Eidgenössische Technische Hochschule Zürich
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Magnetic Saturation of High Power Medium Frequency Transformers due to Semiconductor On-State Voltage Drop and Switching Time Tolerances

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Introduction

High-Power DC-DC Converters with MF Transformers

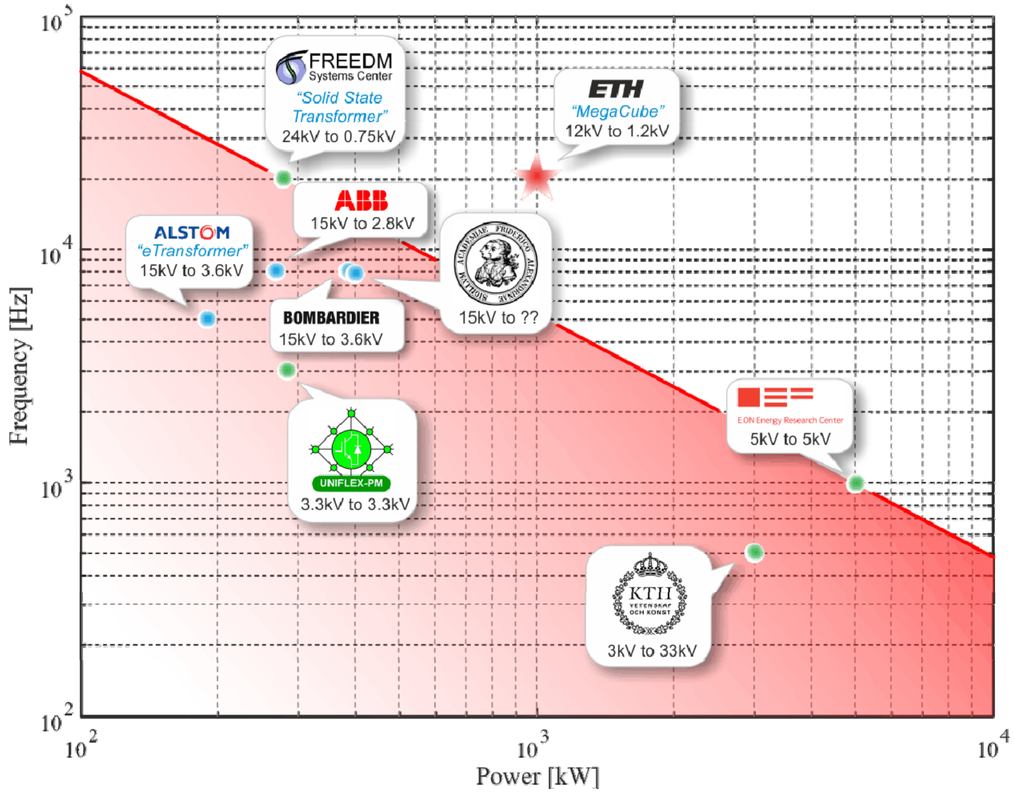
In Renewable Energy Generation

- *Transmission of energy in DC.*
- *Power flow control (Smart Grids).*
- *Reduction in size/weight.*

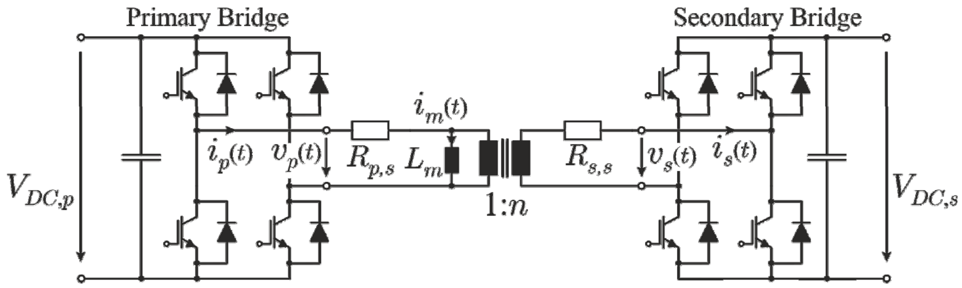
In Traction Applications

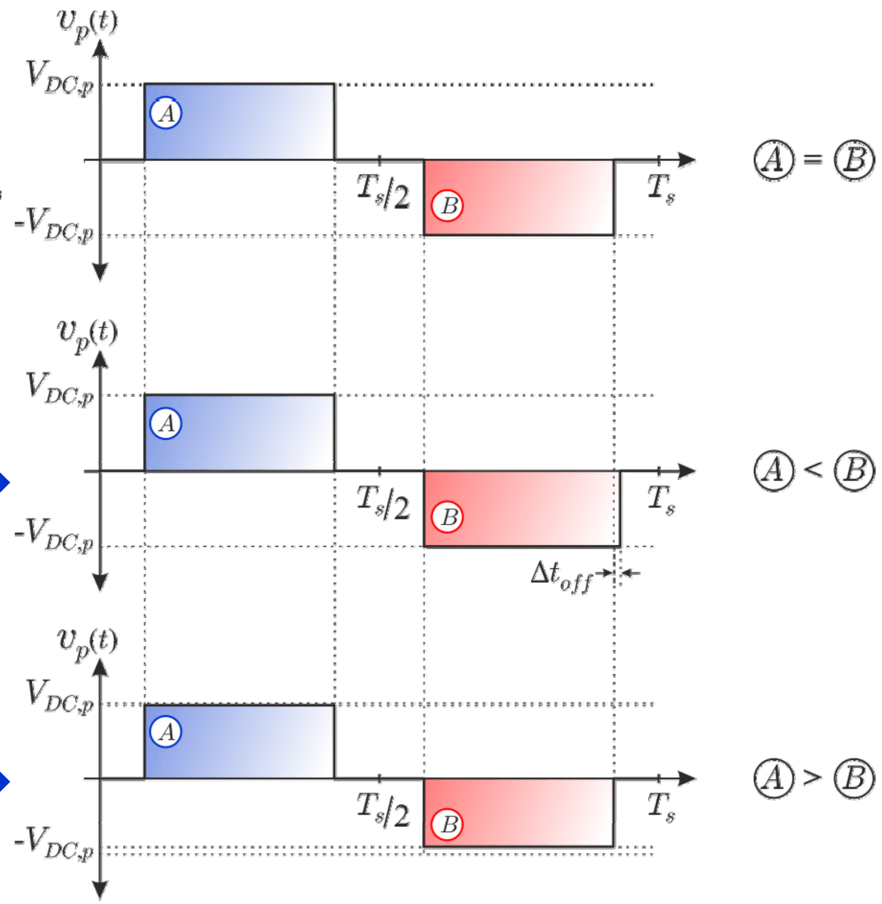
- *Reduction in size/weight.*
- *Increased efficiency.*

High-Power DC-DC Converter
Frequency vs. Power Map



The Dual Active Bridge





Unmatched turn-on/turn-off times

- *Voltage is applied for a longer/shorter time in positive and negative semi cycles.*

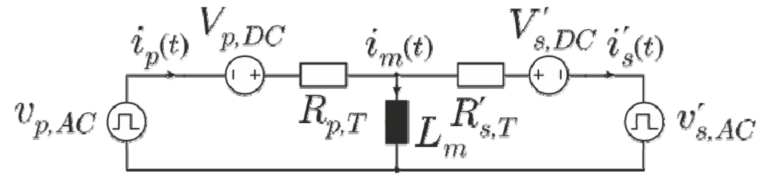
Different output characteristics

- *Different voltage levels are applied during the positive and negative semi cycles.*

Result: Small DC component in voltages applied to the transformer !

DC Magnetization

- ***Equivalent circuit with independent DC and AC voltage sources***



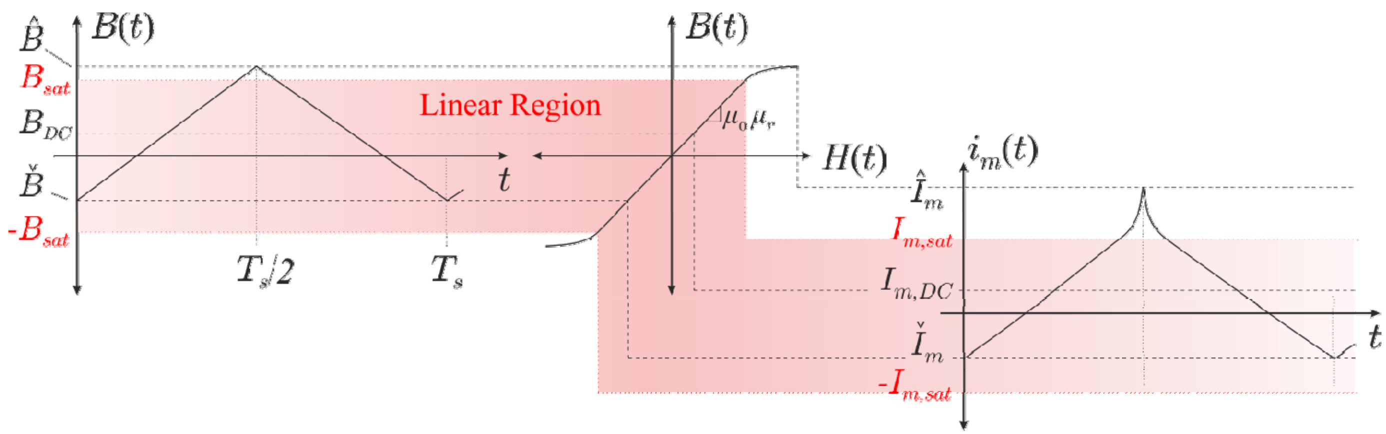
- ***DC component of magnetizing current***

$$I_{m,DC} = \frac{V_{p,DC}}{R_{p,T}} - \frac{V'_{s,DC}}{R'_{s,T}}$$

- ***DC component of magnetic flux density***

$$B_{DC} = \left(\frac{V_{p,DC}}{R_{p,T}} - \frac{V'_{s,DC}}{R'_{s,T}}\right) \cdot \frac{N_p}{l_m} \cdot \mu_0 \bar{\mu}_r$$

Equivalent series resistance limits DC flux density

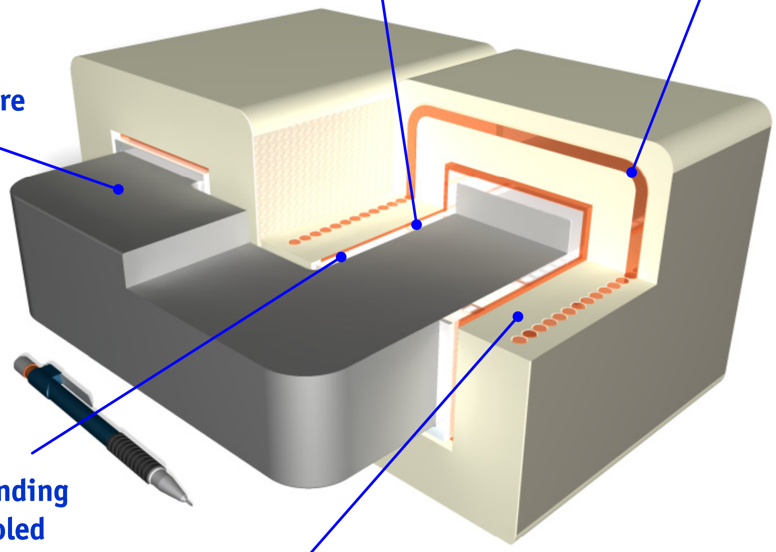


Example: 1MW / 20kHz Transformer

Core-Type Concept

- *Core Material – Vitroperm 500F* ($\mu_r \approx 20000$)
- *LV Winding – Loss Optimized Copper Foil*
- *Equivalent primary series resistance* $R_{p,T}$ = 6.8mΩ

Only 0.25ns of switching miss-match are enough to generate 0.2T of DC flux density bias !

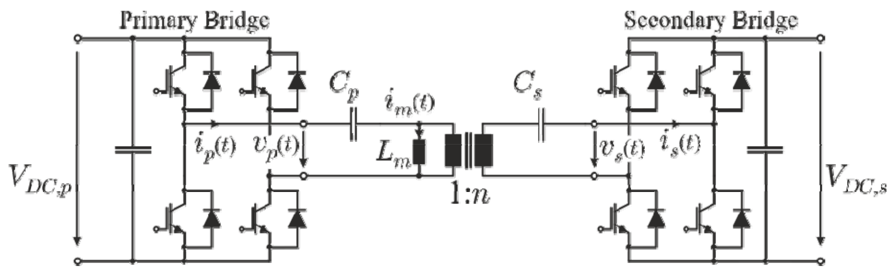


Previously Proposed Methods

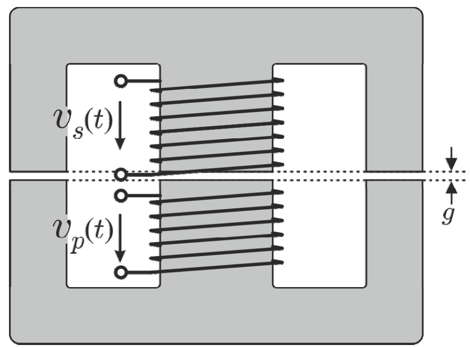
Magnetic Flux Density Balancing

Passive

- **Series capacitor:** *A series capacitor prevents any DC voltage on the transformer. However, it reduces power density and efficiency of the system.*



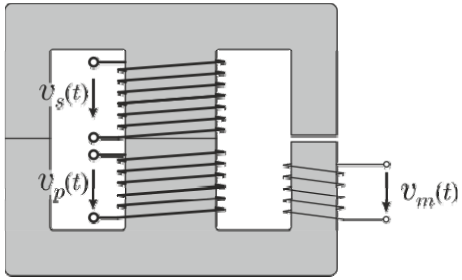
- **Air-gap in magnetic path:** *An air-gap in the magnetic path reduces the equivalent permeability of the core. Therefore a DC component in the magnetizing current generates a smaller DC flux density component.*



Saturation Detection

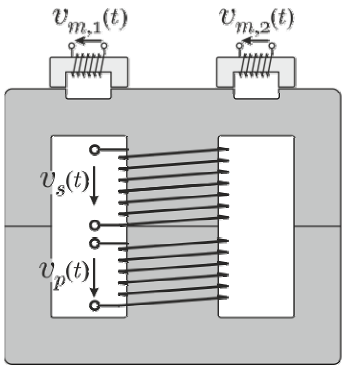
- *E-core with air gap in external leg .*

[R. Patel 1980]



- *Reduced cross-section and additional magnetic path.*

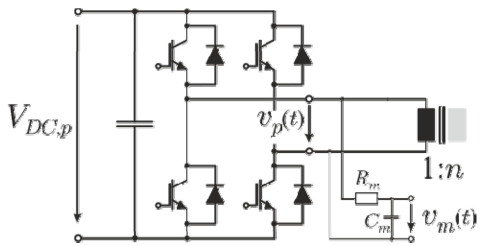
[J.A. Ferreira 1997]



Dynamic Flux Measurement

- *Integration of applied voltage by external RC network.*

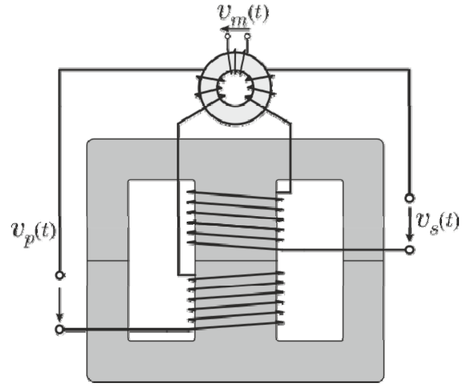
[D. Wilson 1981]



Continuous Flux Density Measurement

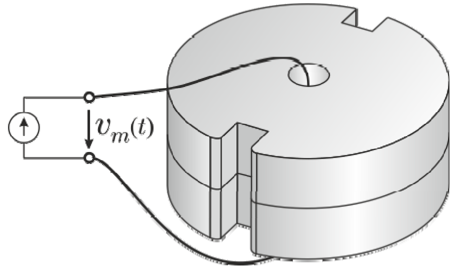
- *Measurement of magnetizing current.*

[J.W. Kolar 2000]

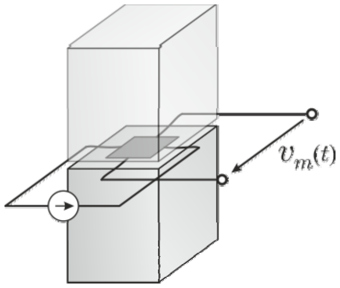


- *Superimposed orthogonal flux density with external coil.*

[S. Cuk 1982]



- *Direct flux density measurement with hall sensor.*



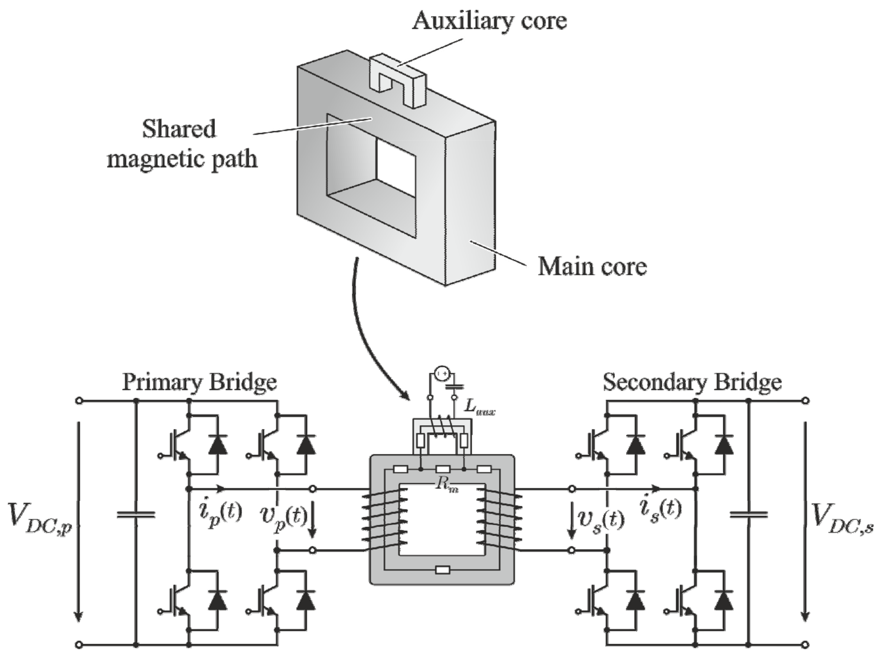
Proposed Flux Measurement Concept

Proposed Flux Measurement Method

Concept

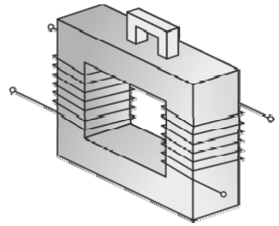
■ *Shared magnetic path between main core and an auxiliary core.*

■ *Magnetic flux density through the main core changes properties of the shared magnetic path, modifying, for example, the inductance seen from the auxiliary core winding.*

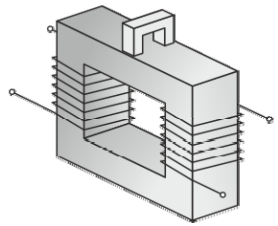


Auxiliary Core Placement

(a) *Auxiliary flux parallel to main flux density.*
(b) *Auxiliary flux orthogonal to main flux density.*



(a)

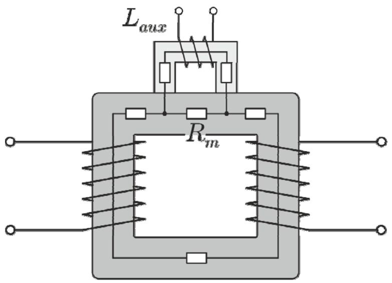


(b)

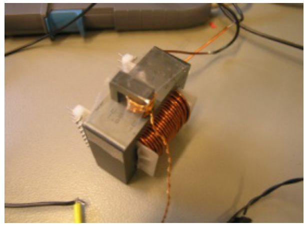
Inductance Measurement

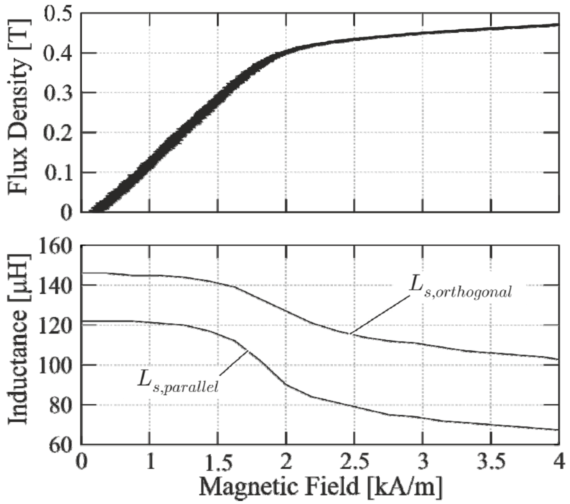
- *The inductance L_{aux} measured on the auxiliary winding terminals decreases as the magnetization of the main core increases.*

- *This measurement was performed on a N27 Ferrite E core and on a Metglas AMCC80 cut-core.*

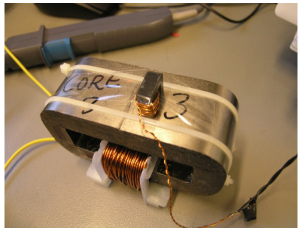


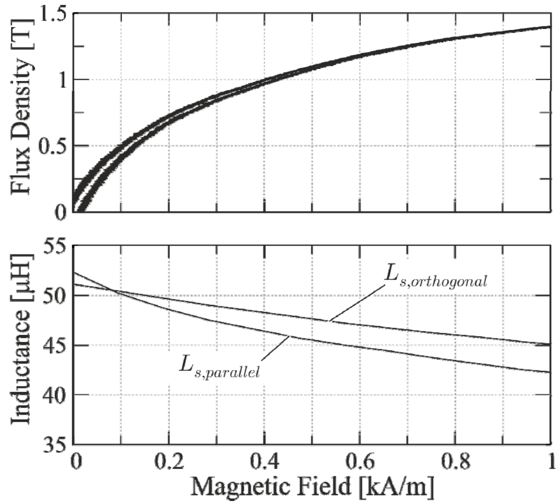
N27 E55 Ferrite





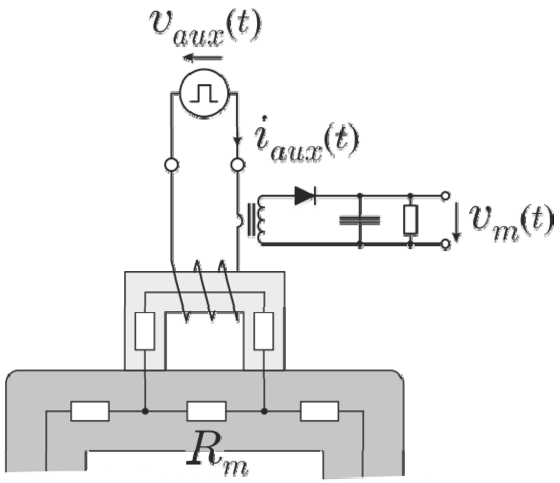
Metglas AMCC80

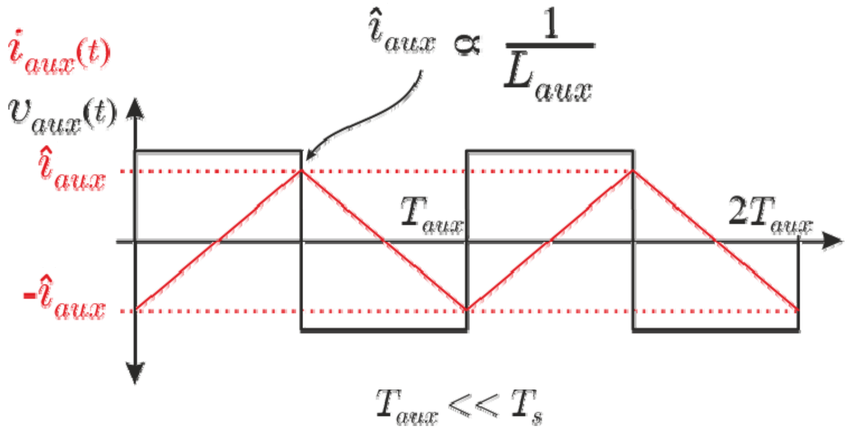




Inductance Measurement Circuit

- *Square-shaped voltage with 50% duty cycle applied to auxiliary coil.*
- *The peak auxiliary current is inversely proportional to the auxiliary inductance.*
- *The auxiliary current is rectified and filtered to obtain an output voltage $v_m(t)$ inversely proportional to the inductance value.*

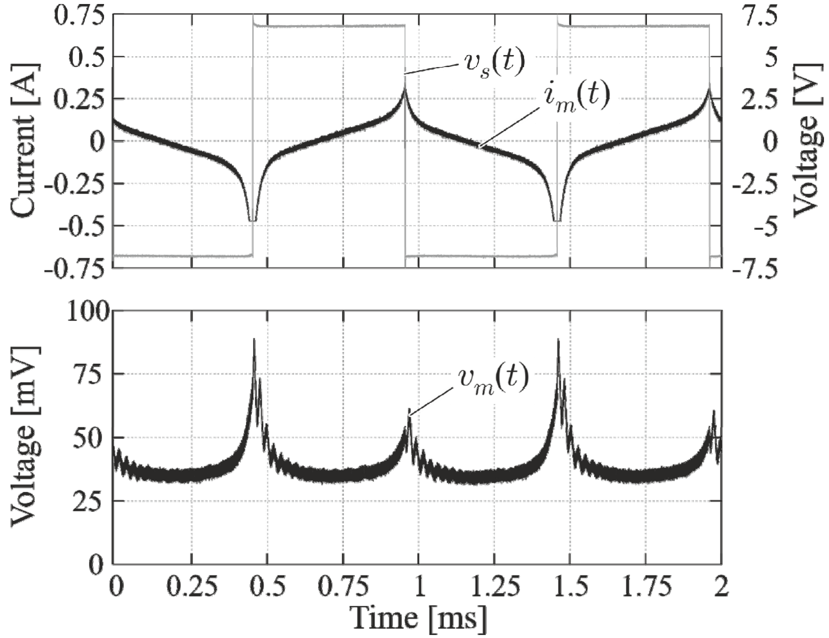




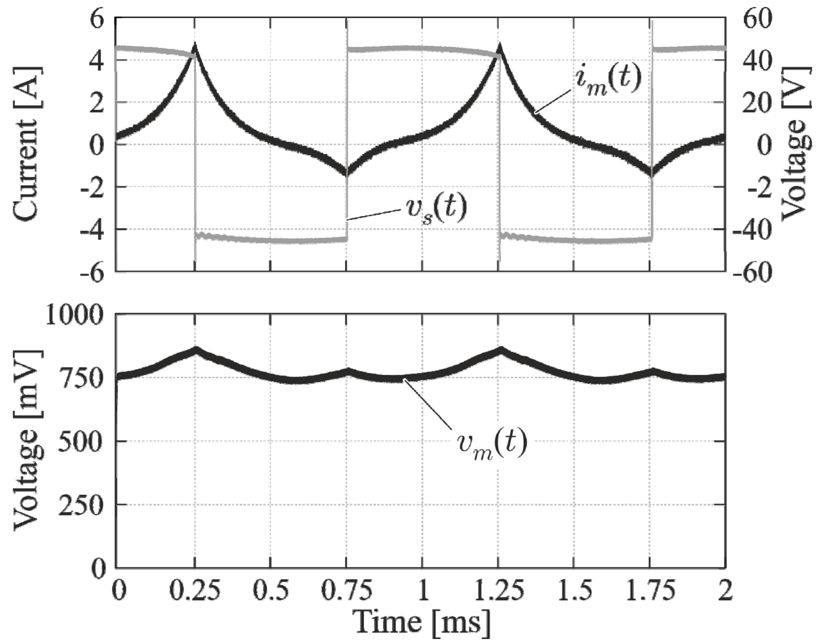
Results

- *The cores were magnetized with a square shaped voltage.*
- *The magnetizing current shows that the core is driven to saturation.*
- *Measurements show a clear relation between the measured voltage $v_m(t)$ and the magnetization state of the core.*

N27 E55 Ferrite



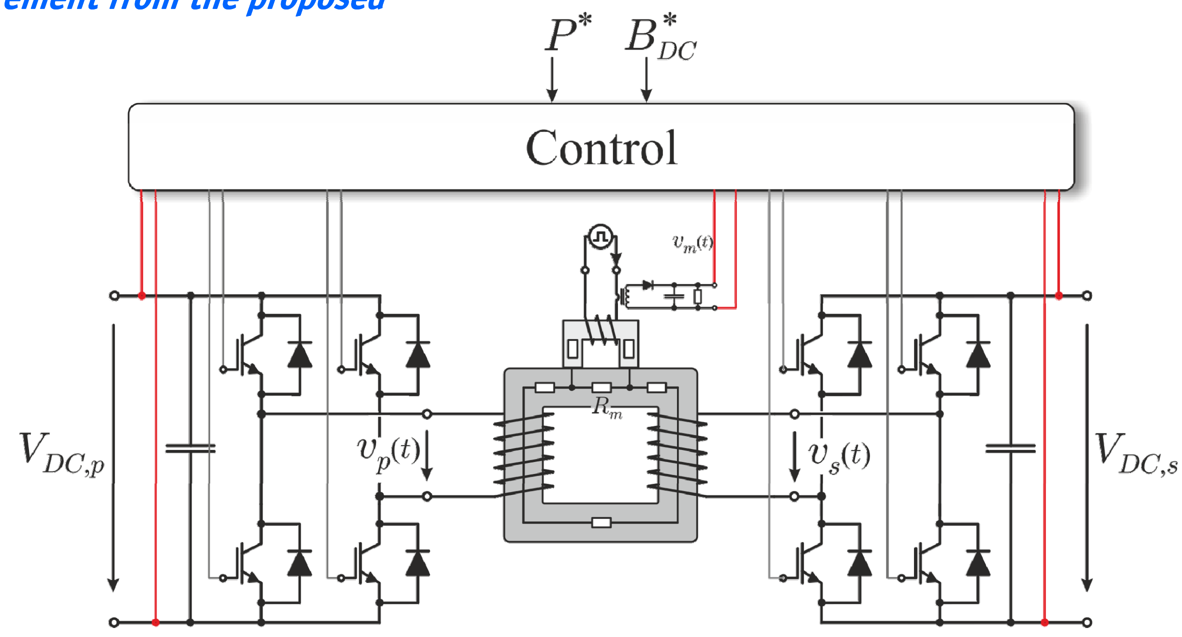
Metglas AMCC80



Control Scheme

- *The signal from the magnetic transducer can be used to actively correct the volts-seconds applied to the transformer .*

- *A central control unit adjusts the gating signals to achieve the desired transferred power. Additionally, small adjustments are introduced to prevent the saturation of the transformer core using the measurement from the proposed transducer.*



Conclusions

Conclusions

Magnetic Cores Saturation in DC-DC Converters

- *Small tolerances in the semiconductors output characteristics and/or switching times can cause DC magnetization of a transformer in a DC-DC converter.*

- *This DC magnetization is limited by the equivalent series resistance of the circuit.*

- *As efficiency is a key aspect in high-power applications, a small equivalent series resistance is desired in order to reduce losses. This in turn increases the risk of reaching high DC magnetization in the core and thus driving it into saturation.*

Proposed Magnetic Flux Density Measurement Concept

- *The proposed flux density measurement concept is based on sharing of magnetic path between the main core and an auxiliary core.*

- *A change in the auxiliary core's inductance was sensed by an additional circuit, giving information about the status of the magnetic flux density inside the main core.*

- *The proposed concept can be used to implement a feedback control that ensures a balanced magnetic flux density in the transformer core.*