IEEE ENERGY CONVERSION CONGRESS & EXPO
Vancouver, Canada Oct. 10-14

NOVEL TRANSFORMER WITH VARIABLE LEAKAGE AND MAGNETIZING INDUCTANCES

Angshuman Sharma, Jonathan W. Kimball
Department of Electrical and Computer Engineering
Missouri University of Science and Technology
Rolla, MO, USA

asc4v@mst.edu, kimballjw@mst.edu

Presentation outline

- ✓ Motivation
- ✓ Introduction to Variable Inductance Transformer (VIT)
- ✓ Analytical model of variable leakage inductance
- ✓ Analytical model of variable magnetizing inductance
- ✓ Design specifications and experimental setup
- ✓ Results
- ✓ Conclusion and future scope

Motivation

- High-frequency transformers are widely used at all power levels
- Conventional transformers are inherently static in nature
  - Static leakage inductance
  - Static magnetizing inductance
- Smooth control of power electronic converters require a precise transformer design
- Any change in leakage or magnetizing inductance involve a complete rewinding of the conventional transformer
- Transformers that can allow dynamic and independent control of its leakage and magnetizing inductances did not exist before

Introduction to VIT

Concept

- Leakage inductance can be varied by varying the extent of overlap ***g*** between the two bobbins
- Magnetizing inductance can be varied by varying the air gap ***G*** between the two E cores
- The two inductances can be varied dynamically and independently by using independent controllers
- Desired leakage and magnetizing inductance ranges can be achieved with a precise design

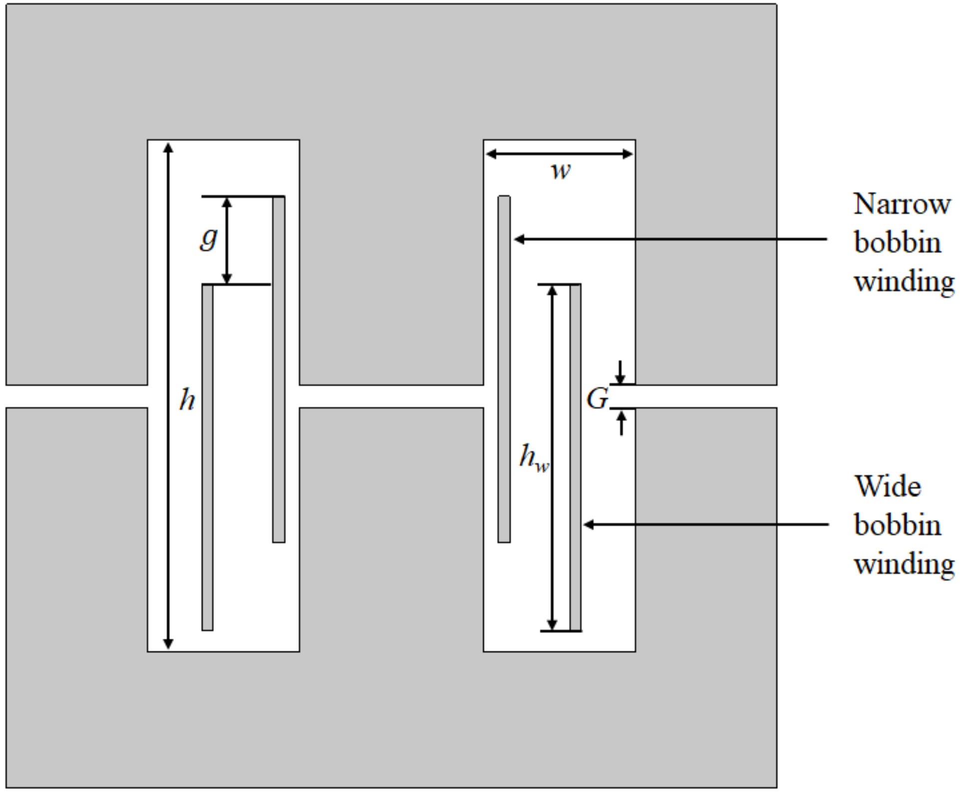


Fig: Variable Inductance Transformer (VIT).

Analytical model of the variable leakage inductance

General form of the Double-2D model

$$L_{lk,\text{Double}-2\text{D}} = s_c \left(L'_{2\text{D(IW)}} d_{l(\text{IW})} + L'_{2\text{D(OW)}} d_{l(\text{OW})} \right)$$

$$s_c = \begin{cases} 1, \text{ core}-\text{type transformer} \\ 2, \text{ shell}-\text{type transformer} \end{cases}$$

- $L'_{2\text{D(IW)}}$ and $L'_{2\text{D(OW)}}$ are the leakage inductances per unit length across the IW and OW planes
- $d_{l(\text{IW})}$ and $d_{l(\text{OW})}$ are the partial leakage lengths across the IW and OW regions

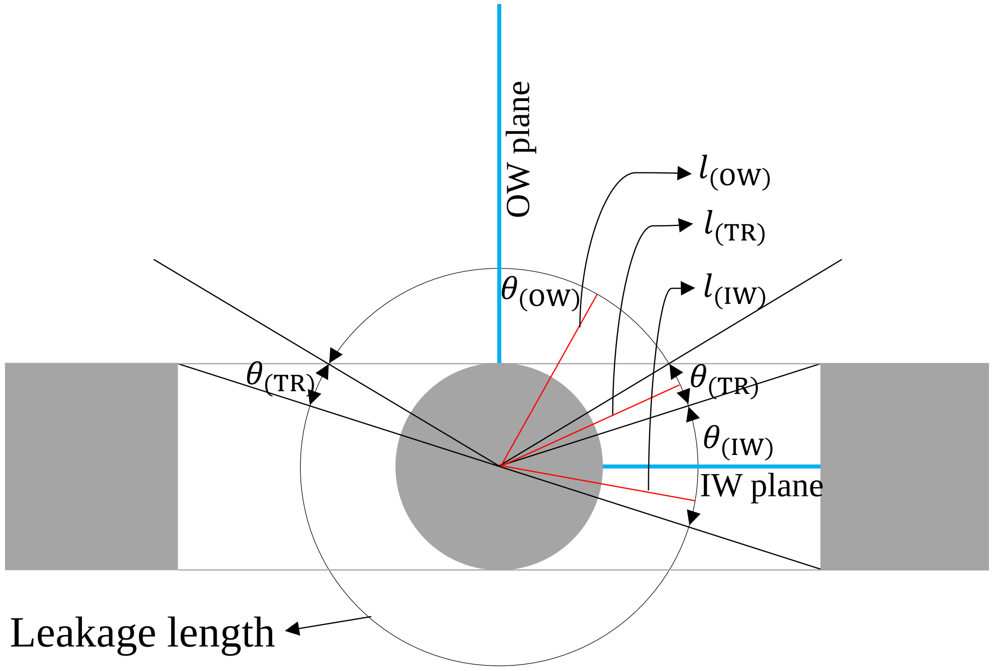


Fig: Double-2D model for shell-type transformer.

IW: Inside Window *OW: Outside Window*

Analytical model of the variable leakage inductance

- The Double-2D model for calculation of leakage inductance involves:
  - the precise identification of the IW and OW regions
  - the accurate evaluation of $L'_{2\mathrm{D(IW)}}$, $L'_{2\mathrm{D(OW)}}$, $d_{l\mathrm{(IW)}}$ and $d_{l\mathrm{(OW)}}$
- Magnetic image method can be used to calculate these parameters
- All mathematical formulations are presented in the paper
- Transition regions are split equally between the IW and OW regions
- A parametric sweep of g across the range [0, g_{max}] gives the range of the variable leakage inductance [$L_{lk(min)}$, $L_{lk(max)}$]

Analytical model of the variable magnetizing inductance

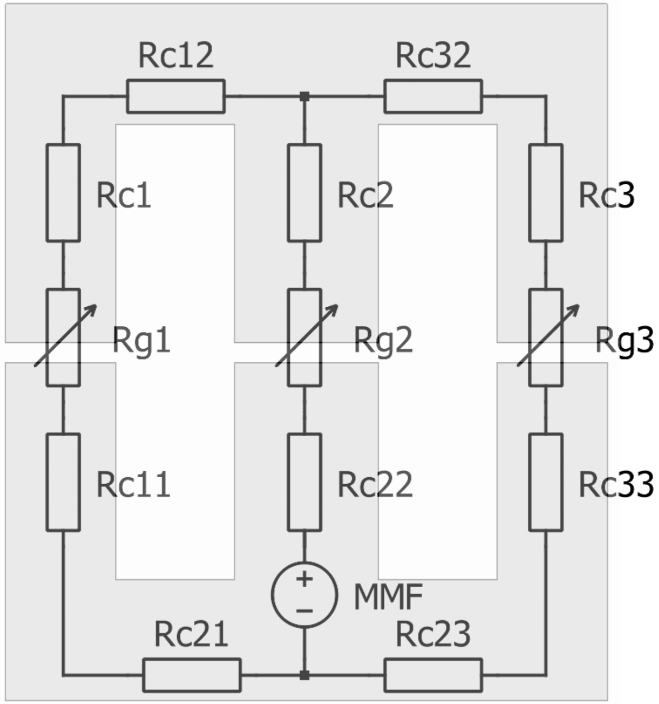
- Variable magnetizing inductance of the VIT is calculated by solving its magnetic equivalent circuit for various airgaps G

$$\mathcal{R} = (\mathcal{R}_{c1}+\mathcal{R}_{c11}+\mathcal{R}_{c12}+\mathcal{R}_{c21}+\mathcal{R}_{g1})\,||\,(\mathcal{R}_{c2}+\mathcal{R}_{c22}+\mathcal{R}_{g2})\,||\,(\mathcal{R}_{c3}+\mathcal{R}_{c33}+\mathcal{R}_{c32}+\mathcal{R}_{c23}+\mathcal{R}_{g3})$$

- Fringing magnetic flux around each air gap should be considered for accuracy
- If N_1 is the number of primary turns, then

Magnetizing inductance, $L_m = N_1^2/\mathcal{R}$

- A parametric sweep of *G* across the range [G_{min}, G_{max}] gives the range of the variable magnetizing inductance [$L_{m(max)}$, $L_{m(min)}$]



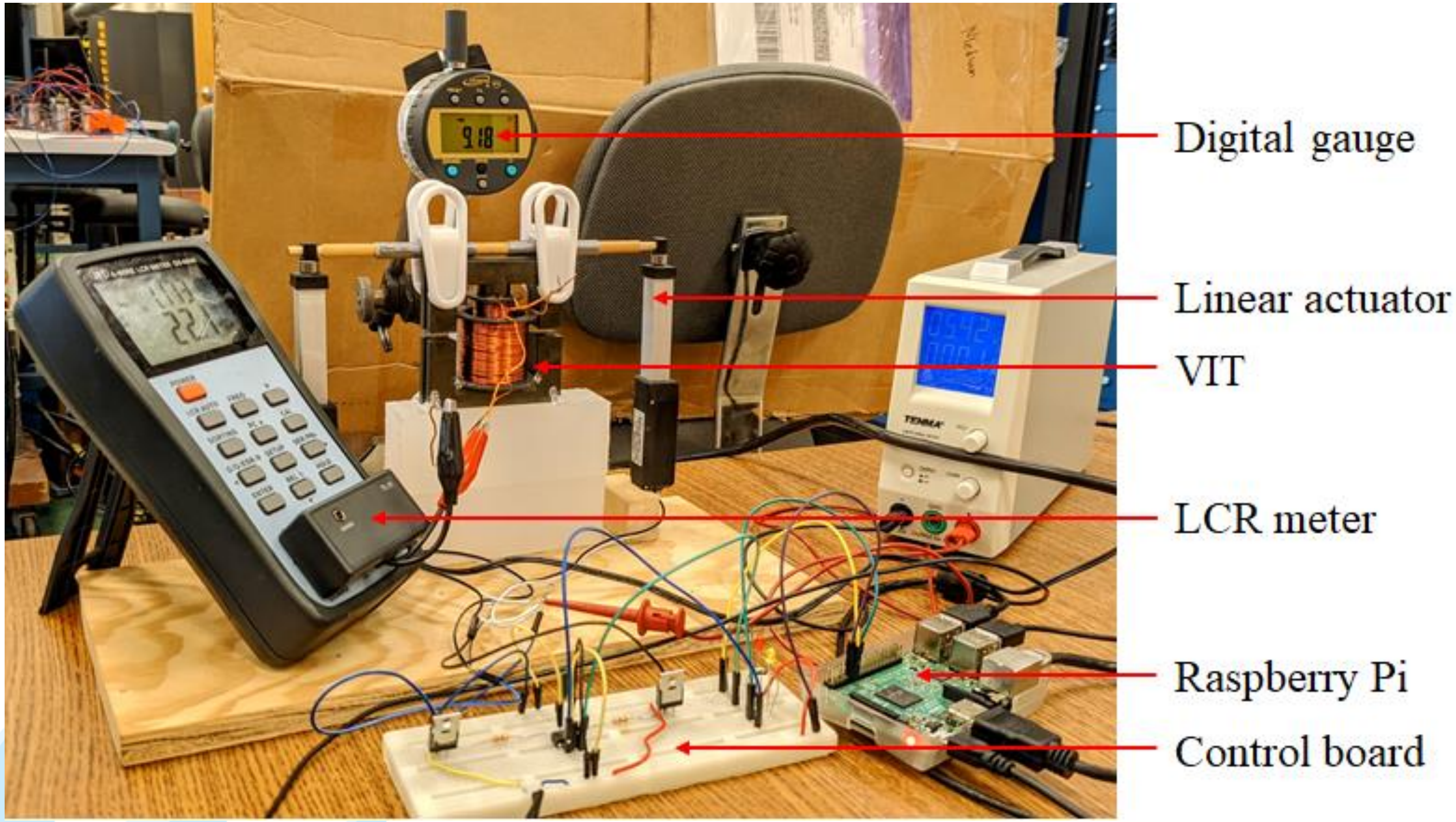
Rc1 = Rc3 = Rc11 = Rc33
Rg1 = Rg3
Rc12 = Rc23 = Rc32 = Rc21
Rc2 = Rc22

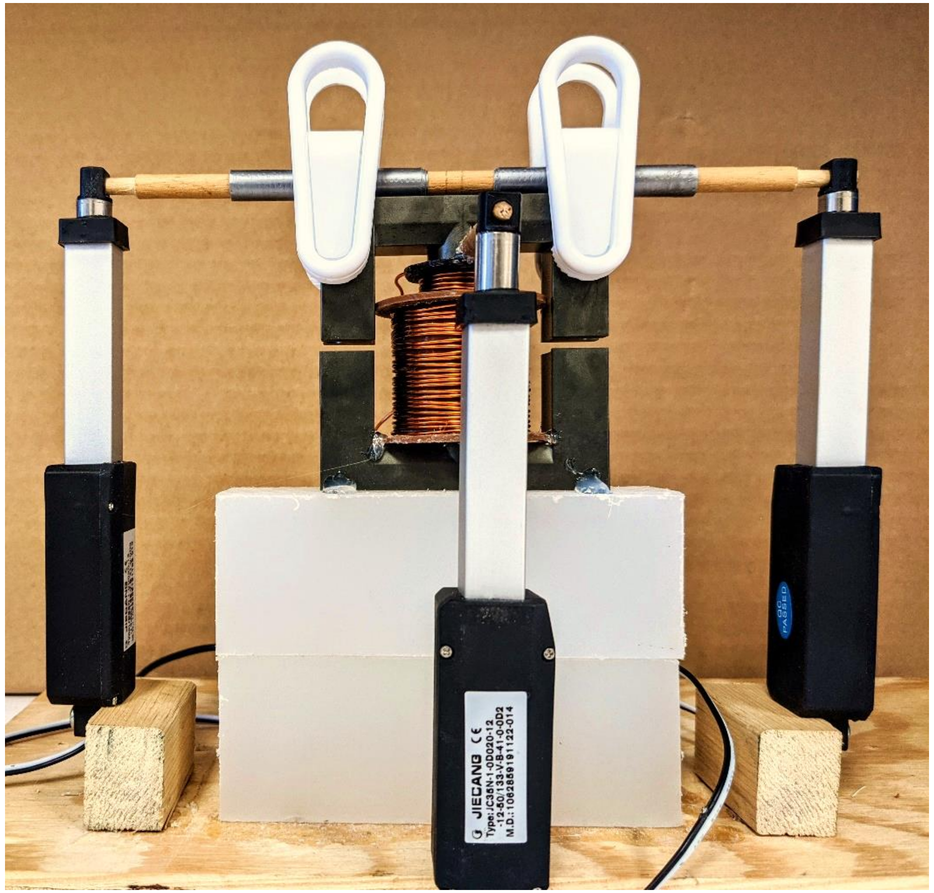
Fig. Magnetic equivalent circuit of the VIT.

Design specifications

Description	Value
Core type and size (part)	EC 70 (EPCOS B66343)
Height of the bobbins	31.5 mm
External diameter of narrow bobbin	19 mm
External diameter of wide bobbin	32.5 mm
Thickness of the bobbins	1.5 mm
Turns ratio	1:1
Number of turns	26
Number of layers	1
Primary current	1 A
Conductor shape/AWG/diameter	Round/19/0.912 mm
Test frequency	1 kHz
Relative permeability of the core	1360
Range of g	0 – 10 mm
Range of G	0.1 – 5 mm

Experimental setup

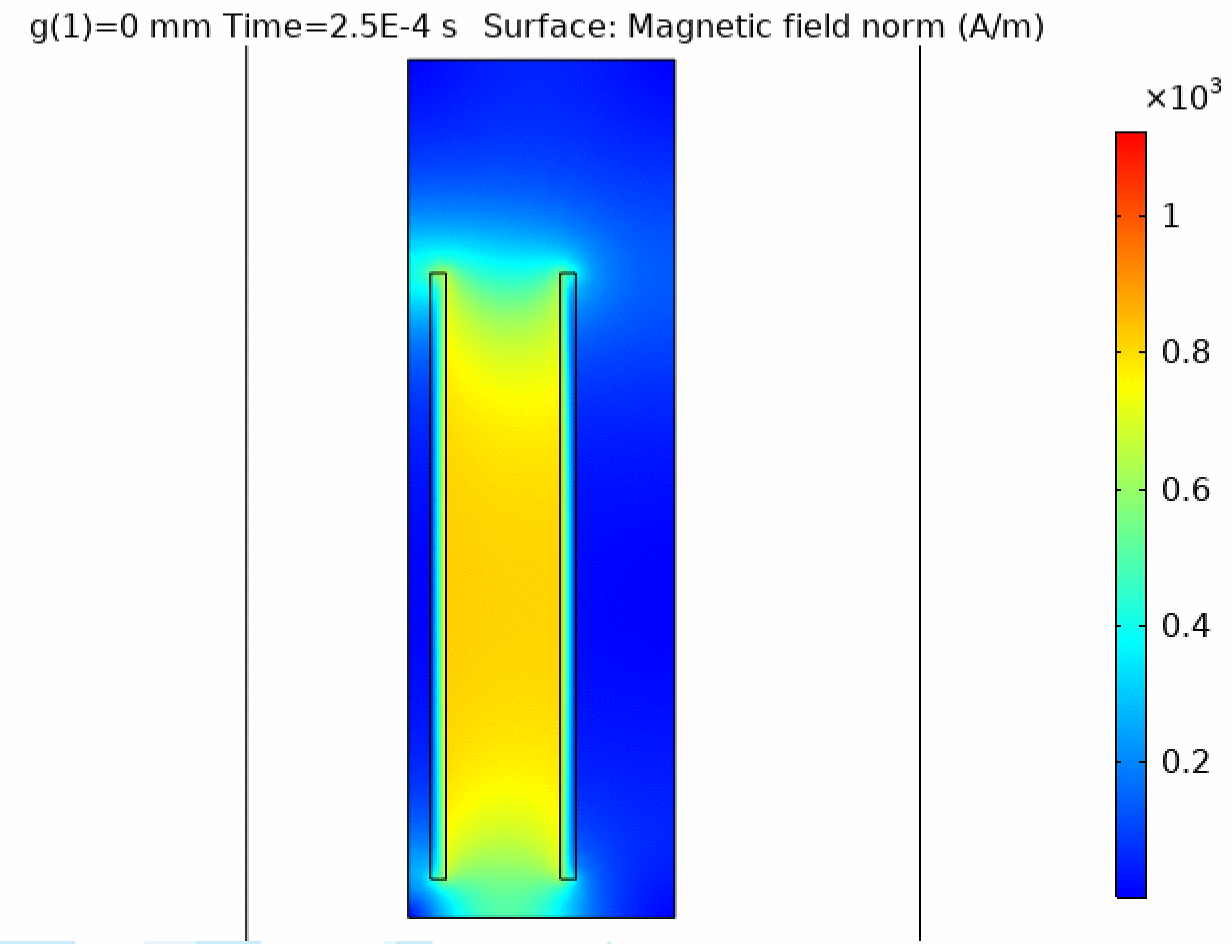




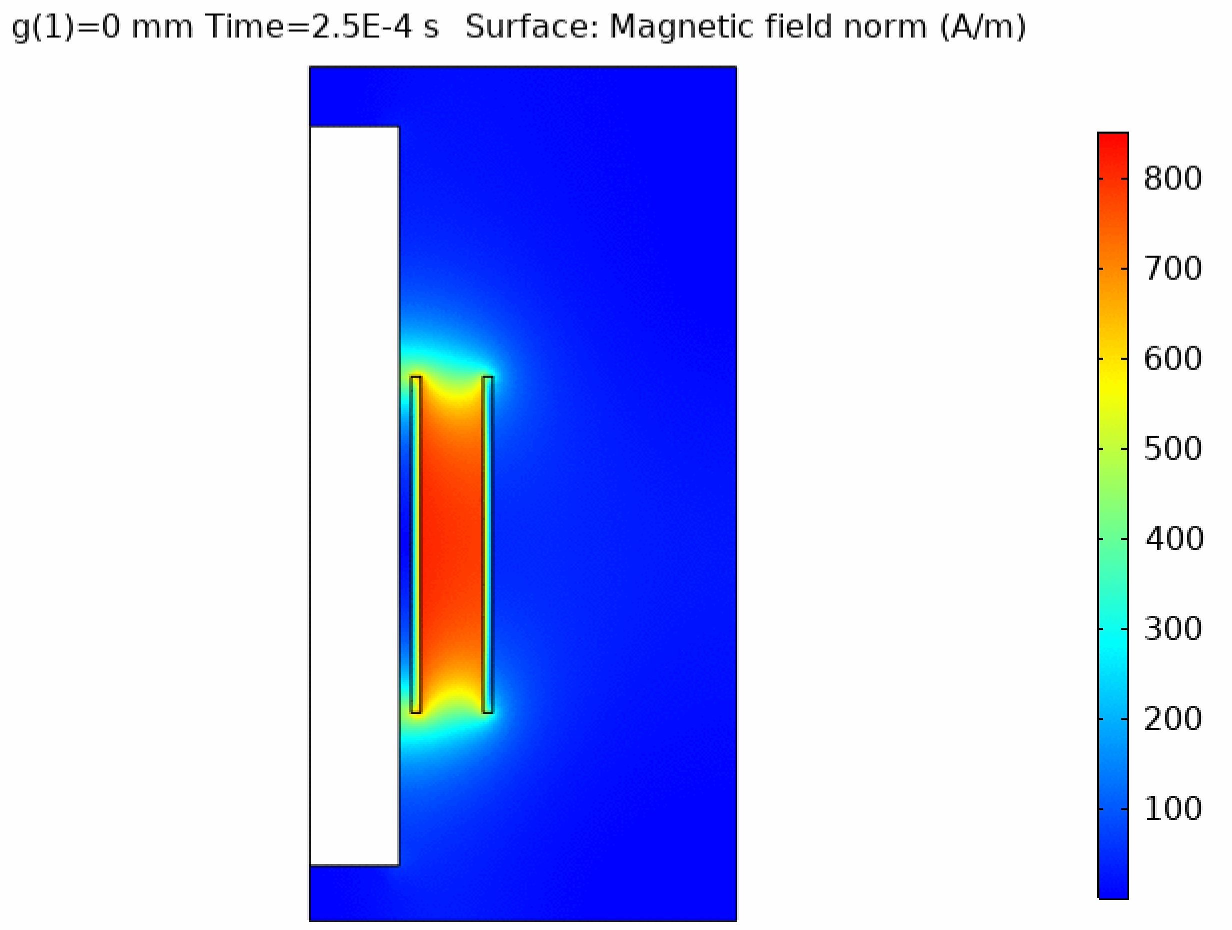
Results: Variable leakage inductance

Category of results (g = 0 mm)	$L'_{2D(IW)}$ (uH/m)	$L'_{2D(OW)}$ (uH/m)	$d_{l(IW)}$ (mm)	$d_{l(OW)}$ (mm)	L_{lk} (µH)	Error (%)
Analytical	153.27	152.54	14.266	27.494	12.761	0.2
3D FEM	-	-	-	-	12.736	0
2D FEM	155.11	149.26	14.213	27.148	12.514	– 1.74

Results: Variable leakage inductance



IW plane



OW plane

Results: Variable leakage inductance

Experimental result

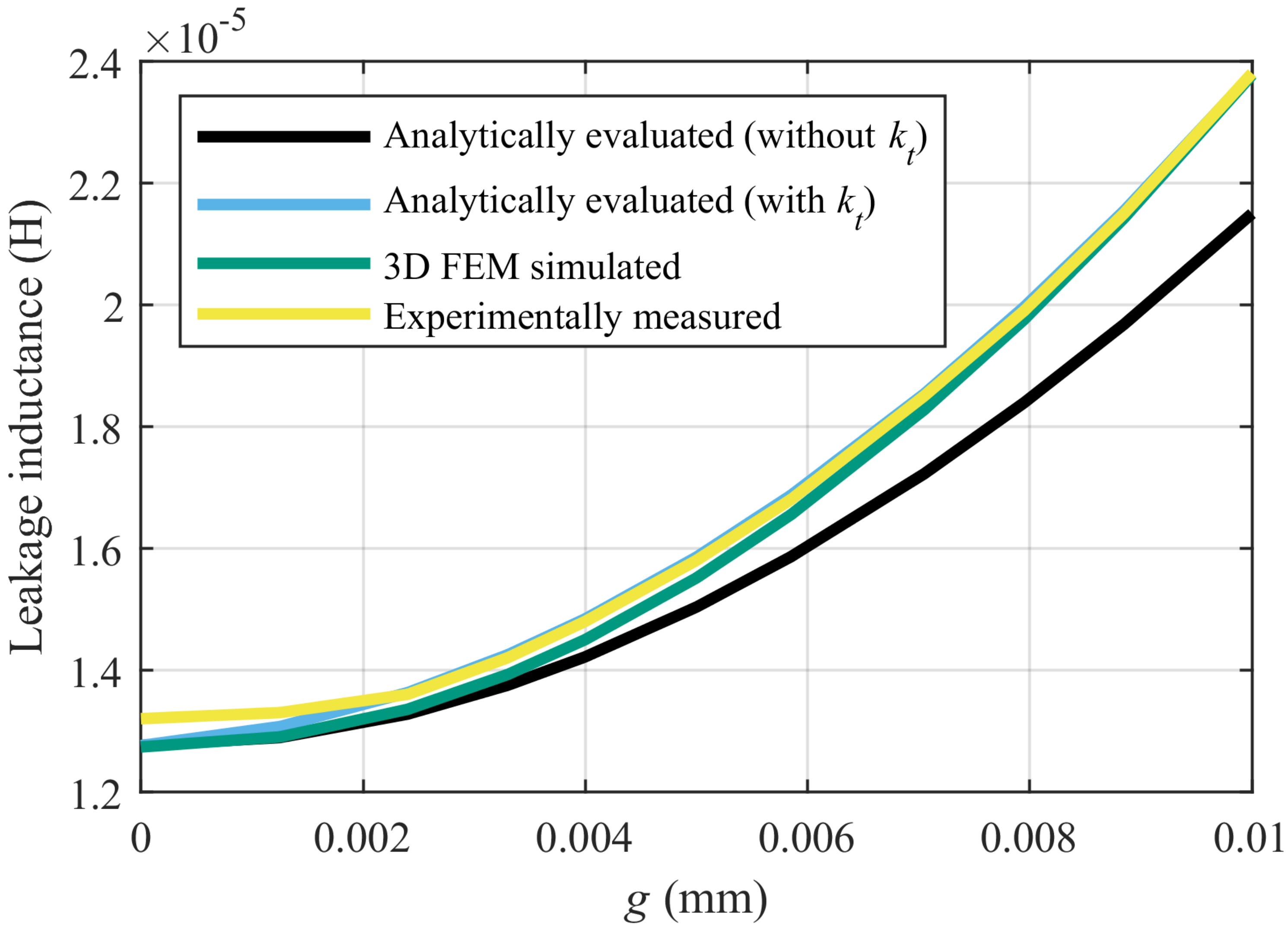
Minimum L_{lk} = 13.2 µH
Maximum L_{lk} = 23.8 µH

Analytical result

$$k_t = \sqrt{1 + {}^{g}/_{h}}$$

$$L_{lk,\mathrm{VIT}} = k_t \times L_{lk,\mathrm{Double-2D}}$$

Maximum error < 2.35 %

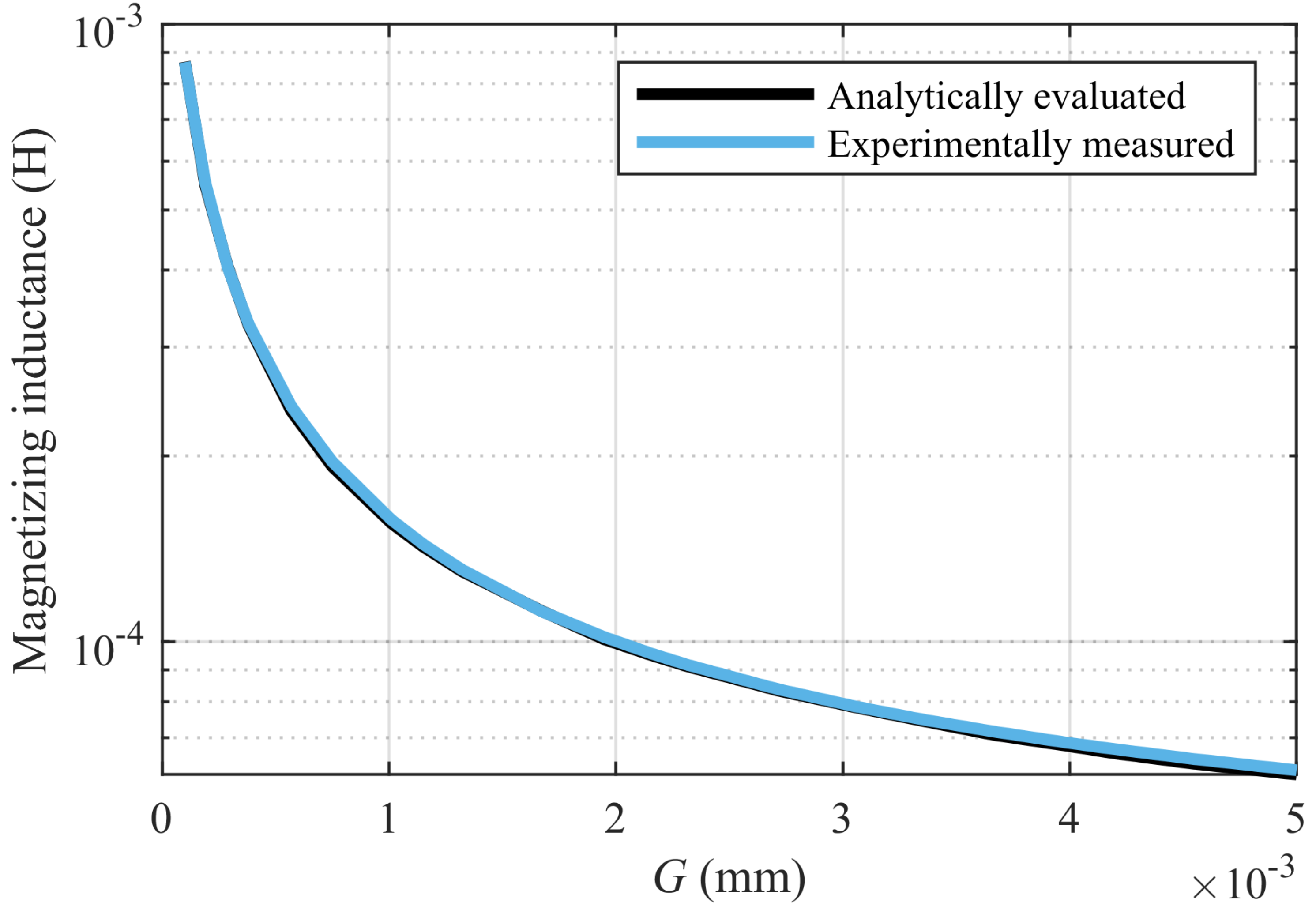


Results: Variable magnetizing inductance

Experimental result

Minimum L_m = 61 µH
Maximum L_m = 868.5 µH

Maximum error < 1.81 %



Conclusion

- The concept of VIT was introduced.
- Analytical model of the variable leakage inductance was obtained.
- Analytical model of the variable magnetizing inductance was obtained.
- An experimental prototype of the VIT was designed.
- The two inductances could be controlled independently and dynamically.
- Analytical results were validated using 3D FEM simulations and experimental measurements.

Future scope

- VIT can prove to be a beneficial tool for the advancement of research in galvanically isolated power electronic converters, especially resonant converters.

- It would be interesting to study the effects of frequency-dependent leakage inductance on the operation of a resonant converter. For example,
  - Leakage inductance decreases as the frequency is increased due to skin and proximity effects
  - The change in leakage inductance will change the resonant frequency, inductance ratio, voltage gain, efficiency, etc.
  - How can the VIT help in maintaining a constant leakage inductance at all operating frequencies?
  - How can the variable leakage and magnetizing inductances play together to achieve the desired voltage gain of the converter at maximum efficiency?


“Thank you”