Axial Flux Permanent Magnet Machine with Novel Flat Winding Made of Conductor Sheet

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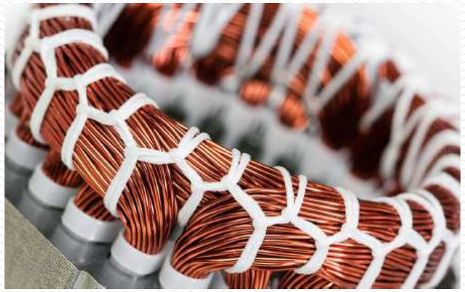
September 2020

METU POWER LAB

Outline

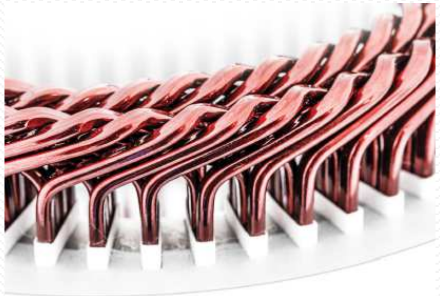
Existing Winding Topologies

Conventional stranded round wires



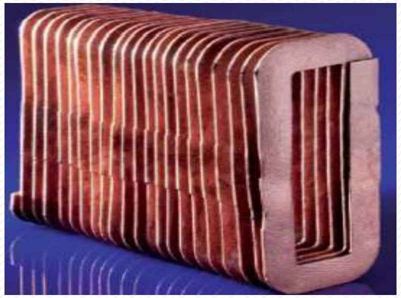
[1]

Hairpin winding



[2]

Cast produced winding



[3]

PCB winding

Merits	▪ Low eddy current loss	▪ Fill factor ▪ Superior current	▪ Easy to manufacture	▪ Easy to manufacture
Challenges	▪ Limited current density (5-6 A/mm^2) ▪ Low current rating ▪ Manufacturing	▪ Eddy current loss ▪ High cost ▪ Manufacturing	▪ Eddy current loss ▪ High cost	▪ High cost ▪ Low current ratings ▪ Low power

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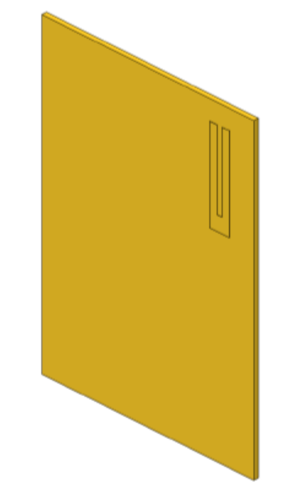
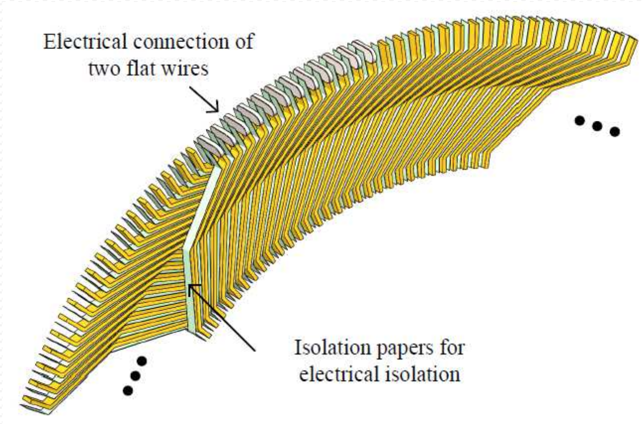
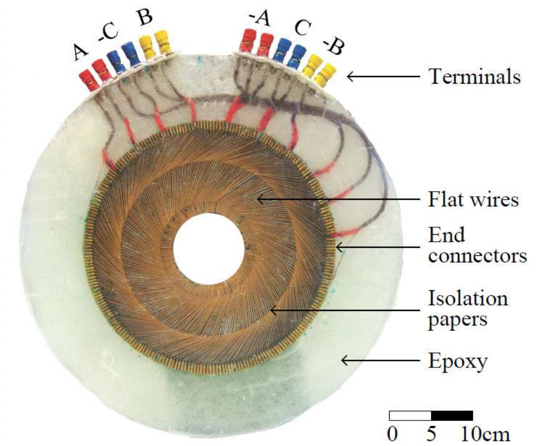
Proposed Solution: Flat Winding[4]







- Take a thin conductor sheet

- Cut pieces with
  - Stamping press
  - Laser cutter
  - Water jet
- Bend them

- Place isolation papers between flat wires
- Solder end windings

- Mold with epoxy
- Create terminals

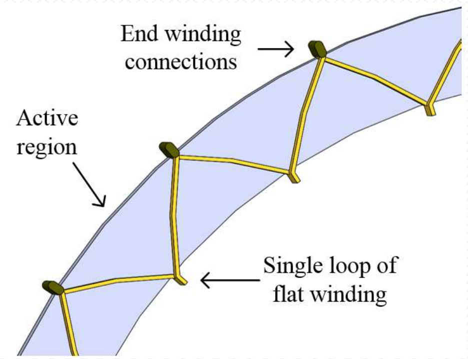
[4] G. Cakal and O. Keysan, (2019). Elektrik Makinaları İçin Bir Sargı Yöntemi (Patent Pending). Türk Patent.

Merits and Challenges of Flat Winding

Merits

- Ease of manufacturing
  - Commonly used tools
- High current density
  - 7 A/mm^2 under natural cooling
- Superior current ratings
  - Eliminating parallel connection
- Decreased end winding length
  - Reduced end winding losses

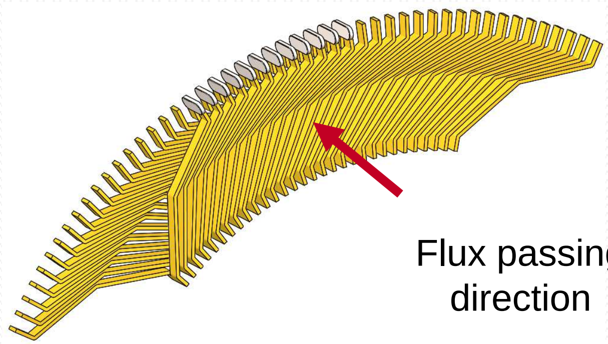
Laser cutting of copper sheet



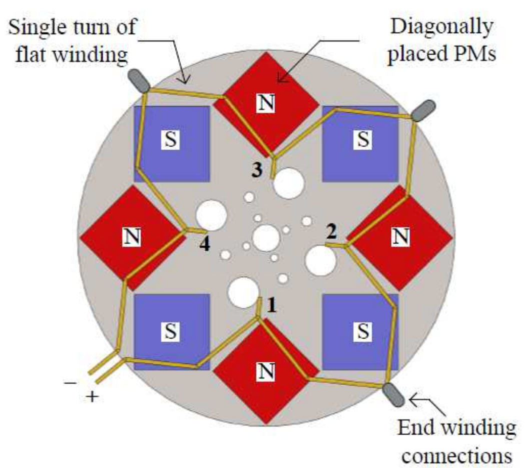
End winding connections

Challenges

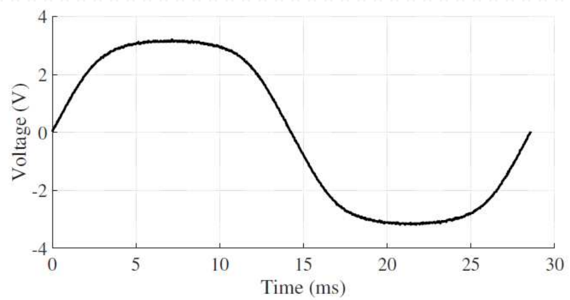
- High eddy currents risk
  - Thin conductor sheet
  - Stacking flat wires in perpendicular to flux passing direction
- Low induced voltage for small machines
  - Use series connection



Implementation on AFPM



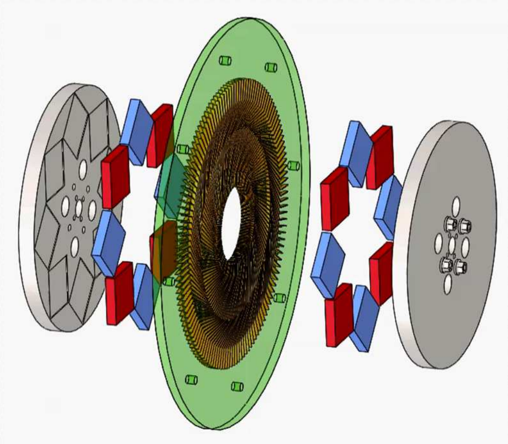
Single turn of flat winding with rotor



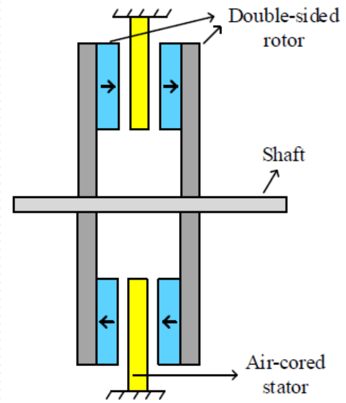
Induced voltage on the flat winding

Topology advantages

- Air cored stator
  - No attraction between rotor and stator
  - Eliminated cogging torque
  - Better demagnetization performance
  - Low magnetic loading
- Stackable in the axial direction
  - Multi-staged designs
  - Increased modularity
- Eliminated AC losses on rotor
  - Except ones due to armature reaction



The proposed topology



Outline

1. Flat winding and implementation on AFPM
2. **Analytical modeling**
3. Experimental verification
4. 1 MW wind turbine generator
5. Conclusions

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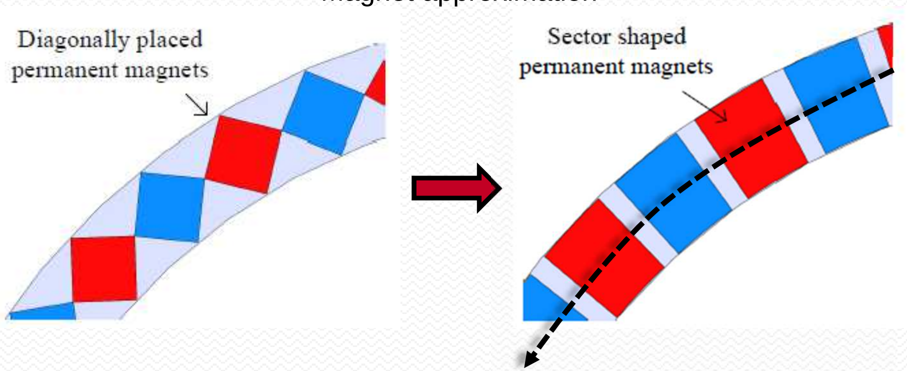
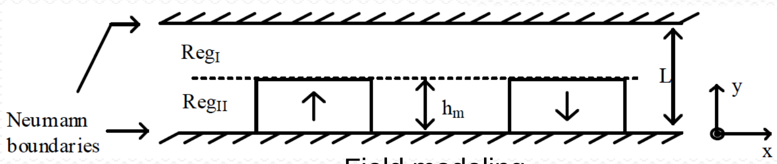
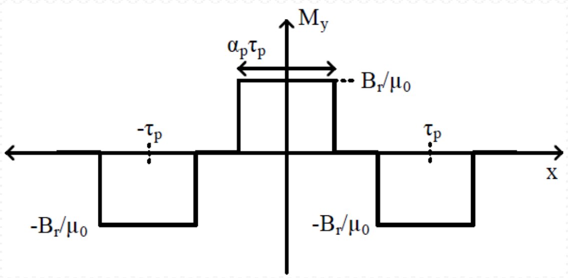
Magnetic Field Modeling

Magnet approximation





Field modeling



Magnetization of the magnets

$$M_y(x) = \sum_{n=1}^{\infty} m_{ycs} \cos\left(\frac{\pi\, n}{\tau_p}\, x\right)$$

$$m_{ycs} = \frac{4\, B_r}{\pi\, n\, \mu_0} \sin\left(\frac{\pi\, n\, \alpha_p}{2}\right) \sin^2\left(\frac{\pi\, n}{2}\right)$$

$$\nabla^2 \varphi = \frac{1}{\mu_r} \nabla \cdot \vec{M}$$

$$\vec{H} = -\nabla \varphi$$

$$\vec{B} = \mu_0\, \mu_r\, \vec{H} + \mu_0\, \vec{M}$$

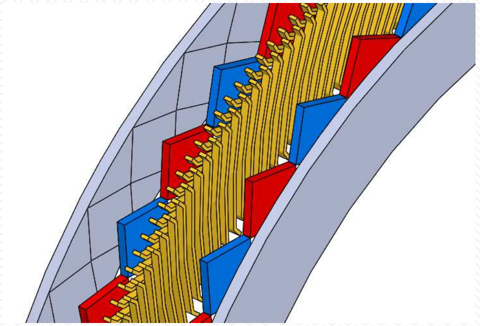
$$B_{Iy} = -\frac{\pi n \mu_0}{\tau_p} \sum_{n=1}^{\infty} \left(C_1\, e^{\pi n y/\tau_p} - C_2\, e^{-\pi n y/\tau_p}\right) \cos\left(\frac{\pi n}{\tau_p} x\right)$$

[5,6]

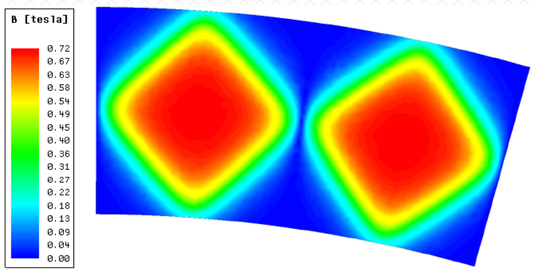
Magnetic Field Modeling

Verification by FEA

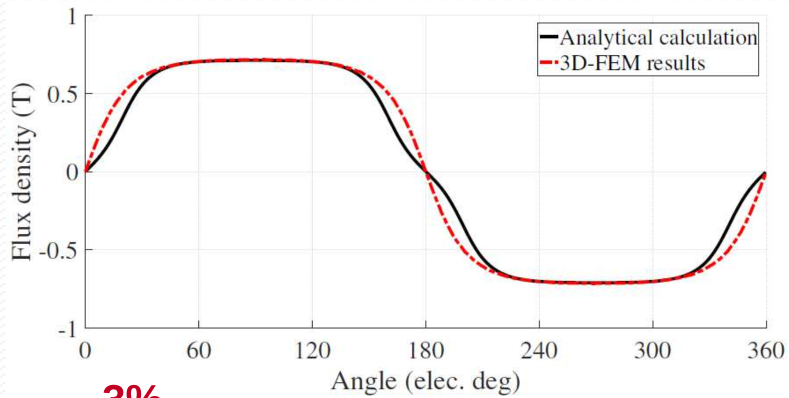
Parameters	Value
Rated power	1 MW
Rotational speed	20 rpm
Diameter	4.8 m
Number of poles	46
Magnet grade	N42M
Remanence flux density	1.29 T
Magnet thickness	36.5 mm
Magnet to magnet distance	47.3 mm

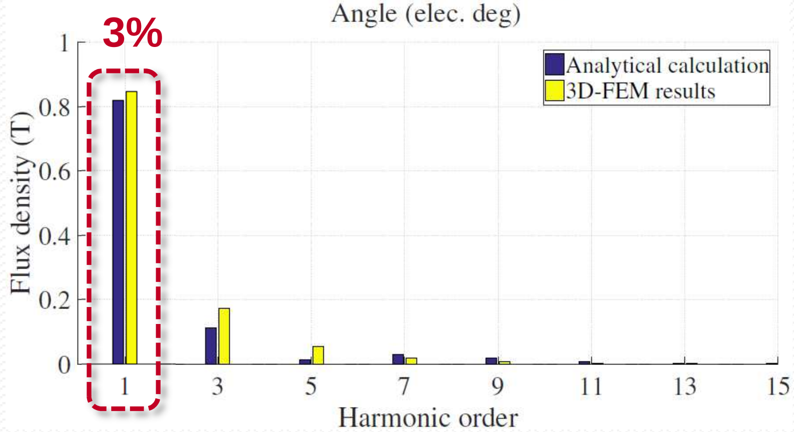


Dummy machine for field verification



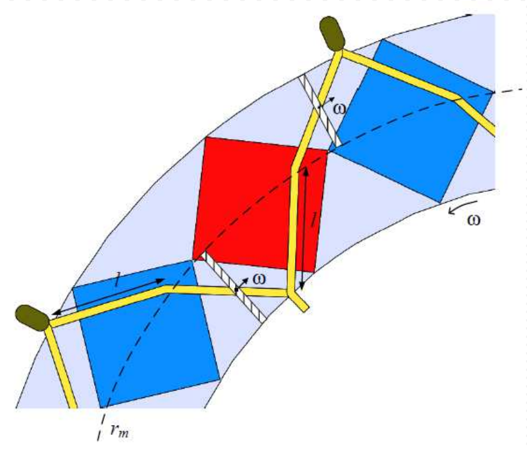
Magnetic flux density distribution by FEA





Other Parameters

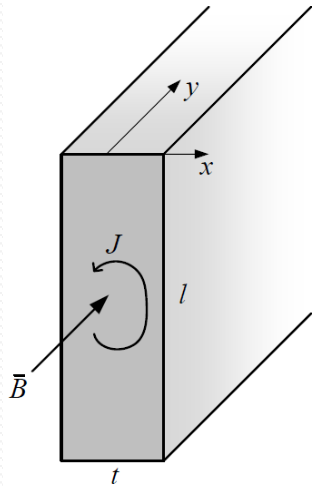
Induced voltage and torque



$$V_{ph} = B_y \, \omega \, r_m \, \frac{l}{\sqrt{2}} \, 2 \, a \, b \, k_w$$

$$T = 3 \, B_y \, r_m \, \frac{l}{\sqrt{2}} \, 2 \, a \, k_w \, I_{ph} \, s$$

Conduction and eddy current losses



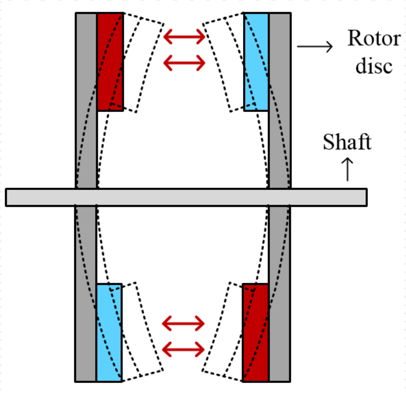
$$P_c = 3 \, {I_{ph}}^2 \, R_{ph}$$

$$P_{sp} = \frac{t^2 \, (2\pi f_e)^2 \, \widehat{B}_{1y}^2}{24 \, \rho} \, k_1$$ [7]

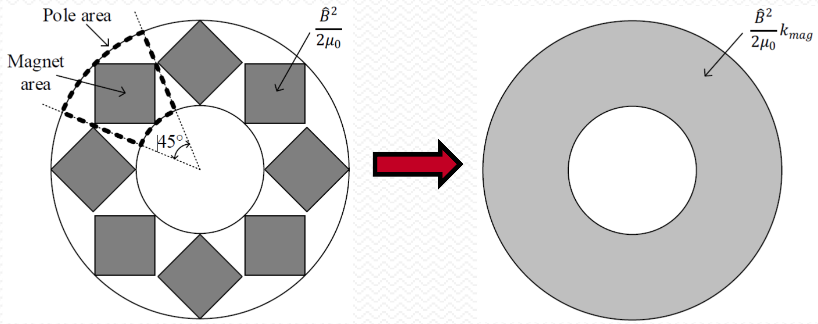
$$k_1 = \frac{\widehat{B}_{1y}^2 + 3^2 \, \widehat{B}_{3y}^2 + 5^2 \, \widehat{B}_{5y}^2 + \ldots}{\widehat{B}_y^2}$$

	Conduction loss	Eddy current loss
Analytical model	75.54 kW	33.17 kW
FEA	75.56 kW	31.39 kW
	<0.1%	5.7%

Deflection Analysis



Deflection of rotor cores



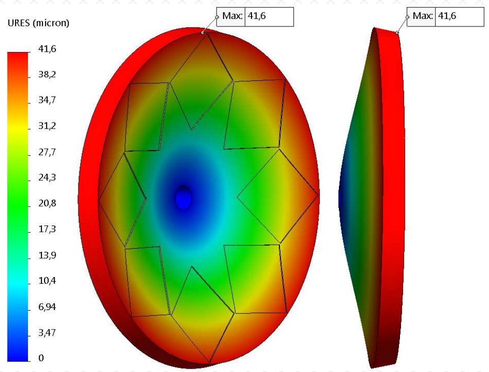
Stress distribution approximation

$$y = M_{rb}\frac{a_r^2}{D}C_2 + Q_b\frac{a_r^3}{D}C_3 - q\frac{a_r^4}{D}L_{11}$$ [8]

$$q = \frac{\widehat{B}_1^2}{2\mu_0}$$

Dummy machine for deflection verification

Parameters	Value
Peak flux density	0.87 T
Outer diameter	300 mm
Air gap clearance	2.3 mm



Deflection analysis by FEA

Deflection analysis comparison

	Deflection	Percentage of clearance
Analytical model	40.4 μm	1.76 %
FEA	41.6 μm	1.81 %

3%

[8] W. C. Young and R. G. Budynas, Roark's formulas for stress and strain; 7th ed. McGraw Hill, 2002.

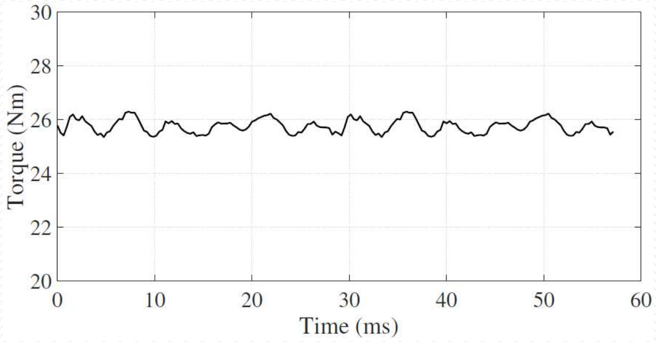
Outline

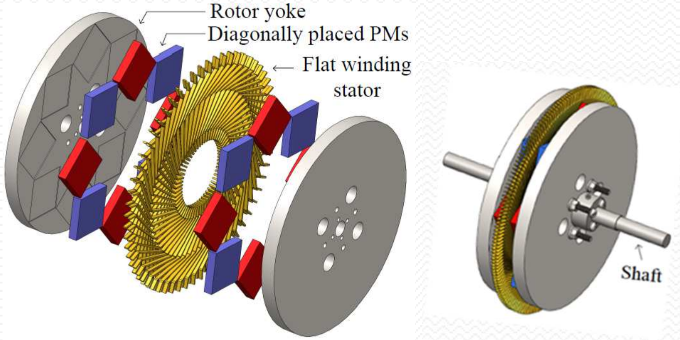
Genetic Algorithm Optimization

- Fully analytical optimization on MATLAB
- Objective function of minimizing active mass
- Optimization variables of
  - Outer diameter
  - Magnetic loading
- Population and generation sizes of 50, both

[9]

Parameters	Value
Rated power	1.4 kW
Line voltage	48 V
Current	20 A
Rotational speed	525 rpm
Rated torque	26 Nm
Pole number	8
Frequency	35 Hz
Outer diameter	300 mm
Current density	4 A/mm^2
Magnetic loading	0.6 T
Conduction loss	110 W
Eddy current loss	53 W
Efficiency	89%
Active mass	29 kg
Air gap clearance	2.3 mm
Flat wire dimensions	1 x 5 mm



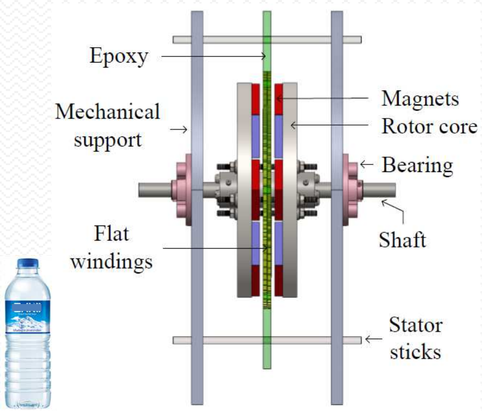


Optimized prototype machine

[9] G. Cakal and O. Keysan, ''A novel flat winding made of aluminum or copper sheet for axial flux machines,'' IET Electric Power Applications, (Review), 2020.

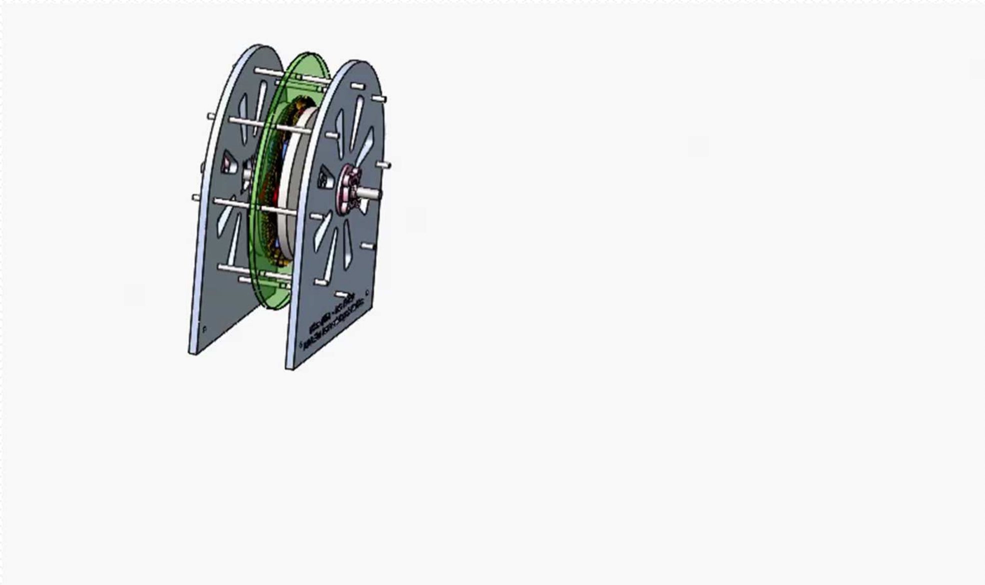
Mechanical Design

Mechanical design



Mechanical design of the prototype

Assembling process



Assembly of the prototype

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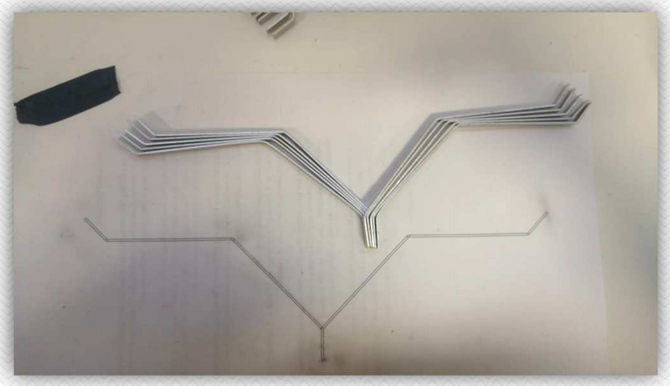
Manufacturing Stages

Laser cutting of copper sheet

Cut pieces



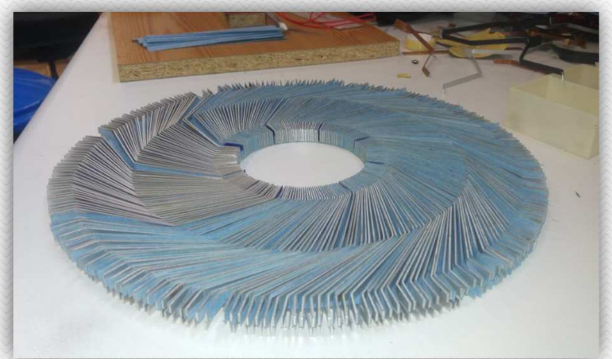
Bending of flat wires

Flat wire placement

Manufacturing Stages

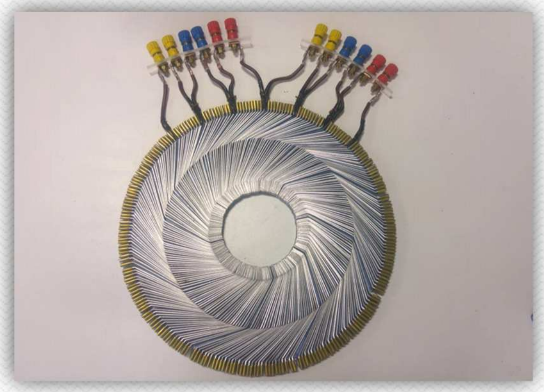

Copper flat wires


Isolation paper


Aluminum flat wires with isolation papers


Connectors at end winding

Manufacturing Stages



Aluminum flat winding stator with terminals

Copper flat winding stator with terminals

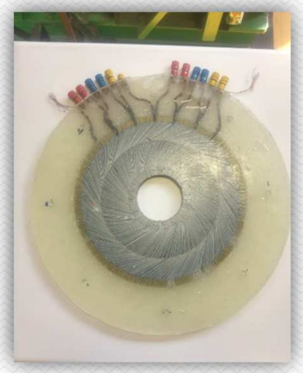
Glass fiber in epoxy molding

Epoxy molding

Manufacturing Stages

Epoxy molding

Stator inside the mold



Final form of the stator

Thermal testing

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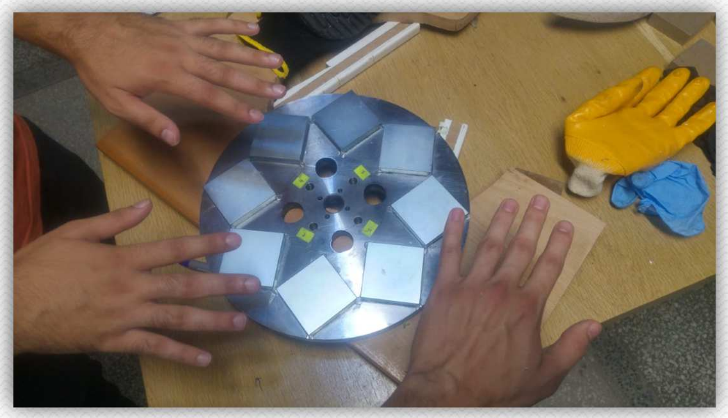
Manufacturing Stages

ST52 rotor steel

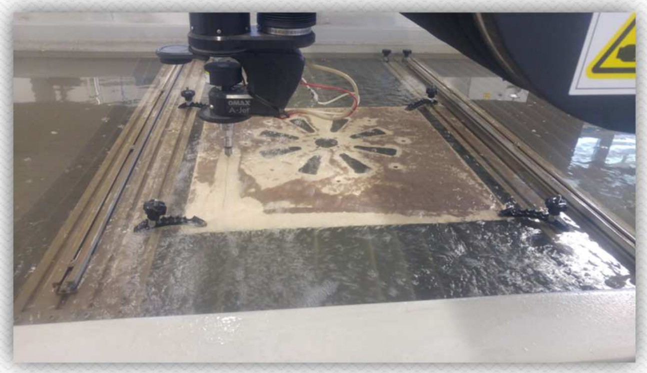
Magnet guides on rotor disc

Assembling magnets with rotor core



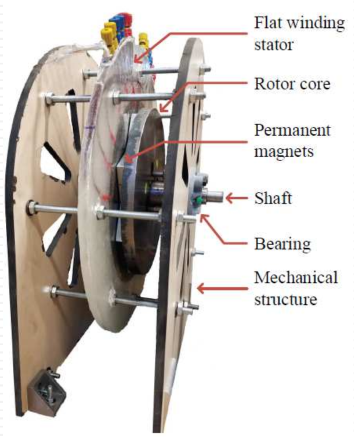
Safe fingers after assembly

Manufacturing Stages

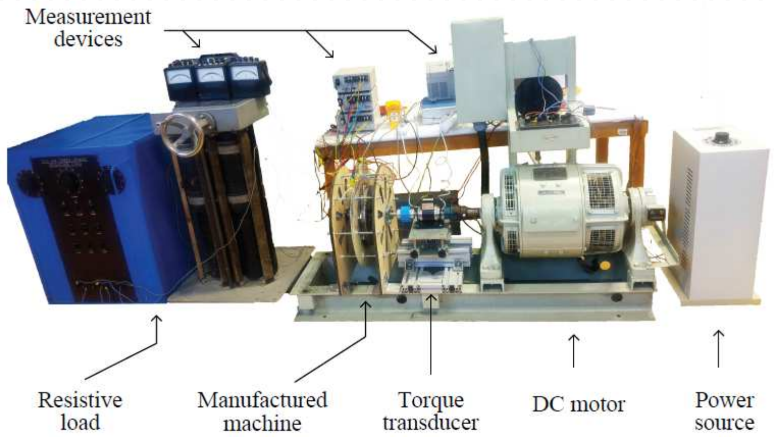


Water jet cutting of mechanical structure

Assembling of two rotor discs



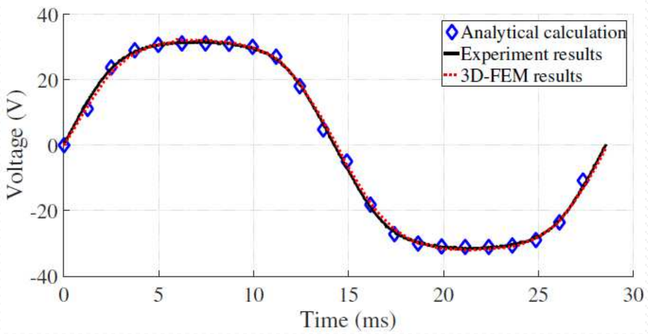
The prototype



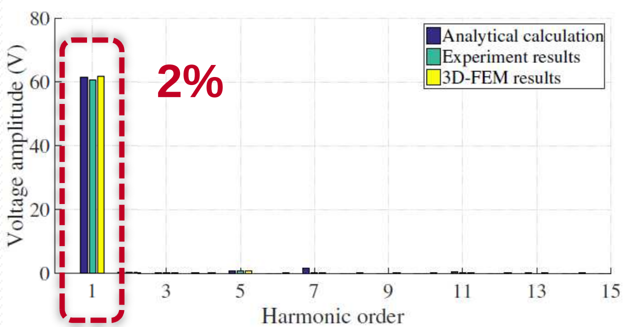
Experimental setup

Experimental Results

Open circuit characteristics



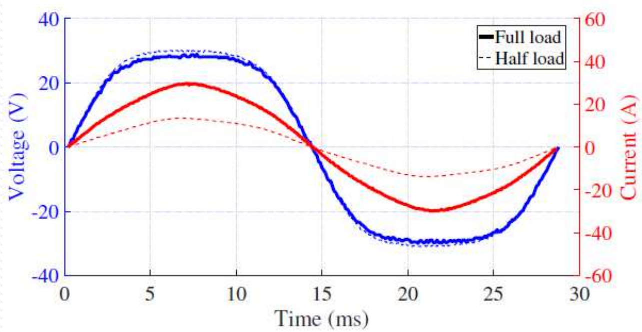
Induced voltages



Harmonics of induced voltages

- Eliminated 3rd harmonics

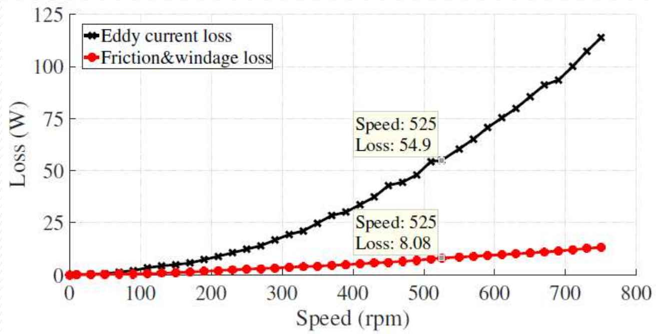
Loading test



Voltage and current measurements

- Full load, 26 Nm
- Half load,13 Nm
- Current harmonics due to unbalanced resistive load

Eddy current and friction losses



Eddy current and friction loss variation against speed

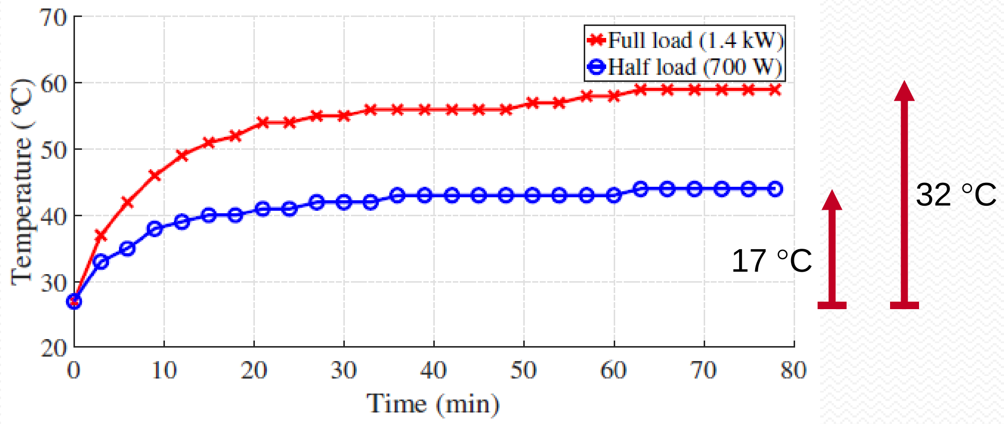
- At rated operation
  - 55 W of eddy current loss
  - 8 W of friction loss

Experimental Results

Losses and efficiency measurement

	Analytical model	Experimental result	
Eddy current loss	53 W	55 W	4%
Conduction loss	110 W	117 W	6%
Phase resistance	93 mΩ	100 mΩ	
Efficiency	89 %	88 %	

Thermal characteristics



Temperature measurement over time

63 W eddy and friction
117 W conduction (*4 A/mm²*)

$\Delta T = 32\ °C$ → $\Delta T = 75\ °C$

63 W eddy and friction
359 W conduction

7 A/mm² for flat wire under natural cooling

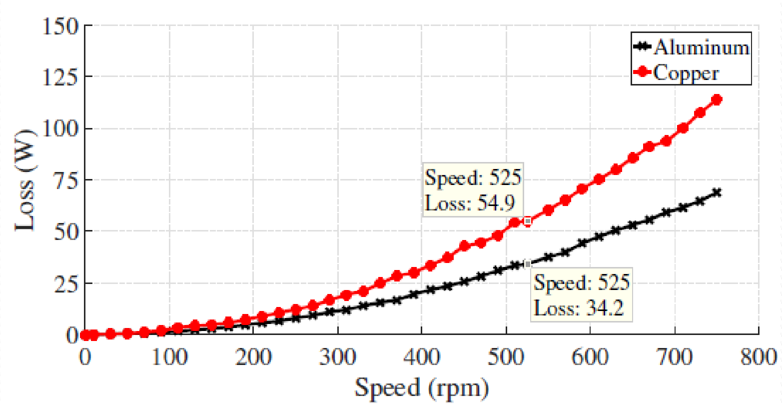
Copper vs. Aluminum Flat Winding

Copper

Aluminum

	Copper	Aluminum
Merits	▪ **63%** more conductive	▪ **70%** lighter ▪ **70%** cheaper
Challenges	▪ High eddy current losses	▪ Welding/soldering

Eddy current losses

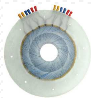


The variation of eddy current loss against speed

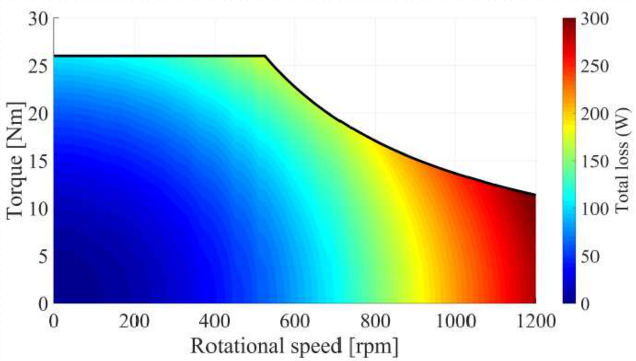
$$P_{sp} = \frac{t^2\,(2\pi f_e)^2\,\widehat{B}_{1y}^2}{24\,\rho}\,k_1$$ [7]

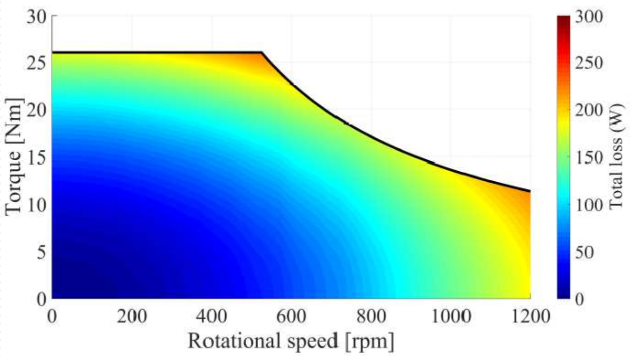
Copper vs. Aluminum Flat Winding

Copper

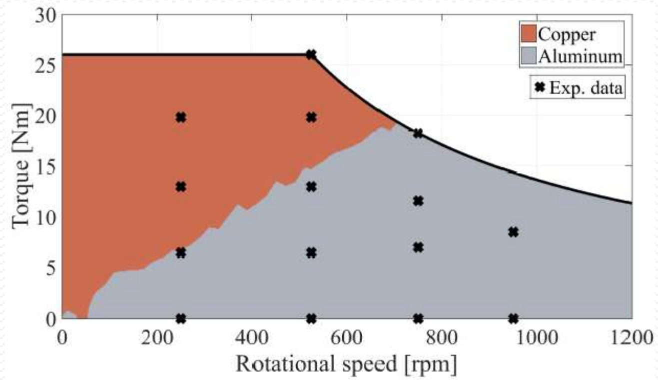


Aluminum



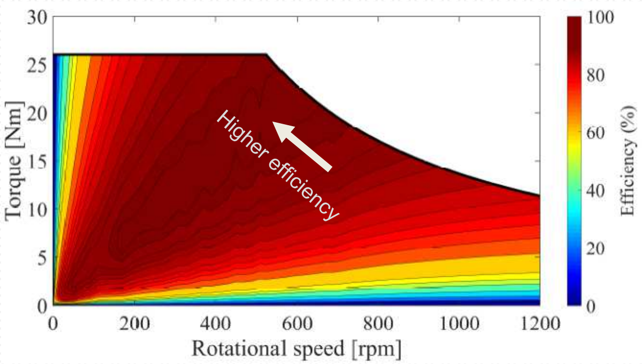


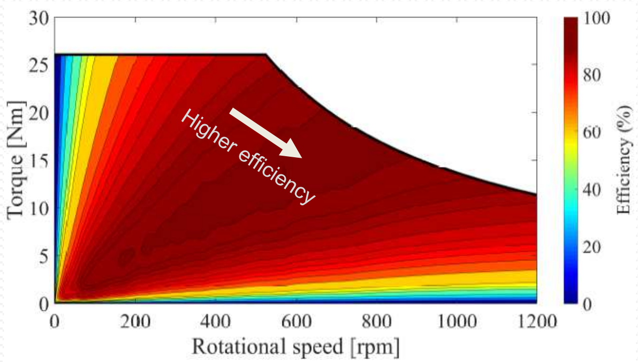
Loss variations on torque speed plane



Material selection

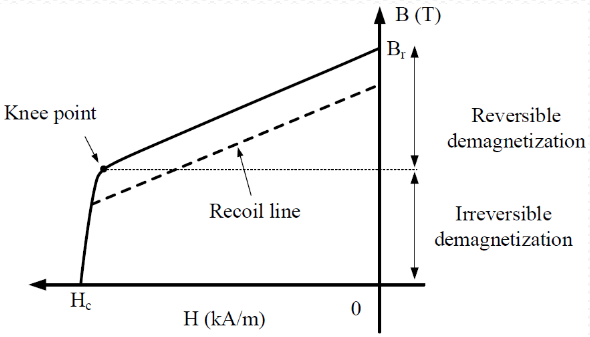
	Copper		Aluminum	
	Rated speed (525 rpm)	High speed (1000 rpm)	Rated speed (525 rpm)	High speed (1000 rpm)
Conduction losses	110 W	31 W	185 W	49 W
Eddy current loss	53 W	199 W	34 W	124 W
Total losses	171 W	246 W	227 W	189 W
Efficiency	89.3%	85.3%	86.3%	88.3%
Winding mass	3.56 kg	→ -70%	1.08 kg	
Material cost	$ 170	→ -93%	$ 12	





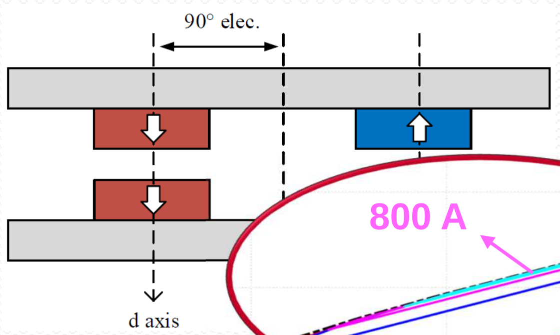
Efficiency maps

Demagnetization Analysis



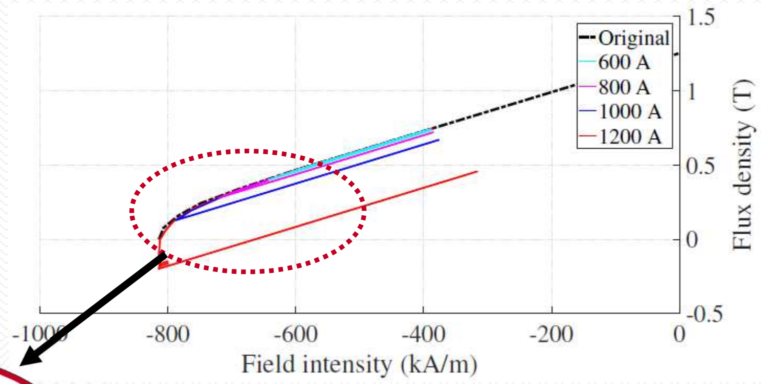
Demagnetization curve of a PM

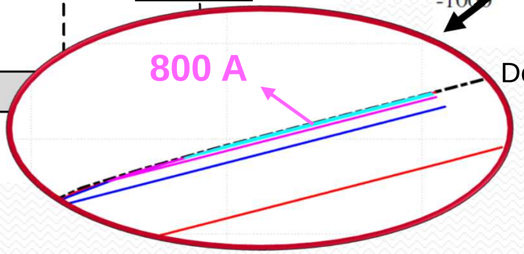
Direct and quadrature axes



Finite element analysis

- -d axis current
- 80 °C operating temperature
- Observation points inside magnet





Demagnetization curve of PM at different currents

Analytical results

- Short circuit at the terminals

$$\hat{I_{sc}} = \frac{\hat{V_{ll}}}{|R_{ll} + j(2\pi f_e)L_{ll}|}$$

$$\hat{I_{sc}} = \frac{60}{|0.2 + j2\pi 35 \cdot 280\mu|} \approx 290 \text{ A}$$

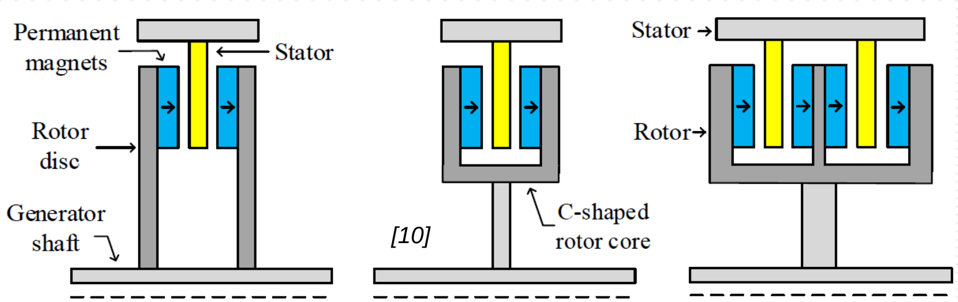
No risk of demagnetization for the prototype

Outline

1. Flat winding and implementation on AFPM
2. Analytical modeling
3. Experimental verification
4. **1 MW wind turbine generator**
5. Conclusions

Mechanical Design and Optimization

Mechanical design



Preferred mechanical models

- Shortened lever arm
- Less deflection
- Decreased structural mass
- Increased torque density
- Increased modularity

Objective function

min(total mass)

Genetic algorithm optimization

Constraints

Parameters	Value
Rated power	1 MW
Rated speed	20 rpm
Efficiency	> 90%
Line voltage	< 690 V

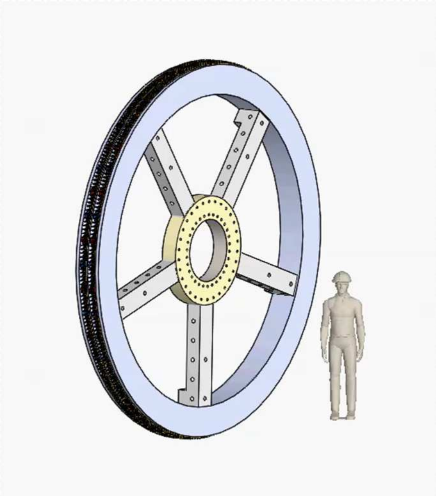
Variables

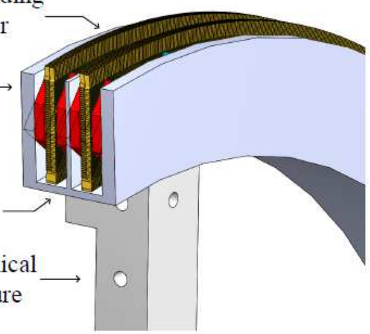
Parameters	Value
Diameter	2 m – 13 m
Flat wire width	5 mm – 50 mm
Flat wire thickness	1 mm – 10 mm
Number of poles	10 – 160
Current density	1 A/mm2 – 9 A/mm2
Number of stages	1 – 14
Number of parallel turns	1 – 8

Genetic Algorithm Optimization

[11]

Parameters	Value
Rated power	1 MW
Torque	480 kNm
Rotational speed	20 rpm
Diameter	4.8 m
Number of stages	2
Voltage	680 V
Current	850 A
Active mass	10.4 t
Structural mass	5.6 t
Total mass	16.0 t
Efficiency	90 %
Number of poles	46
Frequency	7.7 Hz
Current density	3.8 A/mm^2
Flat wire dimensions	3 x 18.6 mm
Total cost	€ 203k
Conduction loss	75 kW
Eddy current loss	31 kW

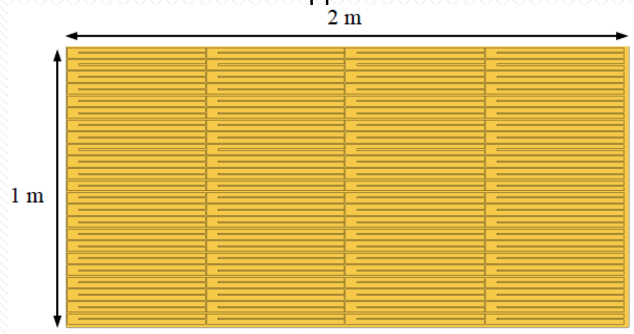




Optimized 1 MW generator

Feasibility

Copper sheet



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Cost analysis

Material cost	€ 45k
Laser cutting	€ 1.2k
Water jet	€ 8.5k

[11] G. Cakal and O. Keysan, "Axial flux generator with novel flat wire for direct-drive wind turbines," IET Renewable Power Generation, (Accepted), 2020.

Comparison

	Li *et al.* [12]	This study	McDonald *et al.* [13]	Maples *et al.* [14]	Versteegh [15]	Bang [16]
Generator type	RFPM	AFPM	AFPM	RFPM	RFPM	RFPM
Power	0.75 MW	1 MW	1 MW	1 MW	1.5 MW	2 MW
Speed	29 rpm	20 rpm	12 rpm	26 rpm	18 rpm	20 rpm
Torque	250 kNm	477 kNm	798 kNm	367 kNm	796 kNm	979 kNm
Number of stages	1	2	4	1	1	1
Active mass	3.1 t	10.4 t	18.6 t	-	16.7 t	14.6 t
Structural mass	-	5.6 t	6.9 t	-	20.8 t	10.4 t
Total mass	-	16.0 t	25.5 t	17.4 t	37.5 t	25.0 t
Torque density by active mass	79.7 Nm/kg	**46.0 Nm/kg**	42.9 Nm/kg	-	47.7 Nm/kg	67.0 Nm/kg
Torque density by total mass	-	**29.8 Nm/kg**	31.3 Nm/kg	21.0 Nm/kg	21.2 Nm/kg	39.2 Nm/kg

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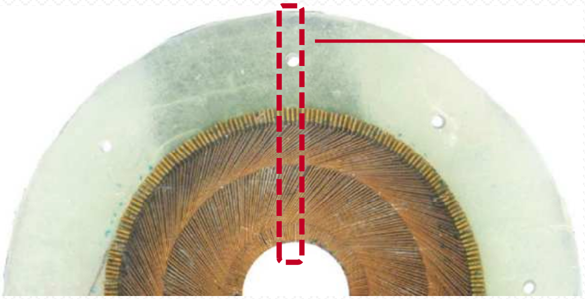
Thermal Analysis

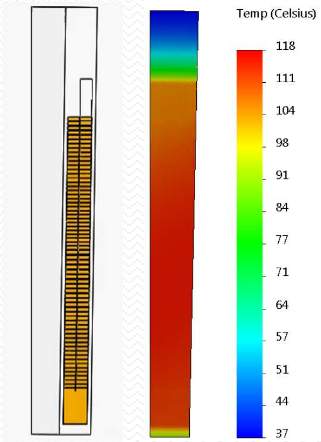
Actual model



Flat winding stator of the generator

- SolidWorks simulation
- 106 kW heat power
  - 75 kW conduction loss
  - 31 kW eddy current loss
- 50 W/(m^{2}K) convection
  - Air cooling

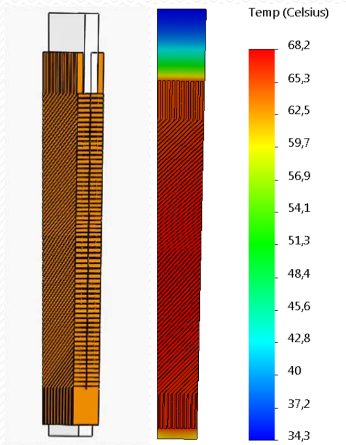
ΔT = 90 °C



Full coating of the windings

Improved model

ΔT = 40 °C



Partial coating of the windings

- Partially coated epoxy
- Increased surface area
- Decreased thermal resistance

66% increase in electrical loading

Outline

1. Flat winding and implementation on AFPM
2. Analytical modeling
3. Experimental verification
4. 1 MW wind turbine generator
5. **Conclusions**

Conclusions

	Flat winding	Conventional round winding	Hairpin winding	PCB winding
Ease of manufacturing	++	+	+	++
Current density	++	-	+	++
Current rating	++	+	++	-
Manufacturing cost	+	+	-	--
End winding loss	++	+	-	+
Eddy current loss	+	++	-	+

- Boosted machine performance
  - Ease of manufacturing
  - Current density up to 7 A/mm2
  - Shortened end windings
  - Lower end winding losses
- Experimental verification on 1.4 kW prototype
  - Good agreement with analytical and FEA results
- Elimination of eddy current losses
  - Thin flat wire
  - Stacking through thickness
- Aluminum alternative
  - At high speed operation
  - Cost and weight advantages
- Performance on MW-class
  - Comparable torque density

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[4] G. Cakal and O. Keysan, (2019). Elektrik Makinaları İçin Bir Sargı Yöntemi (Patent Pending). Türk Patent.

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[9] G. Cakal and O. Keysan, ‘‘A novel flat winding made of aluminum or copper sheet for axial flux machines,’’ IET Electric Power Applications, (Review), 2020.

[10] M. A. Mueller and A. S. McDonald, “A lightweight low-speed permanent magnet electrical generator for direct-drive wind turbines,” Wind Energy, vol. 12,no. 8, pp. 768–780, 2009.

[11] G. Cakal and O. Keysan, ‘‘Axial flux generator with novel flat wire for direct-drive wind turbines,’’ IET Renewable Power Generation, (Accepted), 2020.

[12] H. Li, Z. Chen, and H. Polinder, “Optimization of multibrid permanent-magnet wind generator systems,” IEEE Transactions on Energy Conversion, vol. 24, pp. 82–92, March 2009.

[13] A. S. McDonald, N. Al-Khayat, D. Belshaw, M. Ravilious, A. Kumaraperumal,A. M. Benatamane, M. Galbraith, D. Staton, K. Benoit, and M. Mueller, “1MW multi-stage air-cored permanent magnet generator for wind turbines,” 6th IET International Conference on Power Electronics, Machines and Drives (PEMD 2012), pp. 1–6, 2012.

[14] B. Maples, M. Hand, and W. Musial, “Comparative assessment of direct drive high temperature superconducting generators in multi-megawatt class wind turbines,” Technical Report,National Renewable Energy Laboratory, pp. 1–40, 10 2010.

[15] C.Versteegh, “Design of the zephyros Z72 wind turbine with emphasis on the direct drive PM generator,” Nordic Workshop on Power and Industrial Electronics, pp. 1–7, 2004.

[16] D. Bang, Design of Transverse Flux Permanent Magnet Machines for Large Direct-Drive Wind Turbines. Phd dissertation, Delft University of Technology, Delft, The Netherlands, October 2010.

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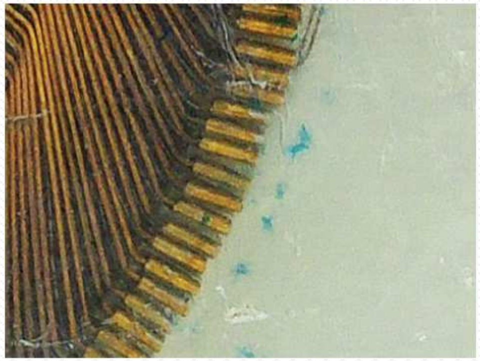
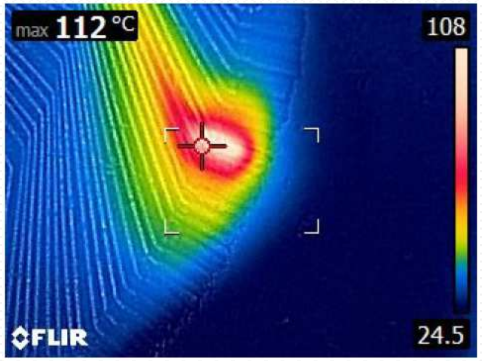
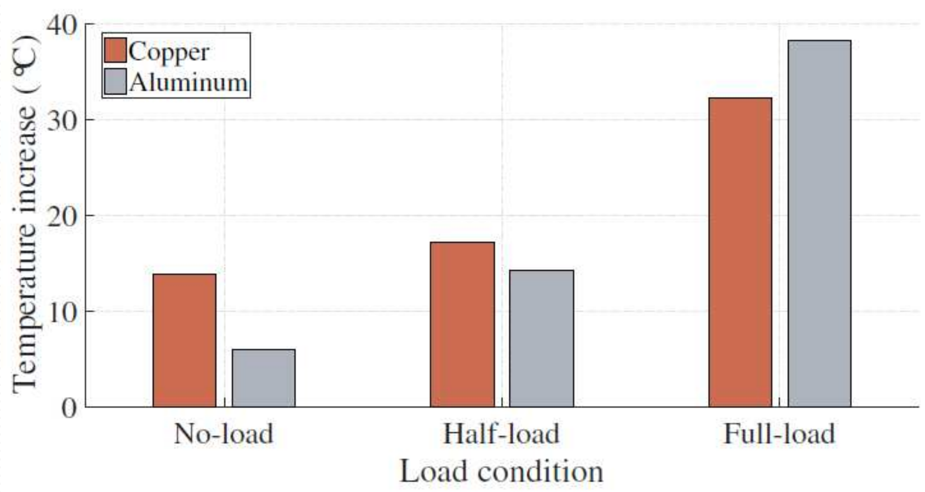
Thanks!

Additional Slides





Hot spot due to weak soldering



Temperature rise at different operating conditions

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Current Density Calculation

55 W eddy
8 W friction
117 W conduction

180 W total

$\Delta T = 32\ ^\circ C$

359 W conduction ← 55 W eddy, 8 W friction

422 W total ← $\Delta T = 75\ ^\circ C$

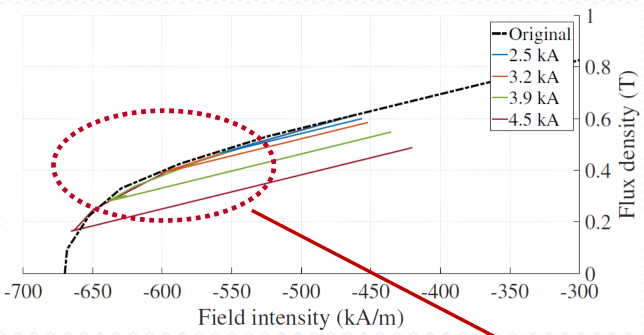
$J = 4\ A/mm^2$ → 117 W conduction

$J = 7\ A/mm^2$ ← 359 W conduction

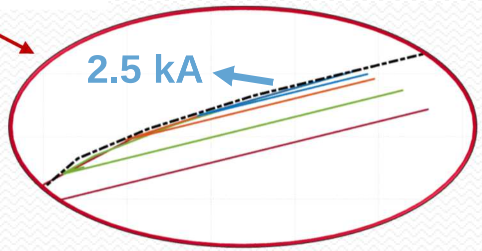
Demagnetization Analysis

Finite element analysis

- -d axis current
- 80 °C operating temperature
- Observation points inside magnet



Demagnetization curve



Analytical results

- Short circuit at the terminals

$$\hat{I_{sc}} = \frac{\hat{V_{ll}}}{|R_{ll} + j(2\pi f_e)L_{ll}|}$$

$$\hat{I_{sc}} = \frac{960}{|0.082 + j2\pi 7.667 \cdot 0.00427|} \approx 4335 \text{ A}$$

Risk of demagnetization

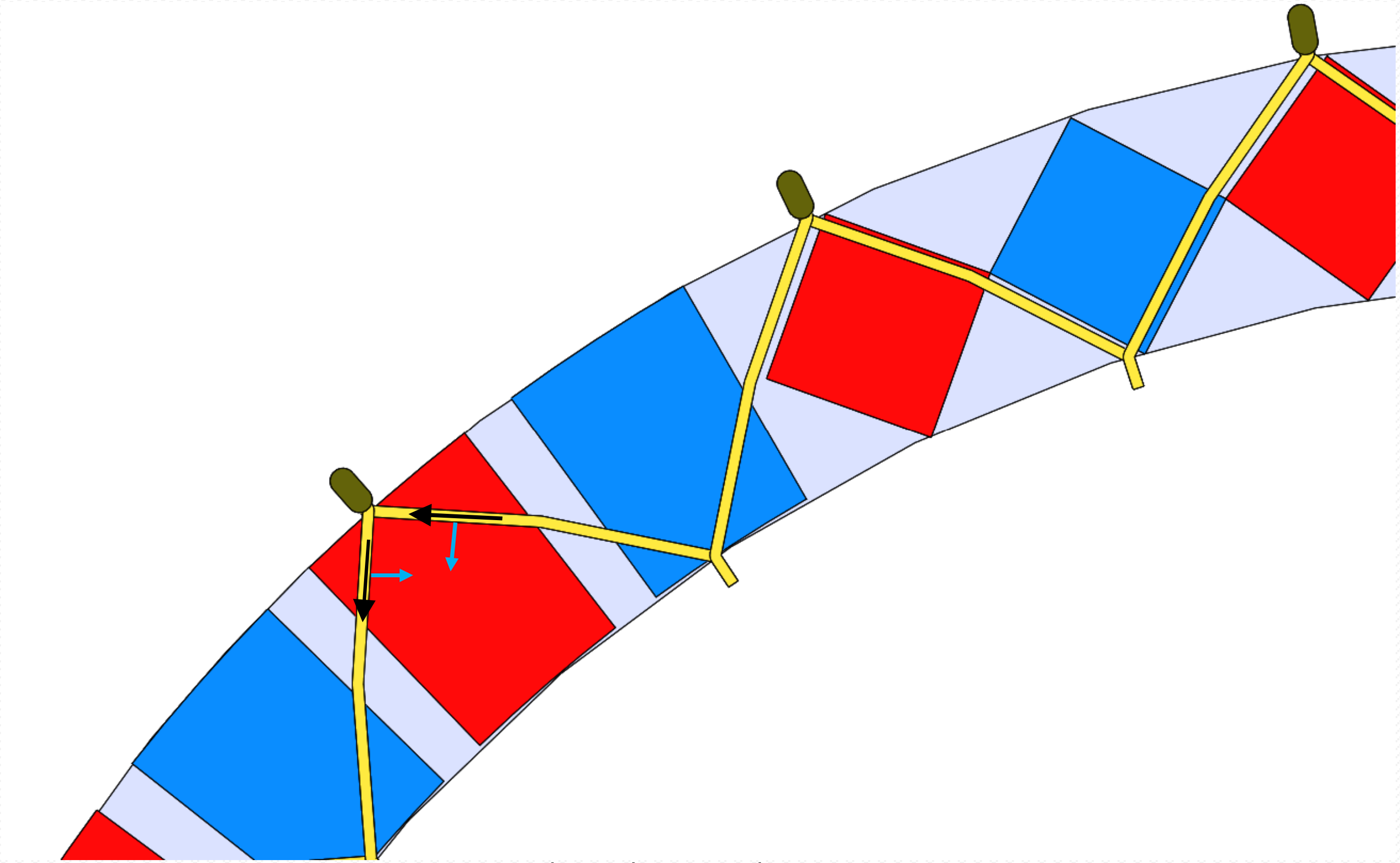
- Use H or UH grade magnets
- 80 °C approximation

Cost Analysis

	Prototype machine	MW-turbine
Permanent magnets	€ 320	€ 135k
Winding material	€ 170	€ 45k
Rotor iron	€ 45	€ 11k
Structural material	€ 5	€ 12k
Total	**€ 540**	**€ 203k**

	Specific cost
Magnet	60 €/kg
Copper	15 €/kg
Rotor iron	2 €/kg
Structural steel	2 €/kg

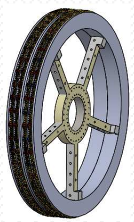
Diagonal Placement

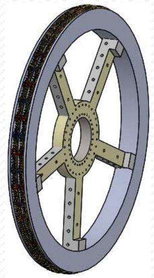


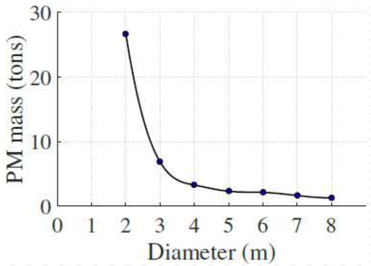
Diagonal magnet placement

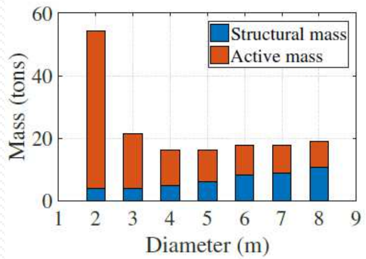
Optimization

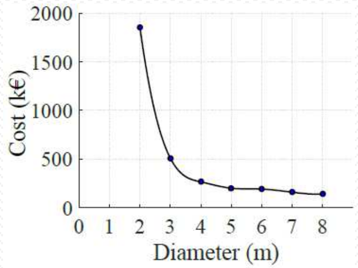
Diameter variation

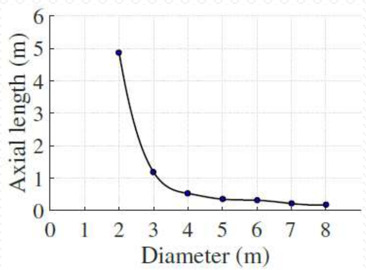












Flat wire thickness variation