

ELECTROMAGNETIC FINITE ELEMENT DESIGN OF AXIAL FLUX PERMANENT MAGNET MACHINES FOR LOW SPEED APPLICATIONS

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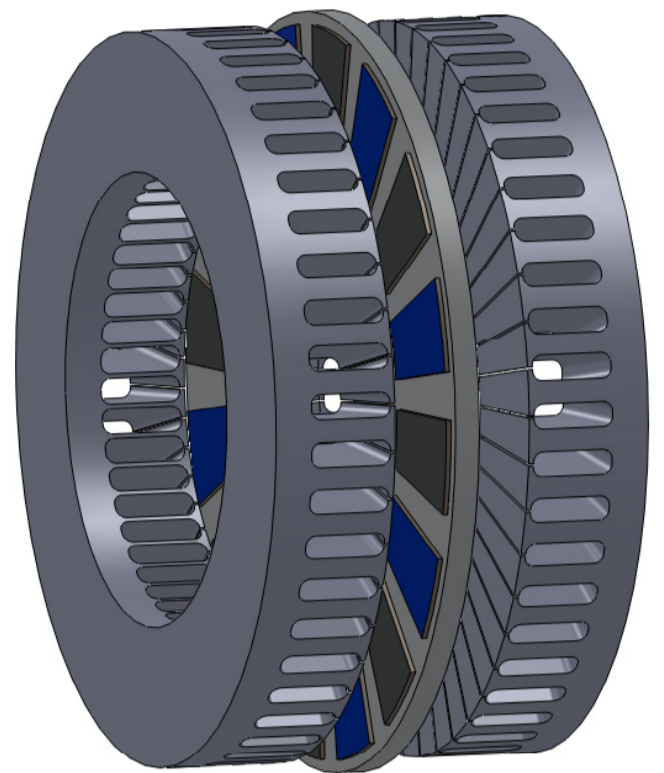
1. ABSTRACT

- The higher torque to volume ratio of Axial Flux Permanent Magnet (AFPM) machines, when compared with their Radial Flux counterparts, is enhanced in multi pole design, making them suitable for low speed applications
- This paper presents a comprehensive approach to the **Finite Element (FE) modelling** of an AFPM machine in a coupled electromagnetic-thermal design
- Special attention is given to **leakage fluxes, synchronous and armature reaction inductances** and **no-load electromotive force** computation
- The evaluation of the FE model routine of the design procedure is performed through experimental validation of a prototype machine

2. AFPM MACHINE

TOPOLOGY

- Double-sided structure with internal rotor
- Three-phase distributed winding, with one slot per pole and phase
- PM located on the surface of a non magnetic rotor disk
- 20 poles



ANALYTICAL ELECTROMAGNETIC-THERMAL DESIGN

- Main dimensions: general sizing equations
- Magnetic loading: non-linear reluctance network
- Thermal modelling: lumped parameter circuit for steady state condition

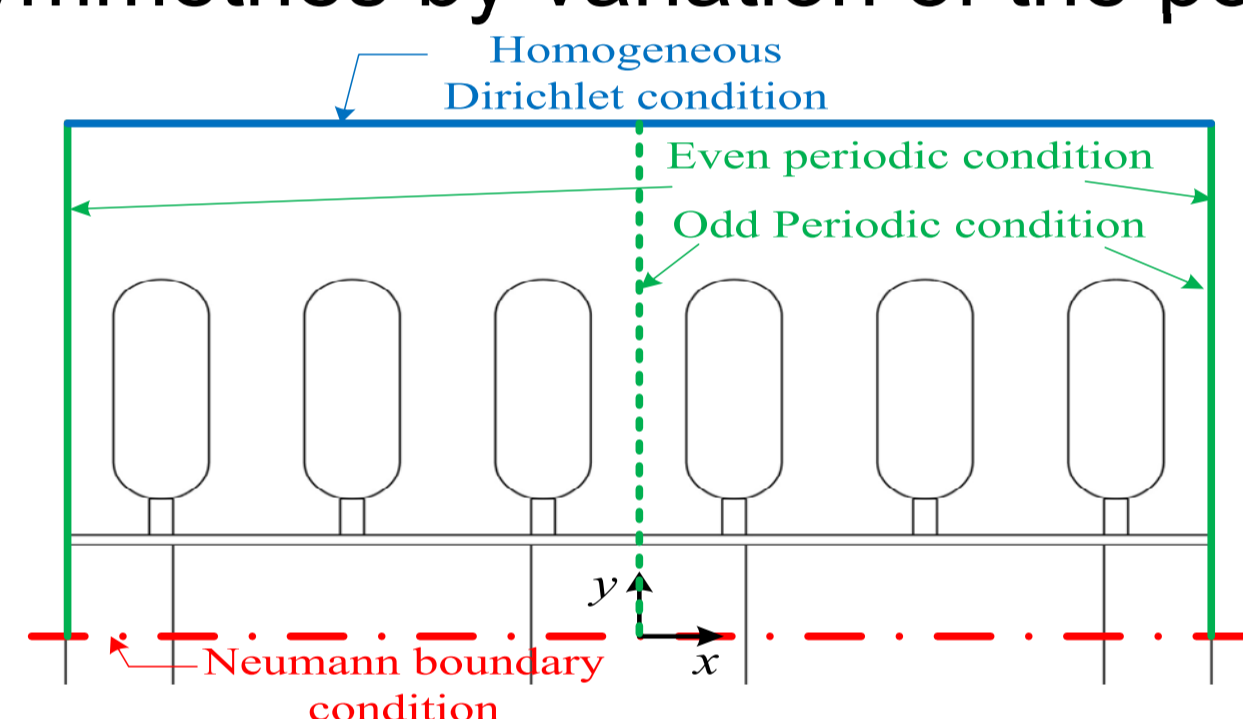
3. FINITE ELEMENT MODELLING

QUASI-3D APPROACH

2D analysis using multiple computational planes in the radial direction

- Excludes border phenomena
- Includes effects due to asymmetries by variation of the pole width

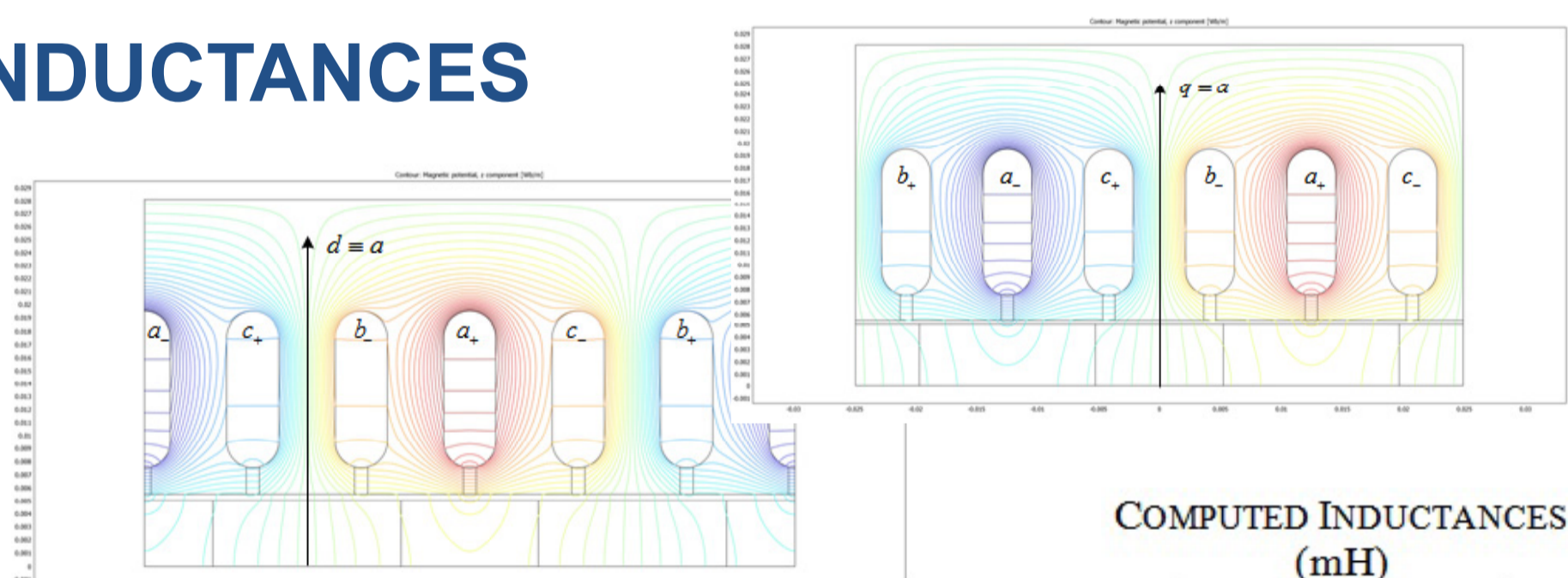
SECTOR MODEL AND BOUNDARY CONDITIONS



SYNCHRONOUS INDUCTANCES

$$L_{sd}(q) = \frac{\lambda_{Id}(q)}{I_{d(q)}} = \frac{\lambda_a}{I_{max}}$$

$$\lambda_a = N_f \frac{2}{S_r} \sum_{i=1}^N \Delta r_i \int_{S_r} A_{zi} ds$$



COMPUTED INDUCTANCES (mH)

L_{sd}	6,95
L_{sq}	6,92
L_{md}	1,98
L_{mq}	1,94
L_{lk}	(1) 4,97
	(2) 4,34

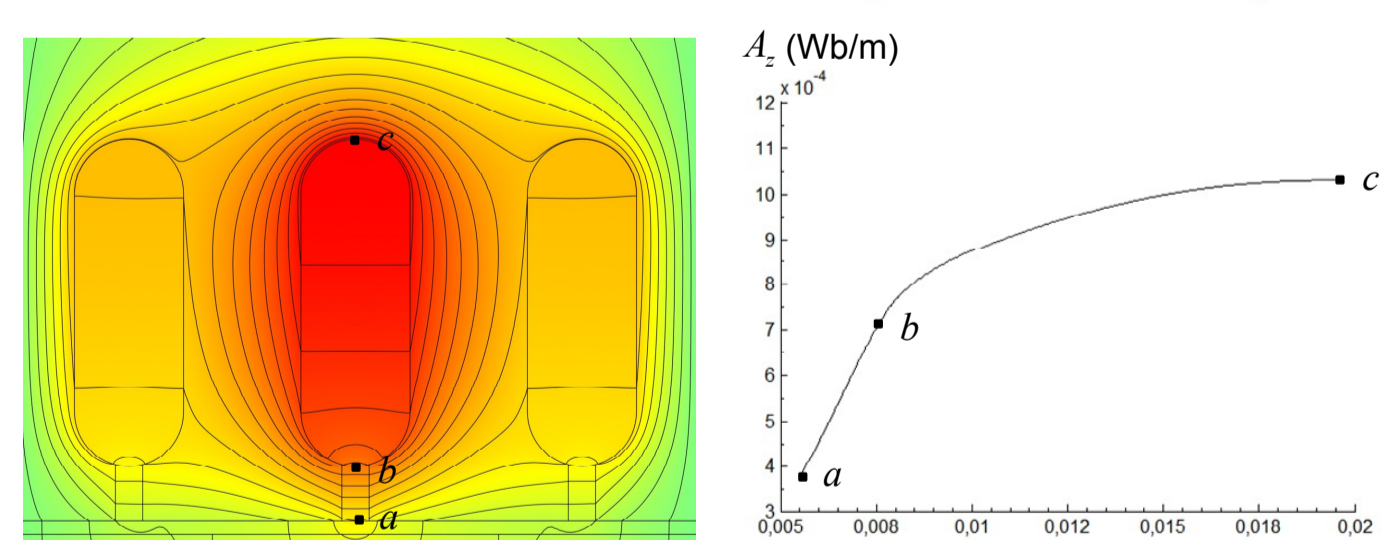
ARMATURE REACTION INDUCTANCES

$$L_{md}(q) = \frac{\lambda_{d(q)}}{I_{max}} \quad \lambda_{d(q)} = k_w N_f \frac{2}{\pi} B_{max I, d(q)} \frac{\pi}{2p} (r_{out}^2 - r_{in}^2)$$

LEAKAGE STATOR INDUCTANCE

$$L_{lk} = L_{sd(q)} - L_{md(q)} \quad (1) \quad \text{or} \quad L_{lk} = \frac{2N_f}{I_{max}} \phi_{r, lk} \quad (2)$$

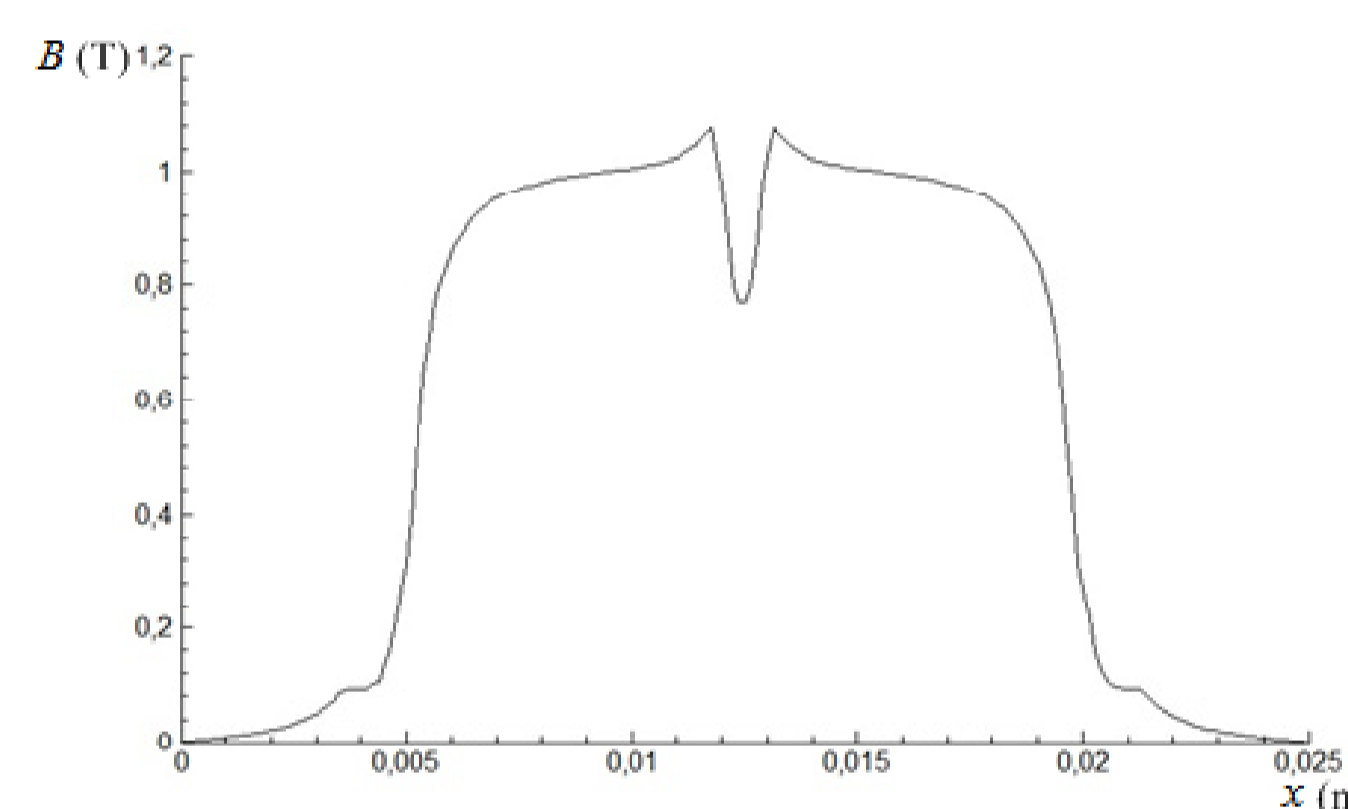
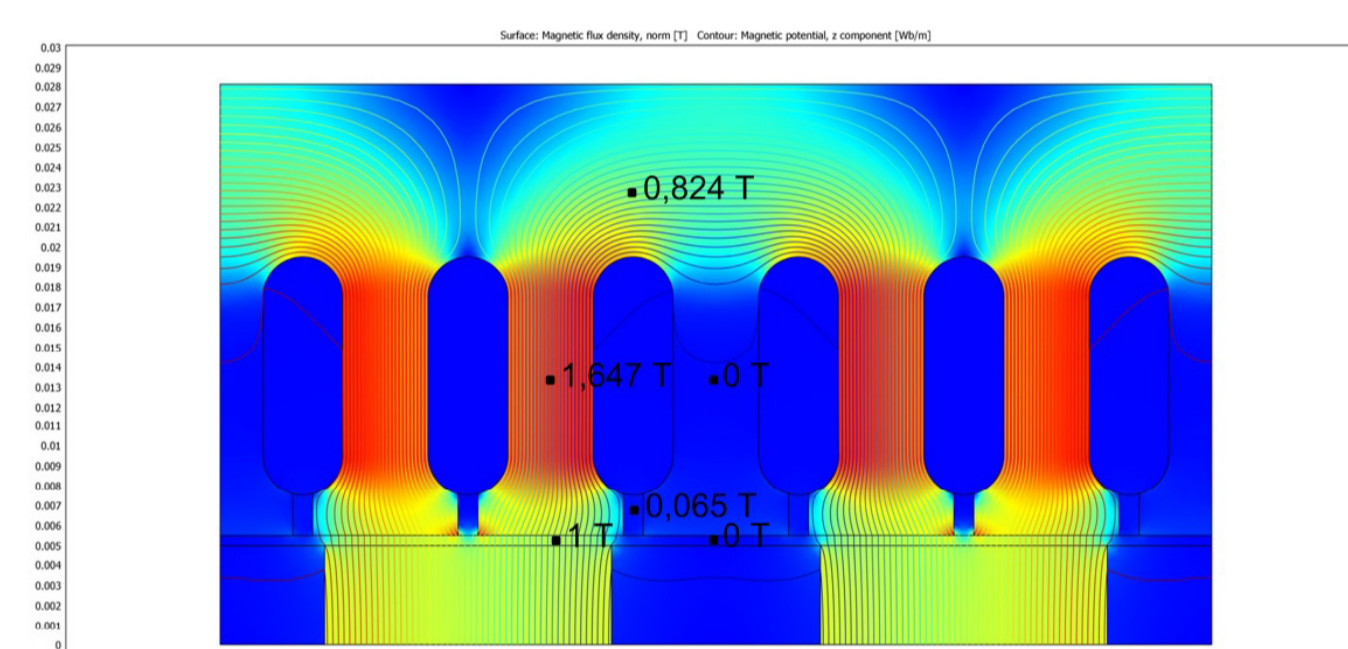
$$\phi_{r, lk} = \sum_{i=1}^N \left(\frac{\Delta r_i}{\Omega} \int_0^{\Omega} A_{zi} \partial \Omega - \Delta r_i A_{z, ai} \right)$$



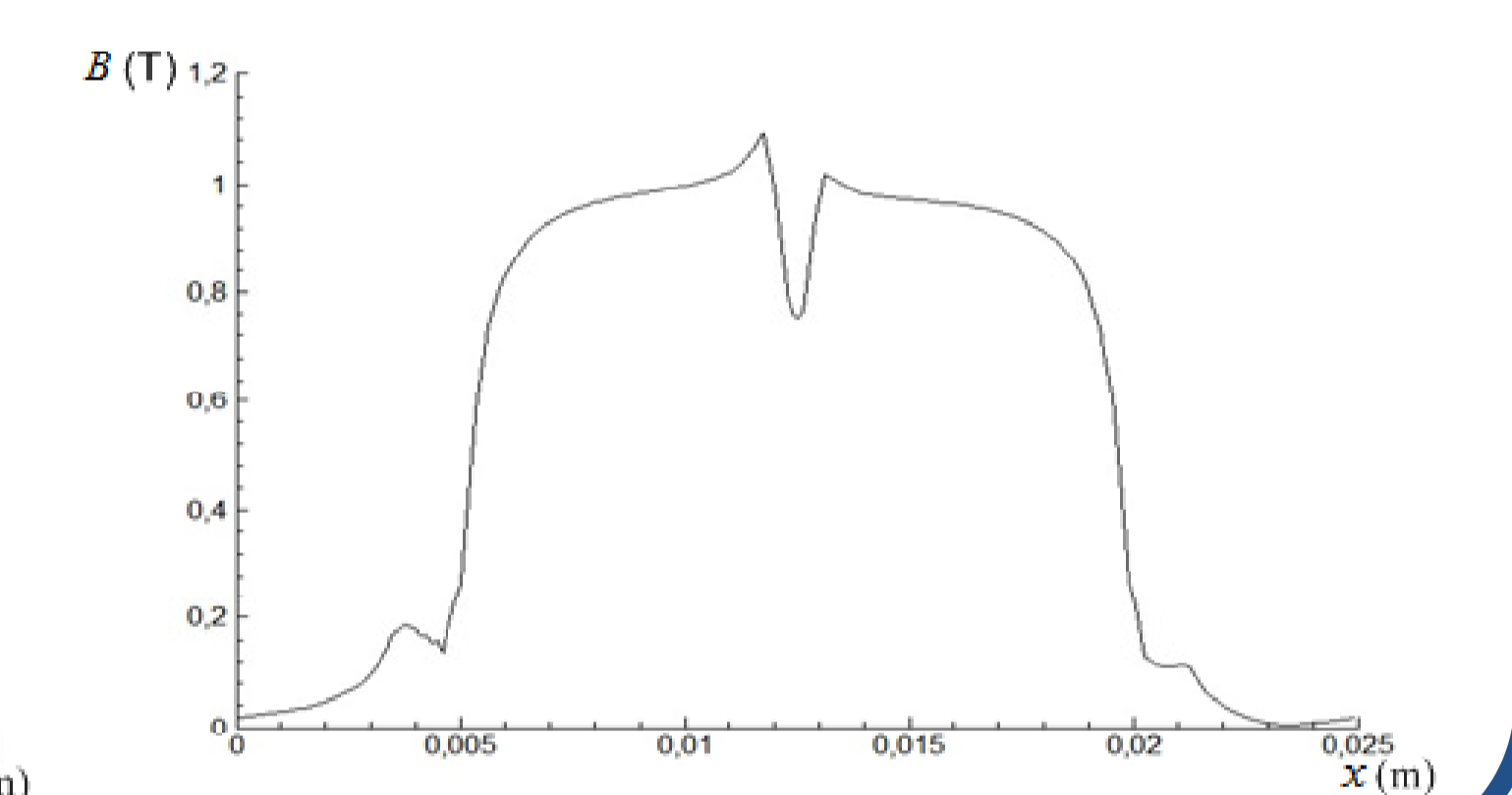
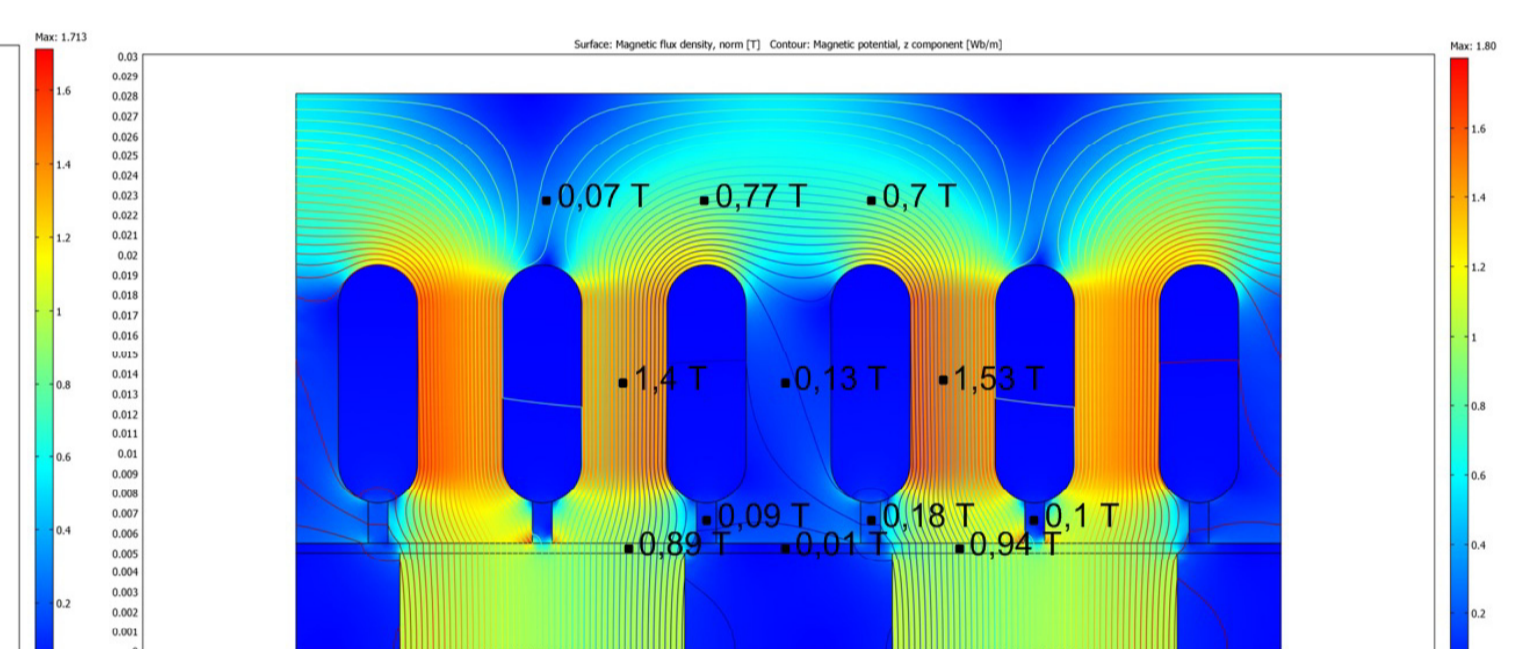
MAGNETIC FLUX DENSITY

@ average radius
@ air gap

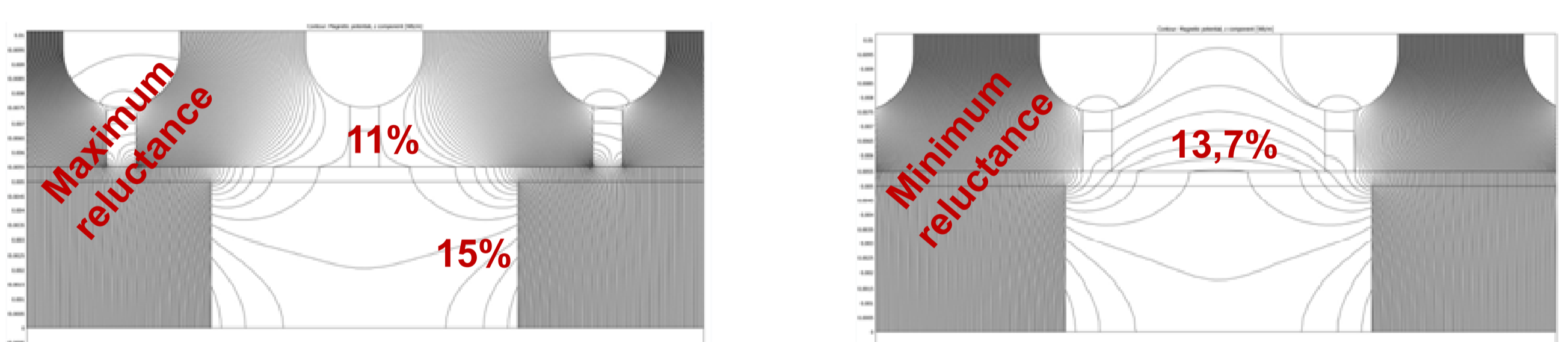
No-Load Condition



Load Condition

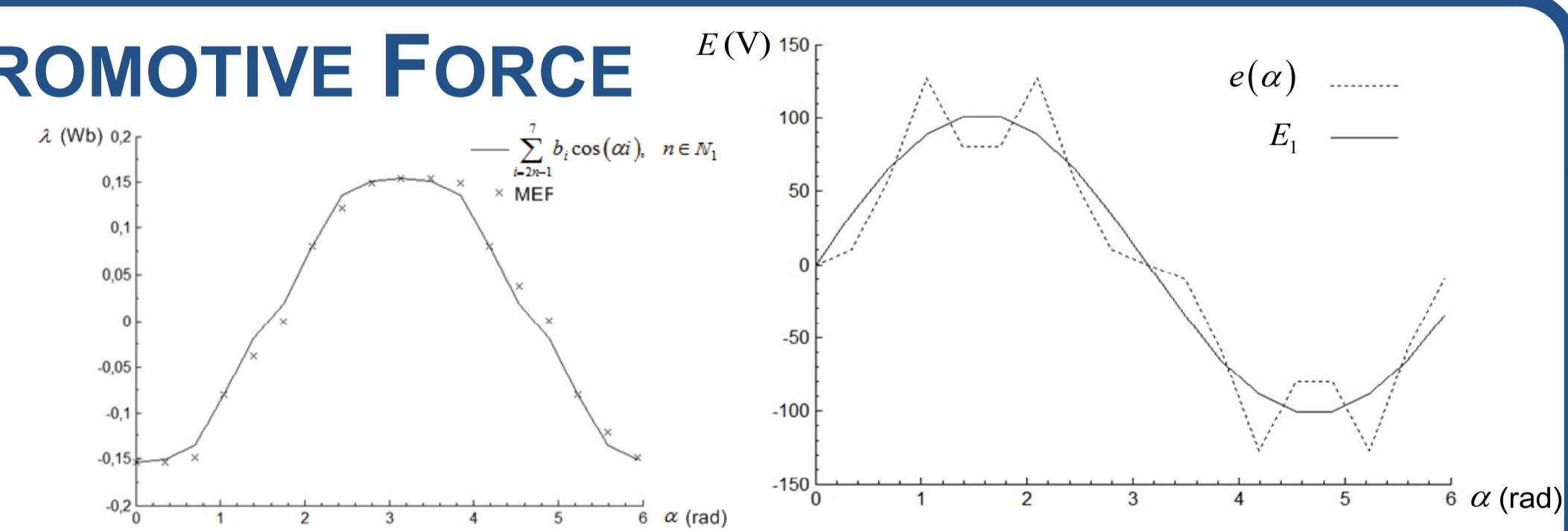


PM AND AIR GAP LEAKAGE FLUXES



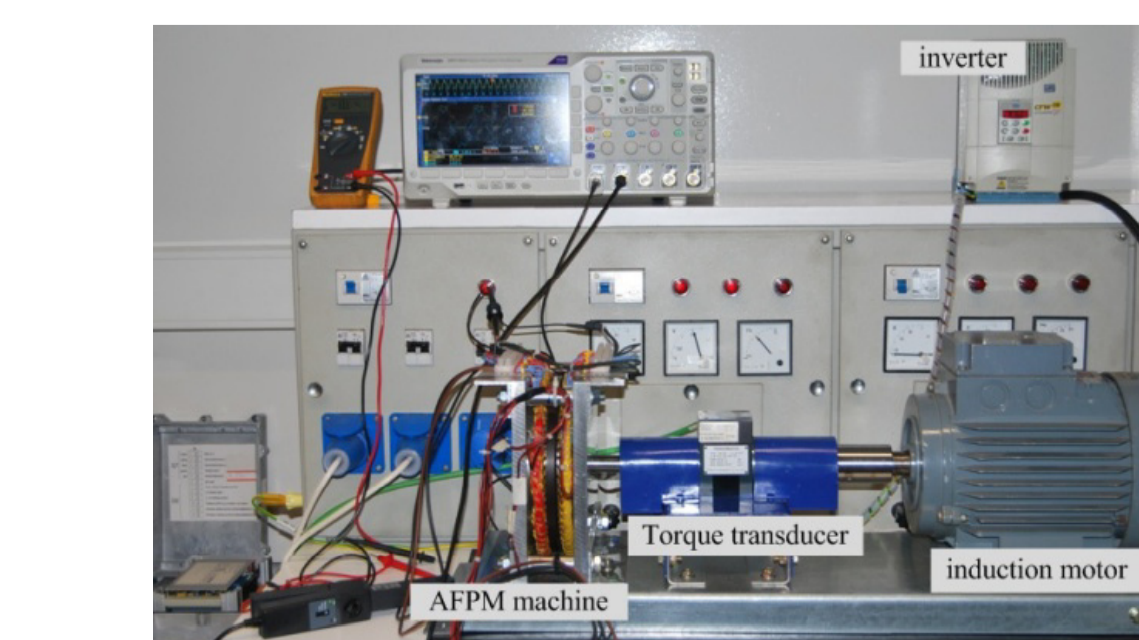
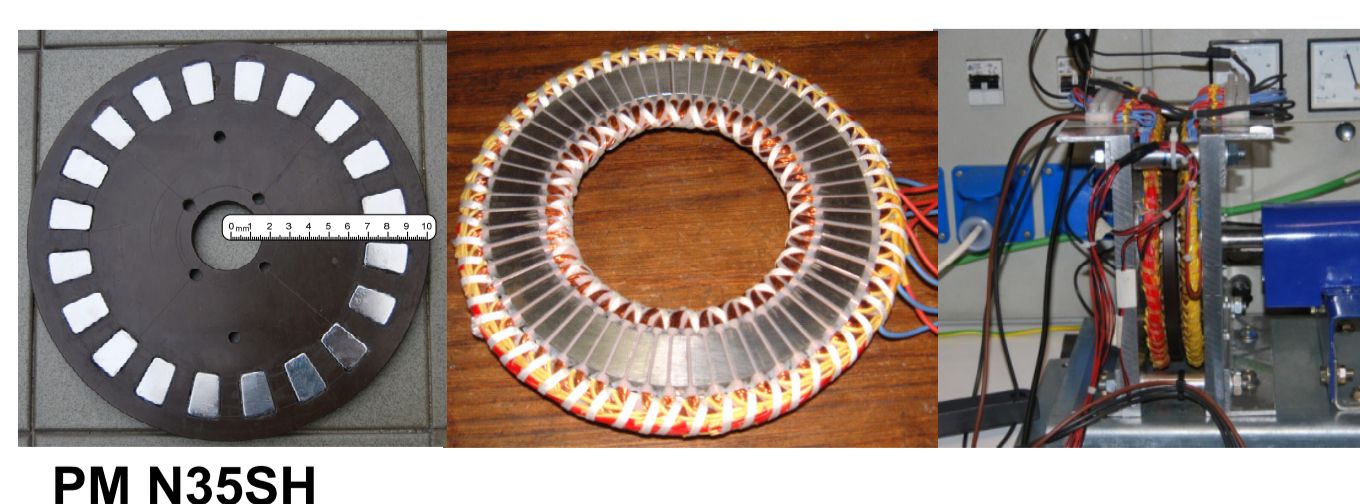
NO-LOAD ELECTROMOTIVE FORCE

$$e(\alpha) = \frac{d\lambda(\alpha)}{d\alpha} \frac{d\alpha}{dt} = \omega \frac{d\lambda(\alpha)}{d\alpha} = -\omega \sum_{i=2n-1}^7 b_i \sin(\alpha i), \quad n \in \mathbb{N}_1$$

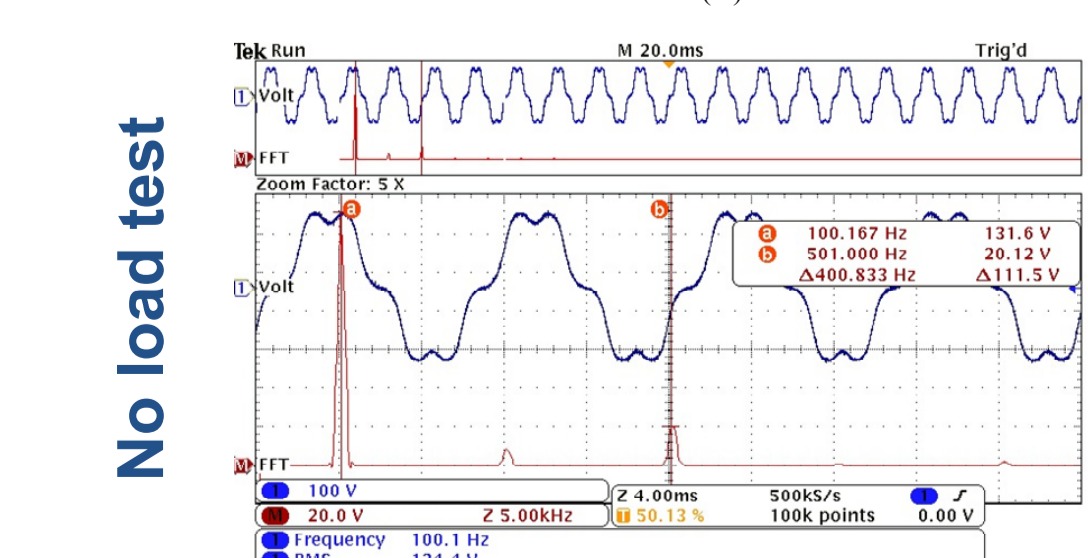
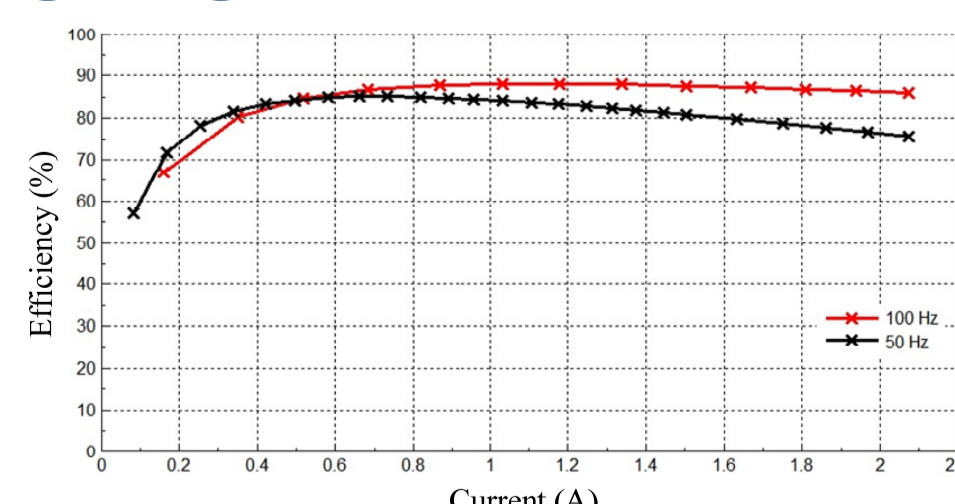
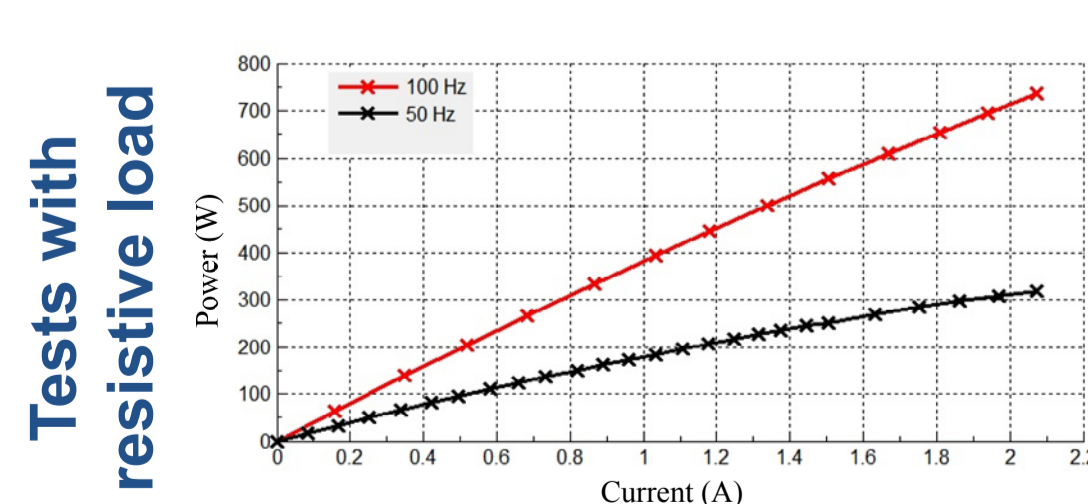


4. VALIDATION OF THE DESIGN PROCEDURE

PROTOTYPE MACHINE



EXPERIMENTAL RESULTS



E_{rms}	= 134,4 V	$\epsilon_{E_{rms}}$	$\approx 11,8\%$
E_1	= 132,6 V	ϵ_{E_1}	$\approx 8,4\%$
$L_{sd} \approx L_{sq}$	= 14,3 mH	ϵ_{L_s}	$\approx 2,7\%$

5. CONCLUSIONS

- This paper presented a comprehensive approach to the FE-aided electromagnetic design of a multi pole double-sided AFPM machine with internal rotor
- The implemented FE model routine is comprised in a coupled electromagnetic-thermal design procedure
- The evaluation of the FE model of the adopted structure was performed through experimental validation of a prototype machine
- Experimental results are in good agreement with the simulated ones