Coupled Inductor Design of Interleaved CF-DAB Converter for Fuel Cell

with Maxwell analysis

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Outline

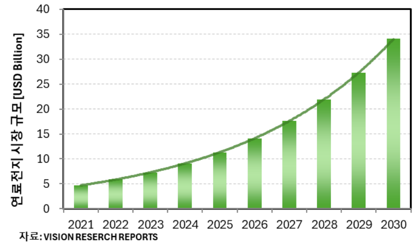
1. Introduction
2. Interleaved CF-DAB converter with coupled inductor
3. Coupled inductor design of interleaved CF-DAB converter
4. Maxwell analysis result
5. Conclusion

Introduction

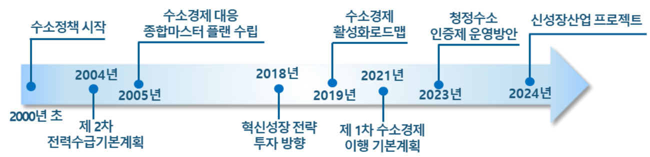
❖ Fuel cell policy and market outlook

- Core technology for distributed/flexible power sources
- Continuous domestic policies related to hydrogen
- Global fuel cell market: $2.62 billion as of 2020
- Korean fuel cell market: Cumulative installed capacity of 611,568 kW as of 2020
- Diversification of application fields such as ships and drones

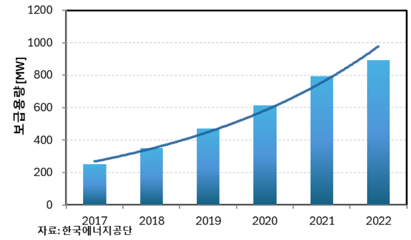
< Advantages of fuel cells>



< Global fuel cell market outlook>



< History of korea's hydrogen policy >

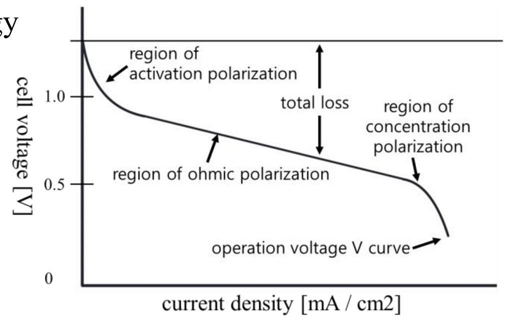


< Cumulative installed capacity of fuel cells(Korea)>

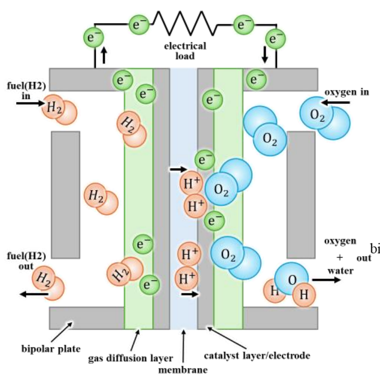
Introduction

❖ Fuel cell operating principles and electrical characteristics

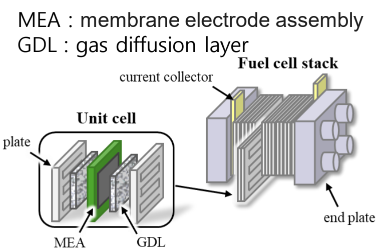
- Converts chemical energy: Hydrogen&Oxygen →Electrical energy
- Stack output volatage drops with increased load
- Low voltage/High current
- Load current ripple → Adversely affects fuel cell stack lifespan



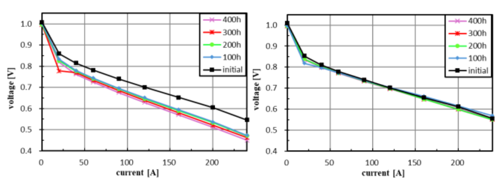
< I-V characteristic curve of fuel cell>



< Fuel cell operating principle>



< Structure of a fuel cell stack>



< Fuel Cell I-V Characteristic Curve >
(Left) Load variation, (Right) Constant current output

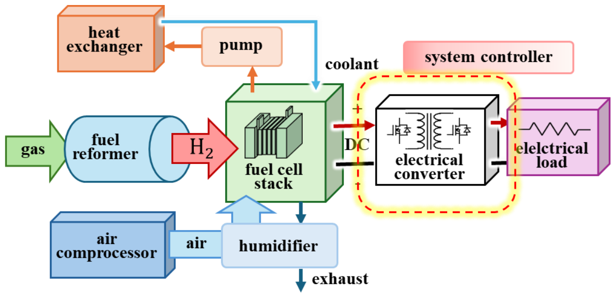
Introduction

❖ Components of the fuel cell system

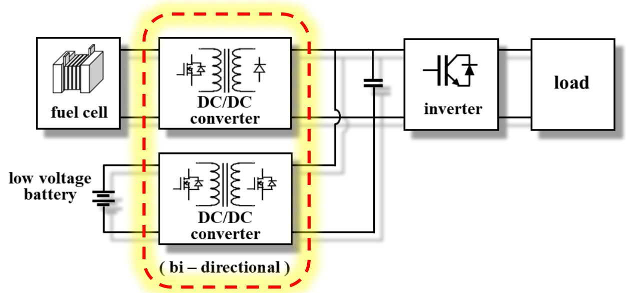
- Fuel cell stack, MBOP(Mechanical Balance of Plant), EBOP(Electrical Balance of Plant), control unit
- EBOP: Converts the electrical energy output of the fuel cell stack into form suitable for load requirements

❖ Evaluation criteria for DC-DC converter for fuel cell system

- High step-up and high efficiency
- Low input current ripple
- Wide input/output range



< Configurations of a Fuel cell system >

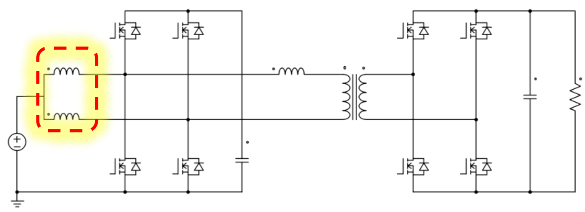


< Fuel cell and battery hybrid system EBOP configuration >

Introduction

❖ 2-phase interleaved CF-DAB(Current Fed Dual Active Bridge)

- Step-up topology; achieved high step-up
- Soft switching(ZVS) operation; achieved high efficiency
- Interleaving structure ; achieved low input current ripple
- Fuel cell application systems; low voltage/high current

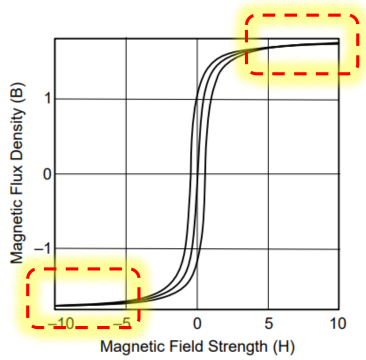


< 연료전지용 인터리브드 전류형 DAB 컨버터>

❖ Design precautions for 2-phase interleaved CF-DAB

- Twice the number of components as single-phase
  → Increased system volume
- Low voltage/high current
  → **High risk of input inductor saturation**

When fabricating a 2-phase interleaved CF-DAB, pay close attention to system size and input inductor saturation



< 코어 B-H 곡선>

Introduction

❖ Research on existing coupled inductor-based DC-DC converters

- Interleaved CF-DAB based on coupled iductor
  ➔ Integrate the CF-DAB input inductor into a coupled inductor
  ➔ Reduce the number of magnetic elements → Reduce system volume

- Interleaved CF-DAB based on dual coupled inductor
  ➔ Integrate two input inductors, a transformer, and leakage inductance into two EE cores
  ➔ Reduce system volume due to reduced losses and fewer magnetic elements

- **No suitability evaluation as a coupling inductor of DC-DC converter for fuel cells**

Introduction

❖ Mathematical modeling and design of coupled input inductor of interleaved CF-DAB

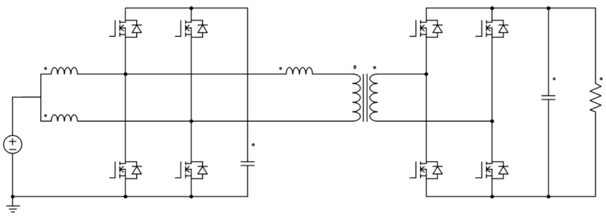
❖ Validation of the coupled input inductor design via Finite Element Analysis(FEA)

❖ Simulation analysis and validation of the interleaved CF-DAB converter with designed coupled inductor

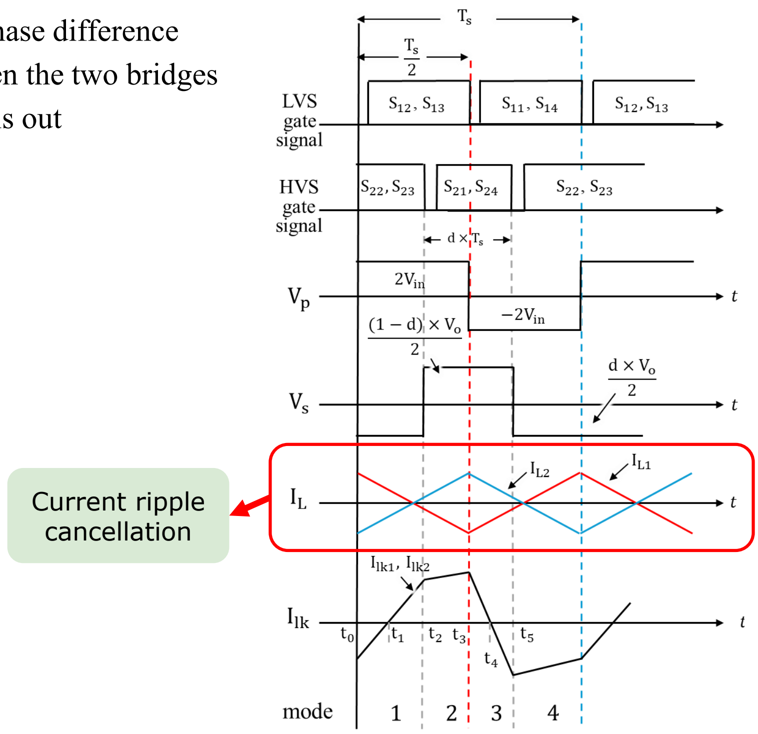
Interleaved CF-DAB converter with coupled inductor

❖ Interleaved CF-DAB
- Interleaving operation with a 180-degree phase difference
- Output control; the phase difference between the two bridges
- Inductor current ripple in each phase cancels out
  → Low input current ripple
- Step-up converter capable of ZVS
  → High efficiency/High step-up

❖ Output equations
- $P_o = \frac{V_{in}V_o}{nfL_{lk}} \times \frac{\theta\cdot(\pi-\theta)}{\pi^2}$
- $I_o = \frac{V_{in}}{nfL_{lk}} \times \frac{\theta\cdot(\pi-\theta)}{\pi^2}$



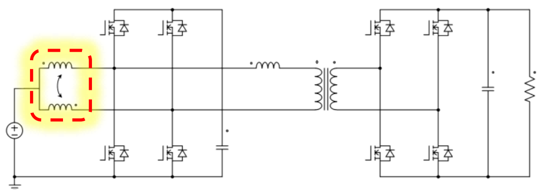
<Interleaved CF-DAB>



<Main waveforms>

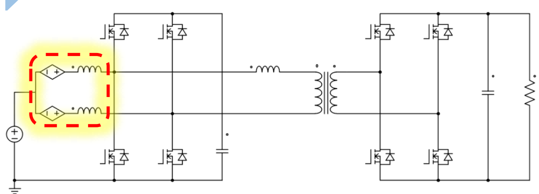
Interleaved CF-DAB converter with coupled inductor

❖ Interleaved CF-DAB wth coupled inductor
- 2 input inductors
  → changed to 1 coupled inductor with a 1:1 turn ratio



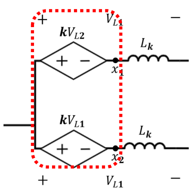
<Interleaved CF-DAB with coupled inductor>

Equivalent circuit

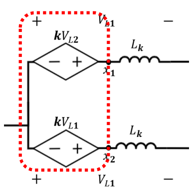


<Coupled inductor equivalent circuit>

❖ Coupled inductor equivalent circuit
- Representing the coupled inductor
  ➔ Dependent source and leakage inductance
- The direction of th dependent source varies
  - Case 1: Directly coupled

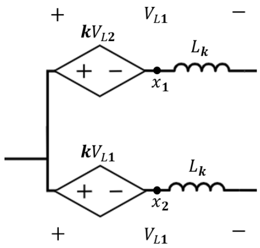
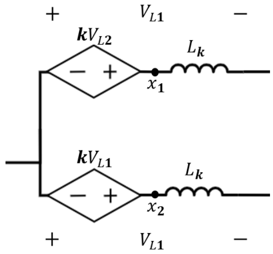


  - Case 2: Indirectly coupled



Interleaved CF-DAB converter with coupled inductor

❖ Comparison of characteristics based on coupling direction

	Directly coupled	Indirectly coupled
Equivalent circuit		
Features	- Alternating current component of the magnetic flux is canceld out - High effieiency by the core loss reduction - Core saturation risk increase	- DC component of the magnetic flux is canceled out - Core weight reduction by the core saturation risk decrease - High current ripple increase
Total magnetic flux Φ_m	$\Phi_m = \Phi_{21} + \Phi_{12}$	$\Phi_m = \Phi_{21} - \Phi_{12}$
Current ripple slope S of each phase inductor	$S = \frac{V_{in} - kV_{L2} - V_{L1}}{L_{lk}}$	$S = \frac{V_{in} + kV_{L2} - V_{L1}}{L_{lk}}$

Interleaved CF-DAB converter with coupled inductor

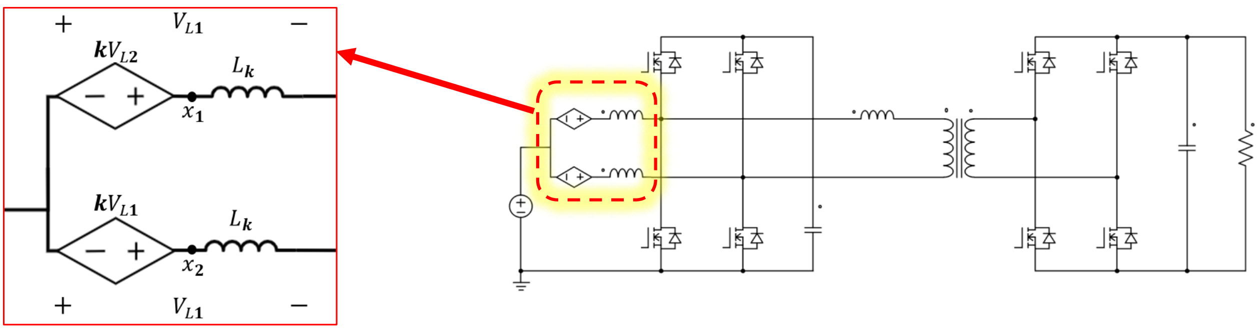
❖ Interleaved CF-DAB with indirect coupled inductor

□ Current ripple ΔI_L, ΔI_{in}

- $\Delta I_L = \frac{(1-k\cdot d_{LV}/(1-d_{LV}))V_{in}}{L_{lk}} \times d_{LV}T_s$
- $\Delta I_{in} = \frac{2(1+k)d_{LV}V_{in}}{(1-d_{LV})L_{lk}} \times (0.5 - d_{LV})T_s$

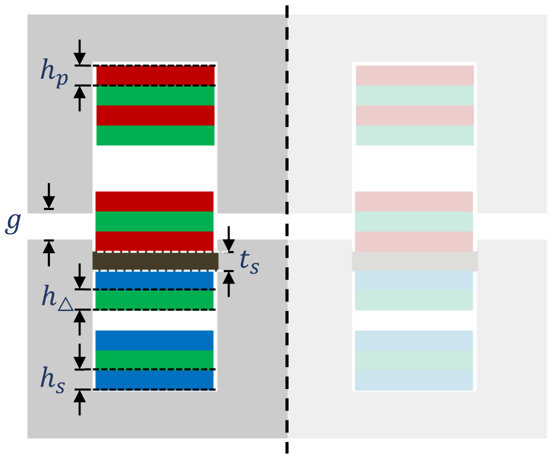
LV-side duty $d_{LV} = 0.5$

- $\Delta I_L = \frac{(1-k)V_{in}}{L_{lk}} \times \frac{T_s}{2}$
- $\Delta I_{in} = 0$

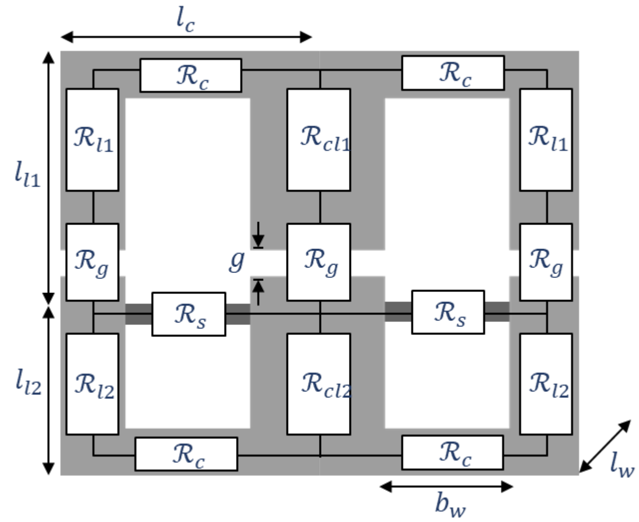


Coupled inductor design of interleaved CF-DAB converter

- Planar coupled inductor
  - Configuration : Type E ferrite core, primary and secondary PCB windings, magnetic sheet
  - Insertion of magnetic sheet between primary and secondary windings→ High leakage inductance
  - Sufficient inter-winding spacing → Copper losses due to proximity effects negligible
  - **Small volume**
  - **High reproducibility** → **Suitable for interleaved converter reauiring identical specifications**



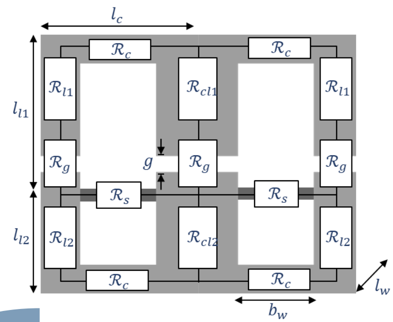
<Planar coupled inductor structure>



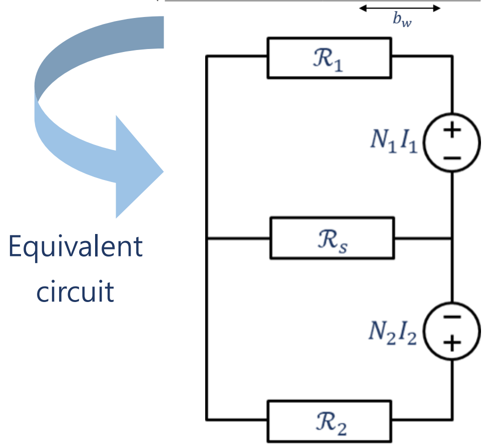
<Planar coupled inductor magnetic circuit>

Coupled inductor design of interleaved CF-DAB converter

- Inductance of planar coupled inductor
  - $L_m = \frac{N^2}{\mathcal{R}_1} \parallel \left(L_{lk} + \frac{N^2}{\mathcal{R}_2}\right) - \left(\frac{N^2}{\mathcal{R}_1} \parallel L_{lk}\right) \cong \frac{N^2}{\mathcal{R}_1} - \left(\frac{N^2}{\mathcal{R}_1} \parallel L_{lk}\right)$
  - $L_{lk} = L_{ksh} + L_{kw} \cong L_{ksh}$
  - $L_{ksh} = 2\mu_0\mu_r \times \frac{{F_s}^2 A_s}{I_1^2 b_w}$



- Reluctance calculation
  - $\mathcal{R}_1 = \frac{2g}{\mu_0 A_g} + \frac{l_1}{\mu_0\mu_r A_c}$
  - $\mathcal{R}_2 = \frac{l_2}{\mu_0\mu_r A_c}$
  - $\mathcal{R}_s = \frac{b_w}{\mu_0\mu_s A_s} = \frac{b_w}{\mu_0\mu_r l_w t_s}$
  - $l_1 = l_c + 2l_{l1}$
  - $l_2 = l_c + 2l_{l2}$

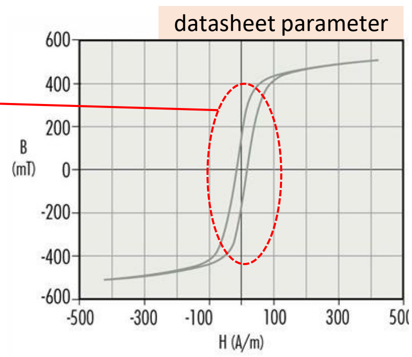


<Magnetic equivalent circuit>

L_{ksh}: Leakage inductance due to magnetic sheet
L_{kw}: Leakage inductance from windings and insulator
N: Inductor turns

Coupled inductor design of interleaved CF-DAB converter

- Saturation of the magnetic core
  - $\Phi_{sat} = A_c \times B_{sat}$
  - $I_{sat} = \frac{NA_c}{L_m} \times B_{sat}$

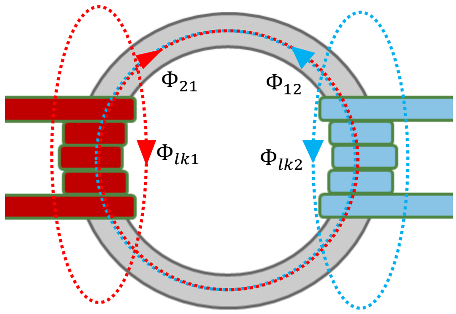


< Core B-H curve>

- Magnetic design of a indirectly coupled inductor
  - $\Phi_m = \Phi_{21} - \Phi_{12}$
    → Where, since the MMF of the two winding ar the same
    → $\Phi_{21} = \Phi_{12}$
    → Thus, $\boldsymbol{\Phi_m = 0}$

  - Magnetic field strength H
    → $H_{max} = 2 \cdot \pi \cdot \frac{N \cdot \Delta i_L}{l_e}$
    → $H_{min} = -2 \cdot \pi \cdot \frac{N \cdot \Delta i_L}{l_e}$

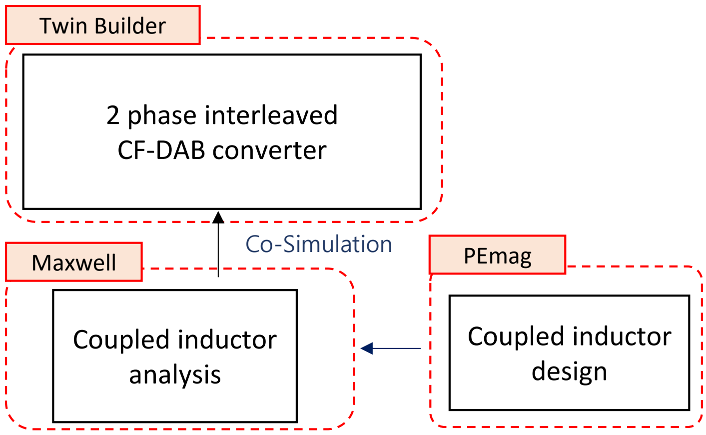
Φ_{sat}: Core saturation magnetic flux
I_{sat}: Core saturation current
B_{sat}: Core saturation magnetic flux density



< Core flux flow diagram>

Maxwell analysis result

- Ansys/Maxwell
  - Finite Element Analysis(FEA)
  - Co-simulation analysis

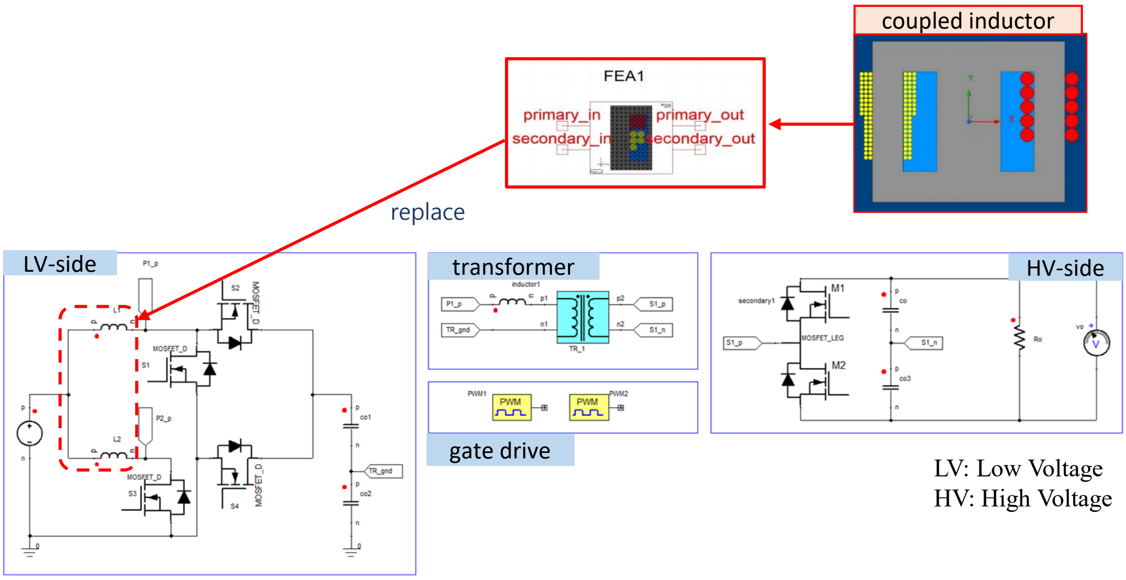


- Evaluation indicators
  - Inductor flux density
  - Input current ripple and phase current ripple
  - Converter input/output voltage/current

Maxwell analysis result

❖ Simulation specifications

- 2-Phase interleaved CF-DAB converter
- 1kW, input voltage: 50V → output voltage: 300V
- Modeling with Ansys/Maxwell
  → 2-Phase CF-DAB simulation via Co-Simulation



LV: Low Voltage
HV: High Voltage

<Simulation curcuit>

Maxwell analysis result

❖ Inductor specifications

Item	Saparated inductors	Coupled inductor	
Core	0077439A7	CR45810EC	
Input inductance	108.2uH	108.6uH	k = 0.85
Turns	31 turn	10 turn	
Magnetic sheet	-	EFW-02-240X80-T0800	
I_{sat}	15 A	15 A	

Conclusion

- Presentation of mathematical modeling/design of the coupled inductor for the interleaved CF-DAB converter
- Verification of feasibility as the MBOP for fuel cells through Maxwell simulation analysis
- Future review of validity through prototype fabrication and experimentation

Thank you for your attentions

Any Questions?

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