Relationship between Rotor Losses and Size of Permanent Magnet Machines

N.Bianchi, D.Durello, A.Fasolo

alessandro.fasolo@studenti.unipd.it

UNIVERSITÀ DEGLI STUDI DI PADOVA

EDLab

Electrical Engineering Department

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N.Bianchi, D.Durello, A.Fasolo

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AIM OF THE WORK

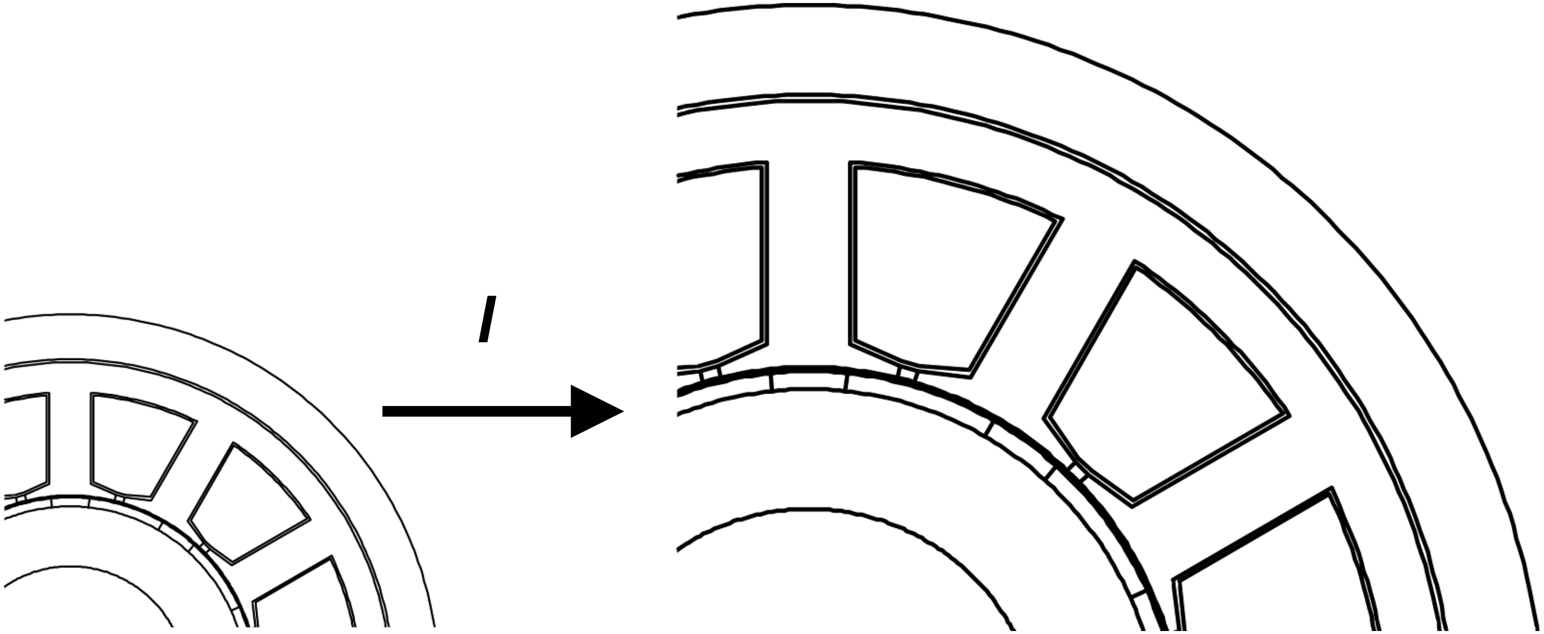
Studying the impact of the size of PM machines on rotor losses

At first all geometric lengths of a PM machine are increased through a linear scaling law for given number of slots and poles

Then two other different machine geometries are compared rearranging the number of slot and poles but keeping the same ratio between themselves

AIM OF THE WORK

Scaling factor *l*



SUMMARY

- INTRODUCTION ON ROTOR LOSSES

- ANALYTICAL RELATIONSHIP

- FINITE ELEMENT ANALYSIS OF A PM MACHINE WITH VARIOUS SIZE

- FINITE ELEMENT ANALYSIS OF A PM MACHINE INCREASING THE NUMBER OF SLOTS AND POLES

- THERMAL EFFECT OF ROTOR LOSSES FOR DIAGNOSTIC PURPOSE

- CONCLUSIONS

INTRODUCTION

Permanent Magnets (PMs) are more and more employed in rotating machines to replace the field excitation

They allow to build a more compact brushless rotor, also characterized by several poles, suitable for low speed direct drive applications

In addition fractional-slot winding are also employed to save material in windings

INTRODUCTION

However the Magnet Motion Force (MMF) of these windings causes space harmonics in the airgap of the machine

The MMF harmonics move asynchronously with respect to the rotor inducing currents in any conductive rotor parts employed in the rotor

INTRODUCTION

In the diagnostic of electrical machines the working temperature are crucial parameters. They are related to the efficiency of the cooling systems and to the losses in stator and rotor

The rotor losses are extremely difficult to be measured, especially in PM fractional slot winding machine, and so it is very important to predict them

ANALYTICAL RELATIONSHIP-STATOR

$$\text{lenghts} \propto l$$

$$\text{surfaces} \propto l^2$$

$$\text{volumes} \propto l^3$$

For a given stator current density:
-the current in the stator slots increases as *l^2*
-the electric loading as *l*

ANALYTICAL RELATIONSHIP-ROTOR

Applying the Ampere's law, the flux density B in the air gap results to be proportionally to *I*, and the magnetic vector potential A, whose curl is B, is proportionally to *I*²

$$J_r = -\sigma \frac{\partial A}{\partial t}$$

ANALYTICAL RELATIONSHIP-ROTOR

Fixing the operating frequency, the induced current density is proportional to *I*².
The losses in the rotor volume due to such induced currents are given by:

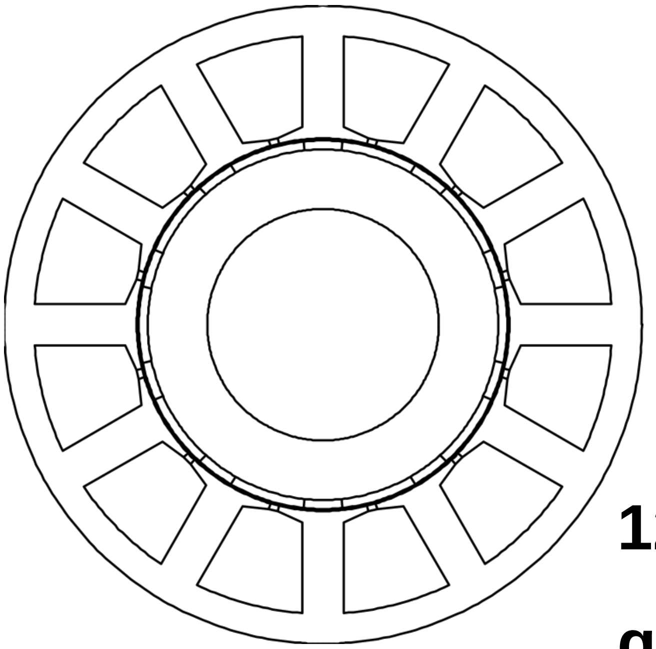
$$P_{rl} = \int \frac{J_r^2}{\sigma} dVol$$

ANALYTICAL RELATIONSHIP-ROTOR

Since the volume increases as l^3 and the current density induced in the rotor Jr as l^2, then the rotor losses result to be :

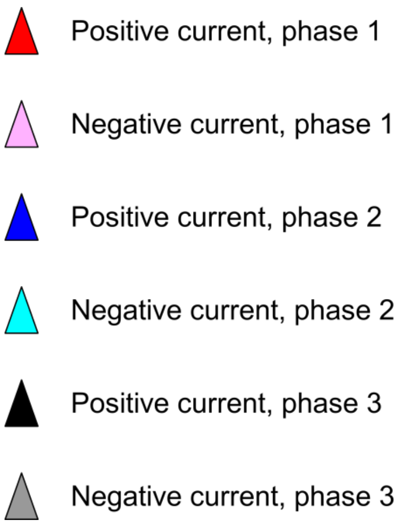
$$P_{r\,l,v} \propto l^7$$

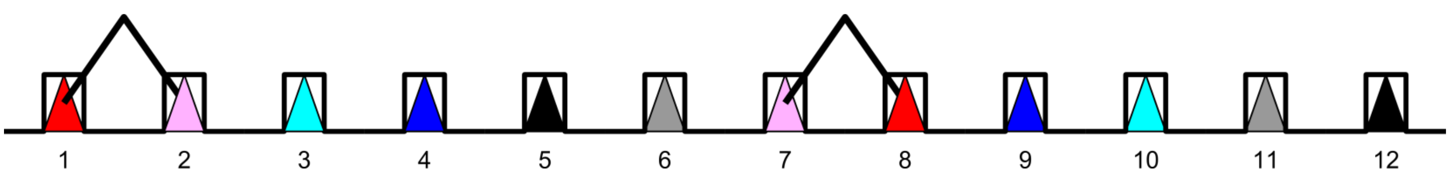
BASIS MACHINE IN THIS STUDY



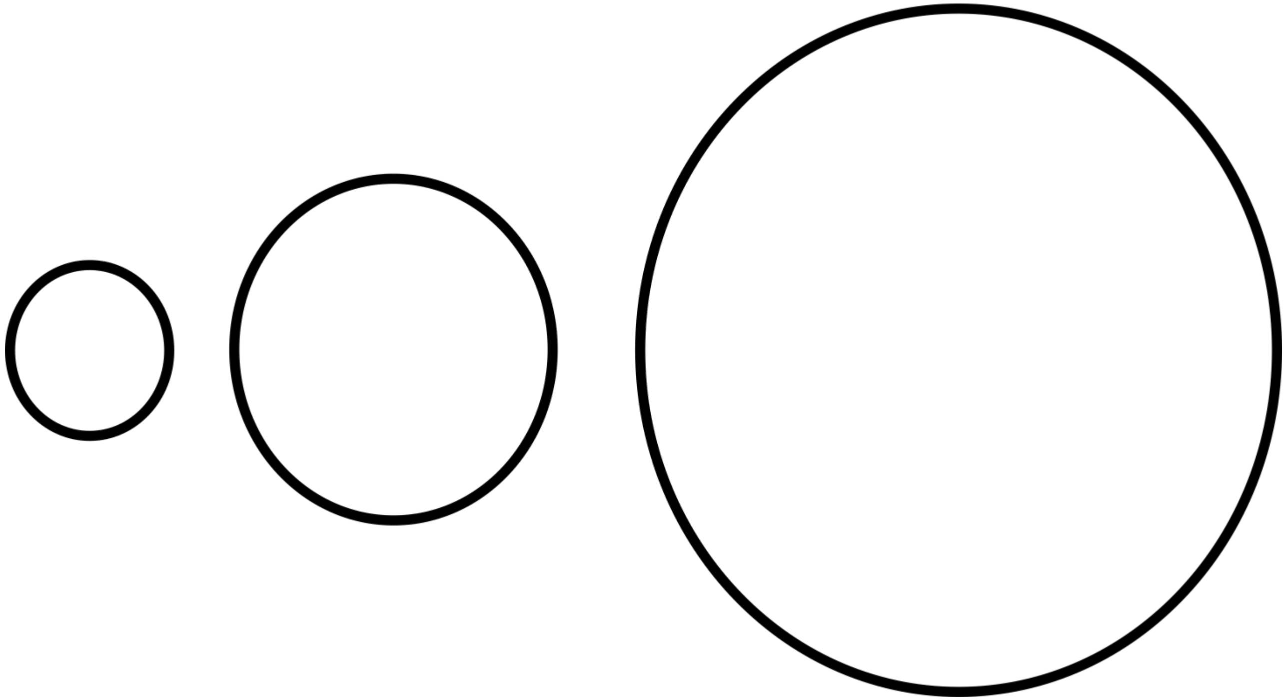
12\10

q = 0.4





MACHINES IN THIS STUDY

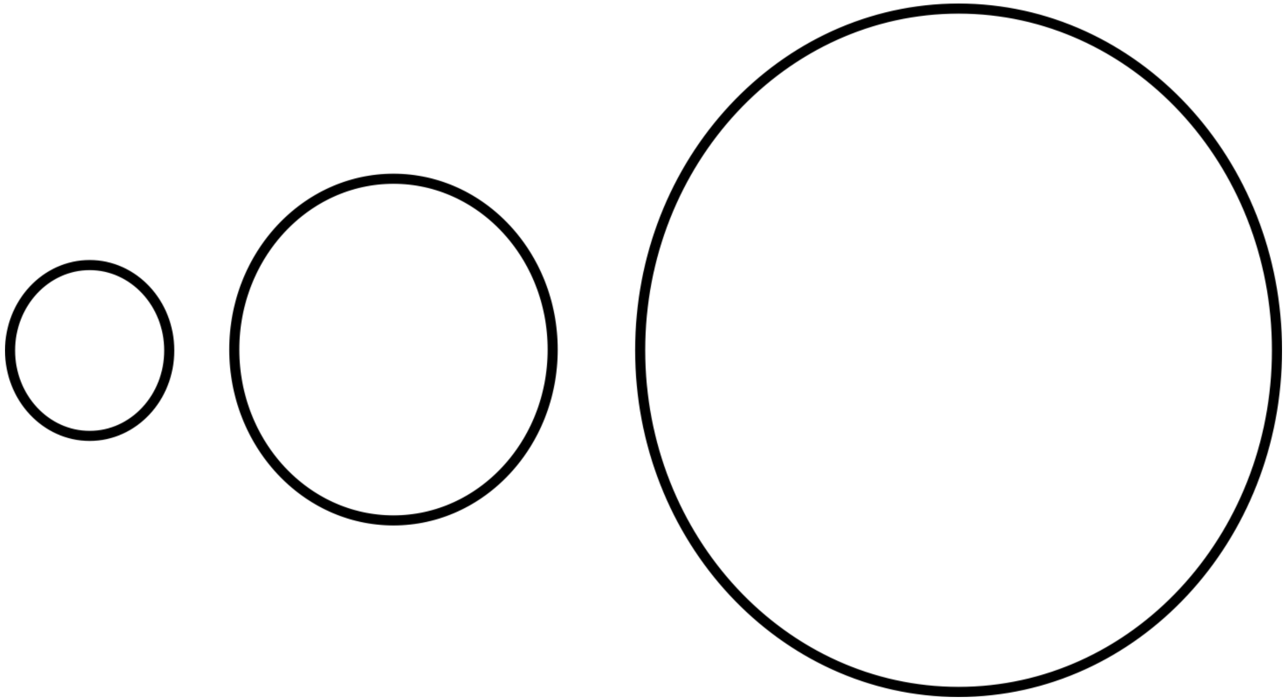


A-125 mm
12/10

B-500 mm
12/10

C-2000 mm
12/10

MACHINES IN THIS STUDY



A’-125 mm
12/10

B’-500 mm
48/40

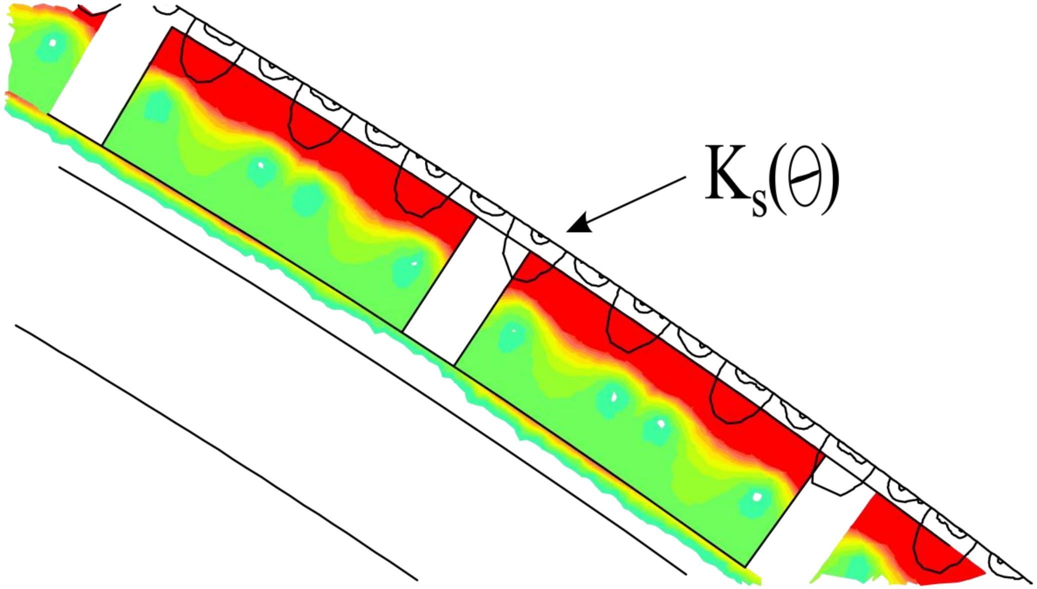
C’-2000 mm
96/80

FINITE ELEMENT BASED ANALYSIS

Machine	Diameter D (mm)	Length L (mm)	gap g (mm)	Slots Q	poles 2p
A	125	100	1	12	10
B	500	400	4	12	10
C	2000	1600	16	12	10
A=A’	125	100	1	12	10
B’	500	100	1	48	40
C’	2000	200	2	96	80

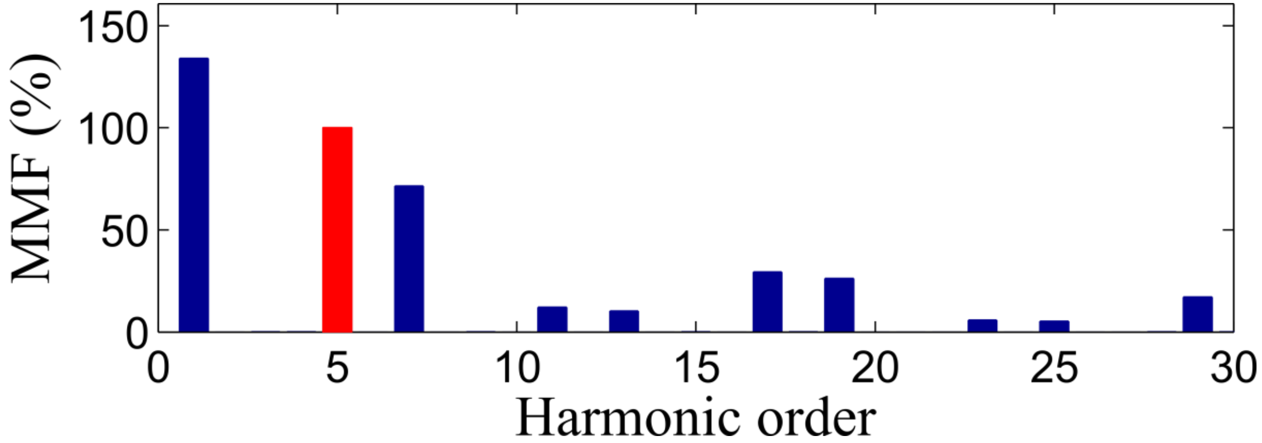
Finite elements models have been realized to evaluate the impact of size, electrical loading, airgap and machine periodicity

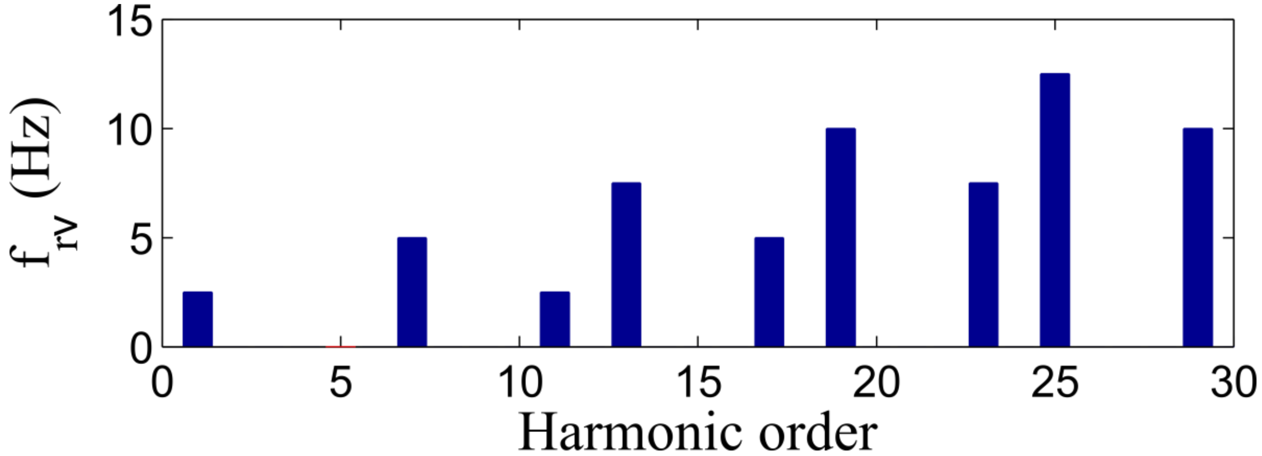
FINITE ELEMENT BASED ANALYSIS



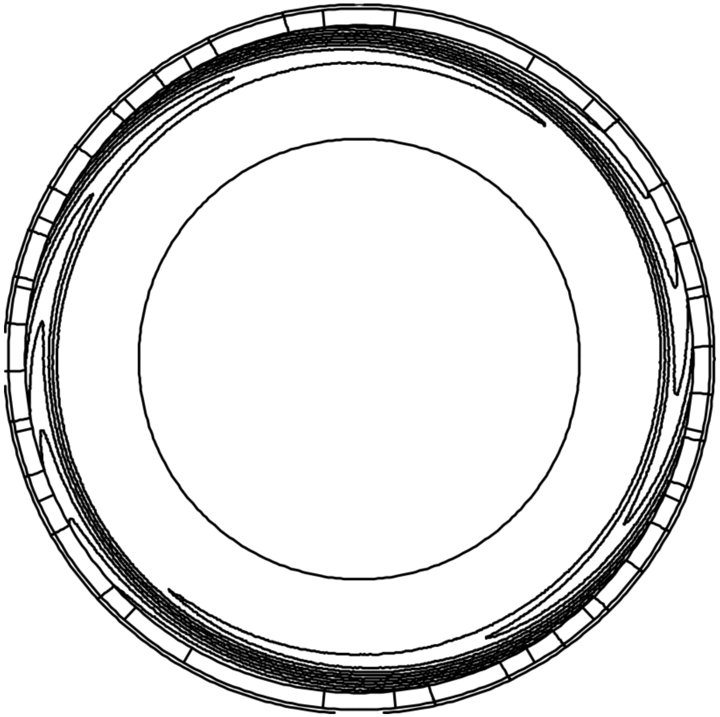
$$K_{s,v}(\theta) = \hat{K}_{s,v} \cdot \sin(v\theta + \omega_v t)$$

MMF HARMONICS AMPLITUDE AND FREQUENCY



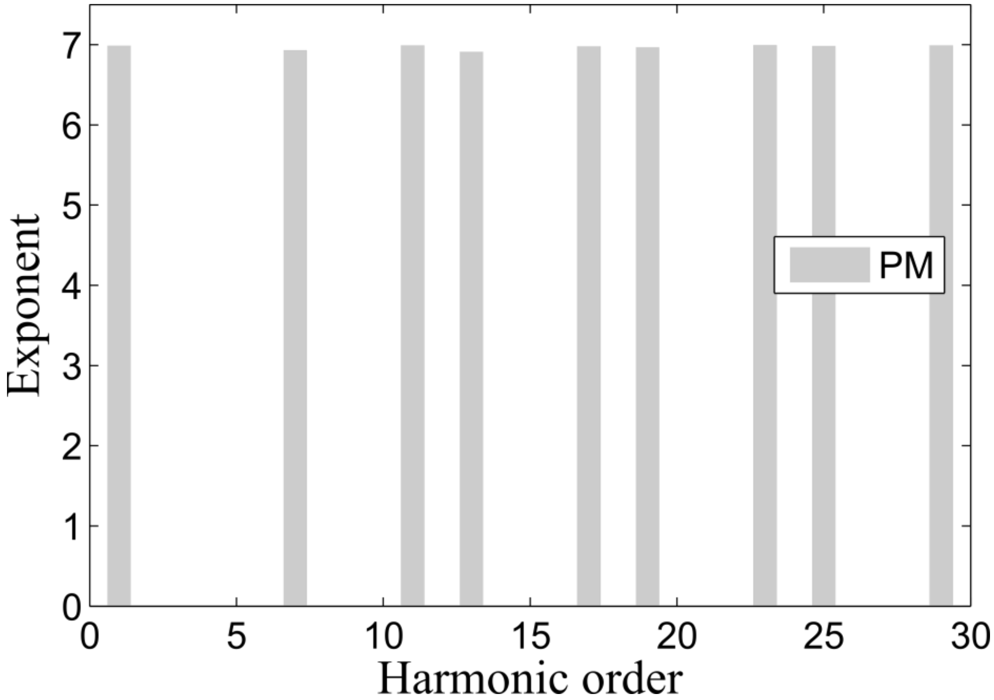


FINITE ELEMENT BASED ANALYSIS



Field lines-subharmonic

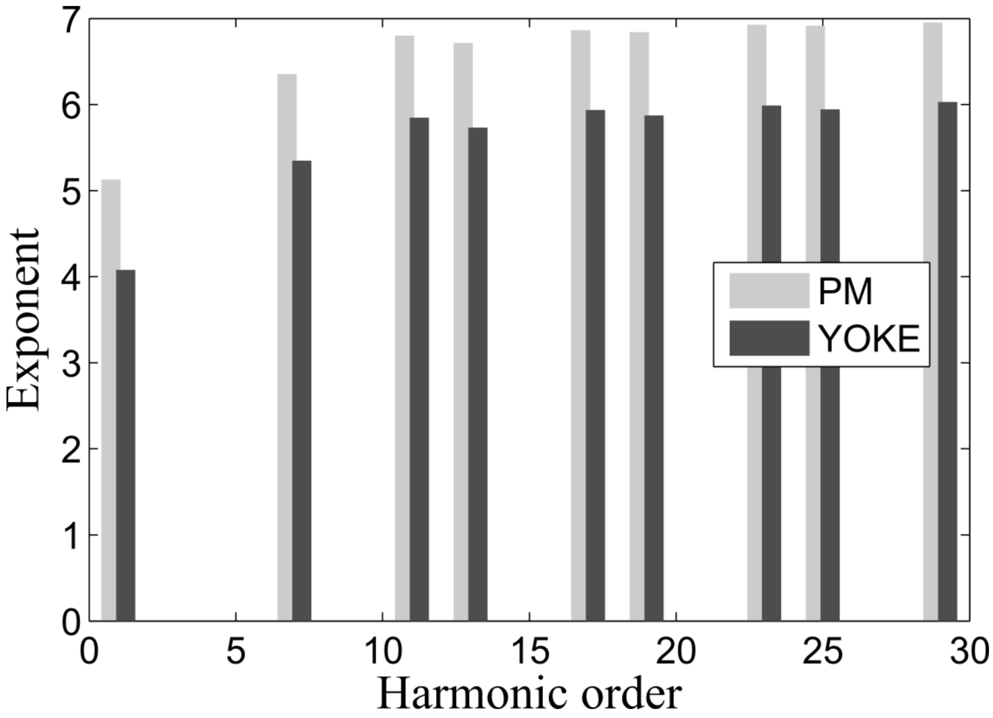
RESULTS WITH LAMINATION-LINEARITY AND FIXED FREQUENCY



$$P_{r\,l,v} \propto I^7$$

Rotor losses behave in agreement with the analytical prediction

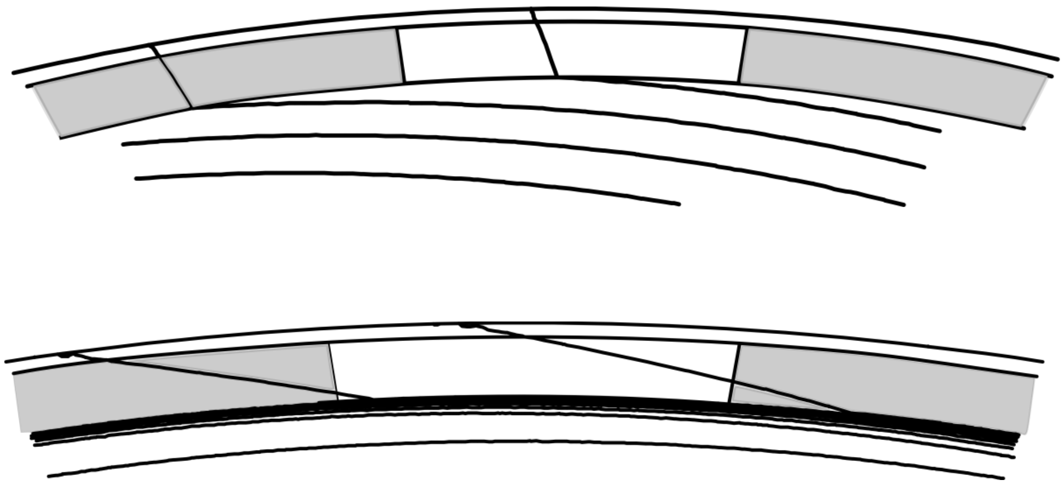
RESULTS WITH SOLID IRON-LINEARITY AND FIXED FREQUENCY



$$P_{r\,I,\nu} \propto I^7$$

For higher harmonics in magnets but not in iron yoke

RESULTS WITH SOLID-LINEARITY AND FIXED FREQUENCY



Reaction due to eddy currents refers to the subharmonic

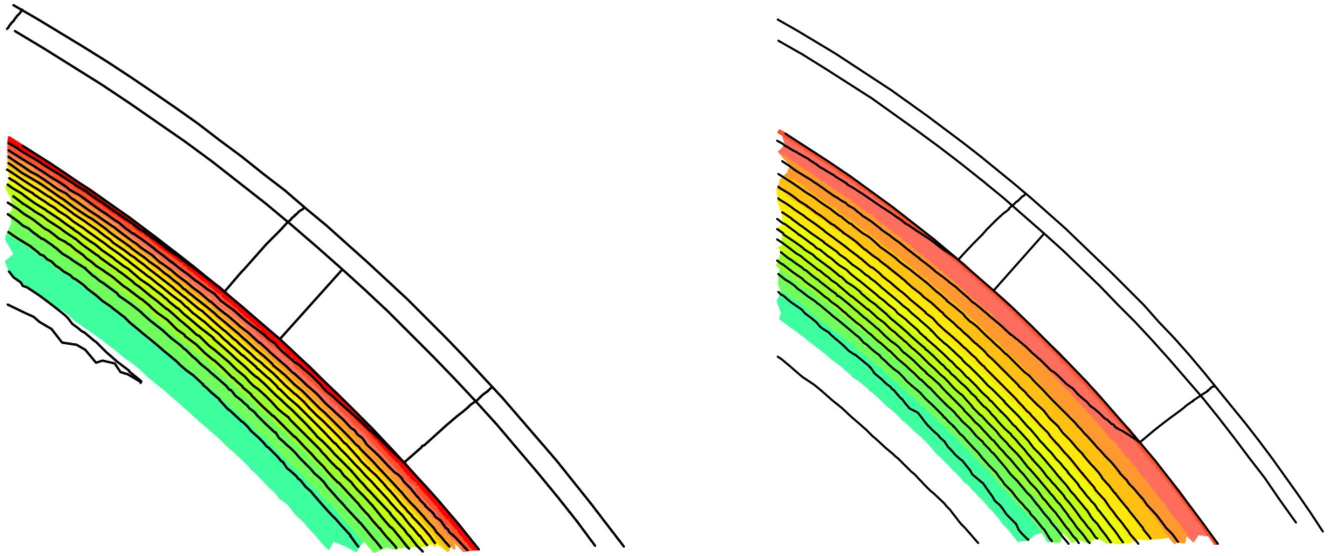
RESULTS WITH SOLID IRON-LINEARITY AND FIXED FREQUENCY

$$\delta = \sqrt{\frac{1}{\pi f \sigma \mu}}$$

$$P_{r\,l,v} \propto I^6$$

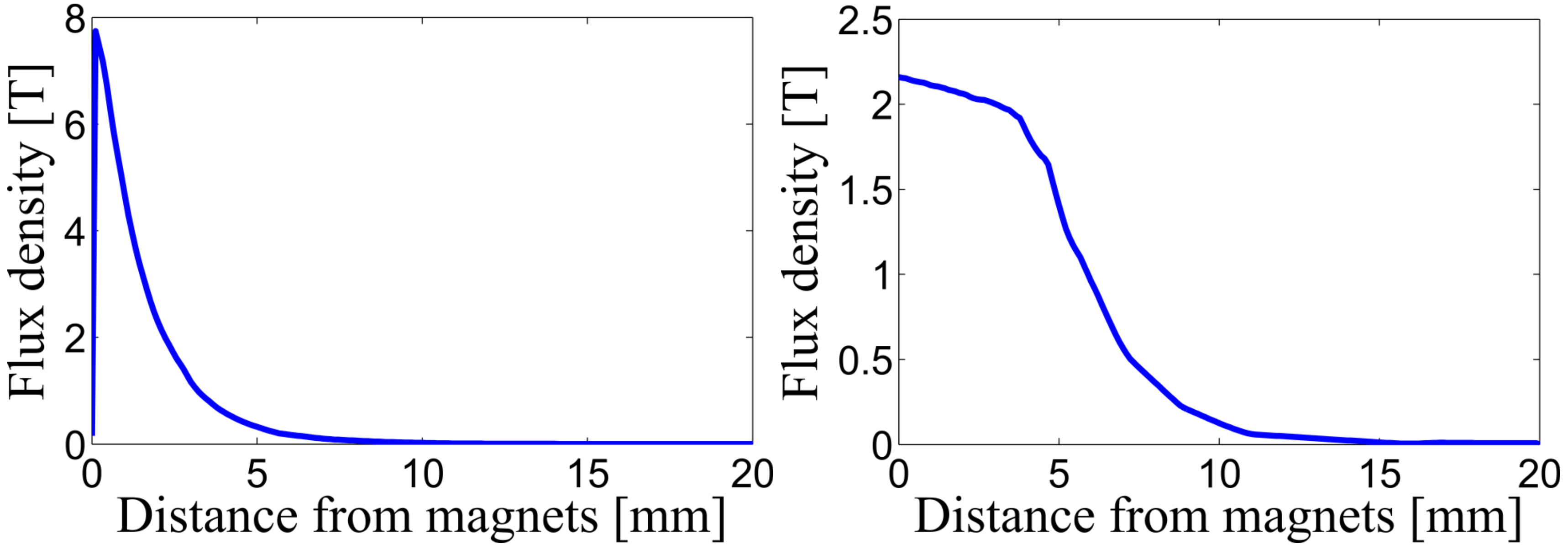
In iron yoke due to skin depth effect

RESULTS WITH SOLID IRON-SATURATION EFFECT



Skin depth in rotor yoke increases due to the saturation in iron

RESULTS WITH SOLID IRON-SATURATION EFFECT



SUBHARMONIC-SATURATION EFFECT

Electric Loading (A/m)	Iron relative permeability	PM loss (W)	iron loss (W)
78 000	$\mu_r = 5000$	0.5	186.4
78 000	$\mu_r = 150$	0.2	376.0
78 000	$\mu_r(B)$	0.2	450.6
30 000	$\mu_r = 5000$	0.1	28.3
30 000	$\mu_r = 150$	0.03	57.0
30 000	$\mu_r(B)$	0.1	58.9
3 000	$\mu_r = 5000$	0	0.3
3 000	$\mu_r = 150$	0	0.6
3 000	$\mu_r(B)$	0	0.3

EFFECT OF THE MACHINE PERIODICITY

The size of the machine increases and the number of slots and poles it is rearranged correspondingly

Typically, when the diameter increases, the number of slots increases as well.
It is reasonable that a large size machine rotates slower, and thus the number of poles increases with the machine size

FINITE ELEMENT BASED ANALYSIS

Machine	Diameter D (mm)	Length L (mm)	gap g (mm)	Slots Q	poles 2p
A	125	100	1	12	10
B	500	400	4	12	10
C	2000	1600	16	12	10
A=A’	125	100	1	12	10
B’	500	100	1	48	40
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Finite elements models have been realized to evaluate the impact of size, electrical loading, airgap and machine periodicity

COMPARISON BETWEEN MACHINES A' AND B'

Machine B' is obtained from machine A' multiplying the machine periodicity by four, that is the same ratio between the inner diameter

If the two machine work at the same frequency the rotor losses increase proportionally to the machine periodicity as confirmed by the results

Machine	PM losses (W)	Back iron losses (W)
A′	1.2	191.7
B′	5.3	815.6

COMPARISON BETWEEN MACHINES A', B' AND C'

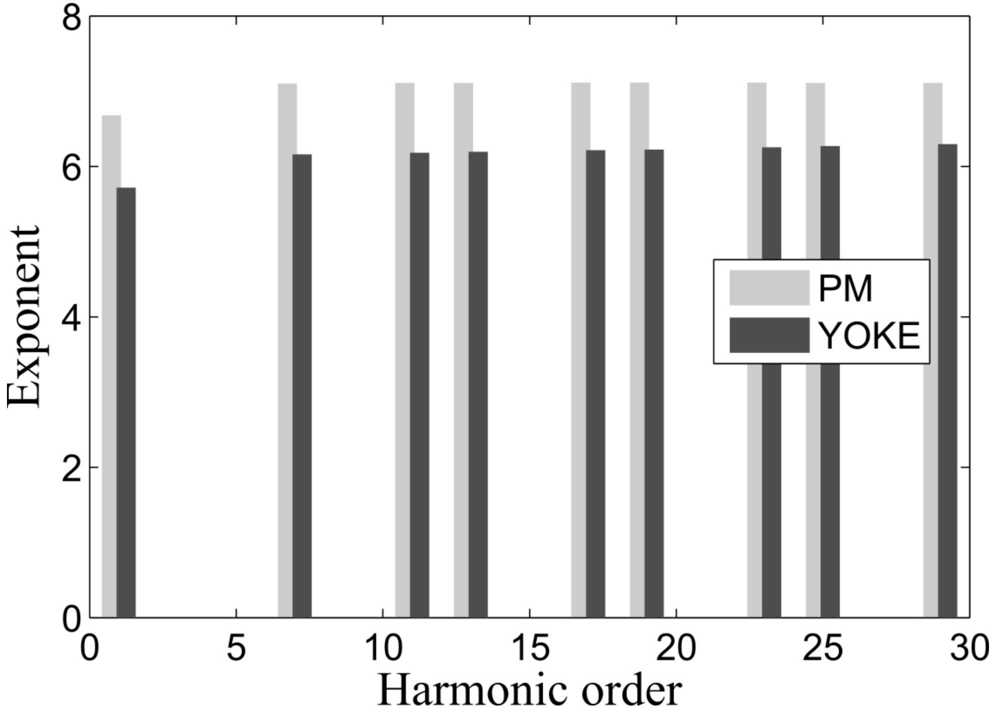
The machine C' has been designed to have the same flux density of the two previous configurations

However while the ratio between the diameters of the machine B' and C' is four, the number of slots and poles is only twofold so the geometrical dimensions are doubled (i.e. *l*=2)

Therefore it is expected that the increase of rotor losses is:

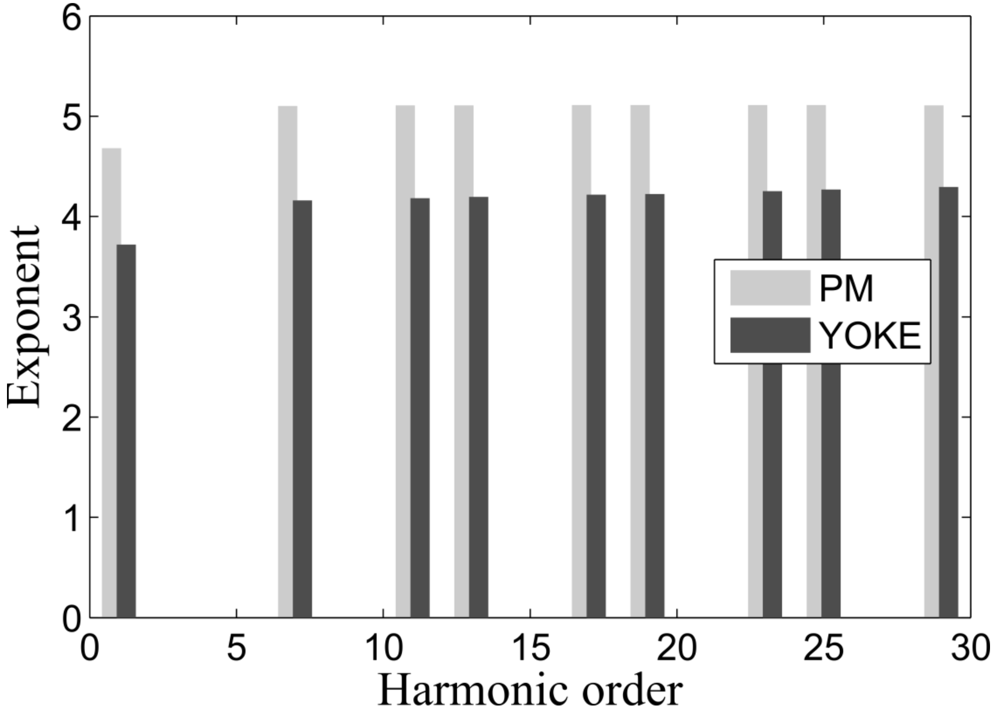
$$P_{r\,l,v} \propto t^{*}l^{7}$$

COMPARISON BETWEEN MACHINES A’ AND C’



Comparison between the machine labeled A’ and 1/8th of the machine labeled C’

LOSSES FOR GIVEN ELECTRICAL LOADING



$$P_{r\,l,v} \propto I^5$$

Due to the increasing of the size of the machine

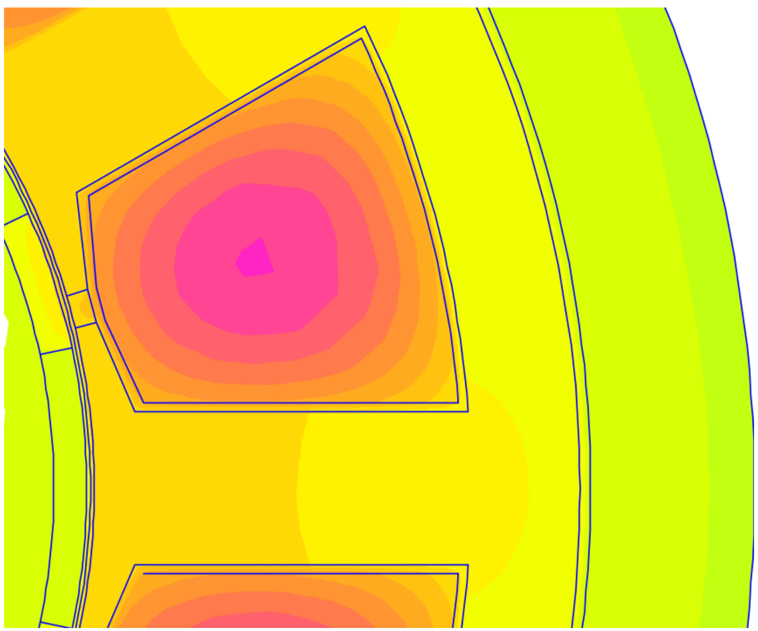
AIRGAP THICKNESS IMPACT

The air gap thickness has a high impact in the rotor losses determination

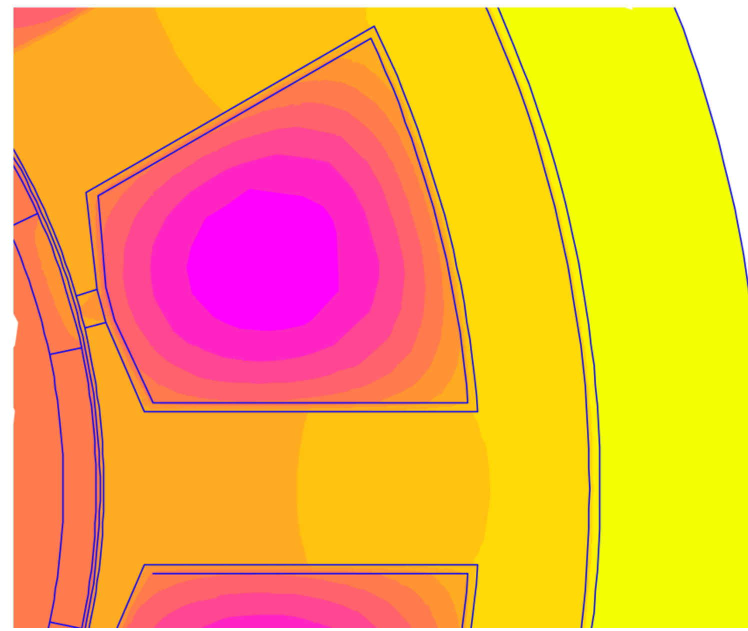
**The increase of the air gap limits the effect of the MMF harmonics, since the corresponding flux density is reduced.
This reduces the eddy currents and the rotor losses consequently**

THERMAL IMPACT OF ROTOR LOSSES

Temperature map



Without rotor losses



With rotor losses

THERMAL IMPACT OF ROTOR LOSSES

	Machine	Temperature of Copper [°C]	Temperature of PMs [°C]
Without Rotor Losses	A'	136	101
With Rotor Losses	A'	142	123
Gap	A'	6	22
Without Rotor Losses	C'	110	69
With Rotor Losses	C'	138	168
Gap	C'	28	99

CONCLUSION

The rotor losses cause the raise of the predicted working temperature

They tend to increase dramatically with the PM machine size

If a simple linear scaling law is applied, the increase of the rotor losses results to be:

$$P_{rl,v} \propto l^7$$

CONCLUSION

In order to limit such rotor losses in large size machine, it is imperative that the machine periodicity is increased

Further strategies are to decrease the surface current density…

…and to increase the air gap thickness when the machine size increases

ED LAB REFERENCE PAPERS:

[3] N. Bianchi, M. Dai Prè, L. Alberti, and E. Fornasiero, Theory and Design of Fractional-Slot PM Machines, Sponsored by the IEEE-IAS Electrical Machines Commitee, Ed. Padova: CLEUP (ISBN 978-88-6129-122-5), 2007.

[6] N. Bianchi and E. Fornasiero, "Impact of MMF Space Harmonic on Rotor Losses in Fractional-slot Permanent-magnet Machines," IEEE Transactions on Energy Conversion, vol. 24, no. 2, pp. 323–328, Jun. 2009.

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Thank you
for your attention

N.Bianchi, D.Durello, A.Fasolo

alessandro.fasolo@studenti.unipd.it

Electrical Engineering Department