A High-Frequency DC-DC Converter for the Next Generation Train (NGT) CARGO HFC Concept

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Athanasios Iraklis
DLR

DLR

Agenda

1. DLR Overview
2. Next Generation Train (NGT) - Project Overview
3. Next Generation Train (NGT)-CARGO - Medium Frequency Transformer (MFT)
4. MFT Sub-system Concept and Requirements
5. Modelling Methodology
6. Technical Specifications
7. Efficiency Analysis
8. Conclusion and Further Steps

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DLR Overview

- Exploration of the Earth and the solar system
- Research aimed at protecting the environment
- Development of environmentally-friendly technologies to promote mobility, communication and security
- Approx. 8,000 employees
- 33 research institutes and facilities
- 20 locations
- Branch offices in Brussels, Paris, Tokyo and Washington

AERONAUTICS	SPACE	ENERGY	Transport	SECURITY

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Next Generation Train (NGT)

Project overview

- Increase of the approved speed
- Reduction of specific energy usage
- Noise reduction
- Greater customer comfort
- Improvement of driving safety
- Reduction of wear and lifecycle costs
- Cost-effective construction through modularization and system integration
- Increased efficiency of development and approval processes

NGT HST

→ Ultra-high-speed train, driving power 16 MW, operating speed 400 km/h [1]

NGT LINK

→ Feeder train, driving power 2.5 MW, operating speed 230 km/h [2]

NGT CARGO

→ Freight train with automatic-moving intermediate cars (e.g. for packages) [3]

[1] J. Winter, S. Kaimer, C. Kalatz, J. Pagenkopf, S. Streit, N. Parspour, M. Böttigherimer, D. Bögle and S. Mayer, "Fahrdrahtlose Energieübertragung bei Schienenfahr-zeugen des Vollbahnverkehrs," 2014.
[2] D. Krüger and J. Winter, "NGT LINK: Ein Zugkonzept für schnelle doppelstöckige Regionalfahrzeuge," in *ZEVrail-Zeitschrift für das gesamte System Bahn*, pp. 442-449, 2017.
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THIS WORK

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Next Generation Train (NGT)-CARGO

Motivation

- Different systems, concepts and niche applications in rail logistics
- Great technical effort in goods handling and train formation

Objective

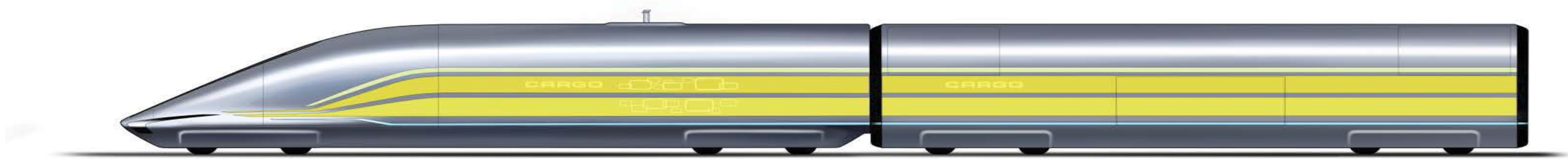
- Development of an efficient overall concept (intercontinental)

High-speed freight train NGT CARGO

Autonomous, self-powered cars

Automated cargo handling

More freight transport by rail



Next Generation Train (NGT)-CARGO

Conventional Traction System Concept

End car:

- AC/DC Catenary-powered
- Low Frequency Transformer
- AC-DC Active Rectifier
- Intermediate Circuit (Filter)
- HVDC Link
- 8 x Traction Drives
- Individually Driven Wheels
- Auxiliary Power Unit (APU)

Intermediate car:

- Traction Battery-powered
- DC-DC Isolation Converter

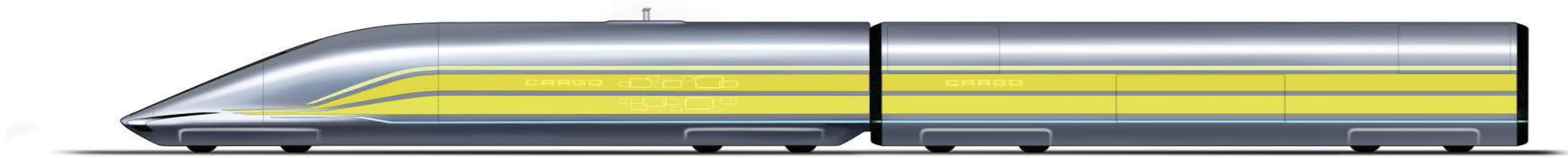
- Intermediate Circuit (Filter)
- HVDC Link
- 8 x Traction Drives
- Individually Driven Wheels
- Auxiliary Power Unit (APU)

Next Generation Train (NGT)-CARGO
Medium Frequency Transformer (MFT)

Motivation

- Reduction of specific energy usage:
  - Reduced mass and volume, increased efficiency characteristics for voltage transformation & rectification
- Modularization and self-powered railcars:
  - Multiple power modules for increased controllability and redundancy, utilization of components with lower ratings
- Integration of different sub-systems:
  - HV AC link, primary and secondary HV DC links, hybridization (Li-ion battery, fuel-cell, charging systems)

Objectives



Next Generation Train (NGT)-CARGO
Medium Frequency Transformer (MFT)

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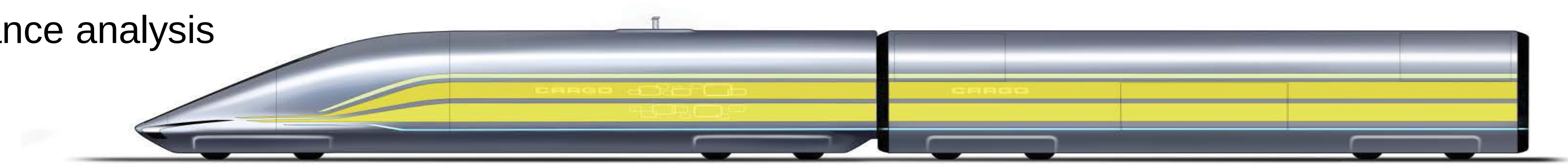
- Integration of different sub-systems:
    - HV AC link, primary and secondary HV DC links, **hybridization** (batteries, fuel-cells, charging systems)

Objectives
- Identify suitable MFT topology for NGT-CARGO (focus on intermediate railcars)
- Requirements-based component selection
- Model-based performance analysis



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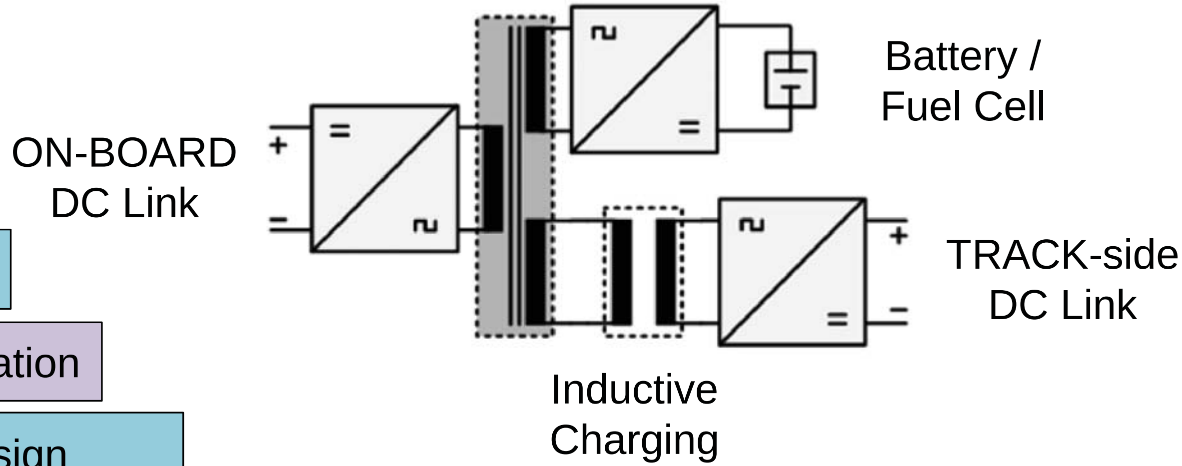
MFT Sub-system Concept and Requirements

Concept

- Electrical interface
- Multiple input/output ports
- Galvanic isolation
- Hybrid system integration
- Modular design
- Distributed power system
- High frequency operation

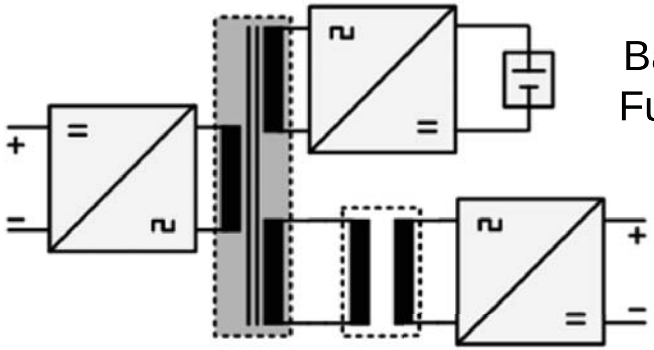


MFT Sub-system Concept and Requirements

Concept

- Electrical interface
- Multiple input/output ports
- Galvanic isolation
- Hybrid system integration
- Modular design
- Distributed power system
- High frequency operation
- Egg-laying Wool-Milk-Sow

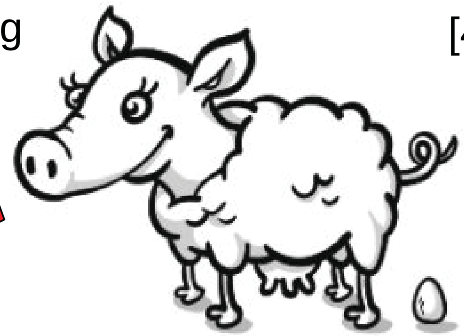
ON-BOARD DC Link



Battery / Fuel Cell

TRACK-side DC Link

Inductive Charging



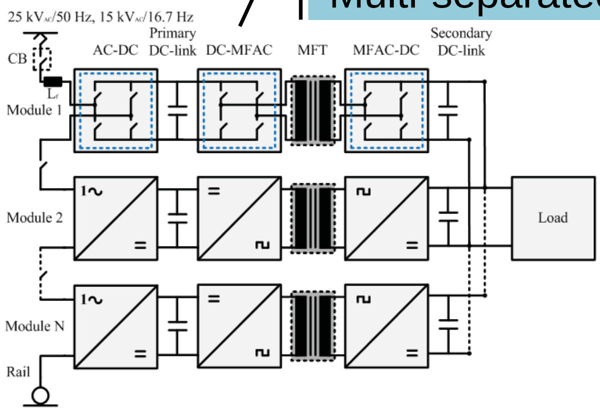
[4]

[4] https://www.joyfullness.net/wp-content/uploads/2017/04/wollmilchsau-S-300x300.jpg

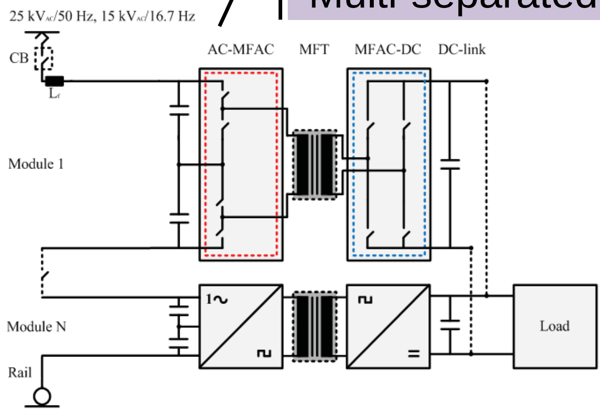
MFT Sub-system Concept and Requirements

Literature Review

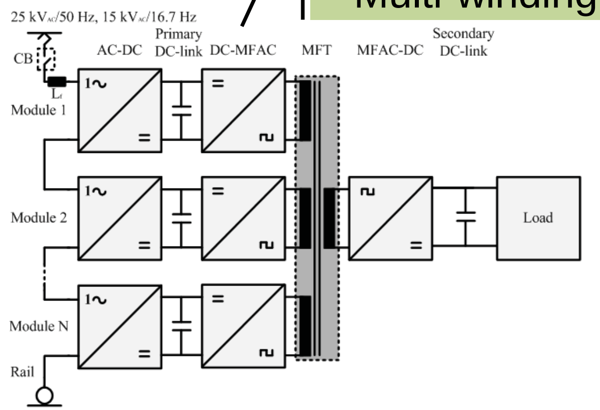
3-stage Multi-separated



2-stage Multi-separated



3-stage Multi-winding



Results of Literature Review:

Pros & Cons

Voltages, Frequencies, Efficiency

Isolation setups

Power modules, # Power switches

MFT Sub-system Concept and Requirements

NGT CARGO Power Requirements

[5]

[6]

End car:

- 14.5 MW_{MAX} at catenary
- 13.5 MW_{MAX} at DC Link
- 25 kV_{AC}/50 Hz, 15 kV_{AC}/16.7 Hz
- Reconfigurable: 3 kV_{DC}, 1.5 kV_{DC}
- 3 kV_{DC} at DC Link (nominal)

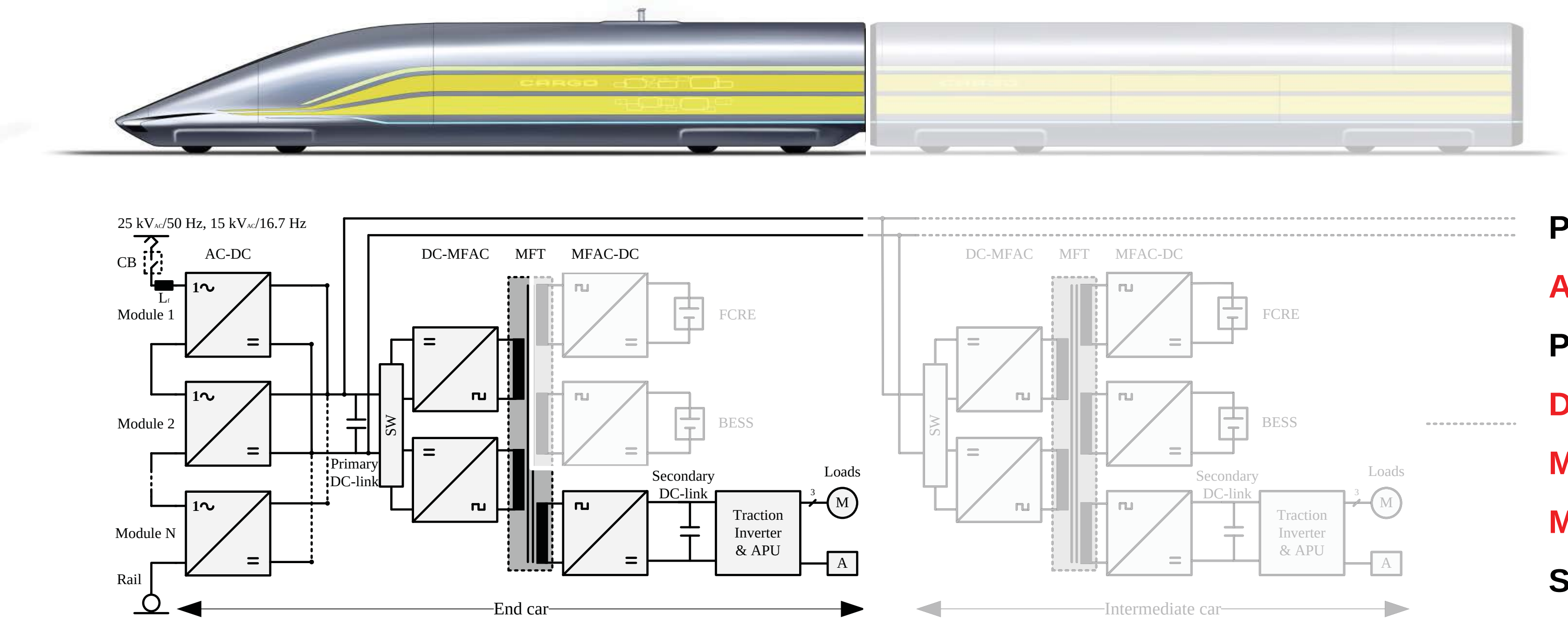
Intermediate car:

- 1.5 MW_{MAX} at secondary DC Link
- 1.5 kV_{DC} at secondary DC Link
- Self-powered for 25 km:
  Battery Capacity 42.5 kWh_{NOM}
  325 kW_{MAX} at 800 V_{NOM} (585-910 V)
- 26 kW Fuel Cell Range Extension (FCRE):
  Utilization of LVDC (85-180 V [6])
  300 A_{MAX} (30 kW_{MAX} [6])
- Galvanically isolated sub-systems

[5] AKASOL AKASYSTEM 18 AKM 53 NMC
[6] Ballard **FCveloCity®-MD** 30 kW

MFT Sub-system Concept and Requirements

MFT Sub-system Concept – End Car



Pantograph

AC-DC Rectifier

Primary DC Link

DC-MFAC Converter

Multi-winding MFT

MFAC-DC Converter

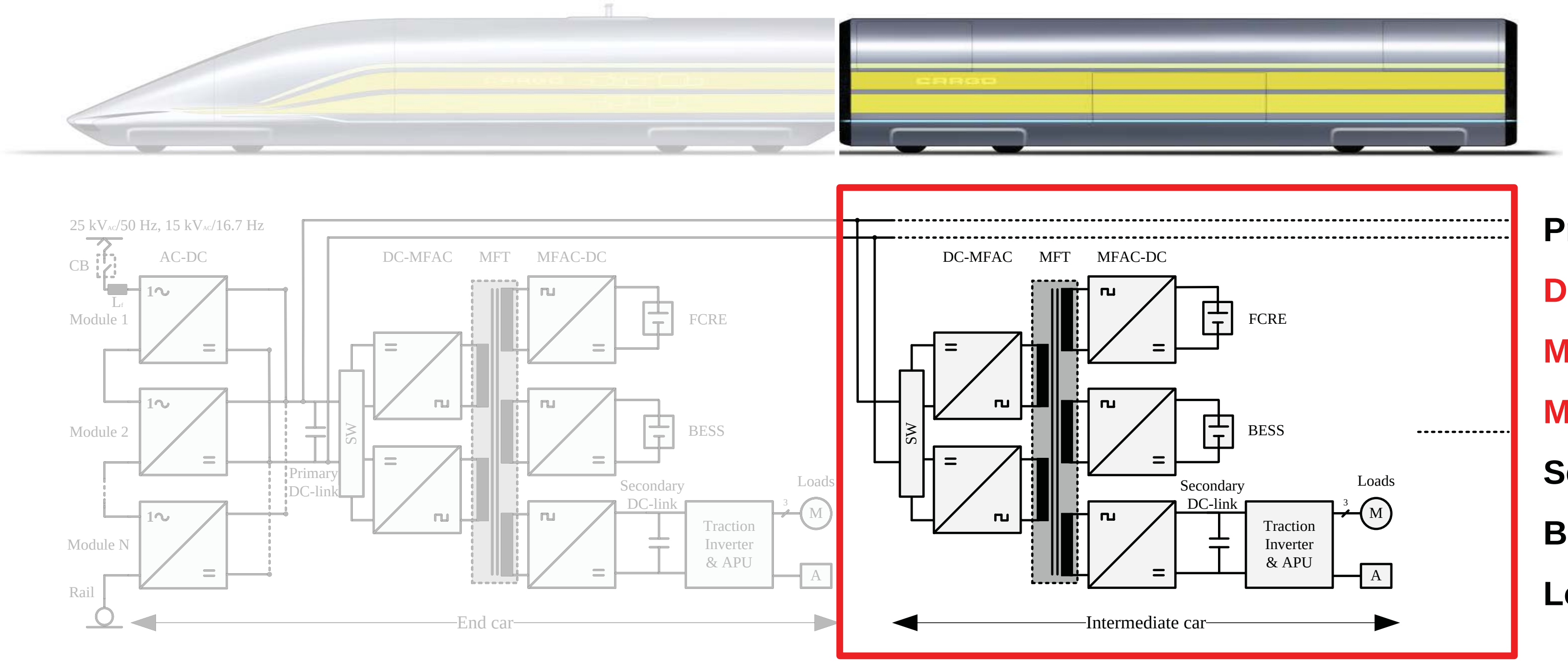
Secondary DC Link

BESS+FCRE

Loads

MFT Sub-system Concept and Requirements

MFT Sub-system Concept – Intermediate Car



Primary DC Link

DC-MFAC Converter

Multi-winding MFT

MFAC-DC Converter

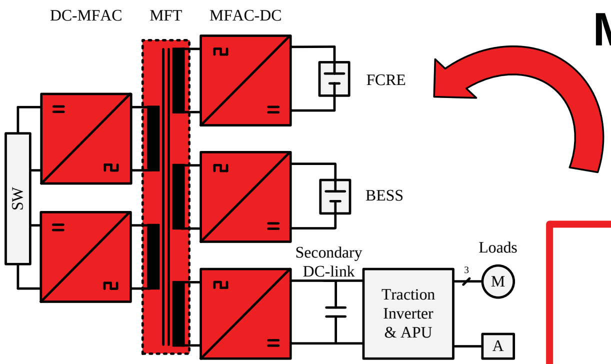
Secondary DC Link

BESS+FCRE

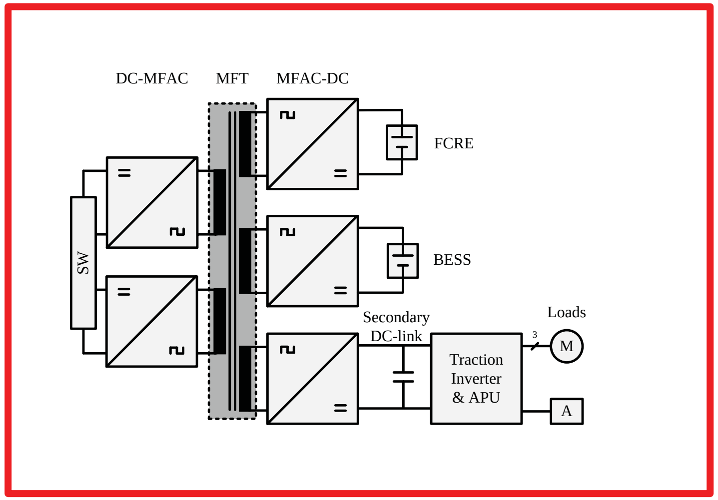
Loads

MFT Sub-system Concept and Requirements

MFT Sub-system Concept – General Project Workflow

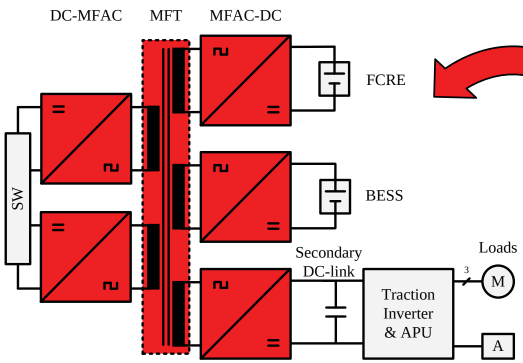


Multi-port Sub-system Design



MFT Sub-system Concept and Requirements

MFT Sub-system Concept – General Project Workflow



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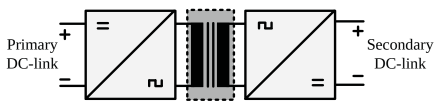
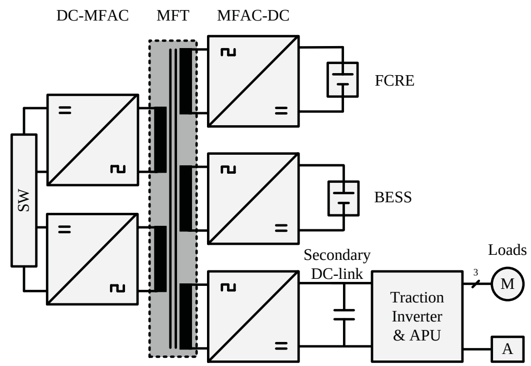


Single-port Module Analysis



MFT Sub-system Concept and Requirements

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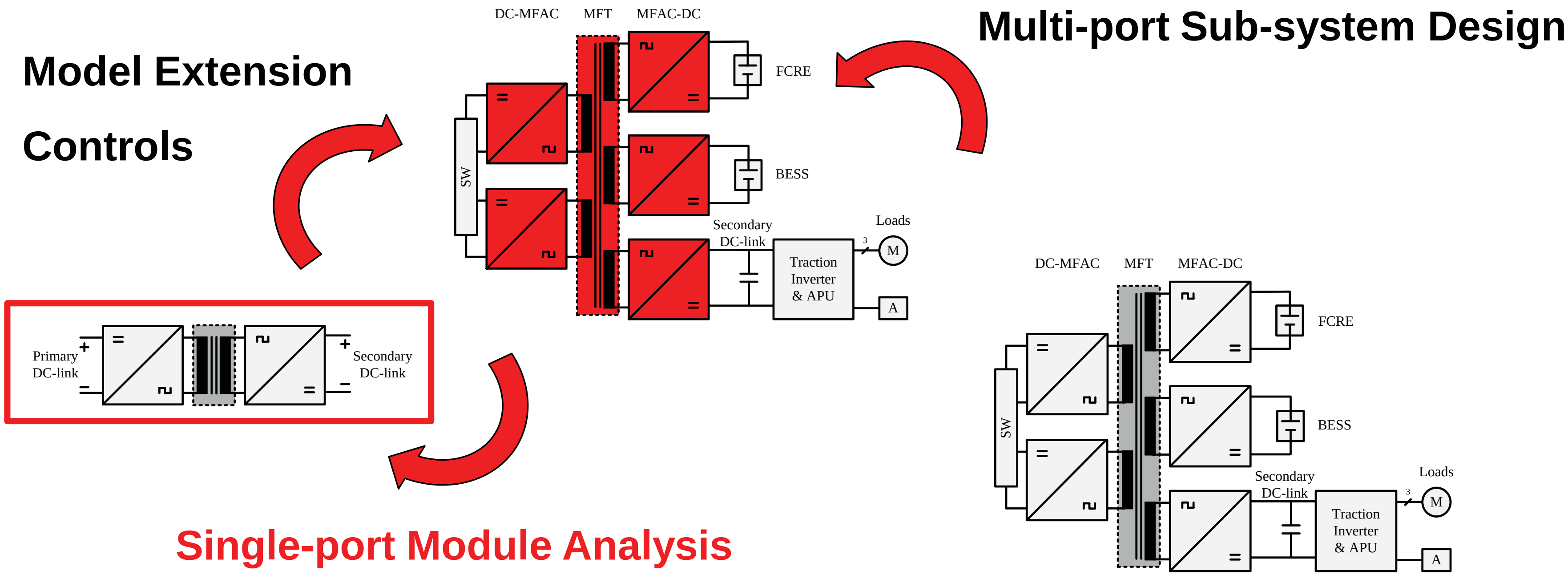

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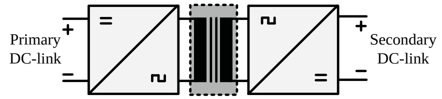
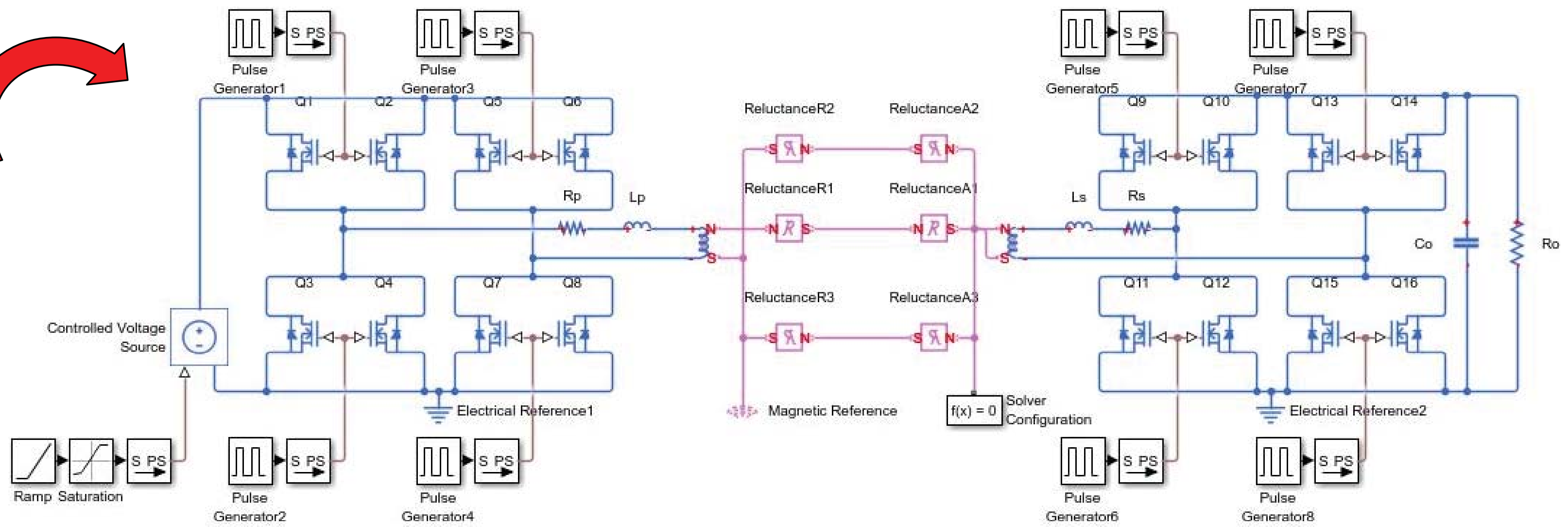
Modelling Methodology

Single-port MFT Model





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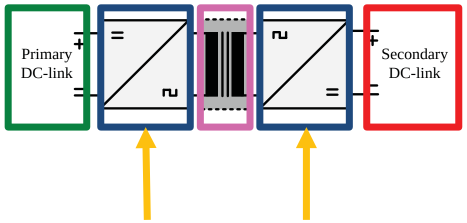
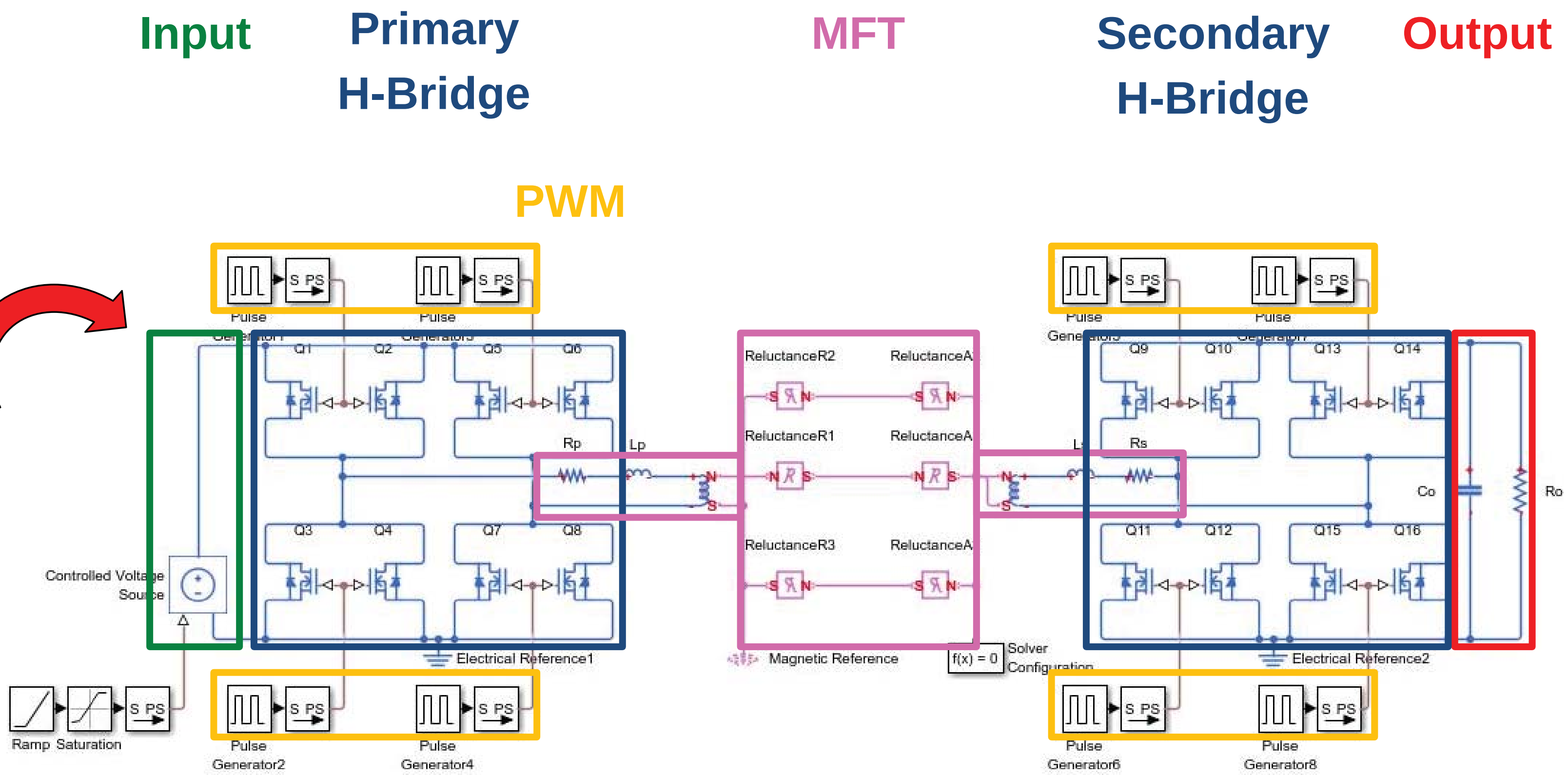




Modelling Methodology

Single-port MFT Model

V_{in}: Fixed DC input voltage

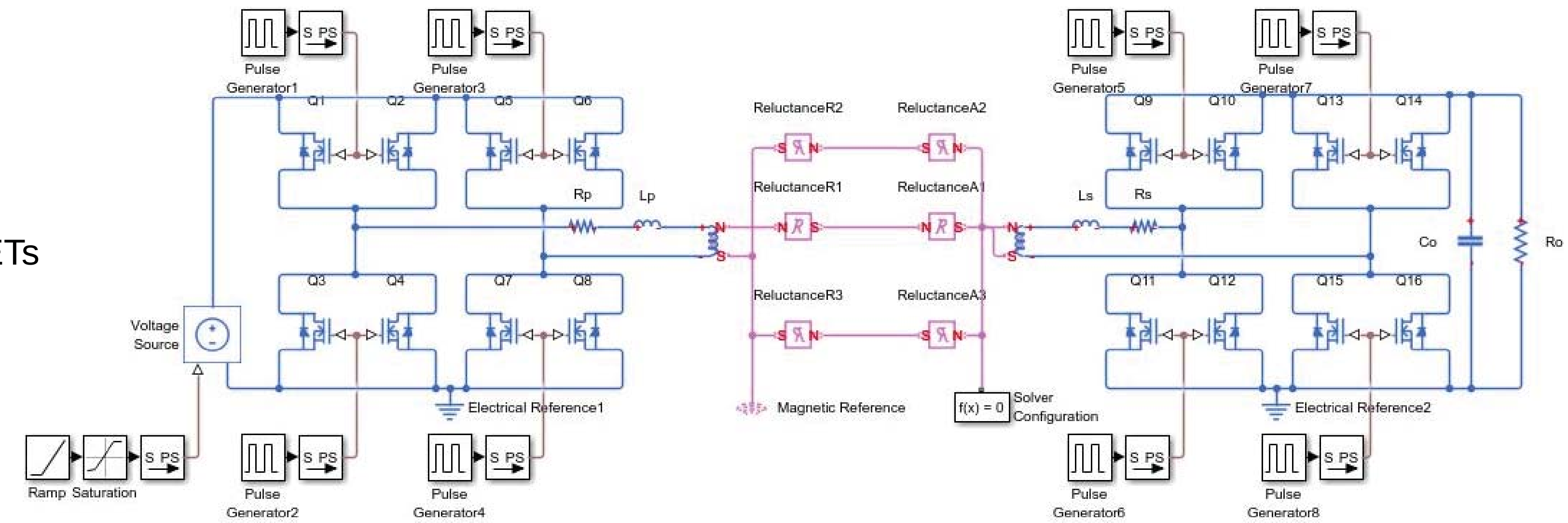
R_o: Fixed resistance as load
C_o: Lossless DC smoothing capacitor

Full Active Bridge (FAB) x 2
= Dual Active Bridge (DAB)
Q_x: Ideal N-channel MOSFETs

$R_{p/s}$: Winding resistances
$L_{p/s}$: Leakage inductances

Equivalent magnetic circuit for magnetic isolation

Input | Primary H-Bridge | MFT | Secondary H-Bridge | Output



Modelling Methodology

Ideal N-channel MOSFET

On-state ($V_{GS} \geq V_{TH}$): Drain-source path = Drain-source on resistance, $R_{ds(on)}$

Off-state ($V_{GS} < V_{TH}$): Drain-source path = Off-state conductance, $G_{ds(off)}$

V_{GS}: Gate-source voltage

V_{TH}: Threshold voltage

Anti-parallel Source-Drain Diode

Protection diode with no dynamics

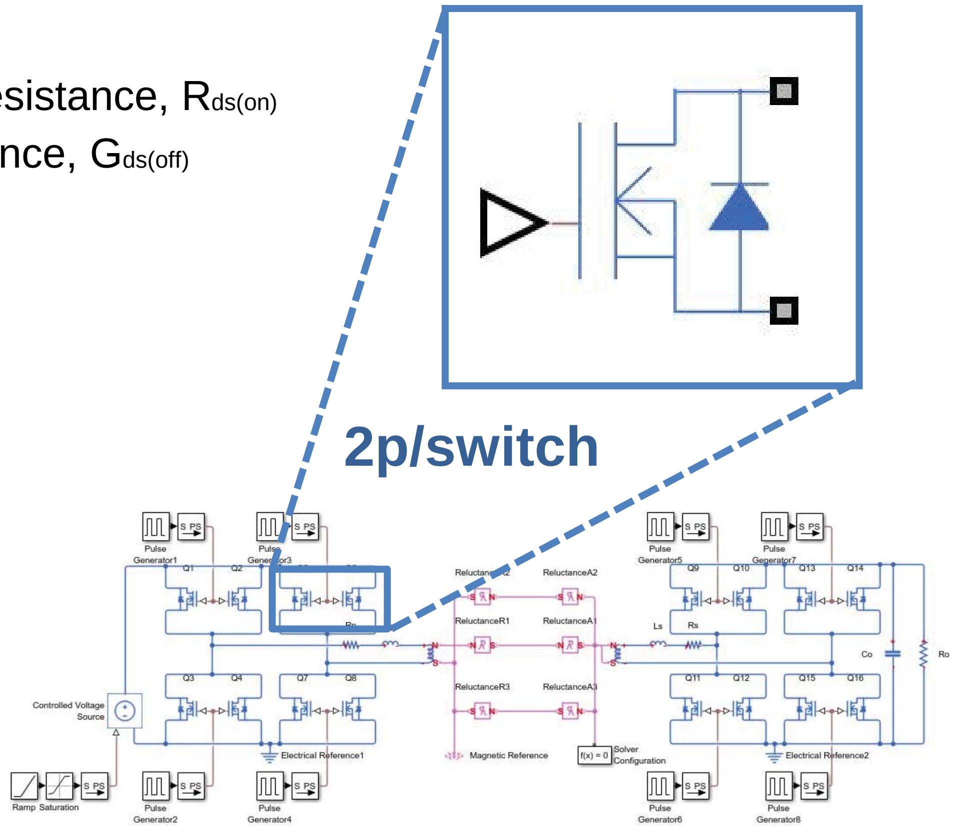
On-state ($V_D \geq V_T$): Forward voltage, $Vf_T = V_T + If*R_{d(on)}$

Threshold voltage, $V_T = 0.975+(T_J*(-1.4)/1000)$

On resistance, $R_{d(on)} = 0.053+(T_J*1.1/1000)$

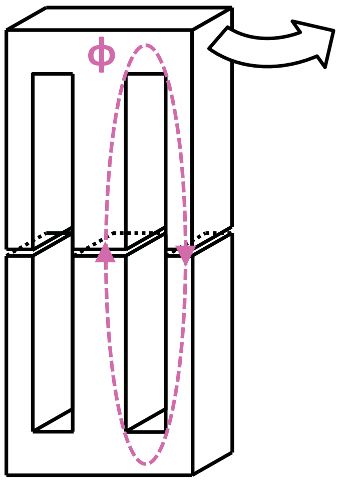
T_J: Diode junction temperature in degrees Celcius

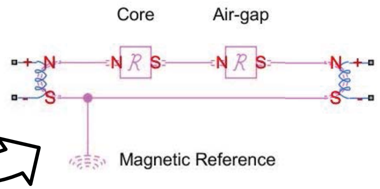
Off-state ($V_D < V_T$): Off-state conductance, $G_{D(off)}$



Modelling Methodology

Magnetic Isolation Stage





<u>Equivalent magnetic circuit</u>:

Magnetomotive force: $MMF_p = N_p * I_p$

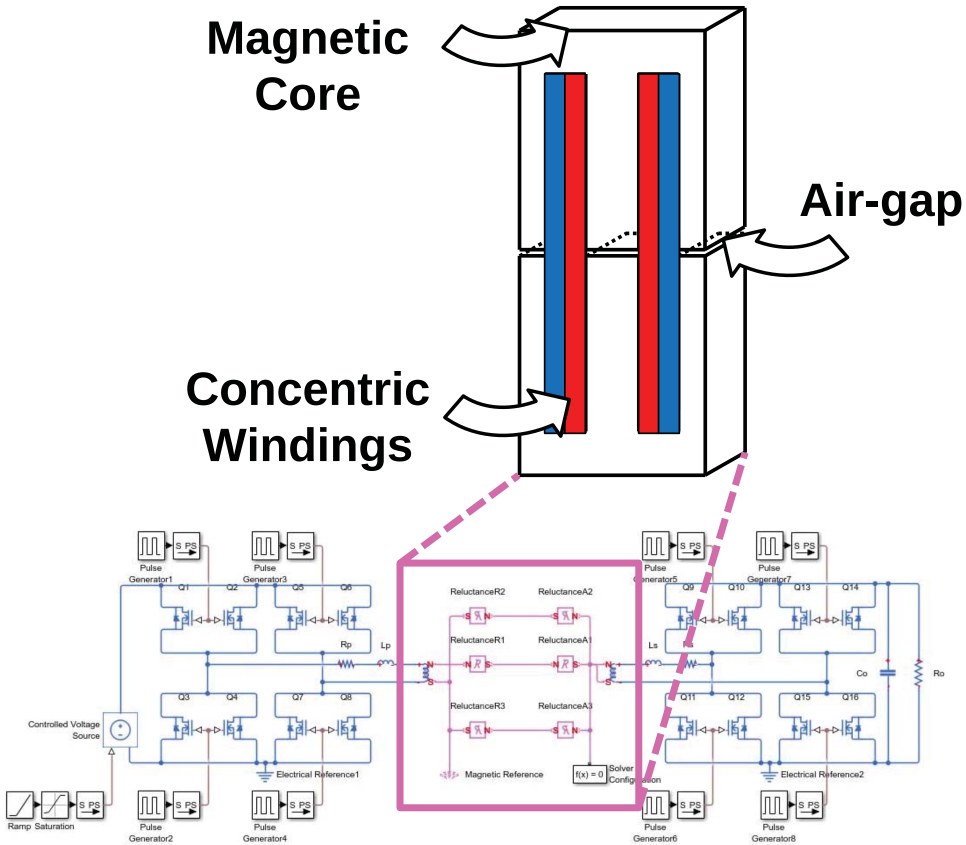
N_p: Number of windings of primary coil
I_p: Current of primary winding

Magnetic reluctance: $R_x = L_x / (\mu_0 * \mu_{r\_x} * A_x)$
Magnetic flux: $\Phi = MMF_p / (R_x + \ldots R_n)$ **(OC)**

L_x: Length of magnetic element
μ_0: Permeability constant
μ_{r_x}: Relative permeability of magnetic element,
A_x: Cross-sectional area of magnetic element

Induced voltage: $V_s = -N_s * d\Phi/dt$

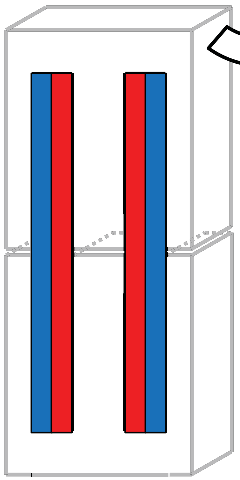
N_s: Number of windings of secondary coil

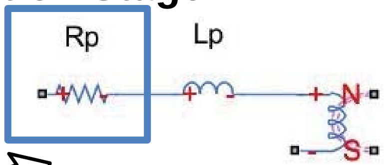


DLR

Modelling Methodology

Magnetic Isolation Stage





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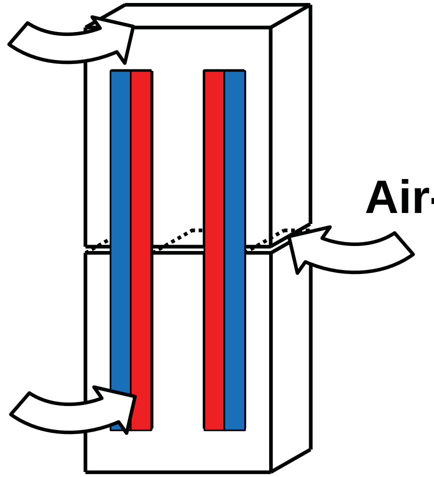


Rectactular wire:

Skin depth: $\delta = \mathrm{sqrt}(1/(\pi * f * \mu_0 * \mu_r * \sigma_w))$

AC resistance:

$R_{AC} = L_w/(\sigma_w * W * T) = R_{DC}$

when $2\delta \geq W_w$ or $2\delta \geq T_w$

$R_{AC} = L_w/(\delta * \sigma_w * (2W_w + 2T_w - 4\delta))$

when $2\delta < W_w$ or $2\delta < T_w$

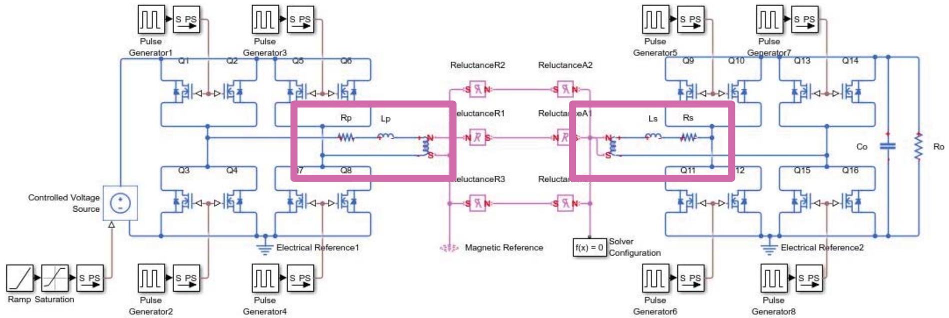
f: Frequency

μ_0: Permeability constant

μ_r: Relative permeability of wire

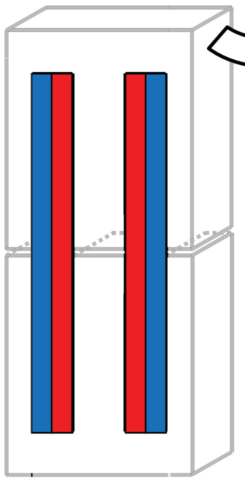
σ_w: Conductivity of wire

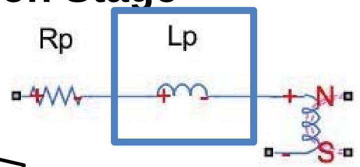
L_w, W_w, T_w: Length, width and thickness of wire



Modelling Methodology

Magnetic Isolation Stage





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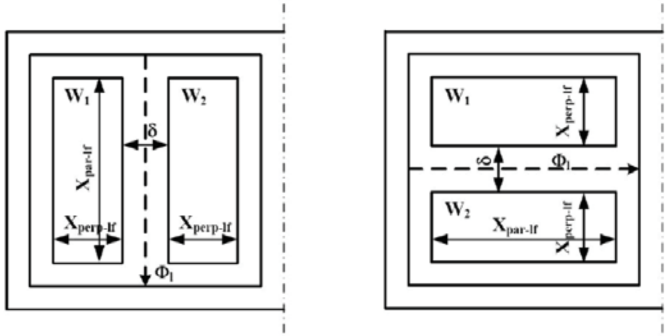
Interleaved windings:



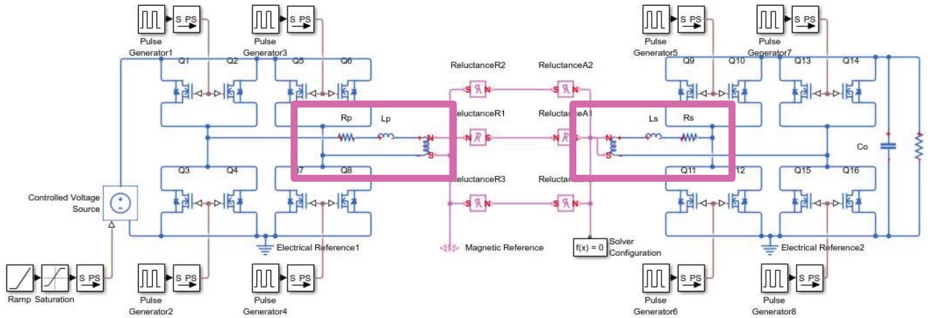
Leakage inductance: $L_L = \mu_0 * N^2 * L_m * \lambda * k_\sigma$

- μ_0: Permeability constant
- N: Number of turns of the winding
- L_m: Mean length per turn for whole arrangement
- λ: Relative leakage conductance
- k_σ: Rogowski factor (~1 for most arrangemenets)

Leakage inductance (Rogowski k_σ = 1):

$$L_L = \mu_0 * N^2 * L_m * (\Sigma X_{perp-lf}/3 + \Sigma\delta)/(n_{if}^2 * X_{par-lf})$$

- μ_0: Permeability constant
- N: Number of turns of the winding
- L_m: Mean length per turn for whole arrangement
- $\Sigma X_{perp-lf}$: Sum of dimensions of sub-windings perpendicular to leakage flux
- Σδ: Sum of thicknesses of insulating interspaces
- n_{if}: Number of insulating interspaces
- X_{par-lf}: Dimension of sub-windings parallel to leakage flux

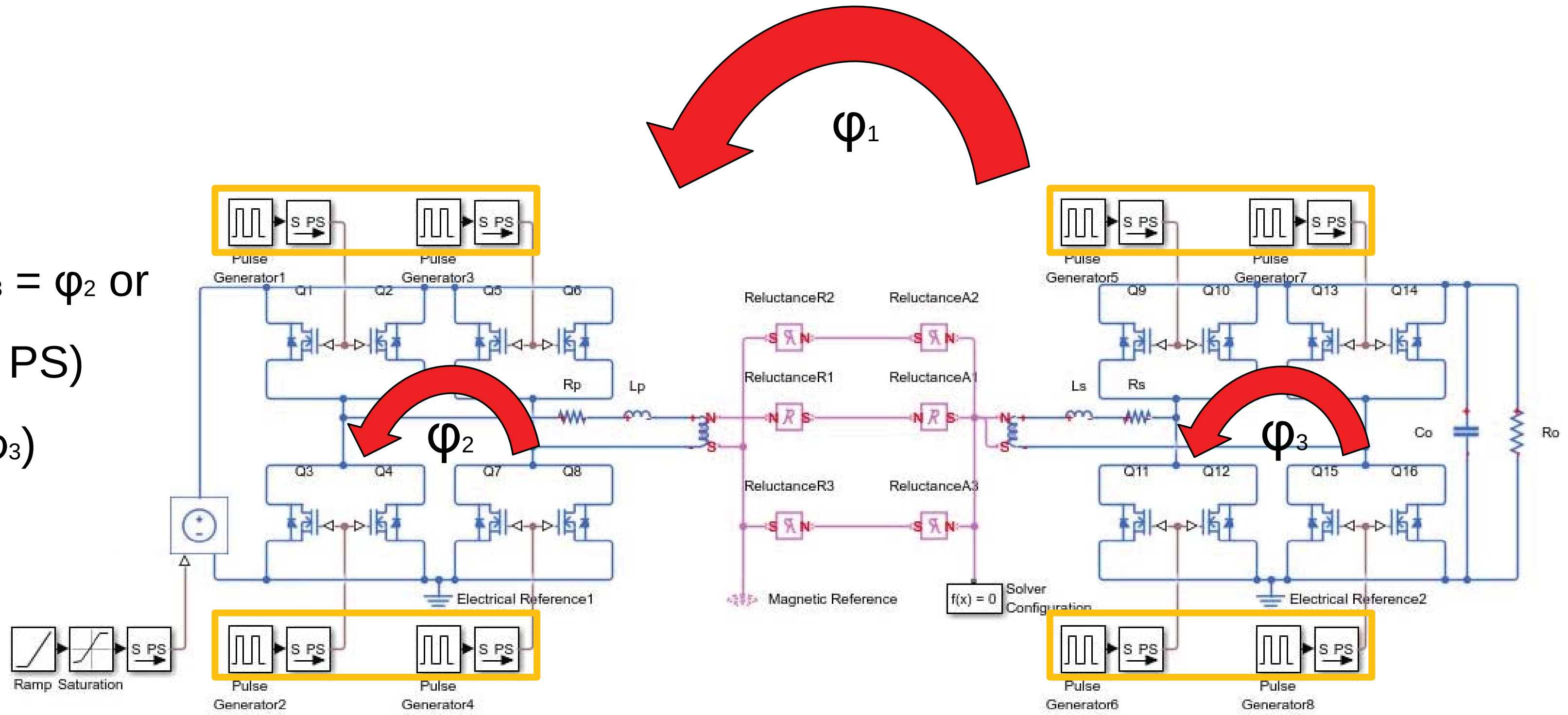


Modelling Methodology

Switching Controls – Phase-Shift (PS: φ, D)

Available PS methods:

- ❑ Single PS (φ_1)
- ❑ Dual PS (φ_1, φ_2, $\varphi_3 = \varphi_2$ or 180° for Extended PS)
- ❑ Triple PS (φ_1, φ_2, φ_3)
- ❑ D: Duty cycle



Modelling Methodology

Switching Controls – Phase-Shift (PS: φ, D)

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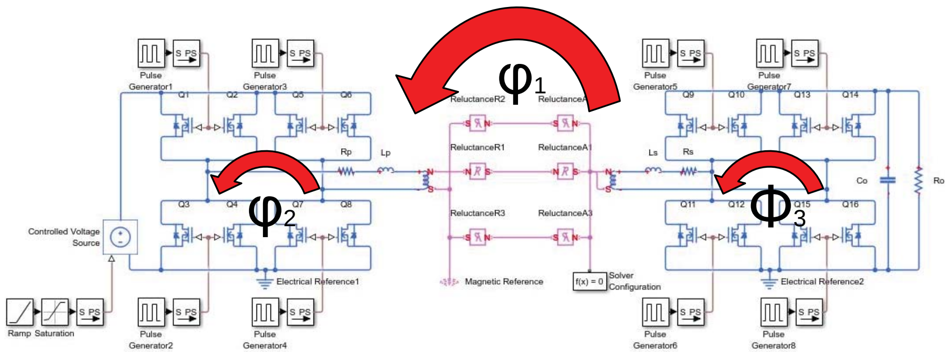
- ❑ D: Duty cycle

[7]

SPS: Low control design complexity.
If the voltages on both sides of the transformer do not match, rms and max currents are high. Soft switching hard to realize.

DPS: Medium control design complexity (favors multi-port setups).
Improved flexibility of the control and improved performance.

TPS: Improved performance at light load (wider soft-switching).
High control design complexity (especially for multi-port setups).



[7] Jiang, L., Sun, Y., Su, M., Wang, H. and Dan, H., 2018. Optimized Operation of Dual-Active-Bridge DC-DC Converters in the Soft-Switching Area with Triple-Phase-Shift Control at Light Loads. *Journal of Power Electronics*, *18*(1), pp.45-55.

Agenda

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Technical Specifications of Single-port MFT Model

Input/Output Ports

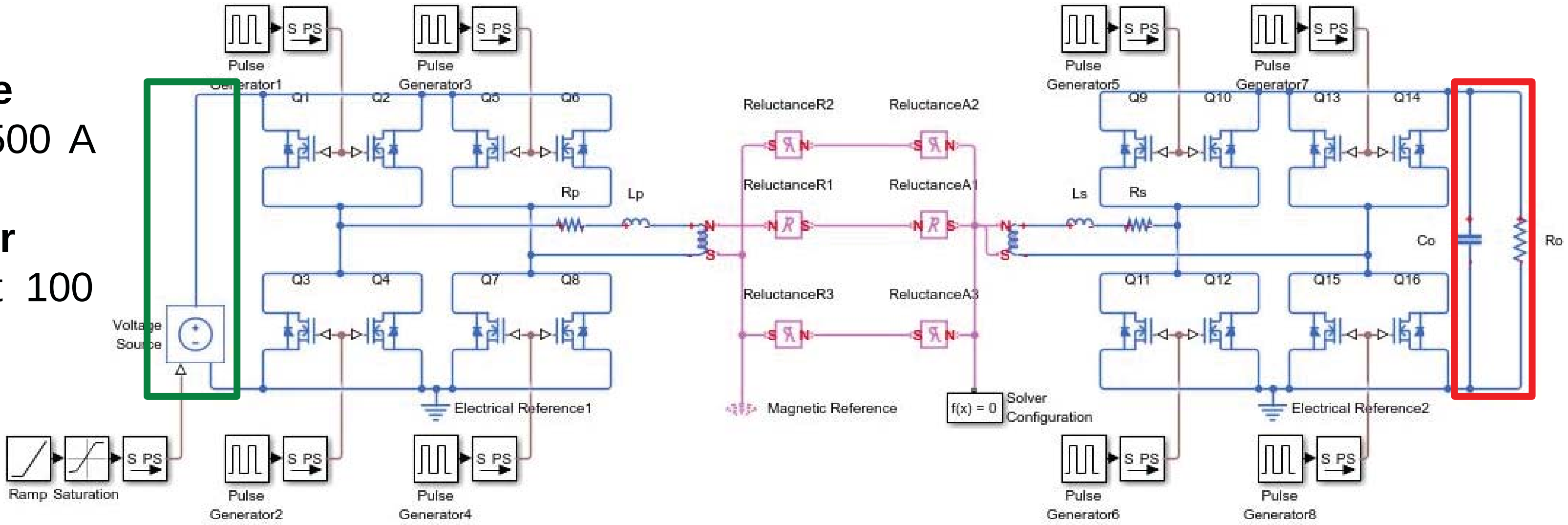
Fixed DC input voltage, V_{in} = 750 V_{DC}

Output (load) resistance
R_o = 1.5 mΩ (350 kW, 500 A at 700 V_{DC})

DC smoothing capacitor
C_o = 30 μF (~±75 V at 100 kHz, 500 A)

Input

Output



DLR

Technical Specifications of Single-port MFT Model

Ideal N-channel MOSFET (1.7 kV SiC MOSFET)

Drain-source on resistance, $R_{DS(on)}$ = 8 mΩ, typical at V_{GS} = 20 V, I_{DS} = 300 A

Off-state conductance, $G_{DS(off)}$ = 0.41 μS

Threshold voltage, V_{TH} = 2.5 V, typical at V_D = V_G, I_D = 15 mA

Switching frequency, f_{sw} = 100 kHz

Duty Cycle, D = 50 %

Anti-parallel Source-Drain Diode (1.7 SiC Schottky Diode)

Forward voltage, $Vf_T = V_T + If{*}R_{D(on)}$

Junction temperature, T_J = 25°C

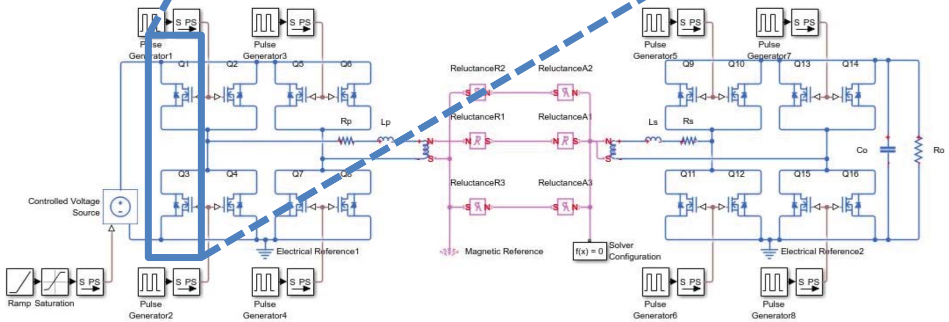
Threshold voltage, V_T = 0.94 V

On resistance, $R_{D(on)}$ = 80.5 mΩ

Off-state conductance, $G_{D(off)}$ = 11.76 nS

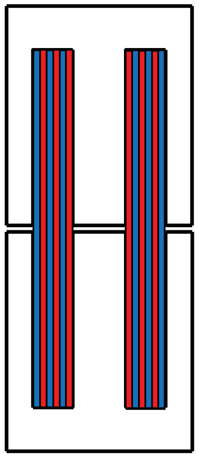
1.7 kV, 325 A

SiC module



Modelling Methodology

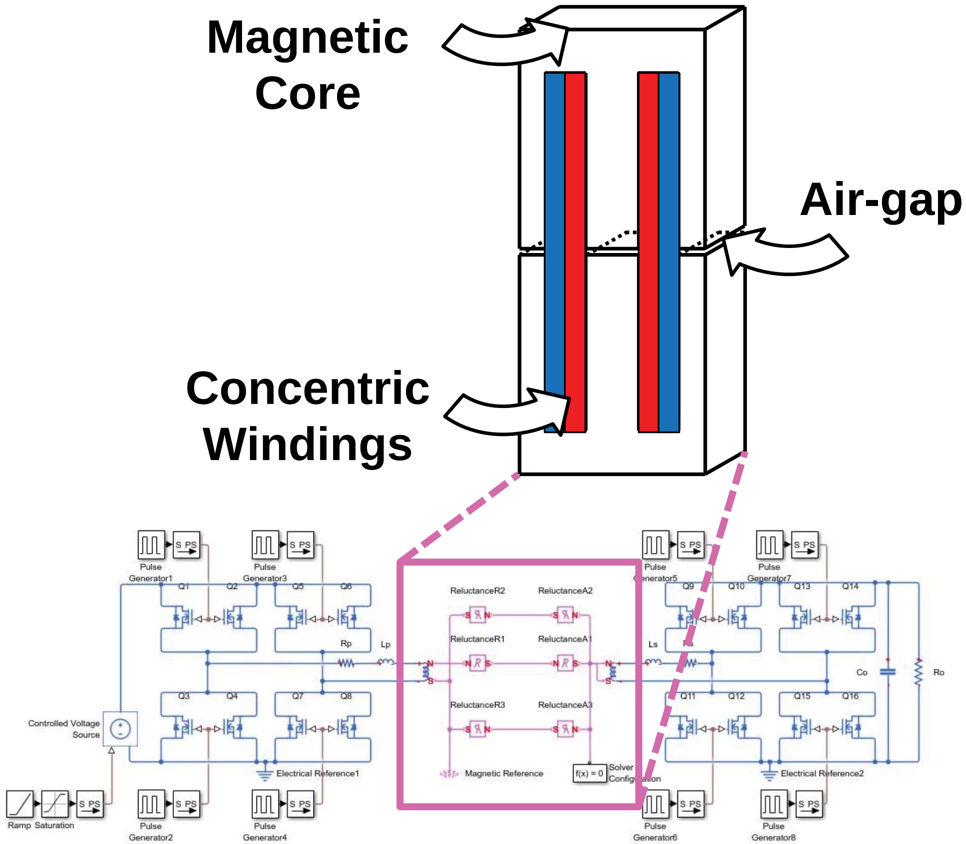
Magnetic Isolation Stage



f_{sw} = 100 kHz
$\mu_0 = 4\pi*10^{(-7)}$ H/m
$\mu_r \sim 1$
$\sigma_w = 5.98*10^{7}$ S/m (copper)

Skin depth: δ = 0.205 mm
N = 1 turn/winding
W = 250 mm
Current density, J ~ 1-1.5 A/mm^2 (low)
T = 0.025 mm (foils) > δ (100% utilization)
Foil number: N_{pf} = 80 (interleaved foils)
Insulation thickness, T_i = 1.5 mm (2x30 mil)

Nomex® paper Type 410
- Dielectric strength, 1.6 kV/mm
- Basis weight, m_i = 1678 g/m^2



Modelling Methodology

Magnetic Isolation Stage

Maximum core flux density, $B_{MAX} = 0.4*B_{SAT}$

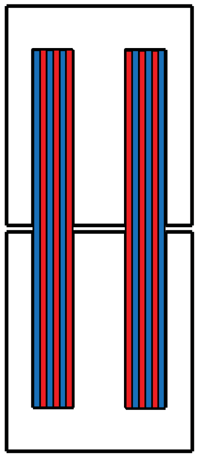
Nanocrystalline VITROPERM 500F

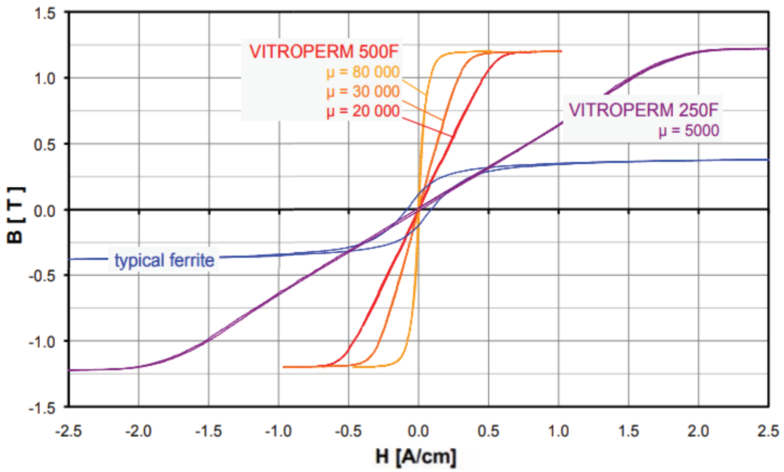
B_{SAT} =1.2 T

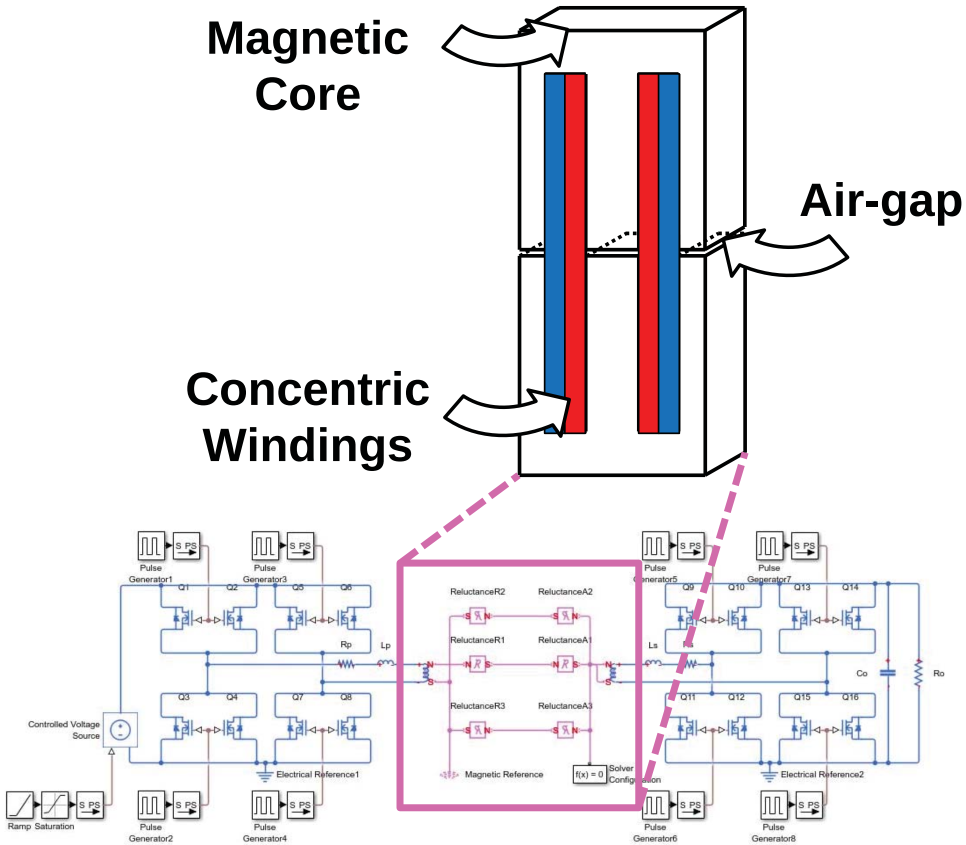
μ_r = 20000

d = 7.35 g/cm^3

P_{Fe} = 80 W/kg (100 kHz, 0.3 T)

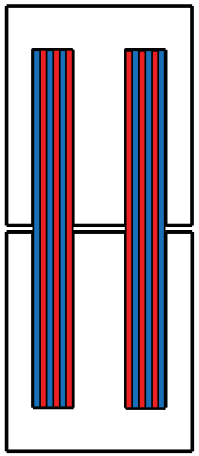


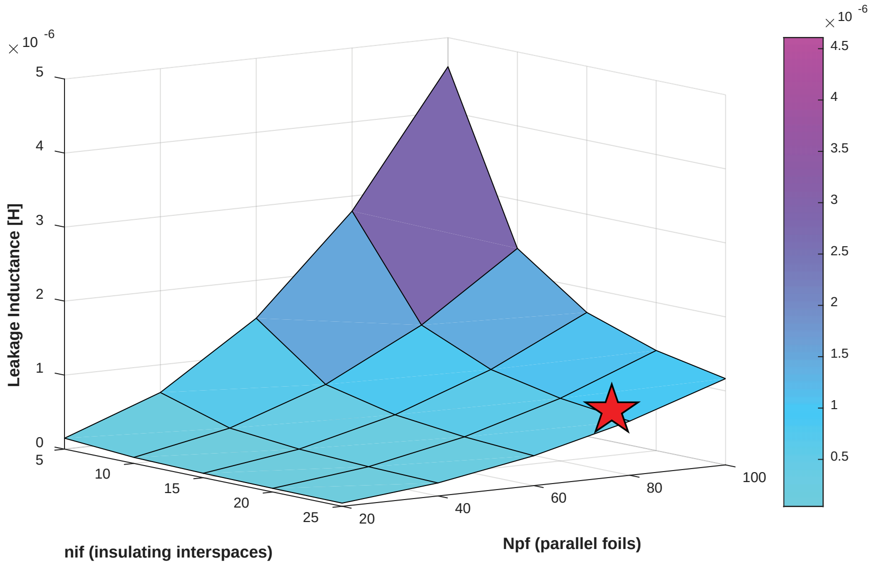




Modelling Methodology

Magnetic Isolation Stage





n_{if} = 24 insulating interspaces

Windings window: 250 mm x 40 mm

B_{MAX} = 0.4*B_{SAT}: B_{MAX} = 0.48 T

Air-gap length, L_a = 0.5 mm for maximum flux Φ_{MAX} = 0,0012 Wb

A_{c1} = 2500 mm^2 (5 cm x 5 cm)

$A_{c2,3}$ = 1250 mm^2 (2.5 cm x 5 cm)

Core: V_c = 0.0017 m^3, m_c = 12.5 kg, P_{l_c} = 1 kW @ 100 kHz, 300 mT

L_m = 36 cm

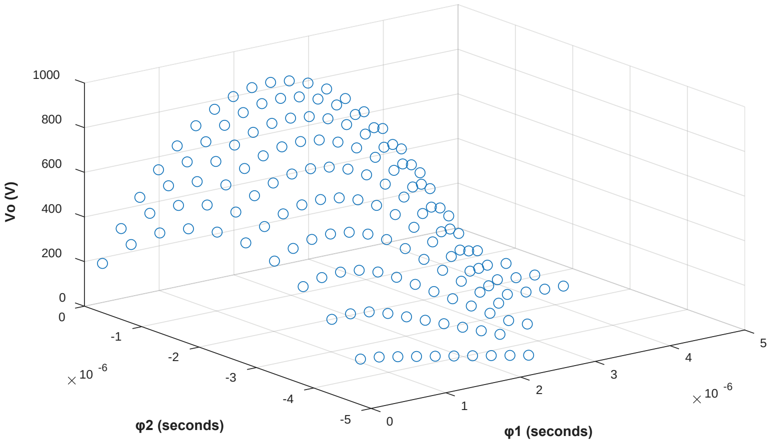
L_L = 0.751 μH

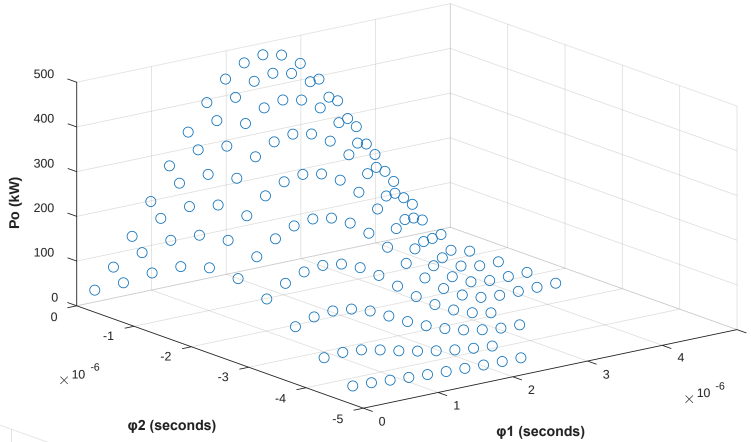
R_{AC} = R_{DC} = 12.04 μΩ

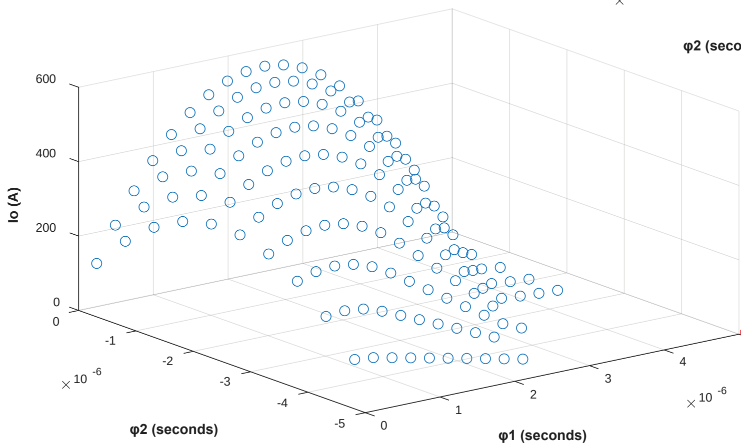
Agenda

Efficiency Analysis

Dual PS (sensitivity on φ_1, φ_2, φ_3 = 180°)







It is possible to cope with Po greater than 350 kW

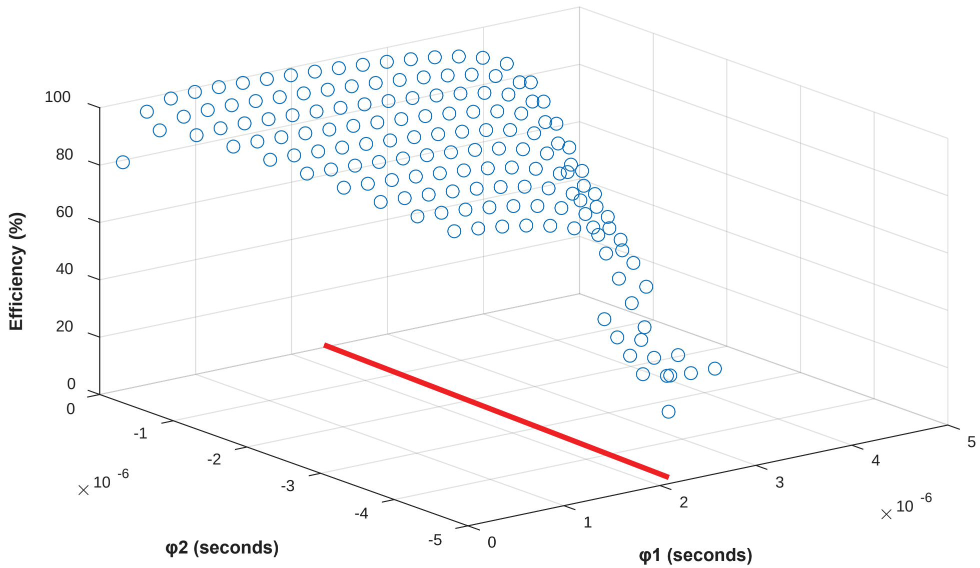
The selection of φ_1 on fixed φ_2 or φ_2 on fixed φ_1 becomes complicated for PI controller

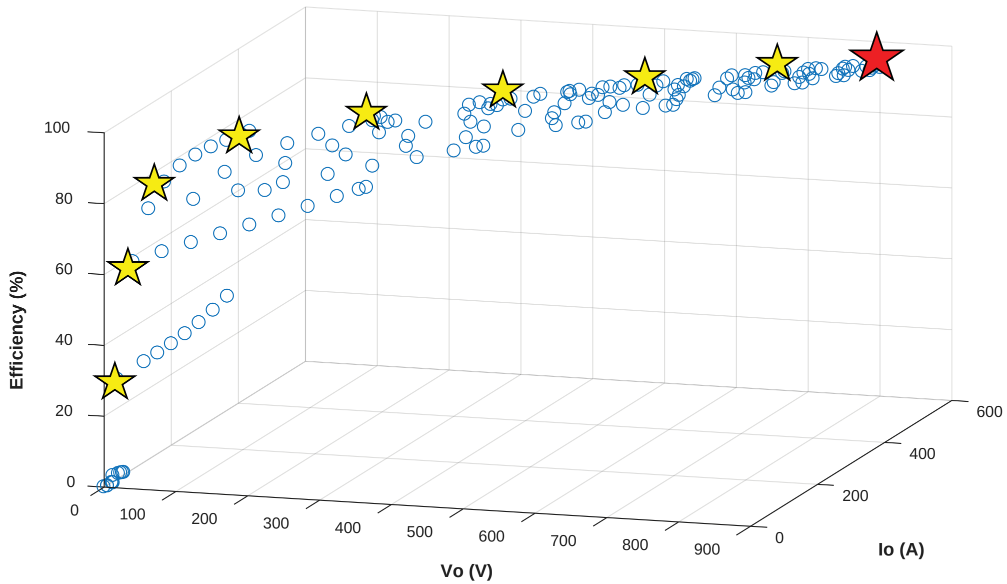
Efficiency Analysis

High efficiency within certain range of external phase φ_1

Potential for efficiency > 95% at high loads
Dual PS does not favor light load

Dual PS (sensitivity on φ_1, φ_2, φ_3 = 180°)



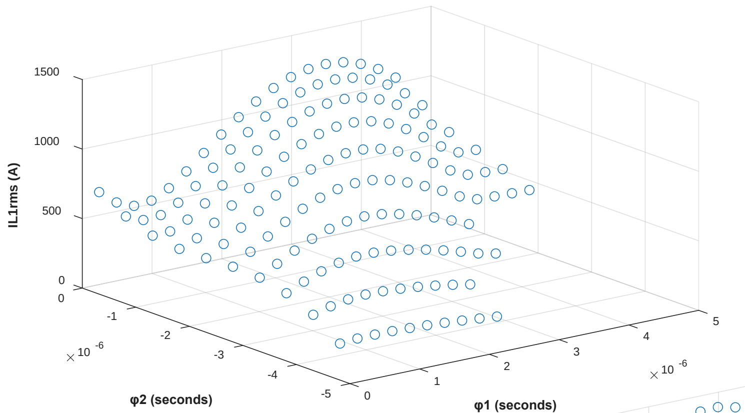


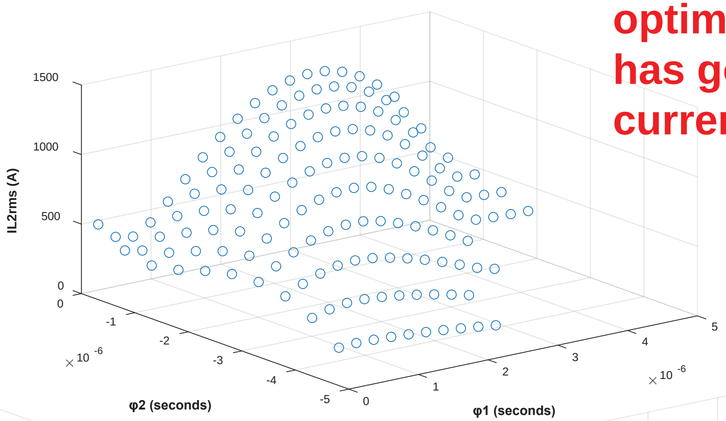
Efficiency Analysis

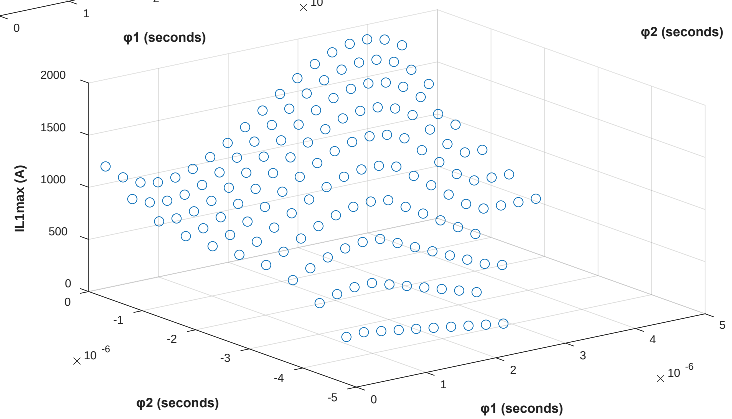
High rms and peak currents

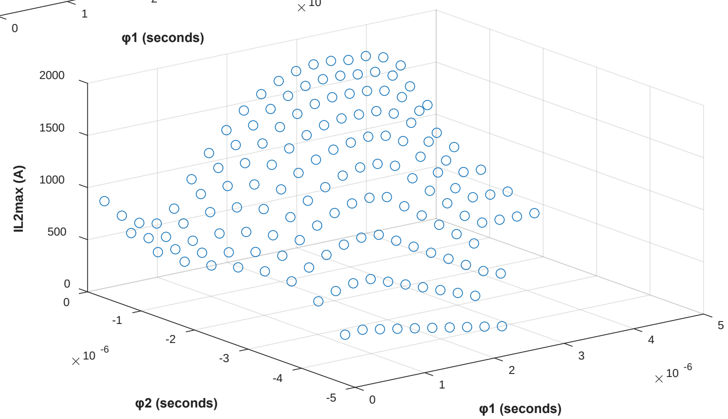
Design and control optimization + compensation has good potential to reduce currents stresses

Dual PS (sensitivity on φ_1, φ_2, φ_3 = 180°)









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Conclusion and Further Steps:

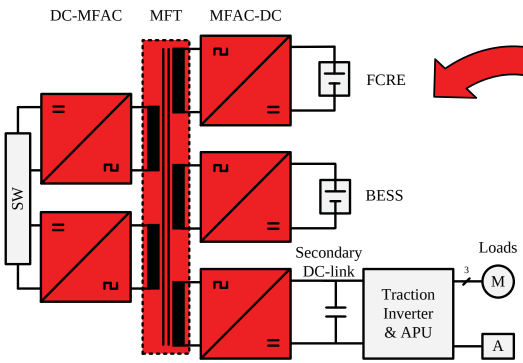
- ✓ **Defined multi-port MFT sub-system concept for hybrid NGT CARGO**
- ✓ **Specified requirements**
- ✓ **Defined methodology for single-port MFT design**
- ✓ **Preliminary analysis of single-port MFT design:**
  - High power density: Reduced copper and magnetic core material due to the utilization of f_{sw} = 100 kHz
  - Reasonably high efficiency is possible if switching losses are controlled
  - Attention: Switching losses, coil rms and peak currents (design and controls)
- ❑ **Update of SiC switch model to include switching behavior**
- ❑ **Parallelization of SiC switches to identify current distribution**
- ❑ **Extension of model and desigh to multi-port MFT setup**
- ❑ **Adoption of resonance-based control with definition of dead times and compensation networks**

MFT Sub-system Concept and Requirements

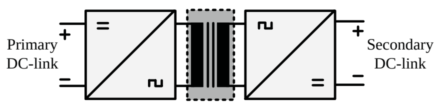
MFT Sub-system Concept – General Project Workflow

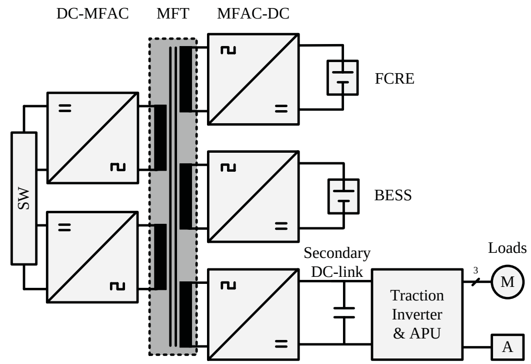
Model Extension

Controls



Multi-port Sub-system Design





Single-port Module Analysis

Questions?

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