Computational Assessment of Eddy Currents in Rotating Machines

Philippe Wendling
philippe.wendling@magsoft-flux.com

Create, Design, Engineer!

adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

1

Disclaimers

The materials for this presentation were developed by the application teams of the Groupe Cedrat, at Cedrat SA and Magsoft Corporation.

The topologies used for the examples are drawn from real devices, they are only representative of the real devices.

adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

2

Introduction

Evaluation of eddy currents in:

- permanent magnets - radial field machines,
- airgap sleeves on rotor – radial field machines,
- coil conductors – axial field machines.

Why? Eddy currents may:

- alter the torque,
- affect the efficiency,
- generate heat.

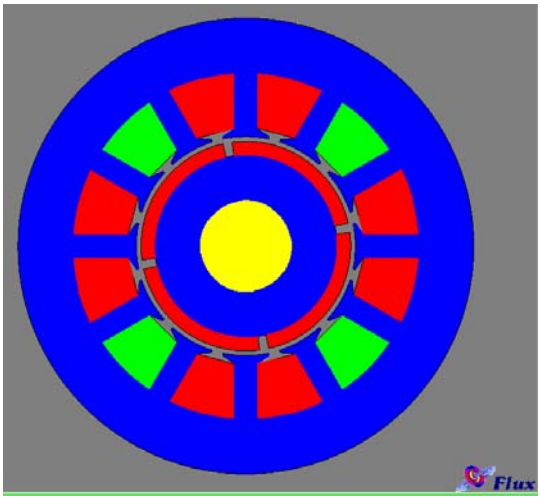
adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

3

Permanent Magnet - Radial

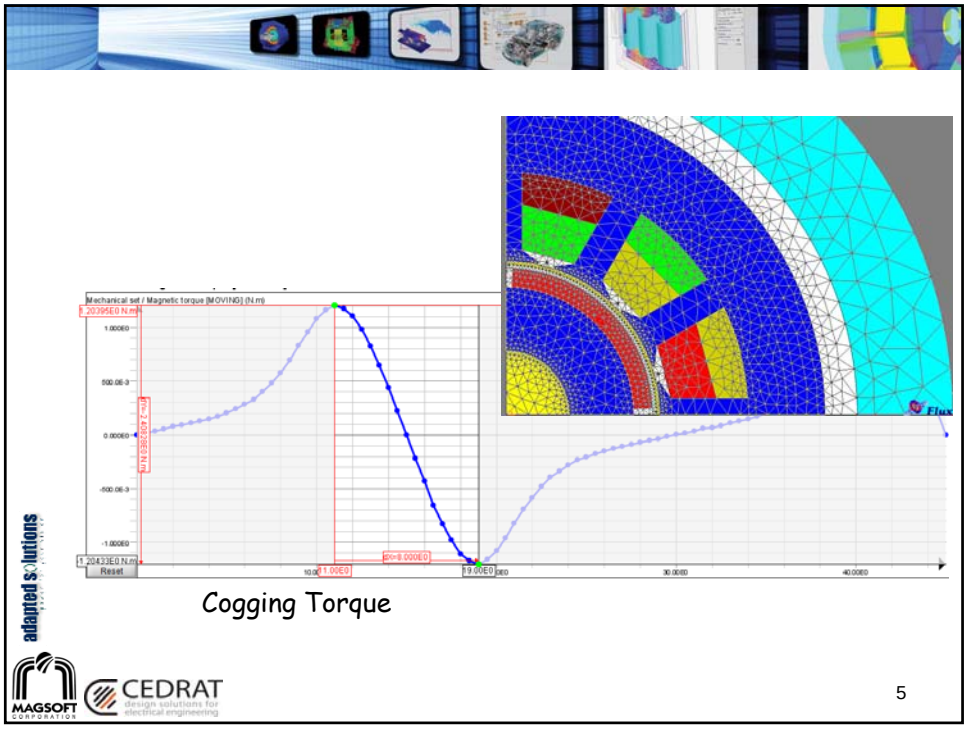
4 poles
12 slots
1 mm airgap
23 mm rotor radius
radial surface magnet
NDFE30
Br= 1.21
Mu= 1.0446
Rho= 1.6e-5 Ohm.m



adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

4



Cogging Torque

adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

5

Eddy currents from motion only

The magnet is conductor, and set in open circuit

- the currents must close back inside the magnet,
- total current in magnet is none.

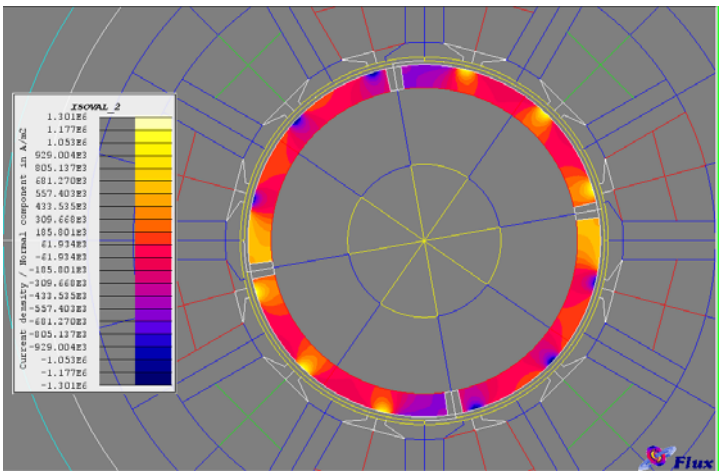
The rotor is set in motion

- no current input – only effect of slotting
- 5 speeds:
  - 500
  - 1000
  - 2500
  - 5000
  - 7500

adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

6

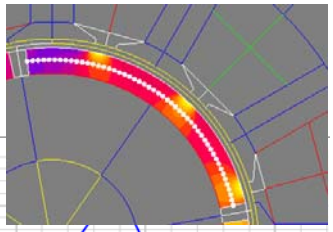


Eddy currents distribution – 7500 rpm

adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

7



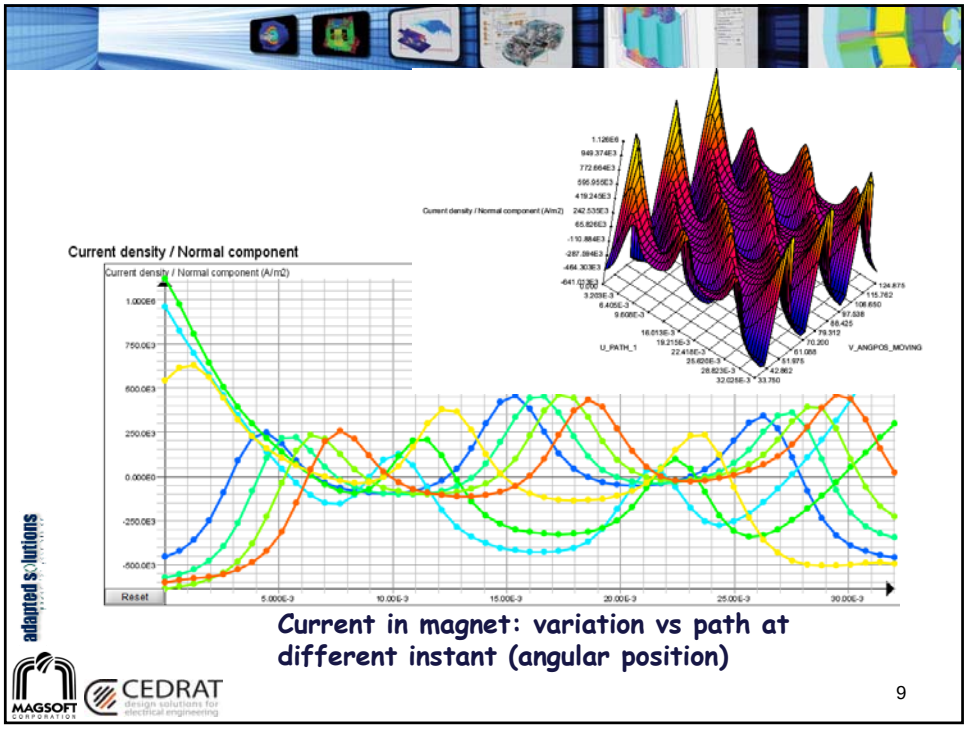
Current vs path – in permanent magnet

Total current through magnet: 4e-13 Amps

adapted solutions

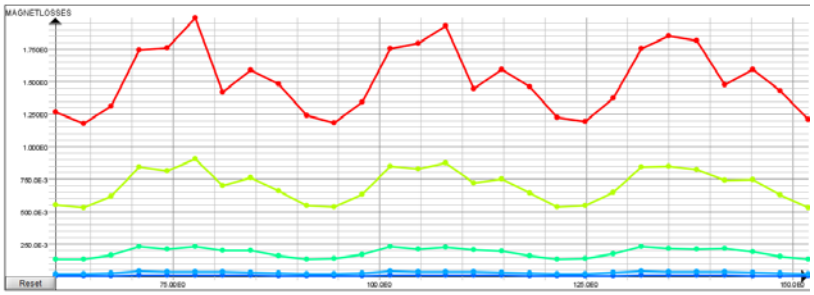
MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

8



Current in magnet: variation vs path at different instant (angular position)

9



Instantaneous losses in magnet over 180 electrical degrees motion of rotor (vs. speed)

Losses:

7,500 rpm – 6.04 W

5,000 rpm – 2.82 W

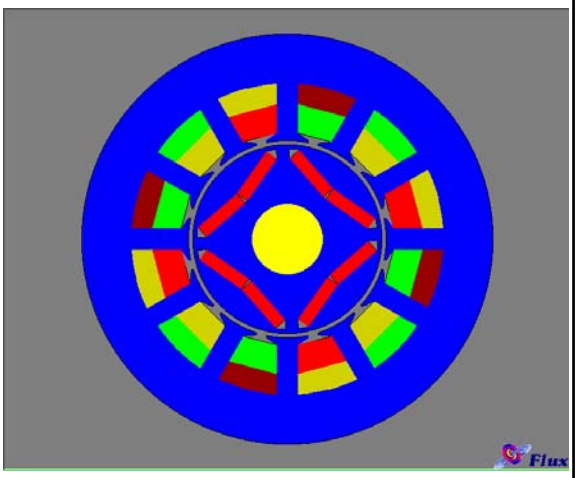
2,500 rpm – 0.75 W

These losses are about 10% of the copper losses (at 5,000 rpm: 1kW output, 22 W copper losses, 2,82 W magnet losses)

10

Permanent Magnet (IPM)- Radial

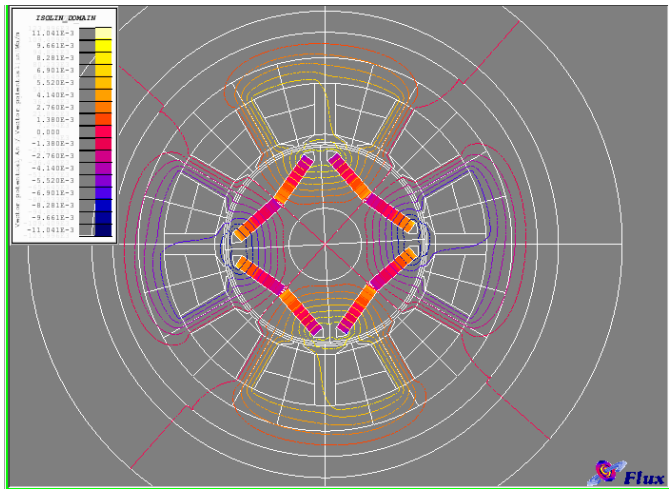
4 poles
12 slots
1 mm airgap
23 mm rotor radius
radial surface magnet
NDFE30
Br= 1.21
Mu= 1.0446
Rho= 1.6e-5 Ohm.m



adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

11

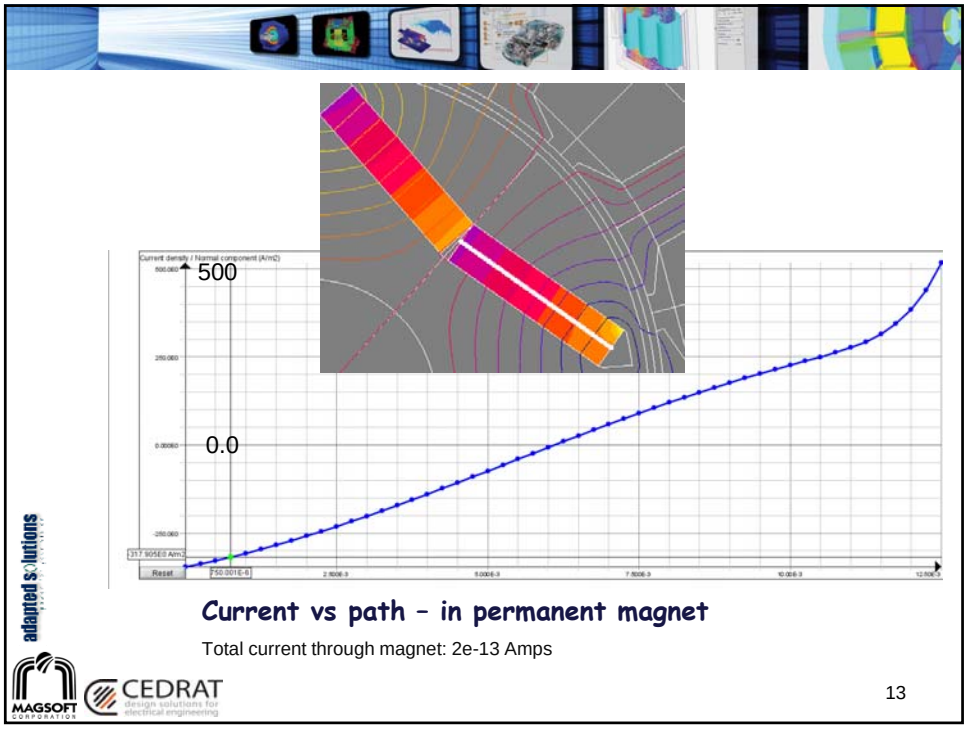


Eddy currents distribution and flux lines – 7500 rpm

adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

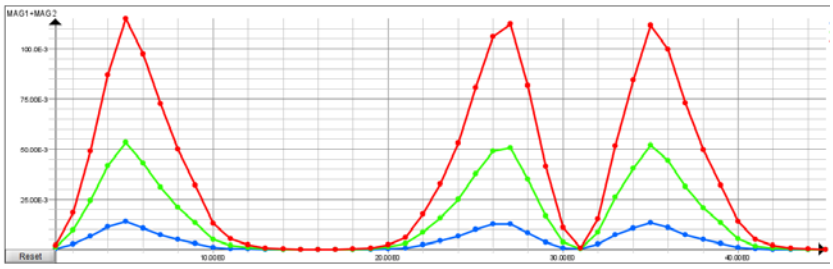
12



Current vs path – in permanent magnet

Total current through magnet: 2e-13 Amps

13



Instantaneous losses in magnet over 180 electrical degrees motion of rotor (vs. speed)

Losses:

7,500 rpm – 0.15 W

5,000 rpm – 0.07 W

2,500 rpm – 0.02 W

These losses are less than .5 % of the copper losses,

14

Eddy currents from motion and pwm current

The magnet is conductor, and set in open circuit:

- the currents must close back inside the magnet,
- total current in magnet is none.

The rotor is set in motion:

- coils are current fed,
- currents are the one generated by the power supply,
- speed is 8,000 rpm.

The topology used is the surface magnet.

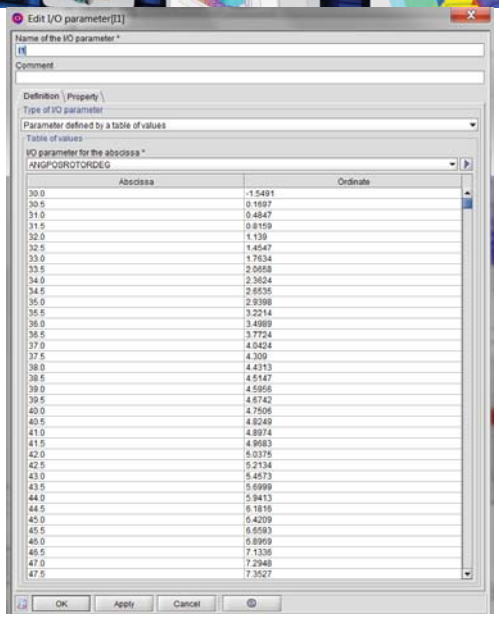
Same materials.

adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

15

current table
current vs. angle
(mechanical angle)
imported from
text file



adapted solutions

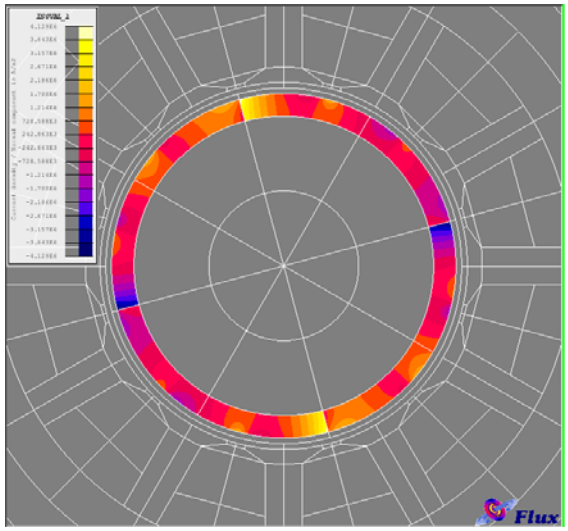
MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

16

Input currents for three phases – 8,000 rpm

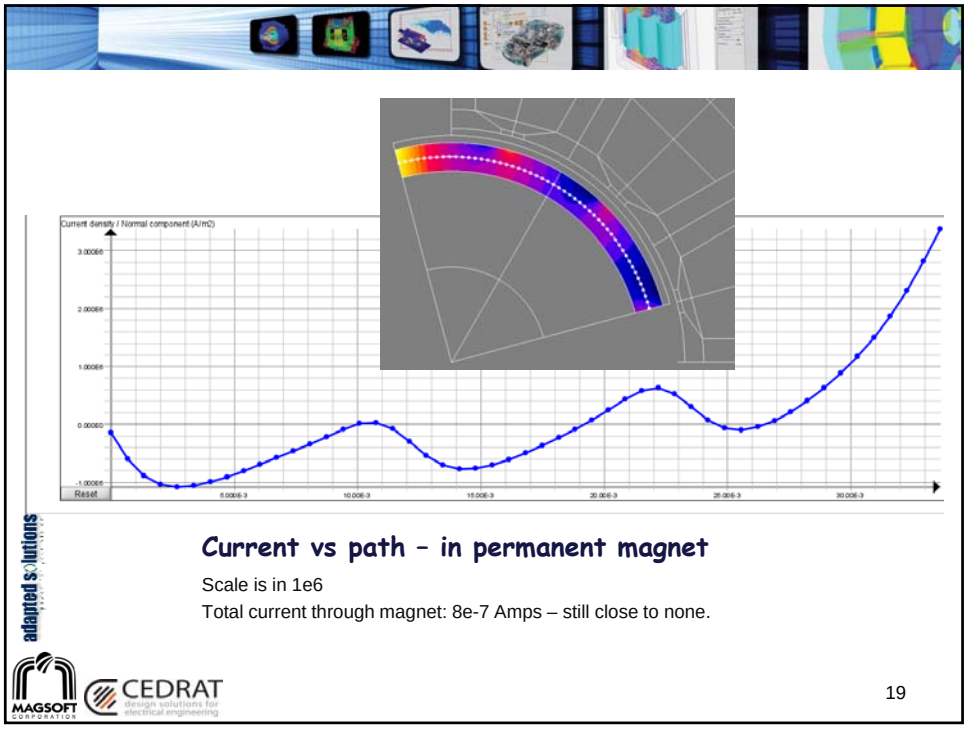
Note the high content in harmonics
Irms = 10 Amps

17



Eddy currents distribution – 8,000 rpm

18



adapted solutions

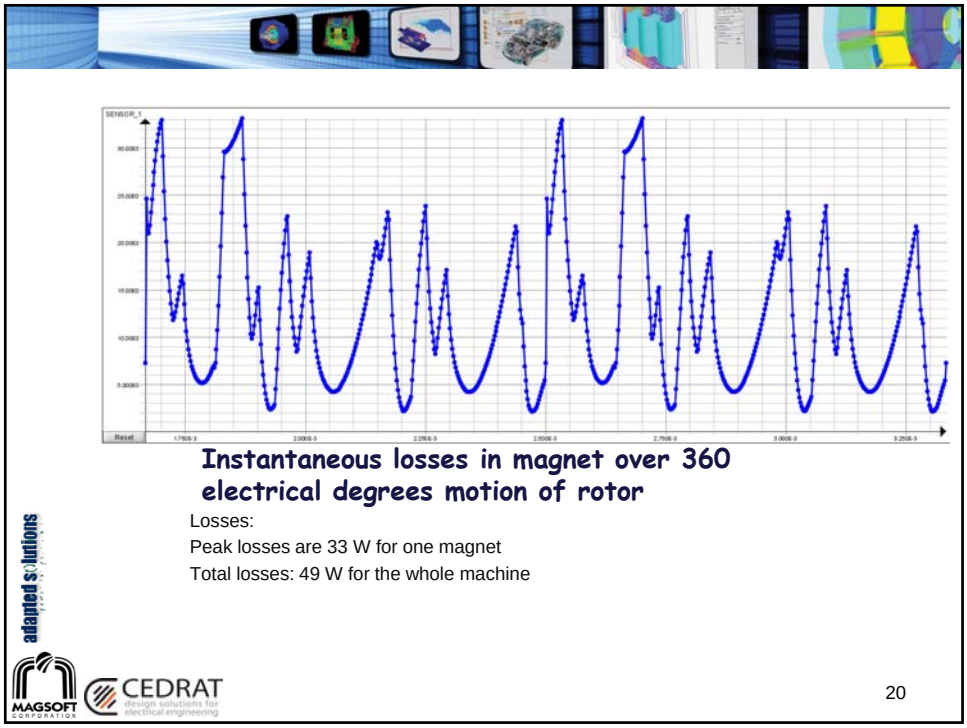
Current vs path – in permanent magnet

Scale is in 1e6

Total current through magnet: 8e-7 Amps – still close to none.

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

19



adapted solutions

Instantaneous losses in magnet over 360 electrical degrees motion of rotor

Losses:

Peak losses are 33 W for one magnet

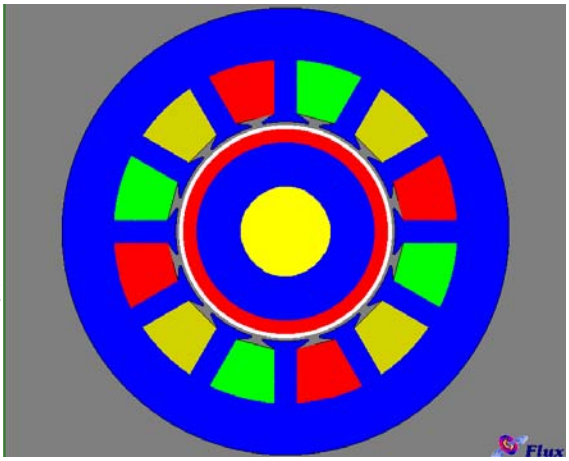
Total losses: 49 W for the whole machine

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

20

Airgap Sleeves on Rotor/Magnets

4 poles
12 slots
1.5 mm airgap
.75 mm can
Rho= 2.93e-8 Ohm.m
23 mm rotor radius
radial surface magnet
Ferrite
Br= 0.4
Mu= 1.0



adapted solutions
MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

21

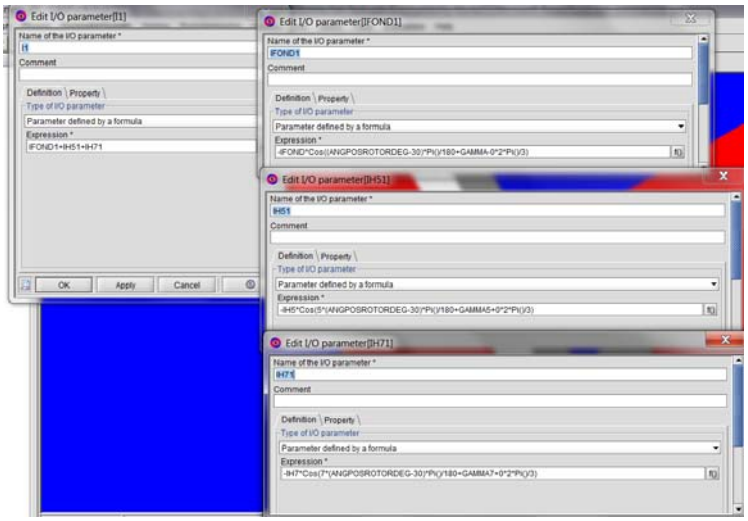
Eddy currents from motion and multi harmonic current

The sleeve is conductor, and set in open circuit
- the currents must close back inside the sleeve,
- total current in the sleeve is none.

The rotor is set in motion
- speed is 18,000 rpm
- coils are current fed
- fundamental, 5^{th} and 7^{th} harmonics are included

adapted solutions
MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

22

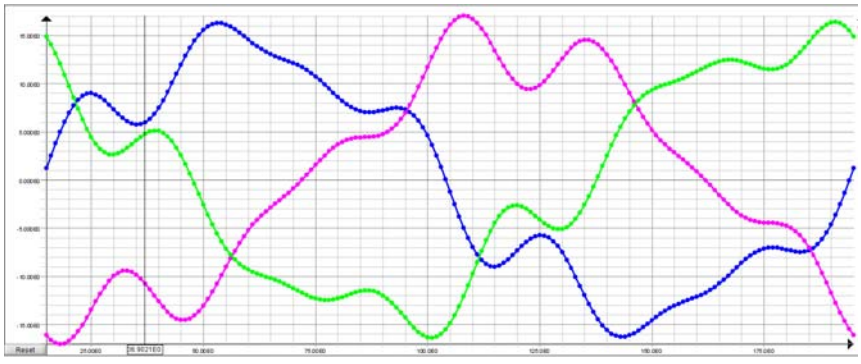


adapted solutions

Current description

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

23



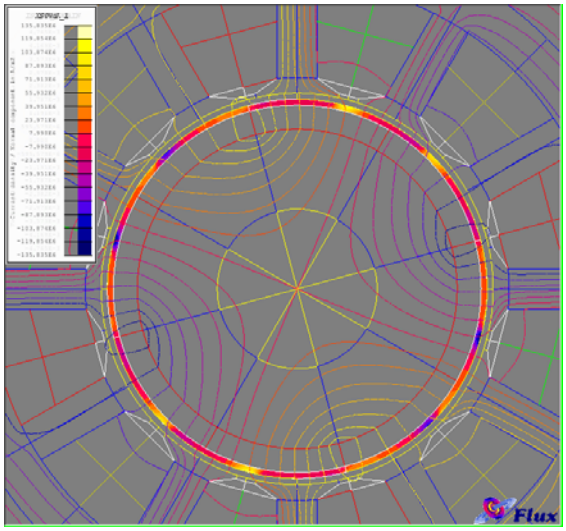
adapted solutions

Input currents for three phases – 18,000 rpm

Note the content in harmonics
Irms = 10 Amps

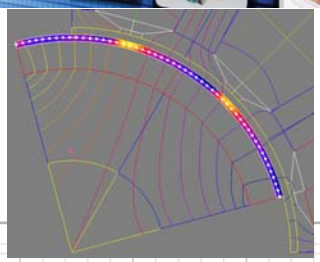
MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

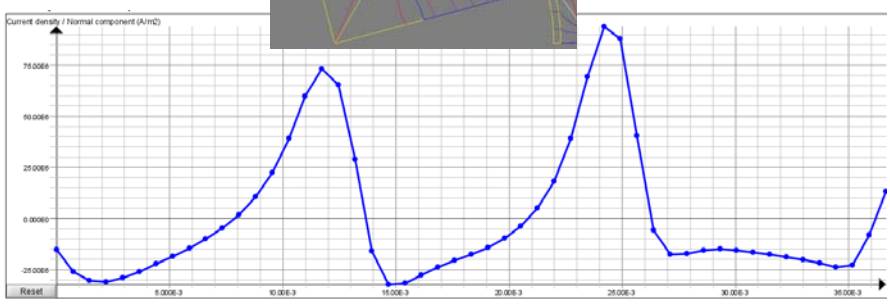
24



Eddy currents distribution in can – 18,000 rpm

25



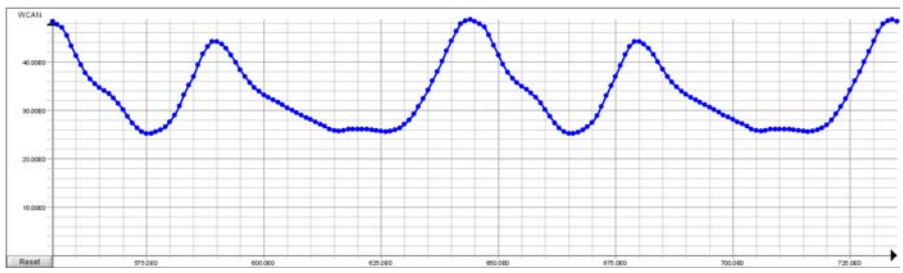


Current vs path – in permanent magnet

Scale is in 25 e6

Total current through magnet: 6e-6 Amps – still close to none.

26



Instantaneous losses in magnet over 360 electrical degrees motion of rotor

Losses:

Peak losses are 49 W for the can

Total losses: 134 W for the whole machine

adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

27

Eddy currents from motion and pwm current

The sleeve is conductor, and set in open circuit

- the currents must close back inside the sleeve,
- total current in the sleeve is none.

The rotor is set in motion

- speed is 18,000 rpm
- coils are current fed
- currents are the one generated by the power supply

adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

28

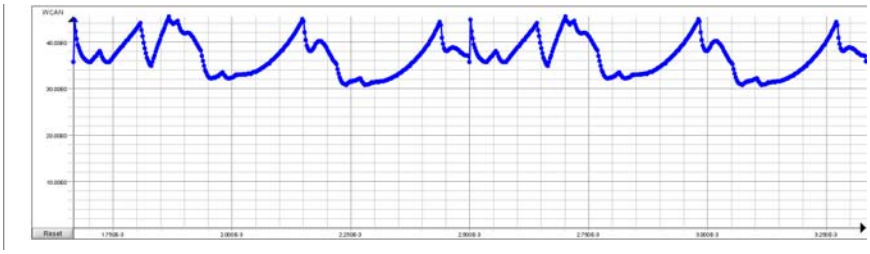
Input currents for three phases – 8,000 rpm

Note the high content in harmonics
Irms = 10 Amps

adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

29



Instantaneous losses in magnet over 360 electrical degrees motion of rotor

Losses:
Peak losses are 45 W for the can
Total losses: 147.56 W for the whole machine

adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

30

Computer Time

The losses is slightly higher than when trying to approximate the current with a formula containing the lower harmonics only (134 W)

721 time samples are needed to capture the harmonics when the current is described by a formula. 25 minutes on a i7 processor

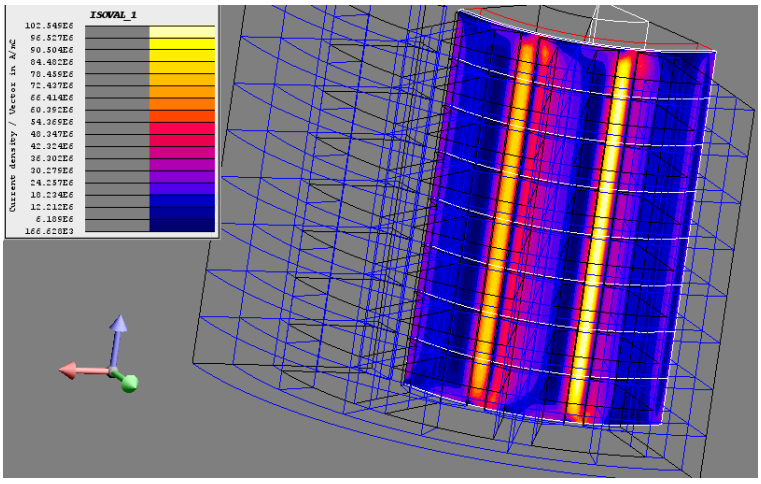
1441 time samples are needed to capture the harmonics when the current is described by the tables 40 minutes on a i7 processor

adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

31

What About 3D



adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

32

The same problem is being treated in 3D

The losses are confirmed at 125.08 W.

The lower number can be explained by the fact that in 2D we are underestimating the resistance in the 3rd dimension

361 time samples were computed in 24 hours on a 64 bit i7 PC with 8GB of RAM

adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

33

Other Machine

Minimization of losses in a PM machine

PM machine, 8 Poles – Coupler

High speed application

Inconel liner in airgap.

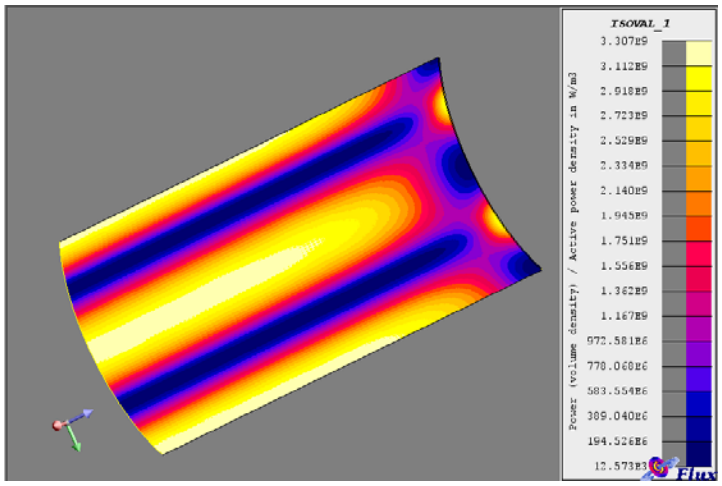
radius 146 mm, 2 mm thick

adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

34

Initial Model



adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

35

Initial Model

Torque = -4069 N.m

Power = 2.55 MW

Losses (computed 1/8th device) = 319.38 kW

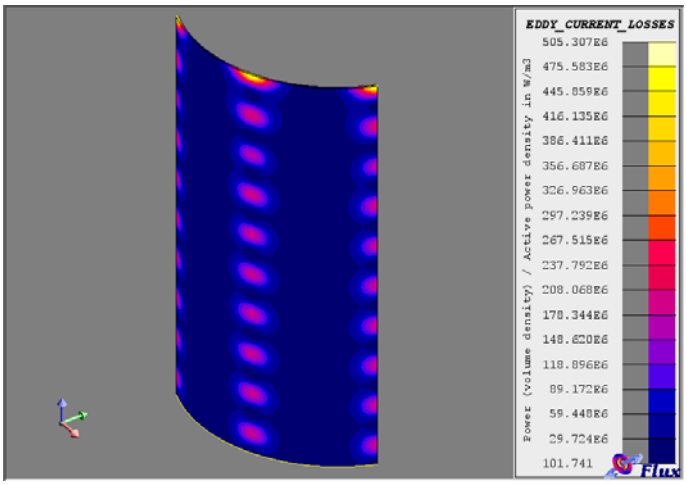
Losses (whole device) = 319.38 x 8 = 2.55 MW

adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

36

Modified Stack Distribution



adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

37

Modified Stack Distribution

Torque = -92.37 N.m

Power = 58.27 kW

Losses (computed 1/8th device) = 7.32 kW

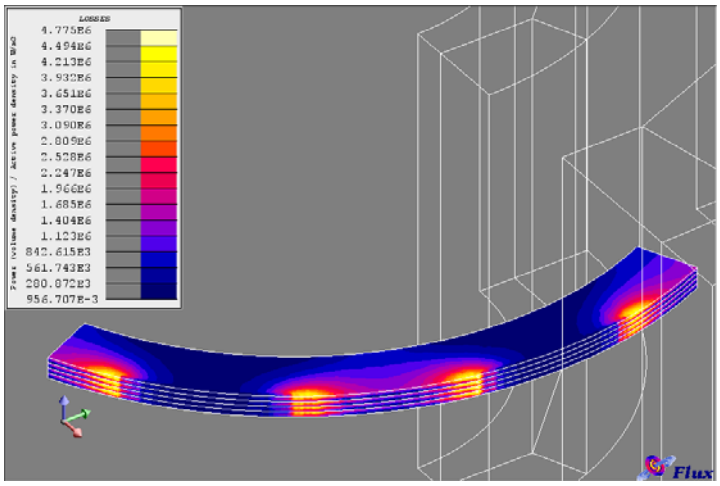
Losses (whole device) = 7.32 x 8 = 58.56 kW

adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

38

Laminated Inconel – Middle of Stack

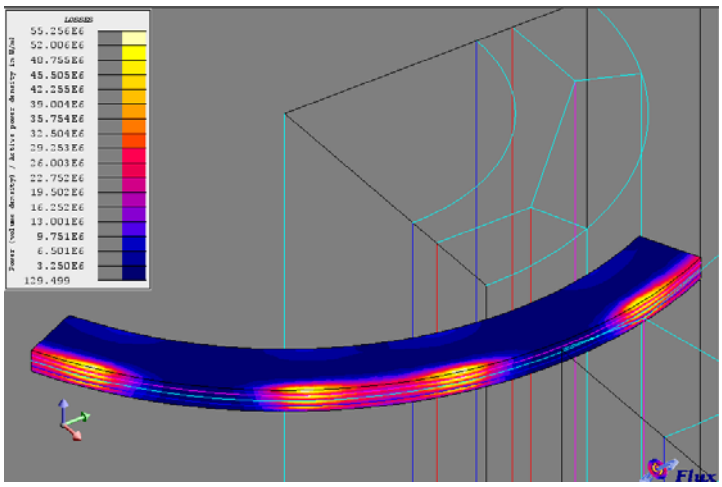


adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

39

Laminated Inconel – End stack

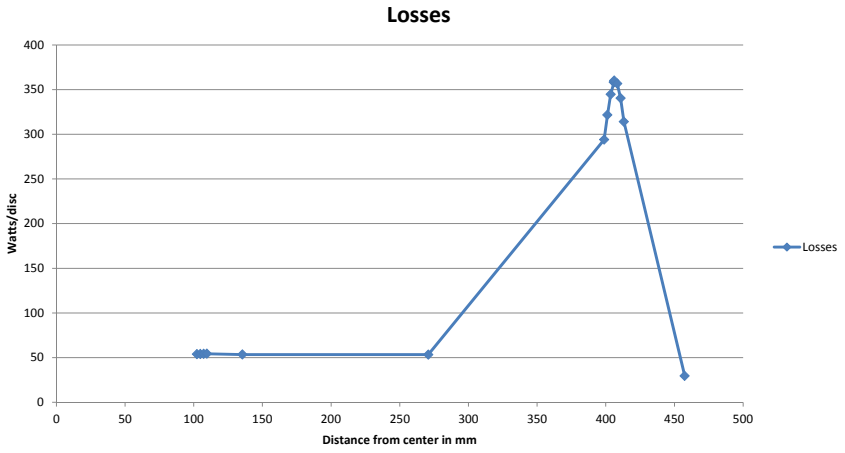


adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

40

Laminated Inconel – Losses vs Position



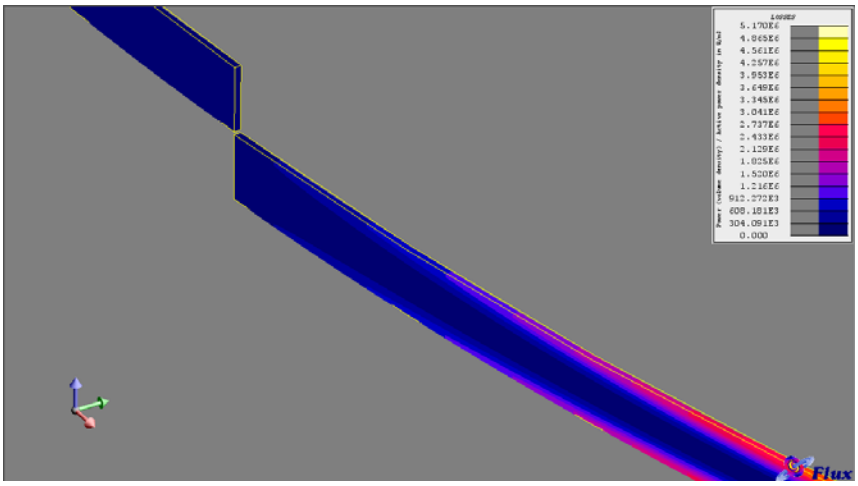
41

Laminated Inconel – Losses vs Position

mm	Watts	
Z	Losses	
102.4	53.92	4 layers inside
104.8	54.04	
107.2	54.2	
109.6	54.36	
135.4	53.424	4 discs
270.8	53.336	
406.2	360.12	
457.5	29.556	
398.8	293.928	4 layers edge 1
401.2	321.536	
403.6	344.768	
406	358.28	
406	358.32	4 layers edge 2
408.4	356.68	
410.8	340.36	
413.2	314	

42

Spiral Sleeve - 1 rev

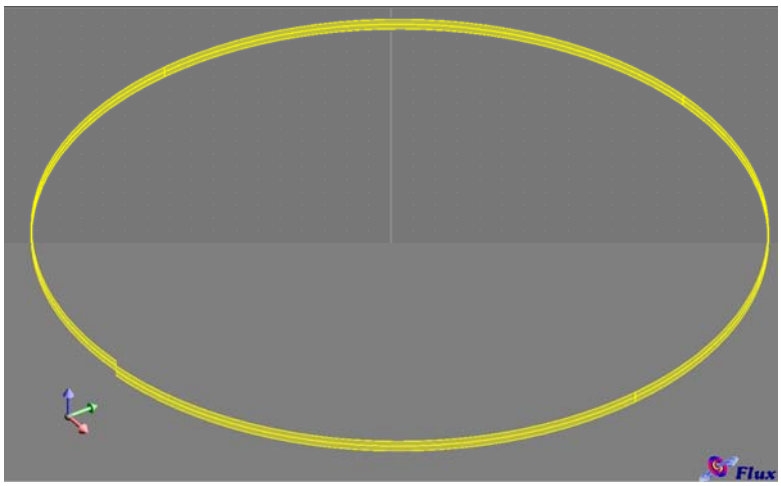


adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

43

Spiral Sleeve - 2 rev

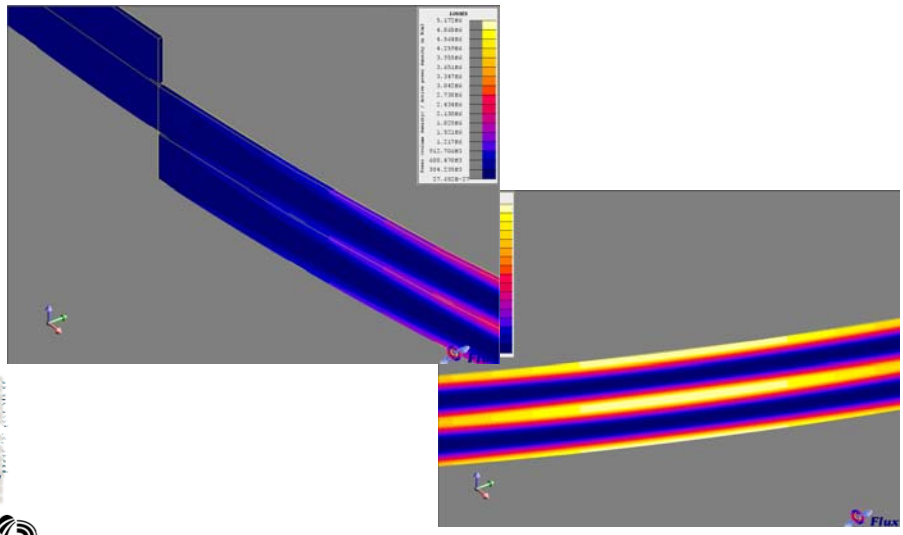


adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

44

Spiral Sleeve - 2 rev



adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

45

Modified Stack Distribution

1 rev. sleeve

- Losses = 0.438 Watts

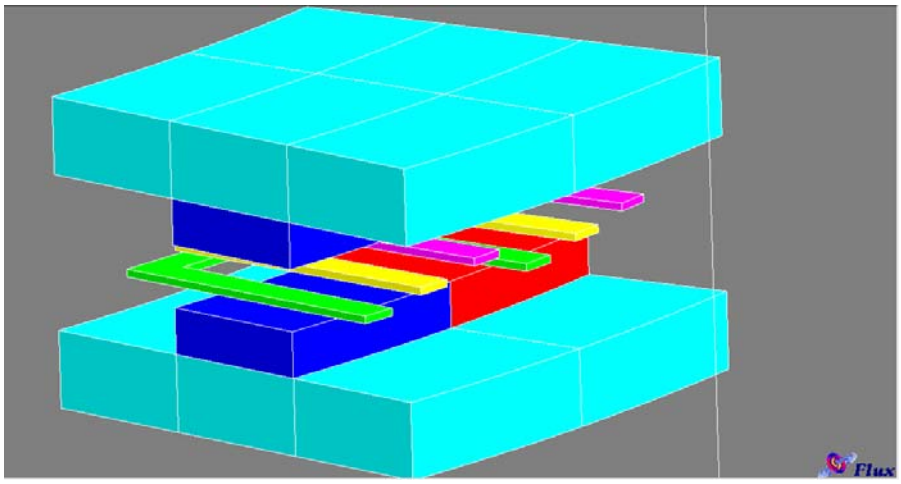
2 rev. sleeve

- Losses = 0.878 Watts

adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

Coil Conductors – Axial Flux Machines



adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

47

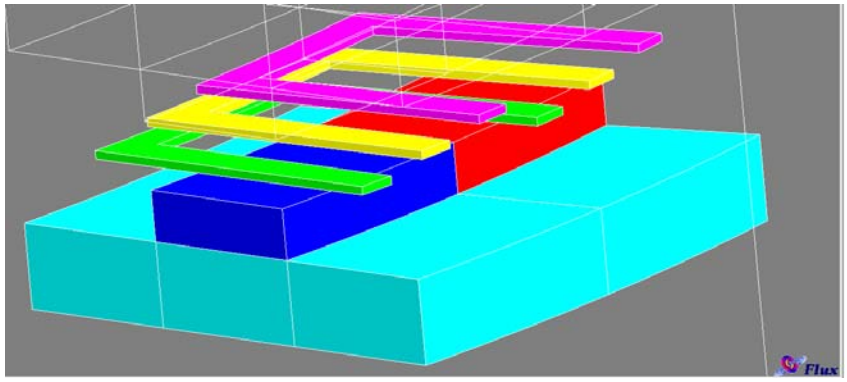
Topology

Two rotors
Airgap winding
3 phases
60 poles
Average radius 140 mm
NDFE30 magnets
Copper coils

adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

48

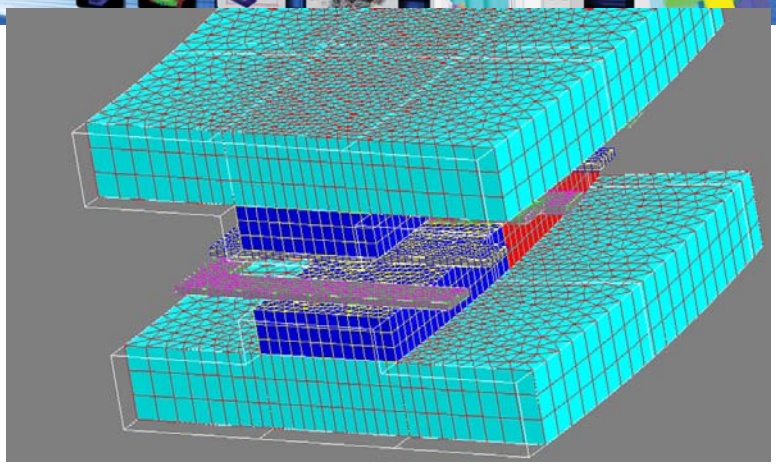


Detail Winding

adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

49



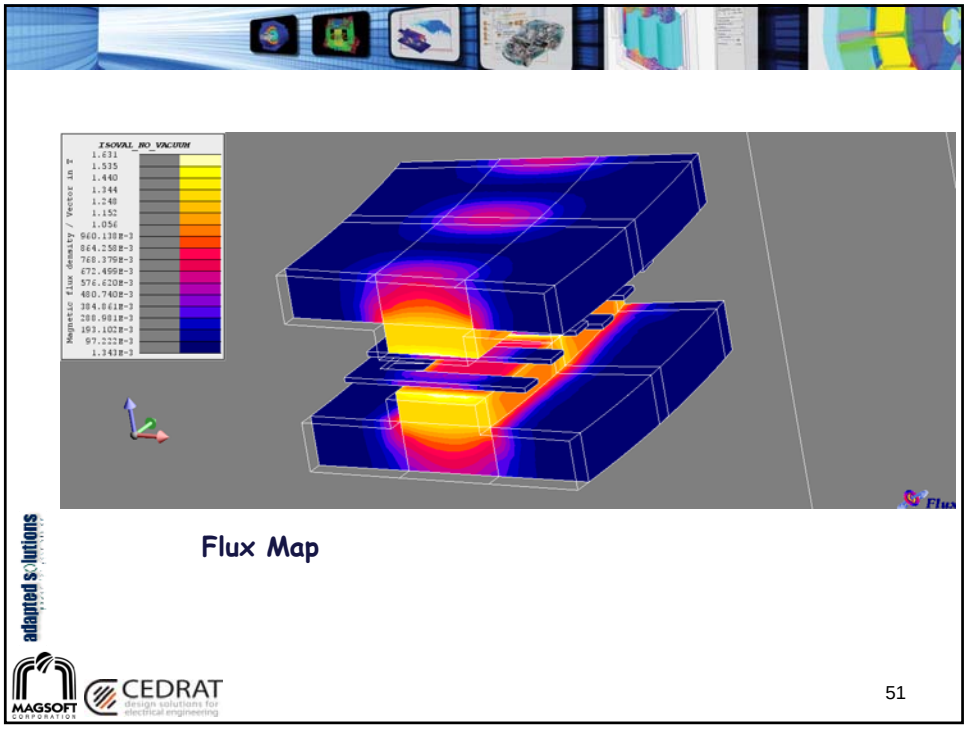
Mesh

47,000 nodes
145,000 1st order elements

adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

50



Flux Map

adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

Eddy currents from motion only

The coils are set in open circuit

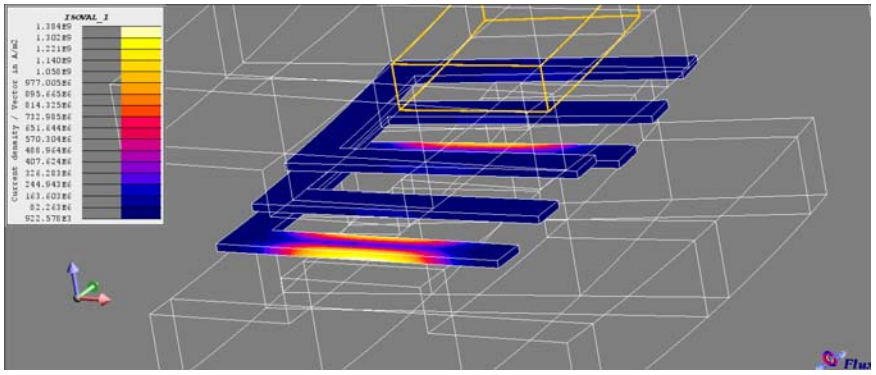
- the currents must close back inside the coils,
- total current across any coil section is none.

The rotor is set in motion

- 5 speeds:
  - 500
  - 1000
  - 2500
  - 5000
  - 7500

adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

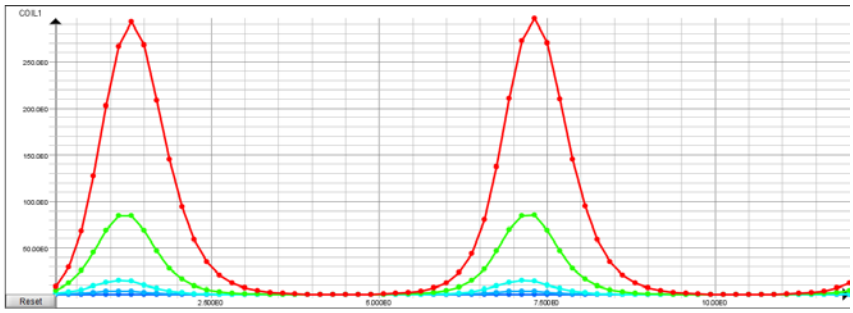


Current Distribution for one position at 5000 rpm

adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

53



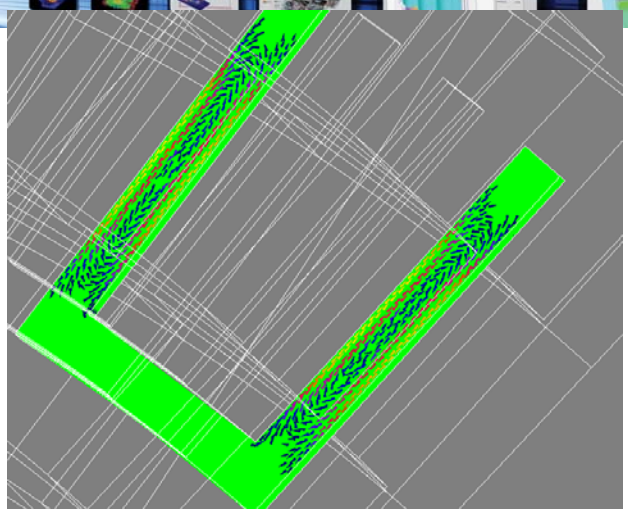
Losses over 360 electrical degrees for different speeds

Peak at 5000 rpm is 396 W

adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

54

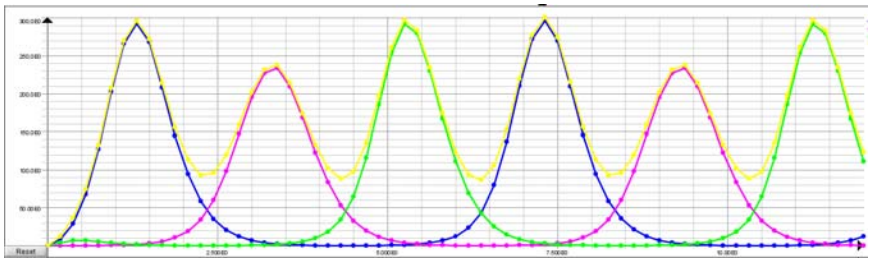


Detail of current flow in one coil at peak current

adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

55



Instantaneous losses in the 3 phases over 2 poles (only two poles included) – 5,000 rpm

Losses:
Peak losses are 300 W for the coils
Total losses: 5,173 W for the whole machine
Total losses at 1,000 rpm: 237 W
65 time samples computed in 22 minutes.

adapted solutions

MAGSOFT CORPORATION CEDRAT design solutions for electrical engineering

56

Conclusion

Eddy currents don't have to remain a mystery
Computers are going faster
Codes are able to take advantage of multicore
Computation where performed on Flux Version 10.4
Flux connects to Matlab Simulink and Portunus
Flux is a component of Isight (SIMULIA)
GOT-It completes Flux with an integrated optimizer.

adapted solutions

MAGSOFT CORPORATION

CEDRAT design solutions for electrical engineering

57