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Design of rotatory transformer for wireless power transfer in the X-rotor wind turbine

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https://xrotor-project.eu

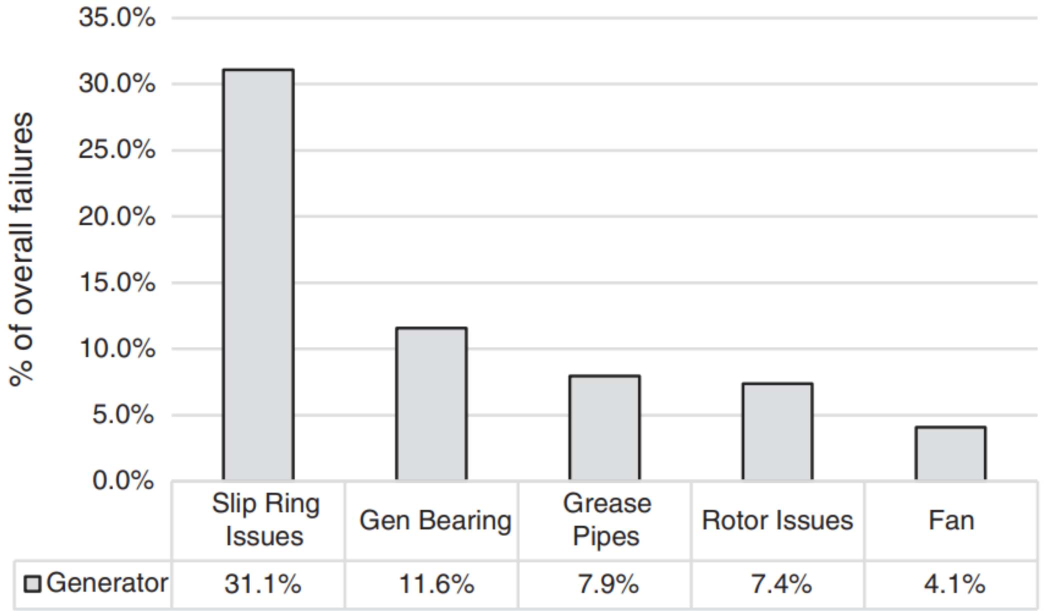
1. Introduction

1.1. Description and purpose

- Design of a rotary transformer configuration capable to handle the MW power transfer requirement of the XROTOR system
  - detailed specification of the rotatory transformer including parameters such as operating frequencies, current density, windings area, air-gap length, etc.
  - The efficiency calculation, and thermal performance analysis
- Design and analysis of a suitable power electronic topology to manipulate the wireless power transfer system
  - electrical operation and energy conversion losses simulation
  - The efficiency calculation, and thermal performance analysis
- The combined efficiency of the rotary transformer with its associated power electronic converter turned to be 96.53% for a 1 MW power transfer system.

1.2. Slip rings in offshore wind turbines

Figure 1 Generator Failure modes



1.3. Inductive Power Transfer

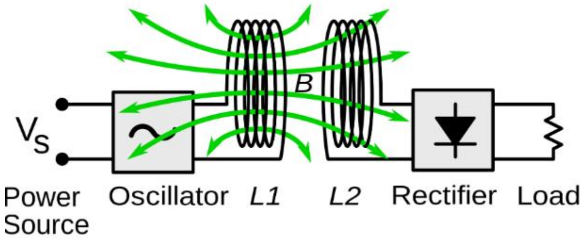


Figure 2. Generic block diagram of an inductive wireless power system

INSTITUTE/ COMPANY	POWER TRANSFER	AIR-GAP (mm)	EFFICIENCY	FREQ. (kHz)	TYPE
KAIST [8-10]	27kW	200	74%	20	Track
	22kW	200	71%	20	Track
WAVE [11]	50kW	178	92%	23.4	Coil
ETH Zurich [12-15]	50kW	100- 200	95.8%	85	Coil
Fraunhofer [16, 17]	22kW	135	97%	100	Coil
KRRI [18]	818kW	50	82.7%	60	Track
Showa Aircraft Co [19]	30kW	150	92%	22	Coil
NYU [20, 21]	25kW	210	91%	85	Coil
Conductix Wampfler [15]	120kW	40	90%	20	Coil

Table 1: Recent high-power wireless power transfer systems in industry

2. Rotary Transformer for the X-ROTOR

2.1 Design

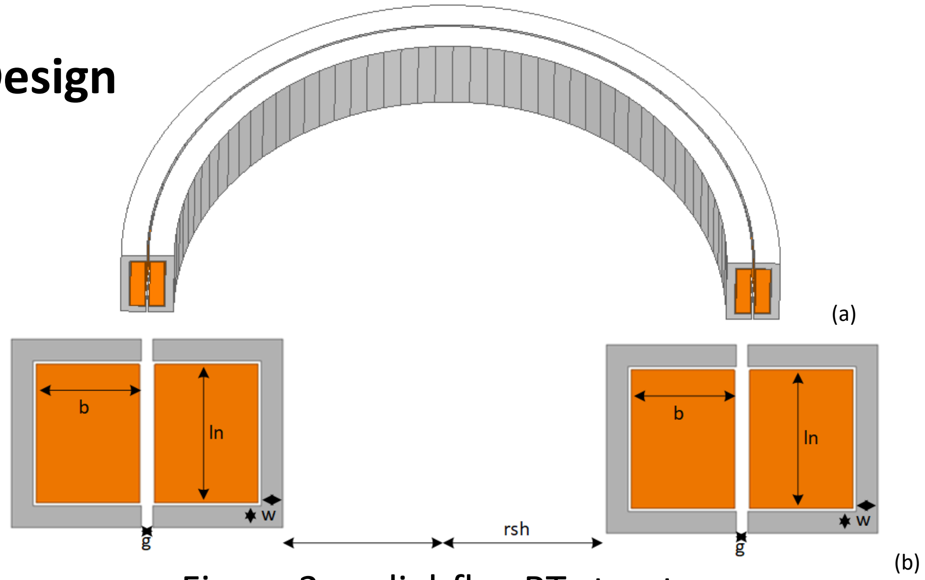


Figure 3: radial-flux RT structure

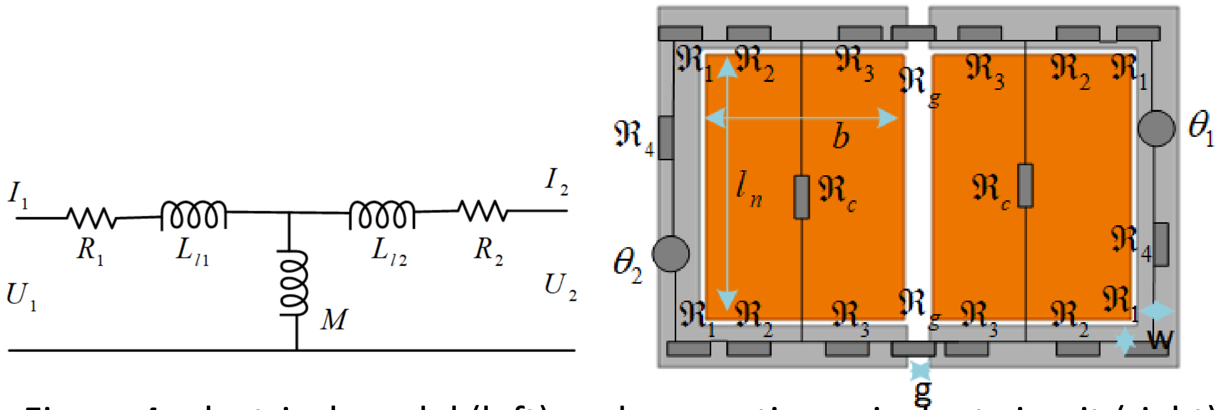


Figure 4: electrical model (left) and magnetic equivalent circuit (right)

Parameter	Value	Parameter	Value
rms voltage (V)	850	rsh (mm)	650.00
frequency (Hz)	2000	g (mm)	5.00
flux density (T)	0.50	ρ_{cu} (copper resistivity)	1.72E-08
Power (VA)	333 KVA	μ_r (relative permeability)	300
winding fill factor	0.30	lamination fill factor	0.85
current density (A/mm²)	2.00	fringing effect factor	1.10

Table 2: preliminary parameters

Parameter	Value	Parameter	Value
rms current (A)	392	b (mm)	40
conductor cross sec. (mm²)	196	N	10
$\boldsymbol{A_w}$ (mm²)	6635	$R_{in,ac}$ (ohm)	0.0113
$\boldsymbol{A_c}$ (mm²)	22162	$R_{in,ac}$ (ohm)	0.0120
$\boldsymbol{w}$ (mm)	20	$R_{out,ac}$ (mH)	2.43
$\boldsymbol{l_n}$ (mm)	166	M (mH)	0.06

Table 3: designed RT

Analytical design using Magnetic Equivalent Circuit

2.2. Compensation Strategy

Compensation circuits are often introduced in an inductive power transfer system to improve the input-power-factor and to increase load power by cancelling out reactive powers generated from loosely coupled coils.

2.3. Engineering Considerations

- Core material

electrical steel for e-mobility and high frequency applications: “powercore® 020-130Y320”

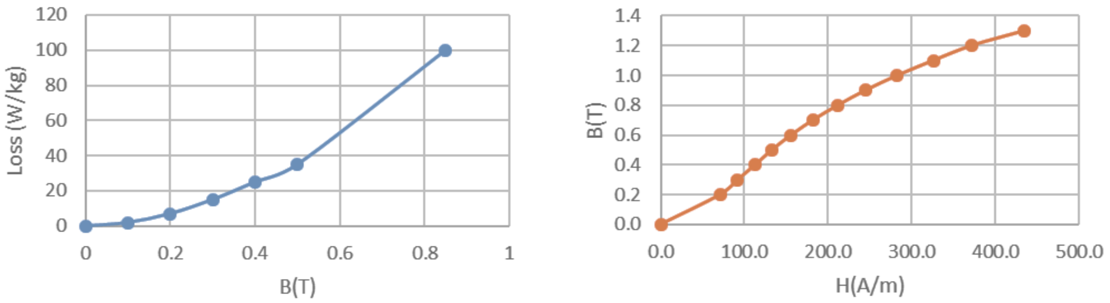


Figure 6: core material characteristics at 2000 Hz

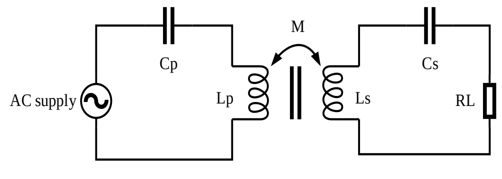
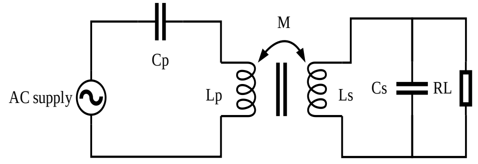
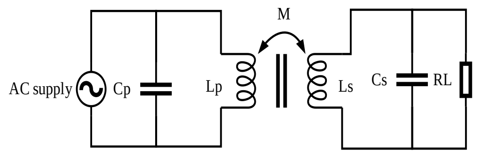
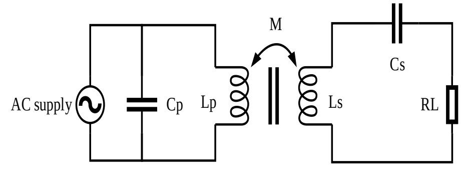
Topology	Circuit
SS	 SERIES TO SERIES TOPOLOGY
SP	 SERIES TO PARALLEL TOPOLOGY
PP	 PARALLEL TO PARALLEL TOPOLOGY
PS	 PARALLEL TO SERIES TOPOLOGY

Table 5: compensation topologies

- **Air-gap**

The air-gap is assumed to be 5 mm. This is reasonable as the rotational speed is low enough and the axial length of the RT is small enough (about 200 mm) to be held constant by proper bearings.

Theoretically, the maximum air-gap is not constrained, but regarding the electromagnetic design and performance of the system, for this RT, the maximum value of a centimetre is recommended.

- **effect of high frequency**

skin and proximity effects on the AC resistance have been considered

2.4. Numerical Simulations

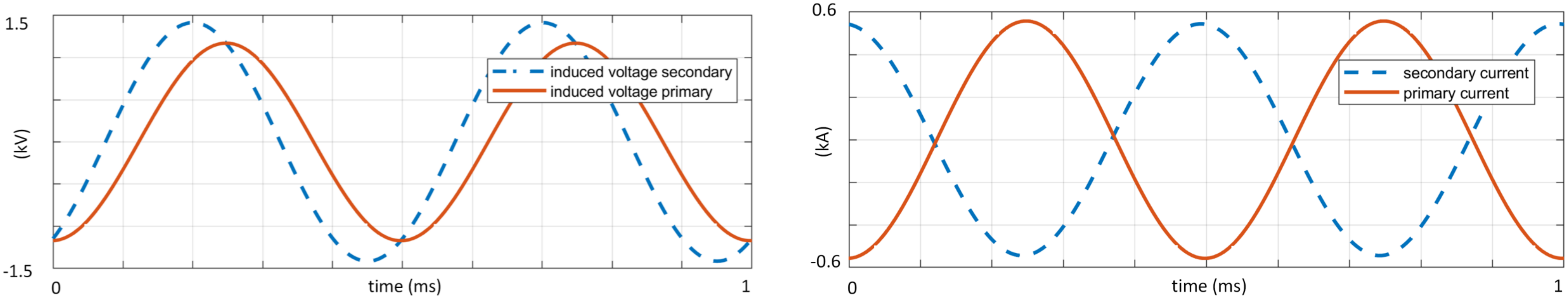


Figure 7: 3D FEA, voltage (left), current (right)

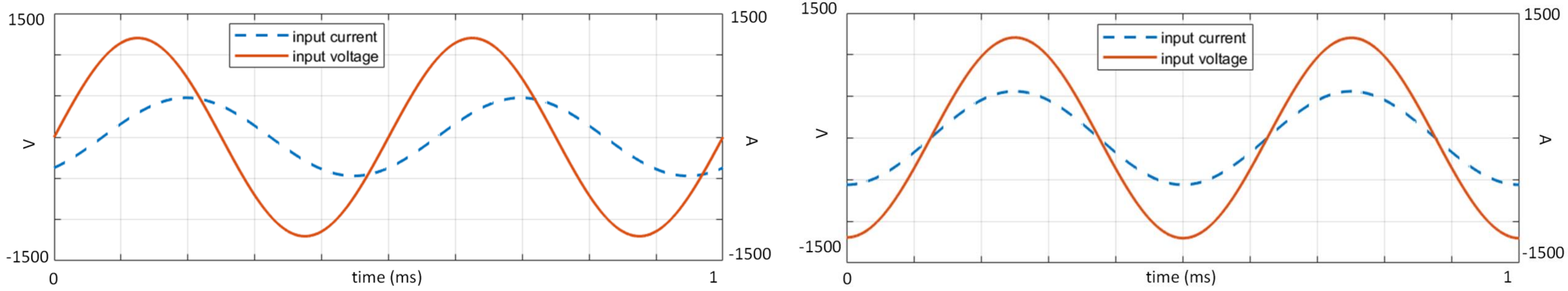


Figure 8: 3D FEA, input voltage and current, before (left), after (right) compensation

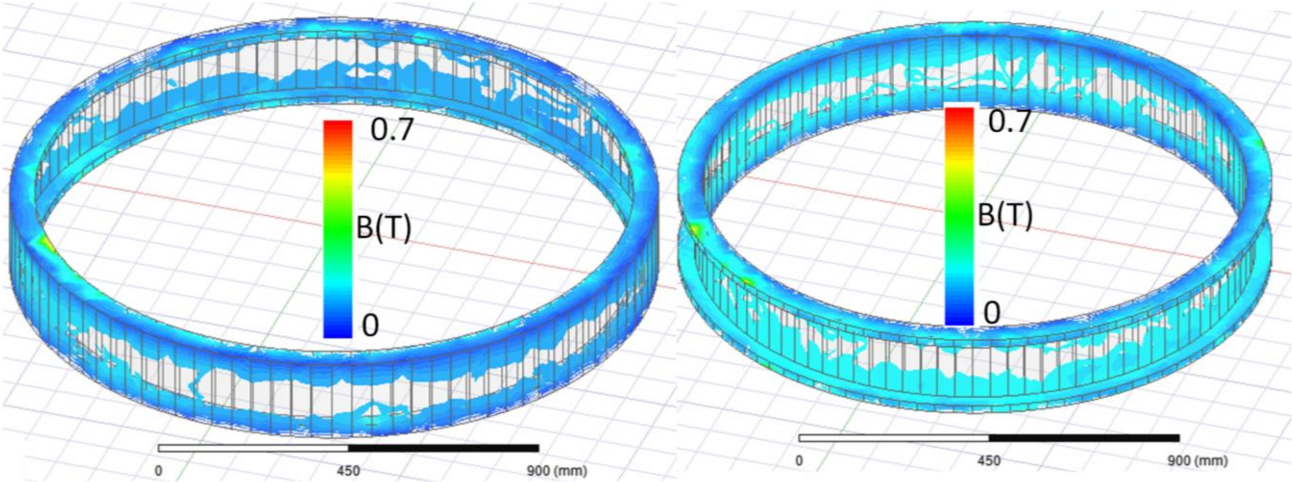
output power	core loss	copper loss
315.7 kW	1.44 kW	3.45 kW
Efficiency		98.5%

Table 4: losses and efficiency

Copper weight	Core weight	Total
157 kg	388 kg	545 kg

Table 5: material usage

2.5. magnetic and thermal analysis



- the ambient temperature is assumed to be 40 °C.

Figure 9: magnetic flux density: secondary (left), primary (right)

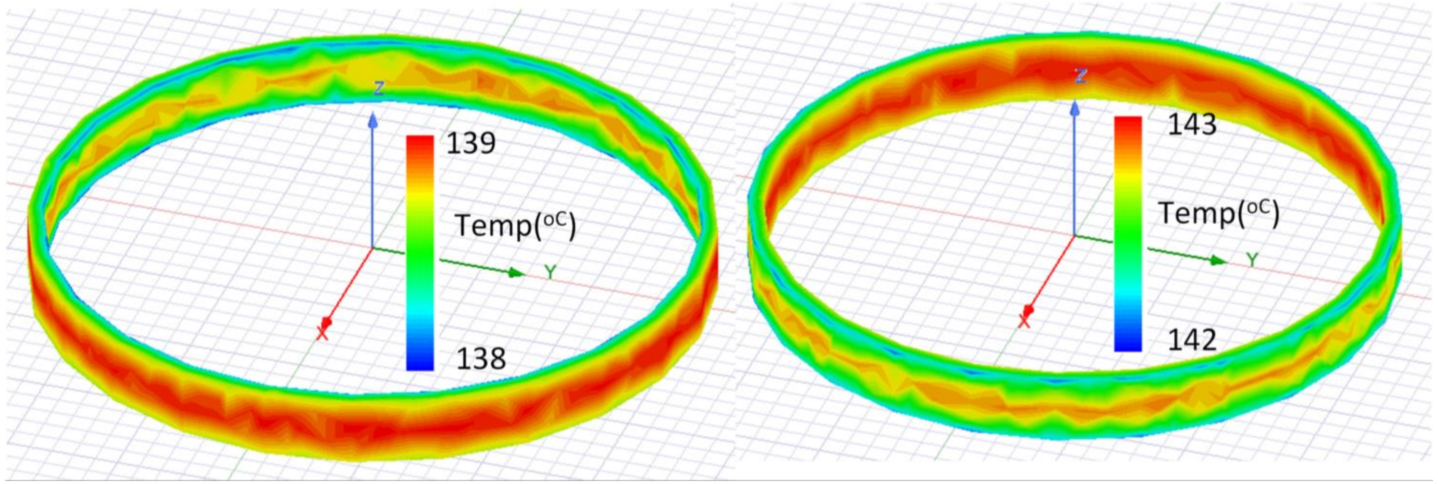
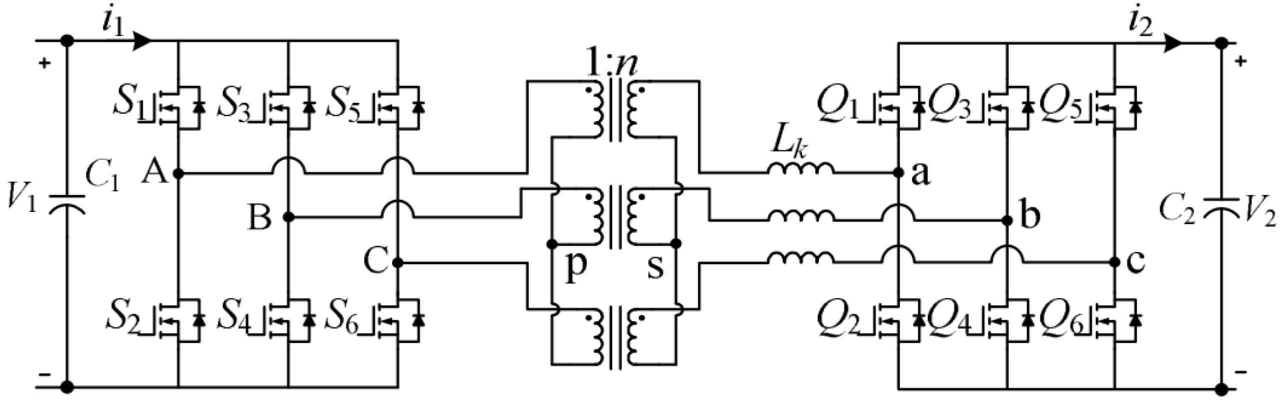


Figure 10: temperature distribution in windings, outer (left), inner (right)

3. Dual active bridge converter

The three-phase DAB converter is generally considered in bi-directional applications since it has the advantages of the single-phase DAB converter such as soft switching capability without additional resonant components and smooth bidirectional power transition using a simple control structure. In addition, the 3P-DAB converter shows low conduction loss and high-power density because of its interleaved structure

Figure 11. Circuit schematics of three-phase dual active bridge converter interfaced with the RT windings



3.1. Design

Design Parameters:

- Rated power: 1 MW
- DC link input voltage: 1800 V
- DC link output voltage: 1800 V
- Switching frequency: 2 kHz

3.2. Simulation of the integrated RT and the DAB converter

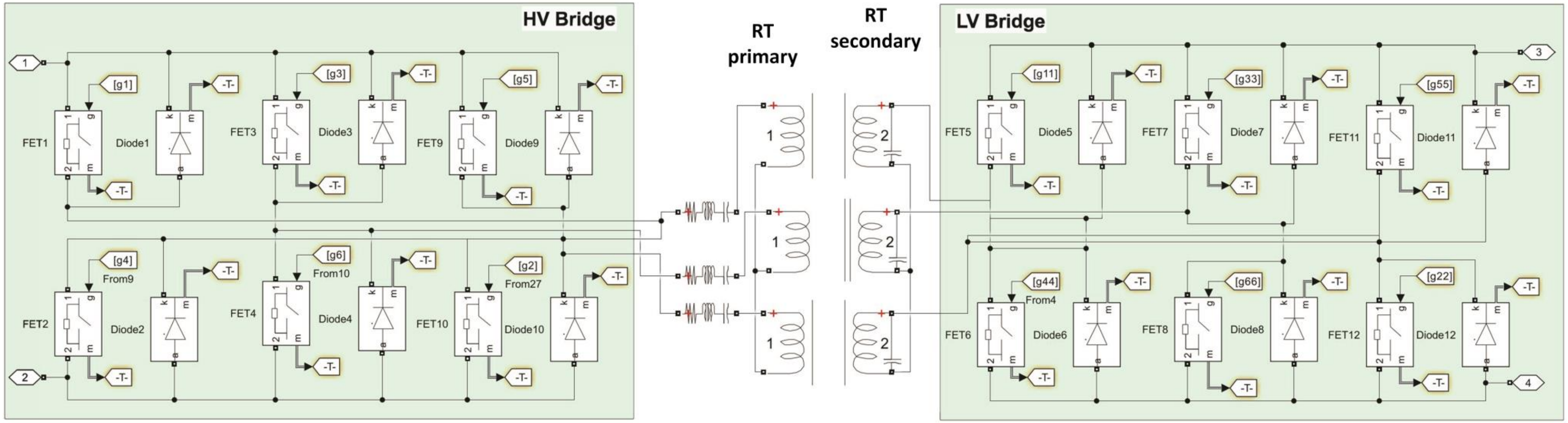


Figure 12. Three-phase DAB converter with rotary transformer simulation in Simulink.

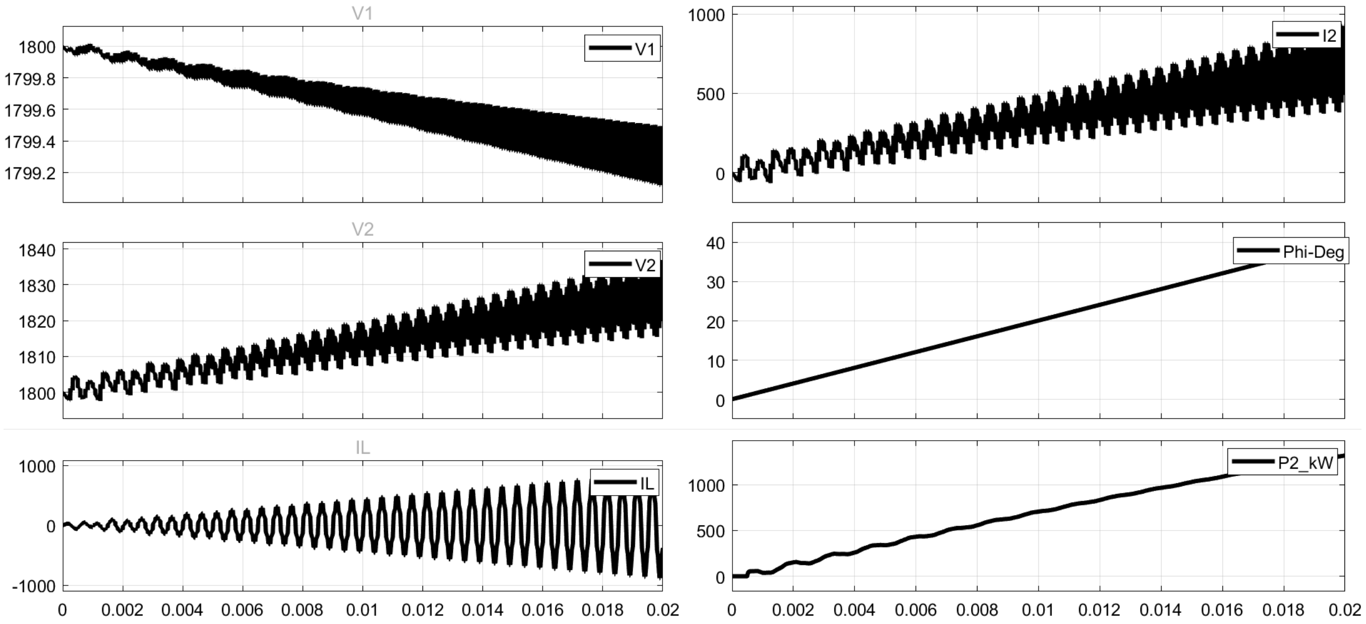


Figure 13. Simulation results for three-phase DAB converter; left: input DC-link voltage, output DC-link voltage, inductor current, right: output current, phase-shift, output power.

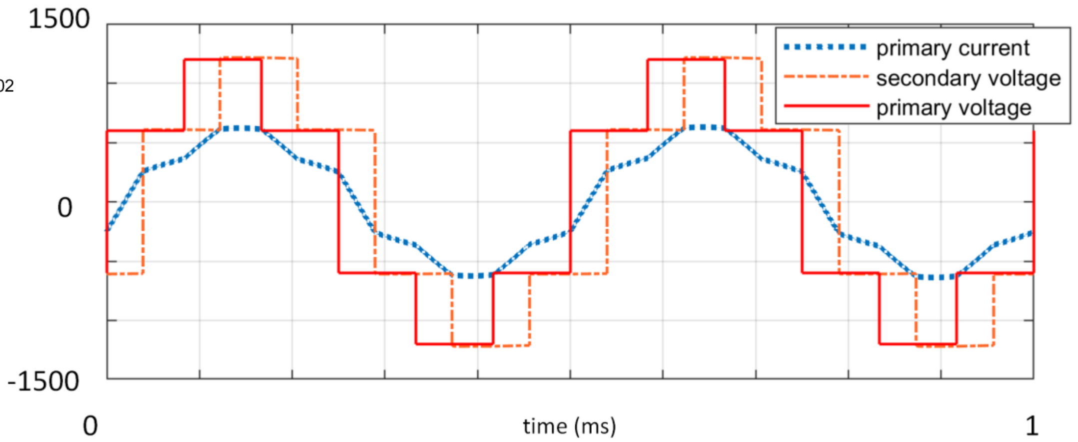


Figure 14. The primary phase voltage, the secondary phase voltage and the inductor current waveforms

3.3. loss and efficiency

- The IGBTs losses include: Turn-on loss, Turn-off loss, Conduction loss,
- The diode's losses include: Reverse recovery loss, Conduction loss,

* considering 40°C for the ambient temperature.

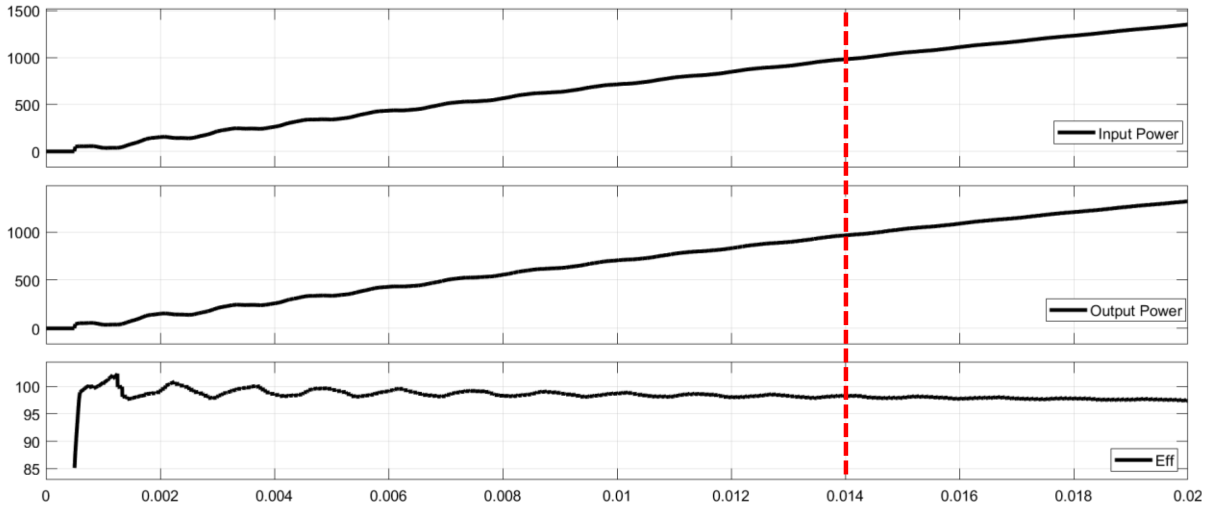


Figure 15. The input power (top), output power (middle) and the efficiency (bottom).

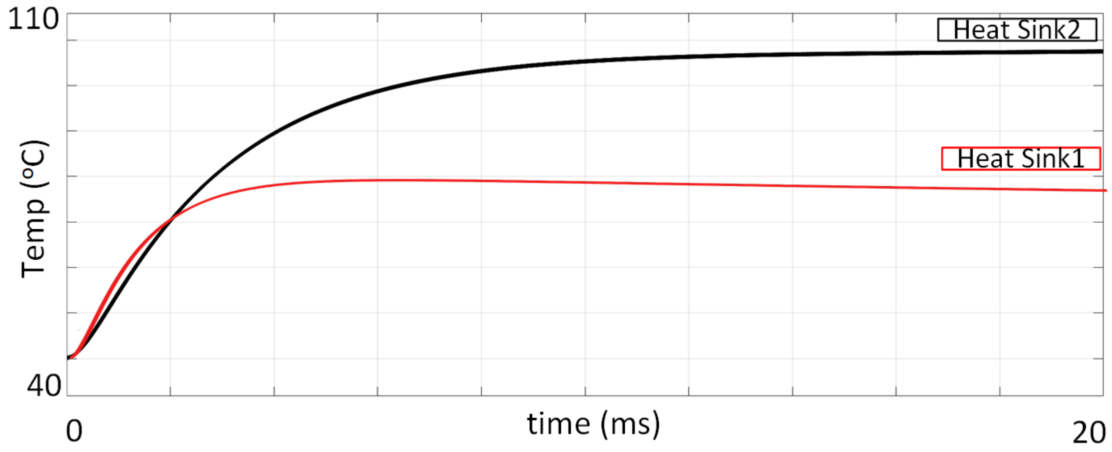


Figure 16. Temperature rise in the heatsink of the input (up) and output (down) converter of the DAB converter.

Table 6: efficiency

Transferred power	**Efficiency**
1 MW	98%

Conclusions

design and analysis of a RT system to transmit power using magnetic wireless power transfer:

- the design methodology was validated using FEA simulation
- all relevant losses (electrical, magnetic) were quantified to determine efficiency
- the engineering considerations to develop the RT system where also revised

a power electronic topology capable to drive power bidirectionally through the RT windings:

- this topology was analysed numerically, electrically, and thermally to quantify performance and efficiency
- the simulation results indicate that bidirectional power control can be obtained at the desired switching frequency

The design methodology presented in this report can be used to <u>increase the power rating</u> of both the RT and the DAB if necessary, or a parallel deployment of several 1 MW systems can be performed to attain a desired power rating.

- ❖ **The selection of any variants of the power generation and transfer elements (PMSG, RT, DAB converter) can be included in a future cost/redundancy analysis.**

X-ROTOR : Design of rotatory transformer for wireless power transfer

X-shaped Radical Offshore Wind Turbine
for Overall Cost of Energy Reduction

University of Strathclyde Glasgow · UCC Coláiste na hOllscoile Corcaigh, Éire, University College Cork, Ireland · NTNU – Trondheim Norwegian University of Science and Technology · TU Delft · CENER

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