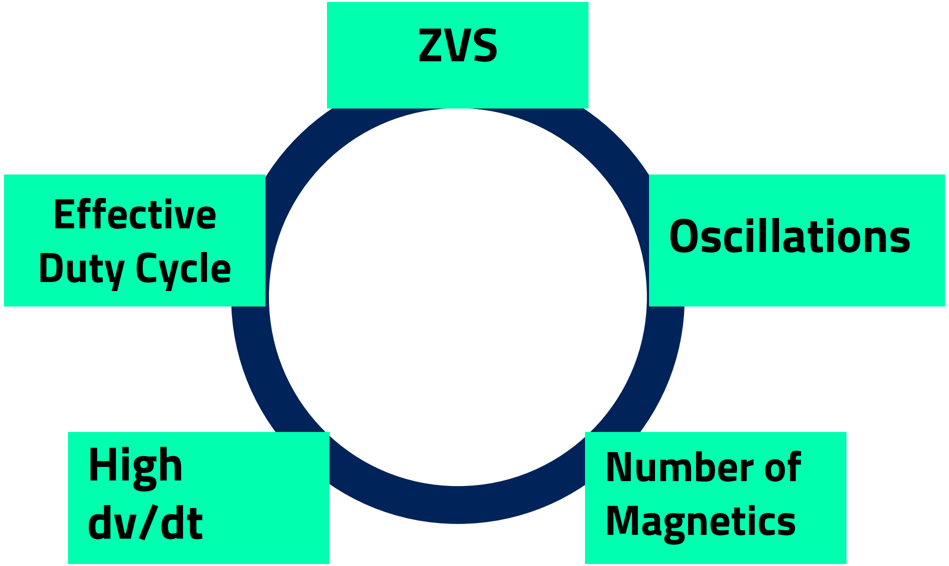




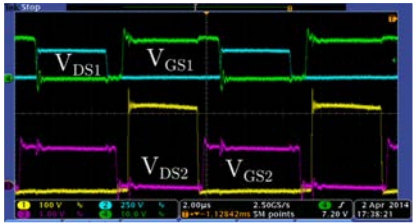


Frenetic

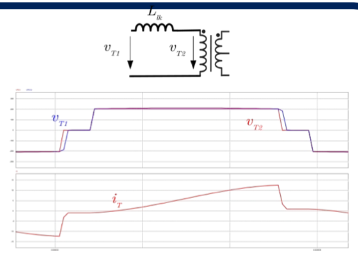
Key parameters of the design



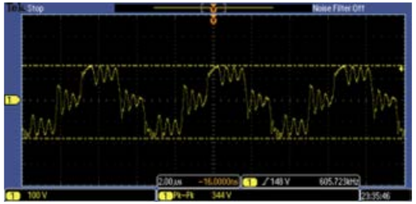
Key parameters of the design



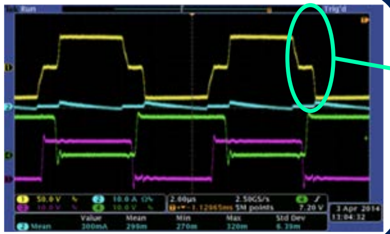
ZVS



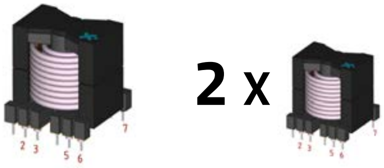
Effective Duty Cycle



Oscillations



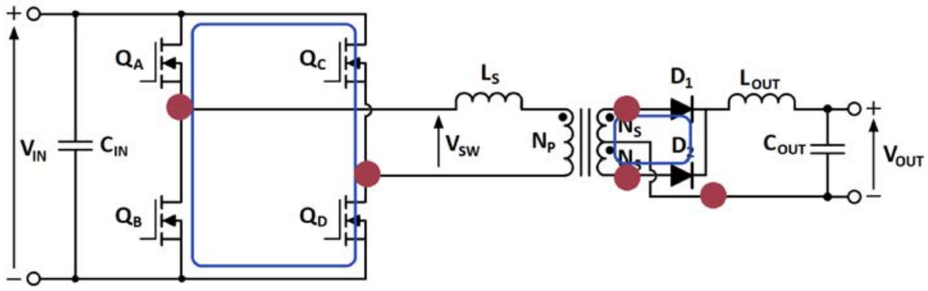
High dv/dt



Number of Magnetics

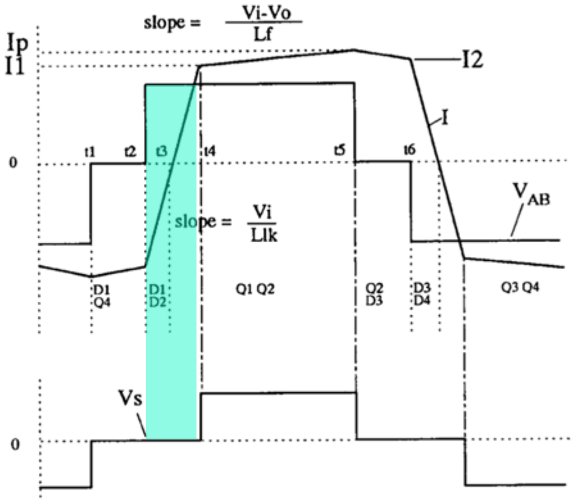
High dV/dT

- Due to the High dv/dt in the nodes A and B, the layout connections should be designed to minimize the distances as much as possible.
- Additionally, the high dI/dt during the transients affects the losses in the magnetics.
- Classical steinmetz equations are not suitable and the modified steimetz or other models could be used.



Duty cycle losses

- Due to the leakage inductance, there is a loss of the effective duty cycle in the transformer.
- This effect should be considered in the turns ratio calculations considering the L_{lk} prediction (or goal)



$$1 \geq D_{max} \geq \frac{N_p}{N_s}\frac{V_{out}}{V_{in}}\left(1 + 4\frac{L_{lk}}{R'}f_s\right)$$

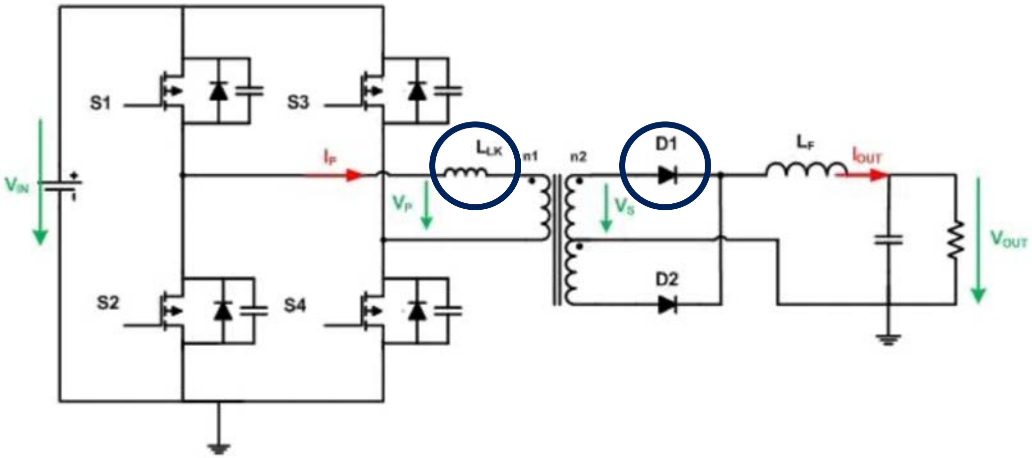
$$\Delta D = \frac{I_1 + I_2}{\frac{V_{in}}{L_{lk}}\frac{T}{2}}$$

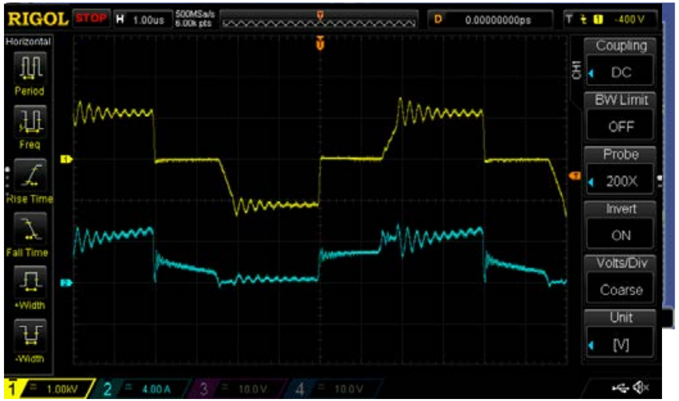
$$D = D_{eff} + \Delta D$$

$$\frac{V_o}{V_{in}} = \frac{N_s}{N_p}D_{eff}$$

Oscillations

It’s very common to find oscillations in the secondary diodes due to the resonance between L_{lk} and the parasitic capacitance of the diodes





ZVS in FBPS

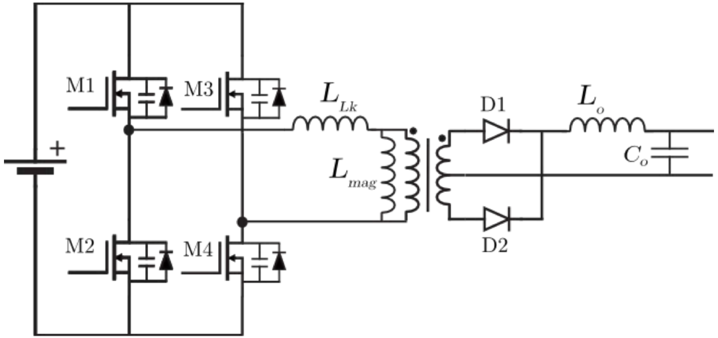
Achieving ZVS in the Full-Bridge Phase Shift is almost mandatory.

ZVS prevents:

- High EMI noise
- Switching losses
- Semiconductor failure rate increase

The main parameters that have an **influence** in achieving ZVS are:

- C_{oss} from the MOSFET
- Transformer parasitics
  - C_{in}
  - L_{mag}
  - L_{Lk}



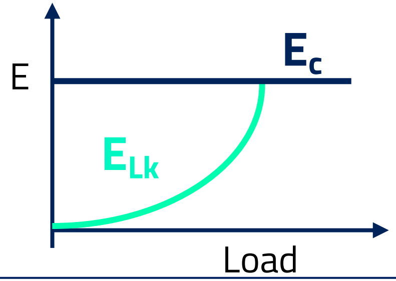
ZVS conditions

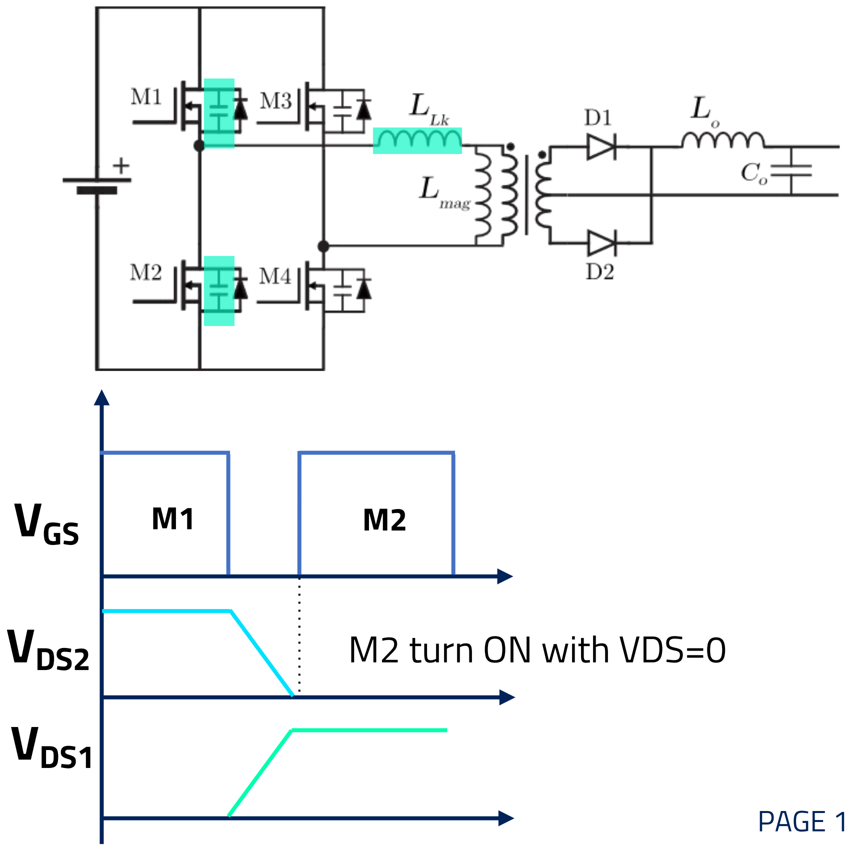
In the phenomenon for discharging the parasitic capacitances, the L_{Lk} is key as explained by [Sabate'90].

If the energy in the L_{Lk} is enough during the dead time for discharging the capacitor, ZVS can be achieved.

$$E_c < E_{lk}$$

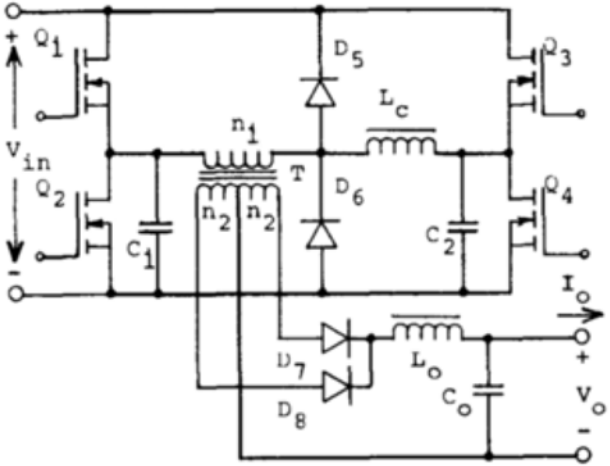
$$E_{lk} = \frac{1}{2} I_p^{\,2} L_{lk} \qquad E_c = \frac{1}{2} V^2 C_{equ}$$





ZVS with additional inductance

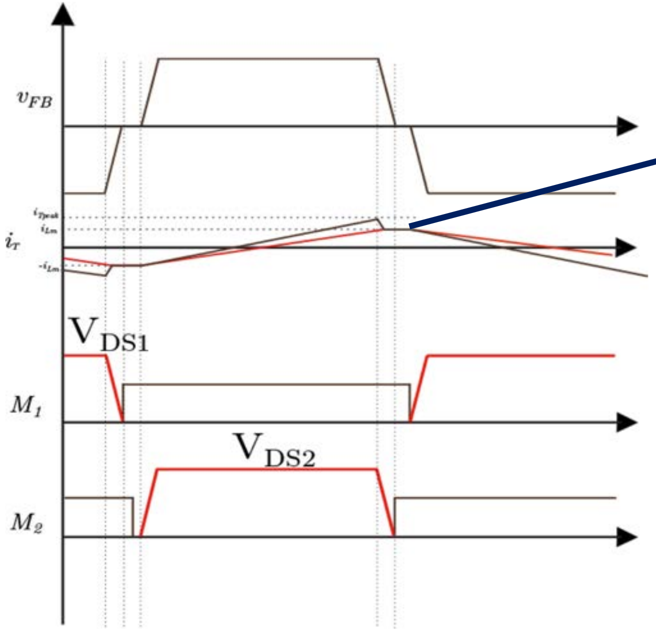
In the publication of Richard Redl ['90], he introduces an additional "commutating" inductor which extends the ZVS range.



$$E_{Lk} + E_{Lc} > E_c$$

ZVS with the Magnetizing current

For very light loads, where the energy in the Leakage inductance is very low, ZVS can be achieved using the magnetizing inductance .



I_{LM} (L_{mag}, V_{in}) is maximum during the commutation instants

José María Molina Thesis, 2017, "Three Phase Buck type rectifier integrated with current fed full bridge"

ZVS considerations

Considerations during the design:

- Too much energy stored in the L_{Lk} (or external inductance), produce an increment in the conduction losses in every component through a circulating current.
- For the magnetizing current, the effect is the same.
- The ideal design will have low magnetizing current, and the leakage inductance integrated in the operation for achieving ZVS without additional inductances.

Which are the key parameters?

ZVS is very recommended for a proper operation of the system.
Transformer **Llk** and Lm are key parameters

ZVS

This effect is mainly produced by the **Llk,** justified by this equation:

$$V = L_{lk}\frac{di}{dt}$$

Effective Duty Cycle

Oscillations between Llk and secondary diodes parasitic capacitance can cause system failure.
Llk is a key element here

Oscillations

Phase Shift and PWM modulations force this dV/dt, increasing the noise.
Semiconductors should are key elements here

High dv/dt

Number of Magnetics

With accurate estimation of **Llk**, a commutating additional inductor could be avoided

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Conclusion: The transformer is a key element

The importance of the transformer in this converter is huge because is the key element for :

- Design decisions (Semiconductors selection, turns ratio)
- Soft switching
- Number of magnetics
- Implementation (Functionality, PCB design)
- Size (It’s the biggest and expensive component)

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Transformer parameters

The parameters with high interest in the case of the FBPS (very similar to any case) are:

- Permeability (for the BH model)
- C_{in}
- R_{dc}
- R_{ac}
- L_{mag}
- L_{Lk}

Transformer parameters

The parameters with high interest in the case of the FBPS (very similar to any case) are:

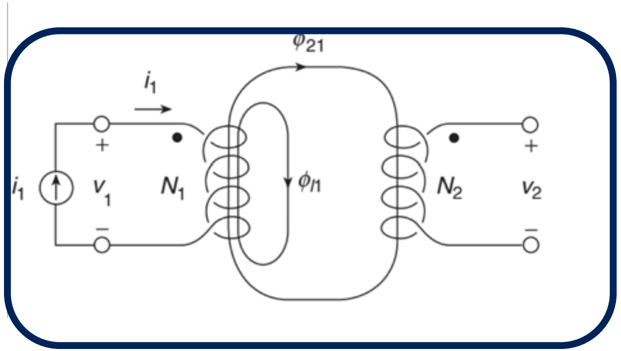
- Permeability (for the BH model)
- C_{in}
- R_{dc}
- R_{ac}
- L_{mag}
- L_{Lk}

L_{Lk} is selected for this analysis because its influence in the FBPS and the difficulties to accurately predict his value

Leakage Inductance (L_{Lk})

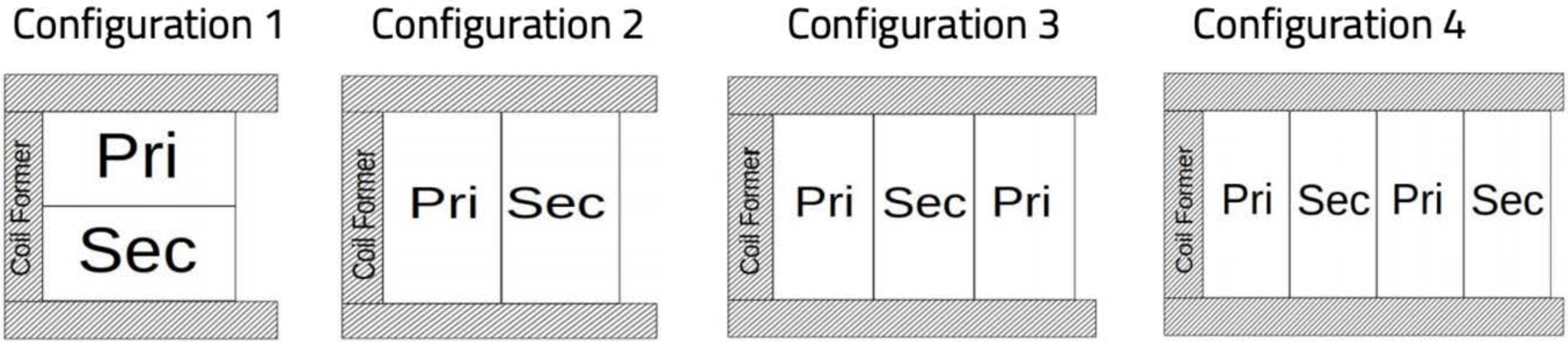
Leakage inductance parasitic effect produced by the imperfect magnetic coupling between the transformer windings. The magnetic flux generated in the primary winding is never transferred 100% to the secondary winding.

This leakage inductance depends basically on:
- The winding geometry
- The core geometry
- Number of turns



Impact of winding configuration in L_{Lk}

One of the ways of "playing" with this parameter is having different winding strategies. The following configuration strategies provide different coupling results



Vertical windings

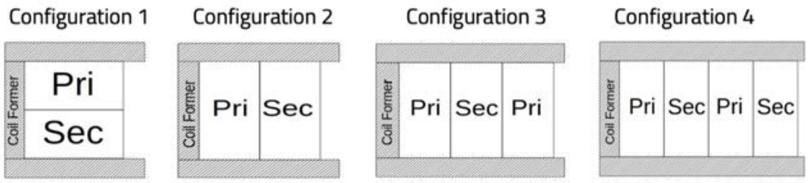
Horizontal Windings

Interleaving

Doble layer Interleaving

Impact of winding configuration in L_{Lk}

The results of leakage inductance for 3 cases with 2 different winding configurations

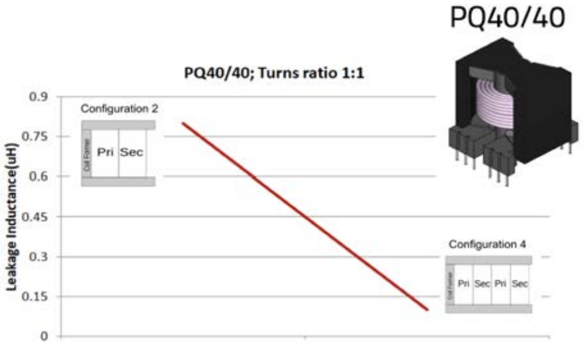


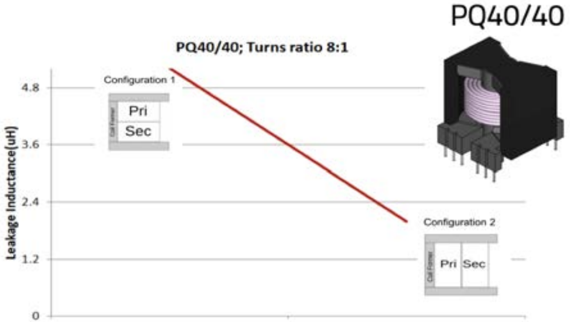
Topology	*Application*	*Power*	*Core Shape*	*Turns Ratio*	*Wire Type*	*Winding arrangement*	*Llk*
LLC	400 V/ 24 V	1,5 kW	PQ40/40	8:1	Litz	Configuration 1	5.2
LLC	400 V/ 24 V	1,5 kW	PQ40/40	8:1	Litz	Configuration 2	2
DAB	400 V/ 400 V	2 kW	PQ40/40	1:1	Litz	Configuration 2	0.8
DAB	400 V/ 400 V	2 kW	PQ40/40	1:1	Litz	Configuration 4	0.2
Flyback	PFC Flyback	60 W	RM8/I	5:1	Round	Configuration 2	11
Flyback	PFC Flyback	60 W	RM8/I	5:1	Round	Configuration 3	4.7

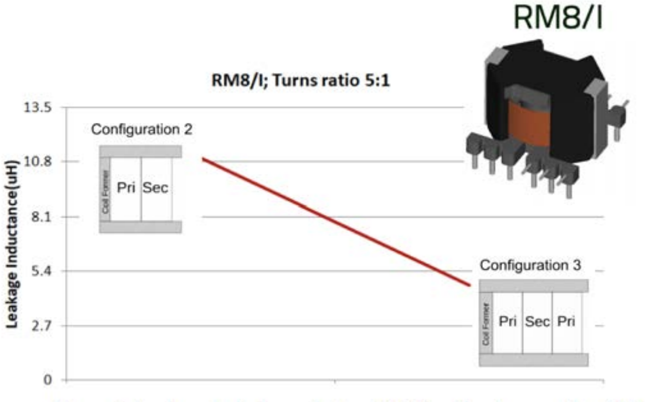
Table 1: Data of the different converters used in the experiment.

https://www.spfrenetic.com/application-note

Impact of winding configuration in L_{Lk}







Horizontal 2 layer to 4 layers interleaved
From Llk =0.8 → 0.2 uH

Vertical 2 layers to horizontal 2 layer
From Llk =5.2 → 2 uH

Horizontal 2 layer to 3 layers interleaved
From Llk =11 → 4.7 uH

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How can we predict L_{Lk}?

1. Classic models
2. Trial and error
3. Finite element analysis
4. New math methodologies and ai (fre19)

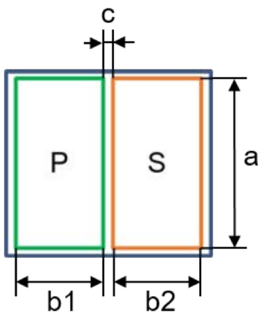
CLASSICAL MODELS

L_{LK} Inductance

A lot of models can be found in literature for calculating the leakage inductance. Two of them are:

CLASSICAL MODEL: This is a simple method for calculating the leakage inductance since only a small number of dimensions are necessary related to the winding geometry.

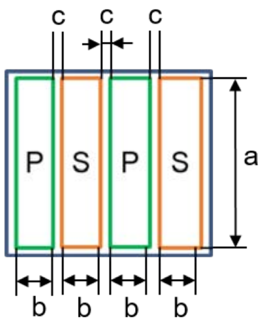
Conventional transformer configuration:



a = winding height (cm)
b = winding width (cm)
c = insulation thickness (cm)

$$L_p = \frac{4\pi(MLT)N_p^2}{a}\left(c + \frac{b_1 + b_2}{3}\right)(10^{-9}), \quad \text{[henrys]}$$

Interleaved transformer configuration:



$$L_p = \frac{\pi(MLT)N_p^2}{a}\left(\Sigma c + \frac{\Sigma b}{3}\right)(10^{-9}), \quad \text{[henrys]}$$

"Transformer and inductor design handbook", written by Colonel Wm. T. McLyman.

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L_{LK} Inductance

STEPHENS-BOYAJIAN MODEL: This model considers the magnetomotive force distribution and requires detailed knowledge about the winding geometry for calculating the leakage inductance radial and axial components, and the Rogowski factor.

Axial component:

$$L_{\sigma(ax)} = K_{\sigma(ax)} N_p^2 \frac{\mu_0}{h} \sum_{k=1}^{n} \left[m_k^2 g_k l_{gk} + \left(m_k^2 + m_{k-1}^2 + m_k m_{k-1} \right) w_k l_{wk} / 3 \right]$$

Radial component:

$$L_{\sigma(rad)} = K_{\sigma(rad)} N_p^2 \frac{\mu_0}{w} l_m \sum_{k=1}^{n} \left[m_k^2 g_k + \left(m_k^2 + m_{k-1}^2 + m_k m_{k-1} \right) h_k / 3 \right].$$

$$\boxed{L_\sigma = L_{\sigma(ax)} + L_{\sigma(rad)}}$$

L. M. R. Oliveira and A. J. M. Cardoso, "Leakage Inductances Calculation for Power Transformers Interturn Fault Studies," in IEEE Transactions on Power Delivery, vol. 30, no. 3, pp. 1213-1220, June 2015. doi: 10.1109/TPWRD.2014.2371877

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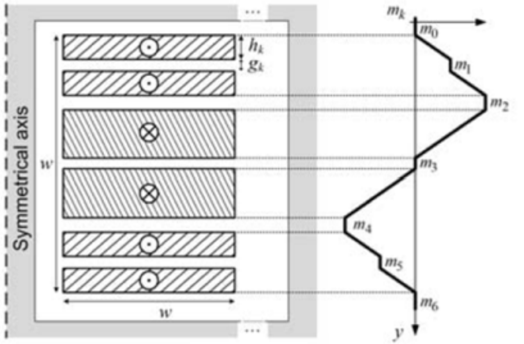
L_{LK} Inductance

STEPHENS-BOYAJIAN MODEL:

Rogowski factor:

$$K_{\sigma(ax)} = 1 - \frac{1-e^{-\pi h/w}}{\pi h/w}\left\{1-\frac{1}{2}e^{-2\pi g_{01}/w}\left(1-e^{-\pi h/w}\right)\left[\frac{l_2}{l_m}+\frac{l_1}{l_m}\left(1+e^{-\pi(g_{02}-g_{01})/w}\right)\right]-\frac{l_1}{l_m}e^{-\pi(h+2g_{02}+2g_{01})/w}\right\}$$

Magnetomotive force distribution:



L_{LK} Inductance

When do we use each model?

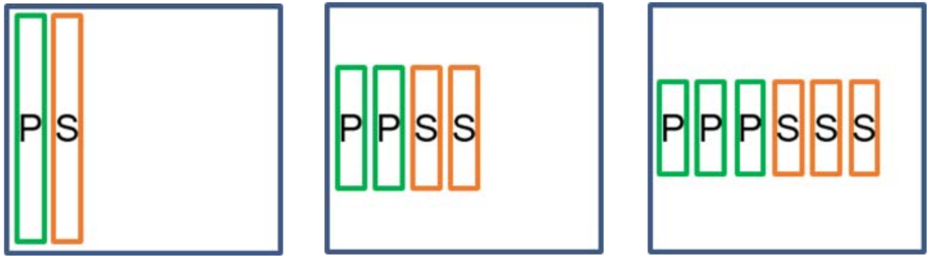
MODEL	WORKS	DOES NOT WORK
CLASSICAL	• Simple winding arrangements.	• Layers with different height. • Nonuniform magnetomotive force distributions. • High-frequency effects.
STEPHENS-BOYAJIAN	• Complex winding arrangements. • Nonuniform magnetomotive-force distributions.	• Layers with different height. • High-frequency effects.

L_{LK} Inductance

Leakage inductance comparison in a conventional winding arrangement:

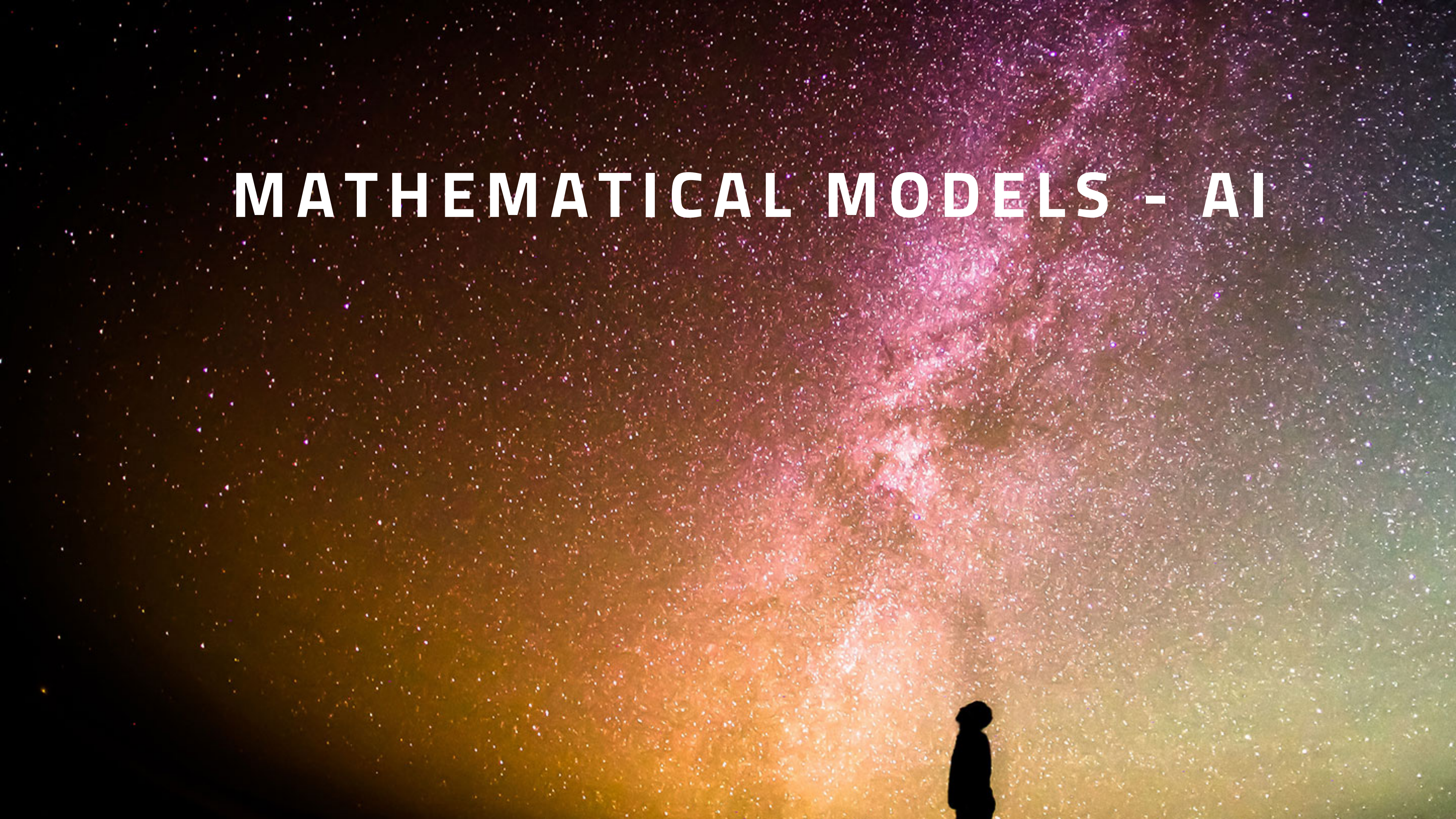
Transformer construction:

- Core shape: PQ40/40
- Core material: Ferroxcube 3F36
- Number turns: 24 / 24
- Wire: Round 12AWG / 12AWG

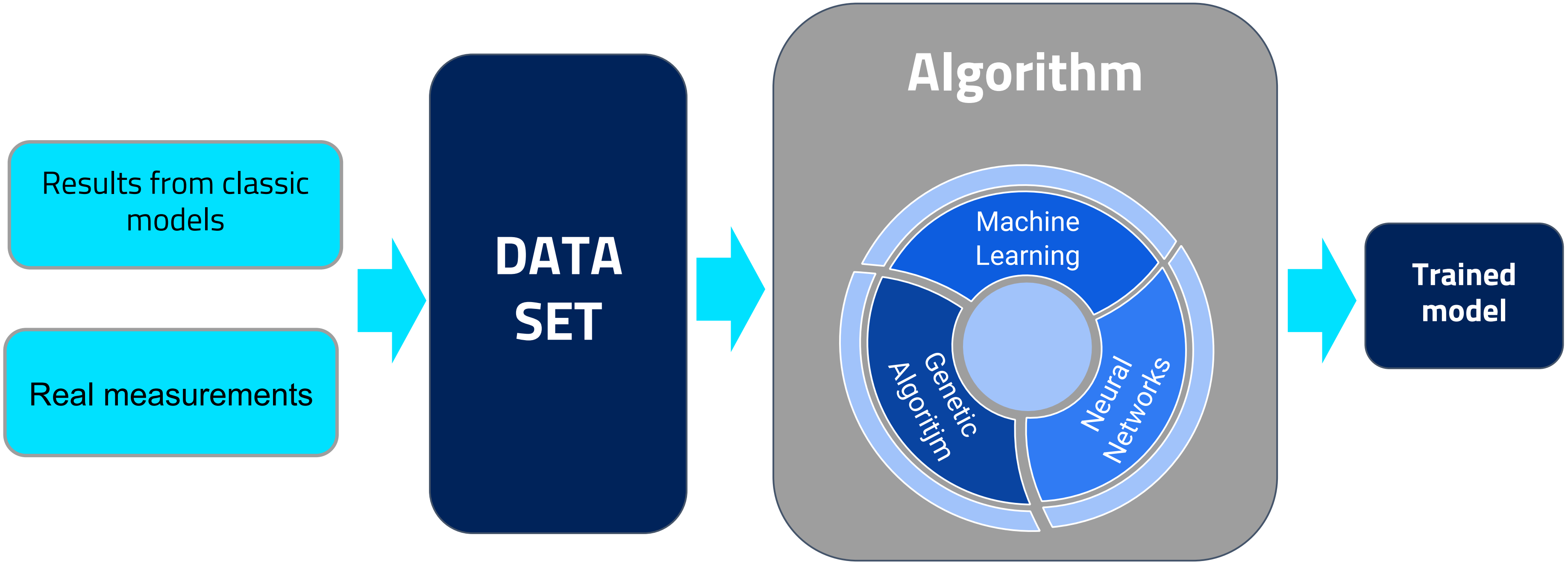


MODEL	CASE A	CASE B	CASE C
CLASSICAL	1.64 μH	6.87 μH	15.69 μH
STEPHENS-BOYAJIAN	1.49 μH	5.65 μH	11.35 μH
MEASUREMENTS	1.01 μH	5.2 μH	5.6 μH

MATHEMATICAL MODELS - AI

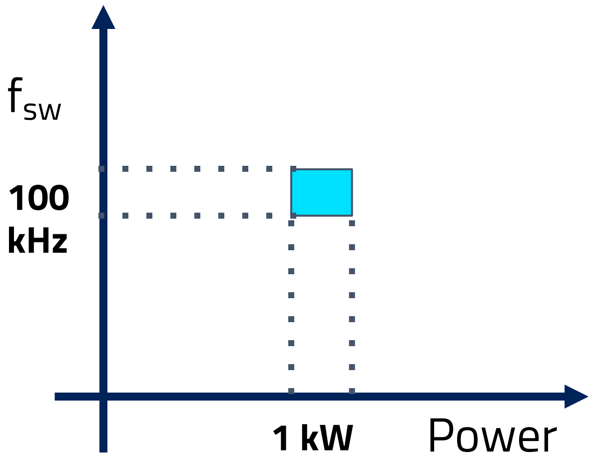


AI used for predicting L_{Lk}



Basic example for predicting L_{Lk} in a specific range of power and frequency

Space of data:
Transformer n=1
1 kW FBPS & 100 kHz



DATA SET

# Data	Core	Primary number of turns	Primary Litz wire	….	Real L_{LK}	Model L_{LK}
1	PQ32/30	21	20	….	2uH	2,2 uH
2	PQ40/40	15	17	….	8 uH	7 uH
n	PQ50/50	10	14		-	10 uH

Basic example for predicting L_{Lk} in a specific range of power and frequency

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..	..	..	..	..	..	..
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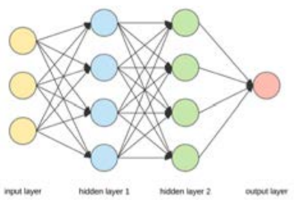
Algorithm

Neural Networks



PQ32/30
N1= 16
N2=18

TRAINED MODEL

L_{Lk}=2 uH

DESIGN EXAMPLE

Frenetic

FBPS Design Example

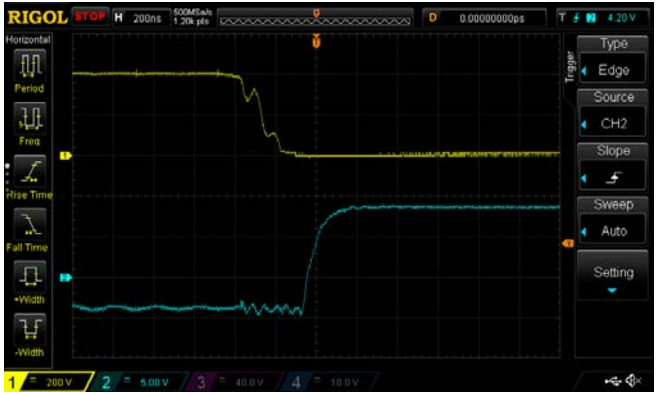
The design of a FBPS with the parameters of the Table is designed and the steps for the magnetics are as follow.

Parameter	Value
Rated power	600 W
Min. input voltage	360 V
Nominal input voltage	390 V
Max. input voltage	400 V
Output voltage	300 V
Max. output voltage ripple	3 V

1. According with Deff and input and output voltage range, the turn ratio is calculated
2. The transformer is designed with the lower L_{lk} possible
3. With Llk, the avaible energy to discharge Coss is known
4. MOSFET are selected considering maximum Coss, power ratios
5. The prototype is built and verified

FBPS Design Example

- Accurate prediction of L_{Lk} helps to have a proper design in the first transformer iteration.
- ZVS is achieved and semiconductors are used without heatsink
- 95% of efficiency is achieved at 500 W



Conclusions

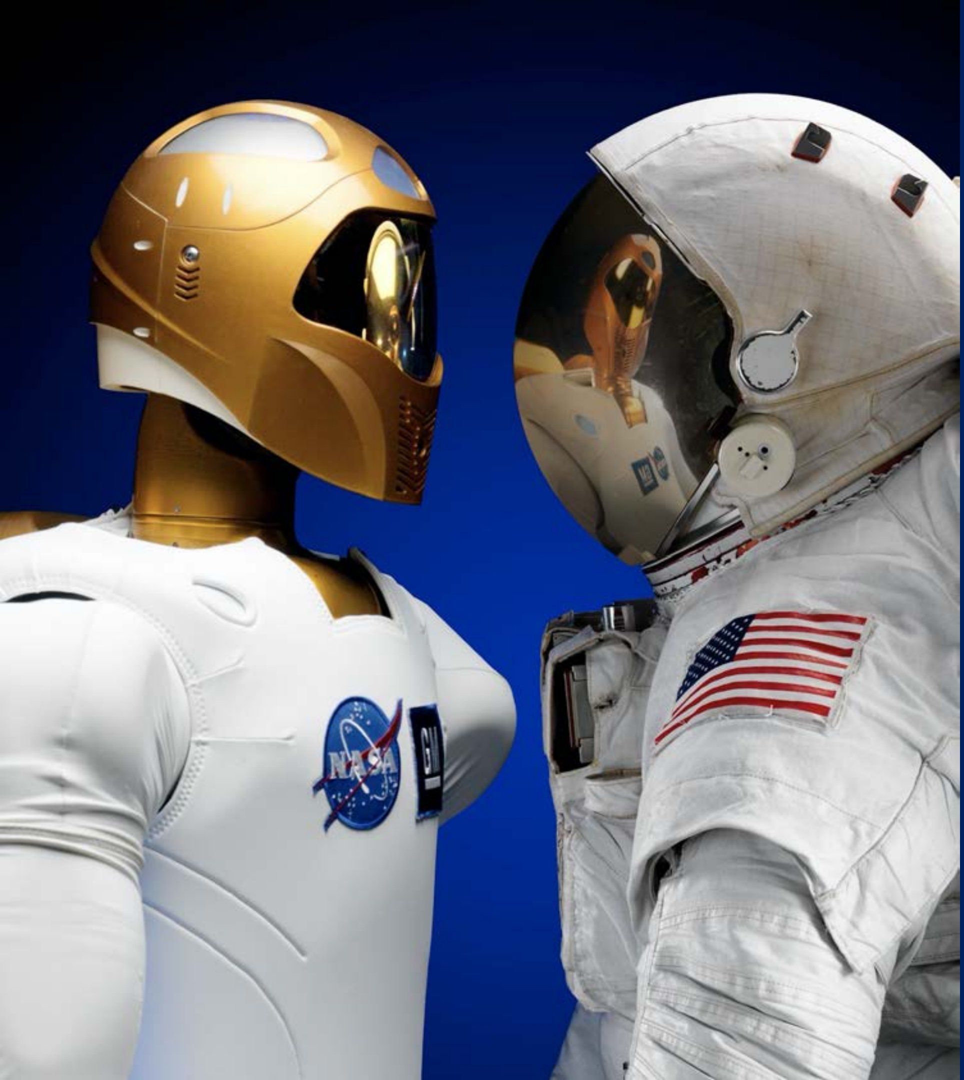
The transformer is the key element in the Full-Bridge performance

Leakage inductance is one of the parameters with more impact

Actual techniques for estimating Leakage inductance are:

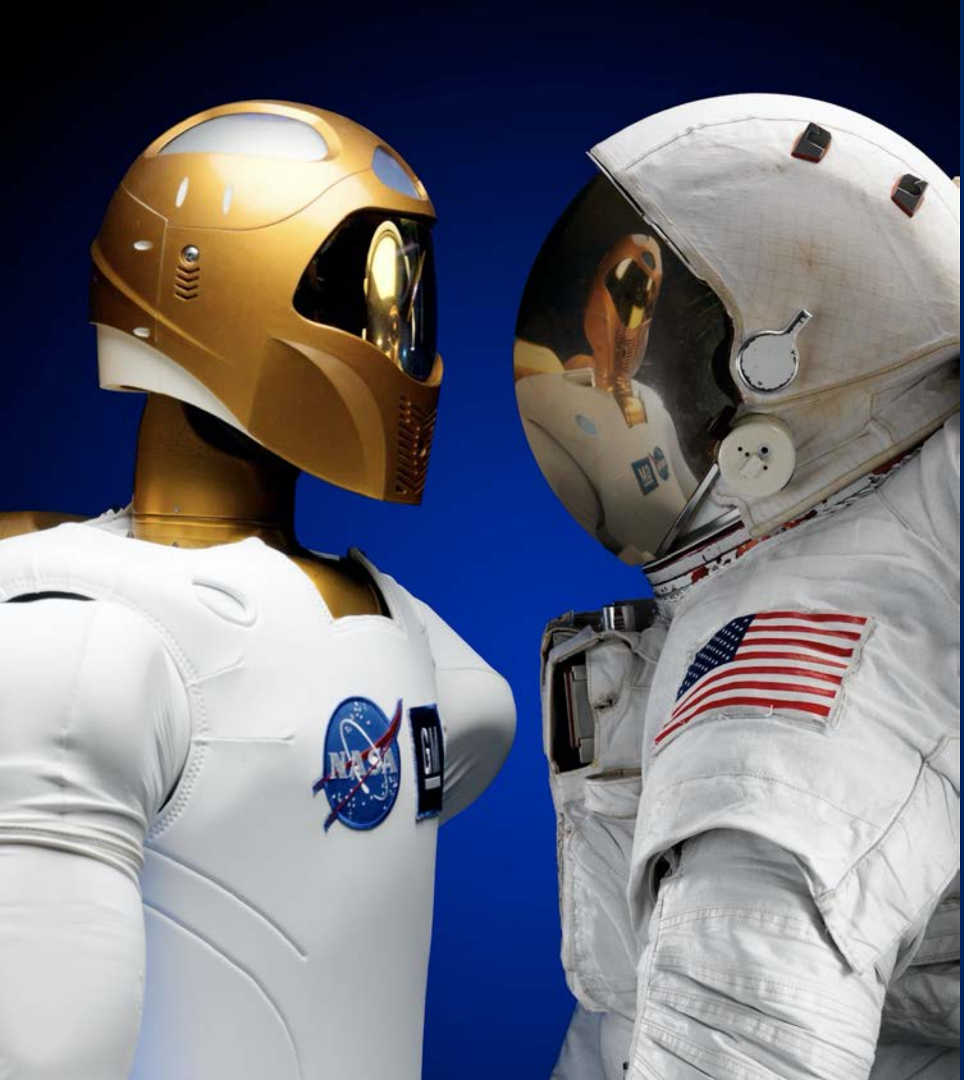
- Not accurate
- Slow
- Not scalable to different cases

Artificial Intelligence methods allows to estimate accurate leakage inductance in seconds.



What if we extend the AI to the rest of the parameters?

AI can complement classical models for a better future



THANK YOU

Q&A