Relating Cost of Energy to the Electromagnetic Design of Wind Turbine Generators

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Relating Cost of Energy to the Electromagnetic Design of Wind Turbine Generators

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Outline

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Introduction

Wind Turbine Generators with Reduced Reliance on Rare Earth Metals

Three year PhD project in electrical machine design. Targets include:

- Design of PMSM wind turbine generators
- Development of optimal machine design process
- Comparison of alternative machines with PMSM

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Introduction

Project Status

- Half-way point has been passed.
- Focus is shifted to non-RE machines
- Delivery in Sept. 2014

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Cost of Energy

A key metric which is often cited in comparing energy sources is the cost of energy (COE).

Estimating the Cost of Energy

- When considering projects, those which would give the lowest COE stand to be the most profitable.
- What must be known to estimate the COE?
  - Capital expenditure (CAPEX) - purchasing and installing
  - Operational expenditure (OPEX) - maintaining and operating
  - Annual energy production (AEP) - the total amount of energy produced in a year

$$COE = \frac{CAPEX + OPEX}{AEP} \tag{1}$$

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Wind Turbine Cost of Energy

For wind turbines, estimating the CAPEX and OPEX is very complicated. A large number of factors must be incorporated:

CAPEX

- Equipment
- Transportation
- Construction

OPEX

- Operation
- Maintenance
- Condition monitoring

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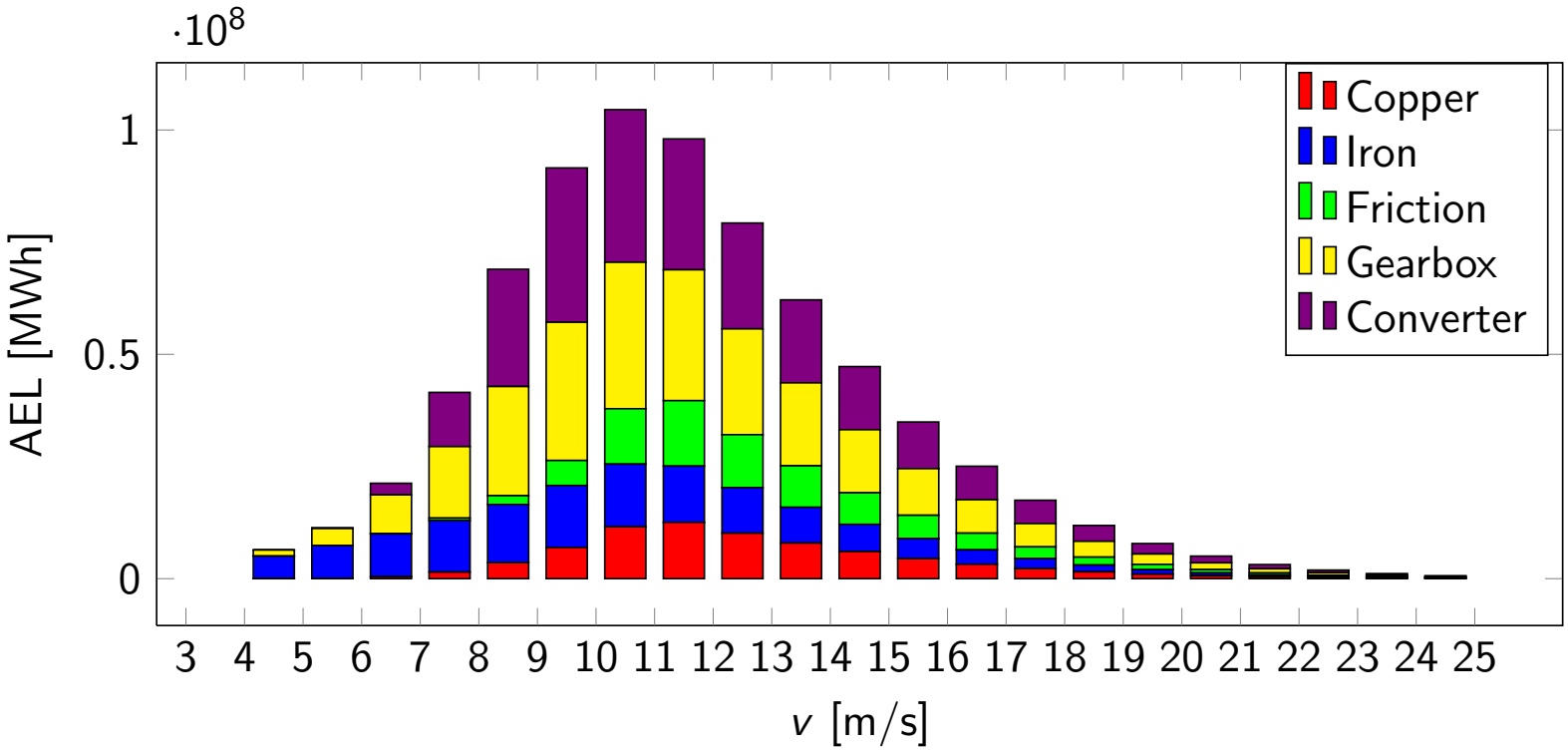
Annual Energy Production

Need a process for estimating the yearly losses



For a wind climate described by Weibull parameters k=2 and A = 9

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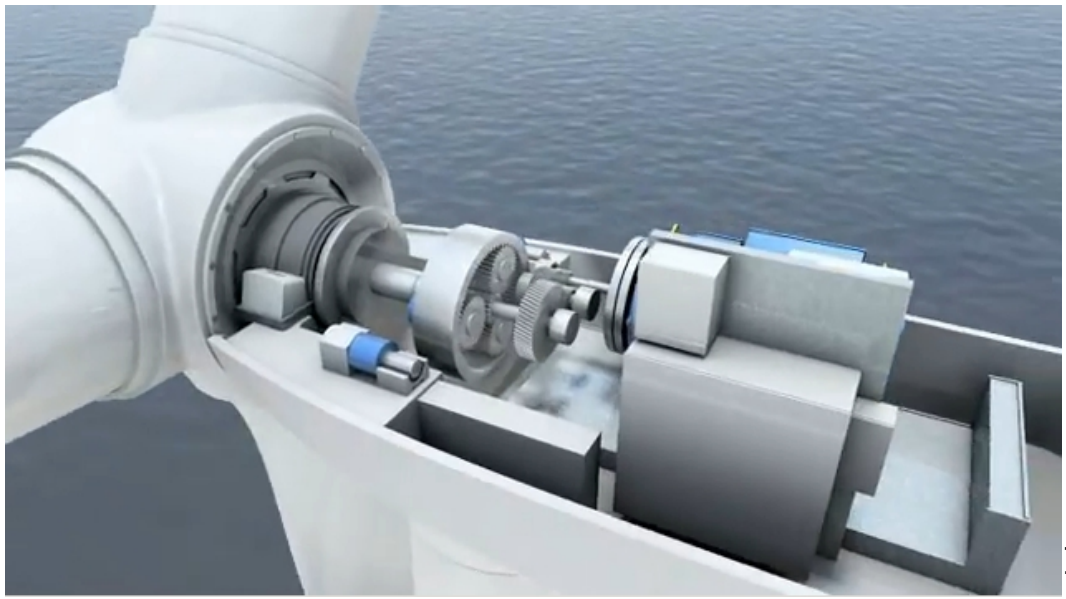
Power Conversion

Wind turbine topologies are characterized by the selection and usage of the power conversion devices:

- Gearbox
- Power electronic converter
- Generator



[1]

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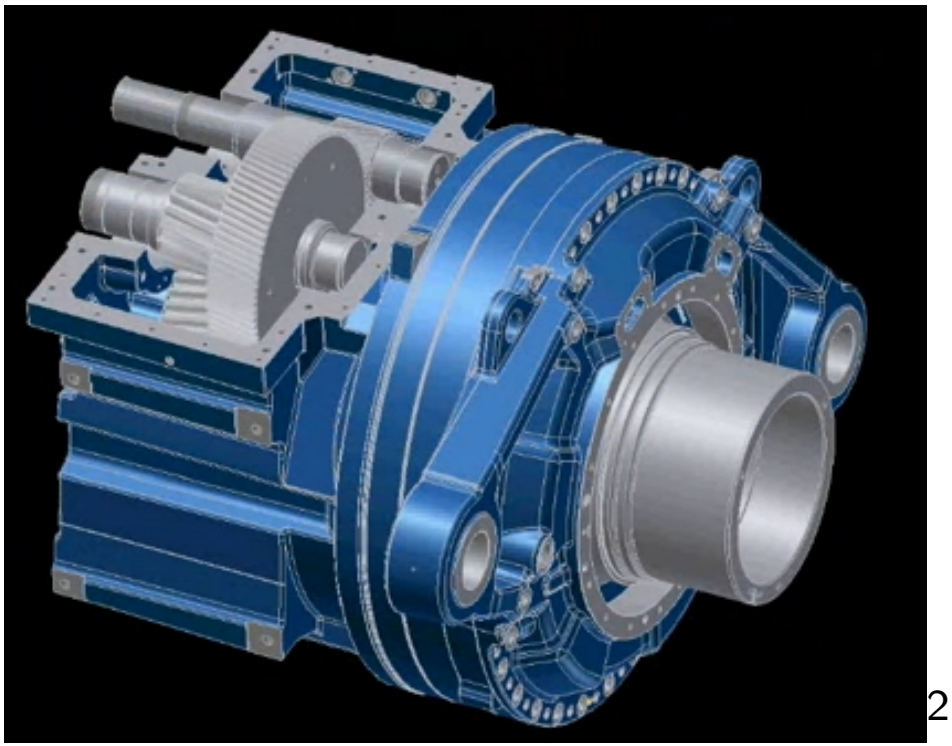
[1] Image from www.ZF.com

Gearboxes

Gearboxes (when present) reduce the input torque to the generator and increase the speed.



[2]

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[2] Image from www.ZF.com

Gearboxes - modeling

- May consider single-stage, or multi-stage configurations
- Rated losses: 0.5% P_{rated} for planetary stages, 1% P_{rated} for parallel stages
- Split into torque dependent and torque independent components
- Assumed cost: 3.5€/kW

Power electronic converter

- Power electronic converters convert variable electrical quantities of the generator to grid compliant frequency and amplitude.

[3]

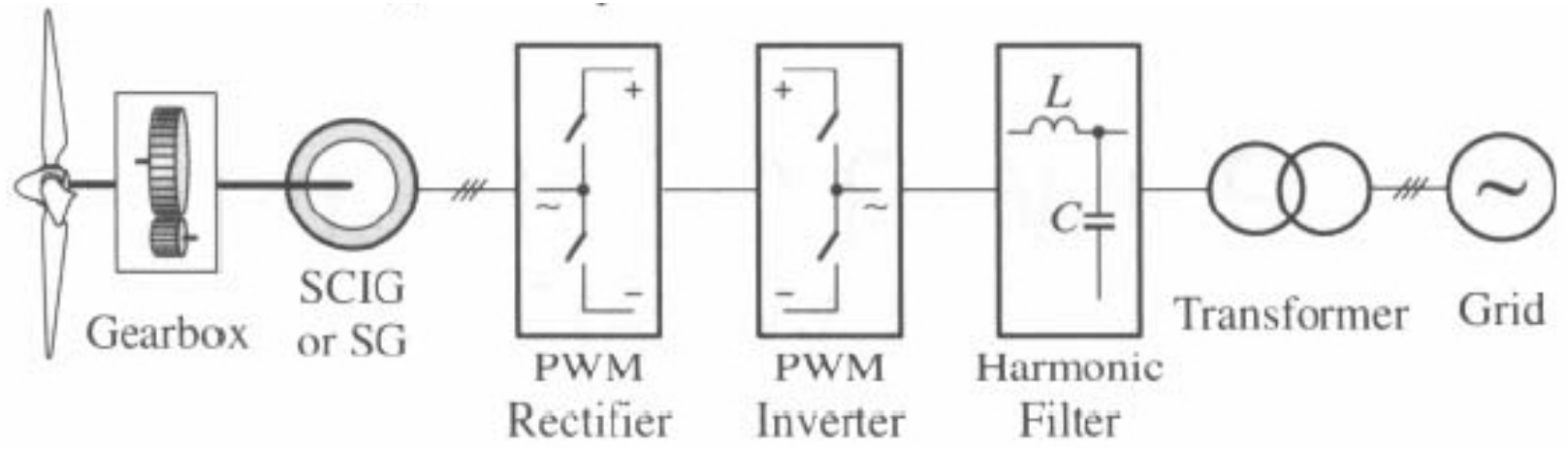
[4]

- Nowadays, the discussion is centered on two major types:
  - Fully rated, used with synchronous generators
  - Partially rated, used with doubly-fed induction generators

[3] Image from www.infineon.com
[4] Image from www.ABB.com

Power converter - modeling

- 6-pulse, fully rated, back to back with DC link
- Rated losses: 2% P_{rated}
- Losses split into constant, linear current- and quadratic current-dependent components
- Assumed cost: 30€/kVA



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Generators

Generators convert mechanical power to electrical power.

[5]

[6]

[5] Image from www.theswitch.com
[6] Image from www.ingeteam.com

Generator - modeling

- PMSM with NdFeB, SCIG, SynRel, others...
- Rated losses: found by FEA
- Assumed cost: by material
  - Copper: 15€/kg
  - Laminations: 5€/kg
  - Magnet: 75€/kg

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Generator Design

Torque production is a matter of size, current, and flux density.

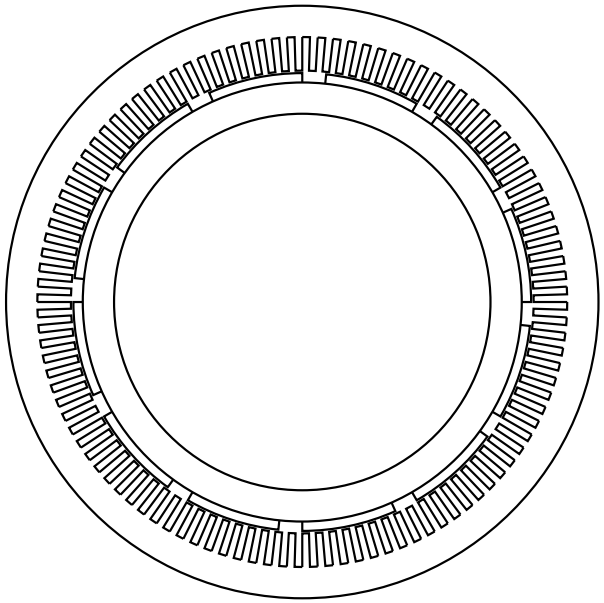
$$T_{max} = \sqrt{2} V A \hat{B} \tag{2}$$

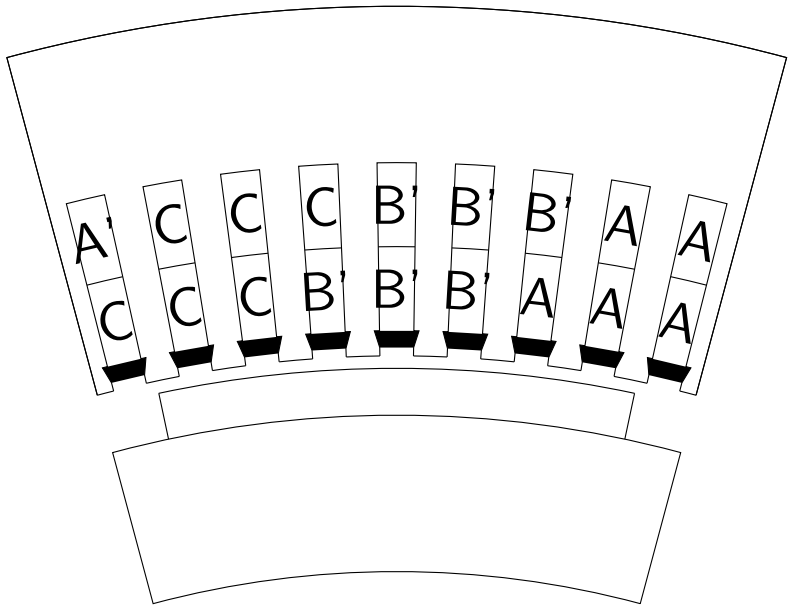
The designer must choose the proportions of these three to be taken, in order to achieve the required torque.

Generator Design

Moving on, many degrees of freedom may be present:

- Axial length
- Inner radius
- Outer radius
- Air gap length
- Materials
- Air gap length
- Slot dimensions
- And many more...





Generator Design

Several aspects of the generator will influence the cost of energy:

- Cost
- Losses
- Reliability

My philosophy: optimize the machine design to reduce the cost of energy

Design Study

The expected cost of energy is assessed for PM machines designed by three optimization strategies:

1. Full load efficiency
2. Cost of generator
3. Cost of energy

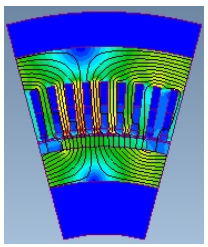
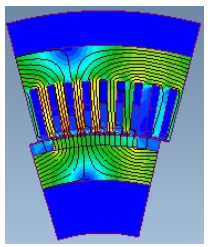
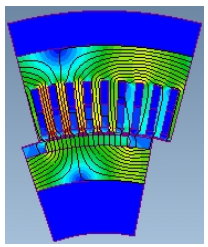
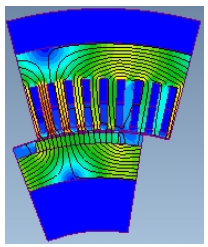
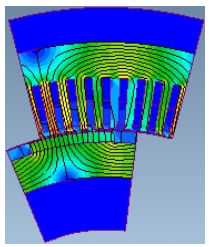
The design is based on a fictional 3MW wind turbine, with the generator driven at 1200rpm through a 3-stage gearbox.

Optimal Design

A parameterized generator model is analyzed, with several constraints:

- Rated torque requirement
- Slot dimensions (not too thin)
- Synchronous reactance ($\geq$ 0.5pu)
- Air gap length (no smaller than 0.1% of diameter)

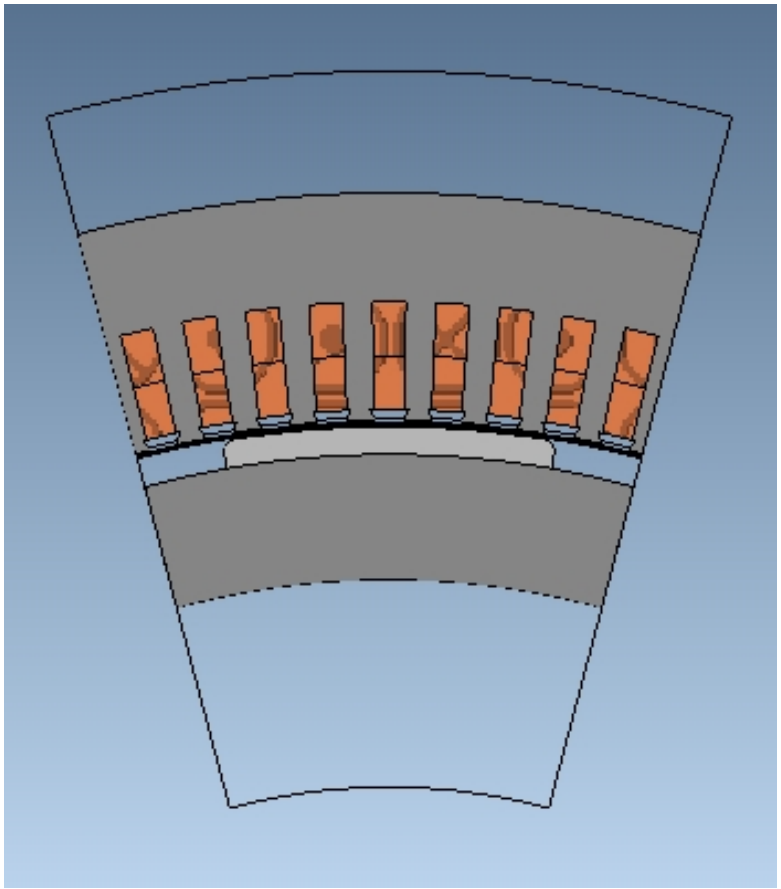
Design variables include electrical loading, magnet height, and most mechanical dimensions.

Results

Optimized for generator cost

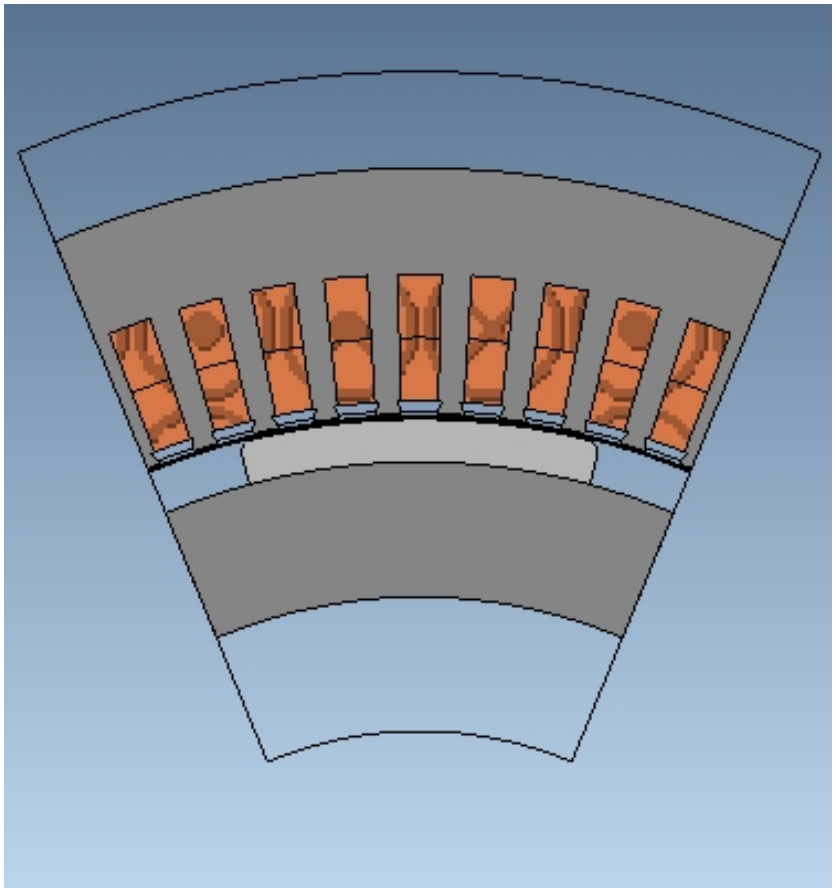
- Length: 0.5m
- Diameter: 1.0m
- Cost: 34.2k€
- Full load efficiency: 96.4%
- Estimated cost of energy: 0.28€/kWh



Results

Optimized for full load efficiency

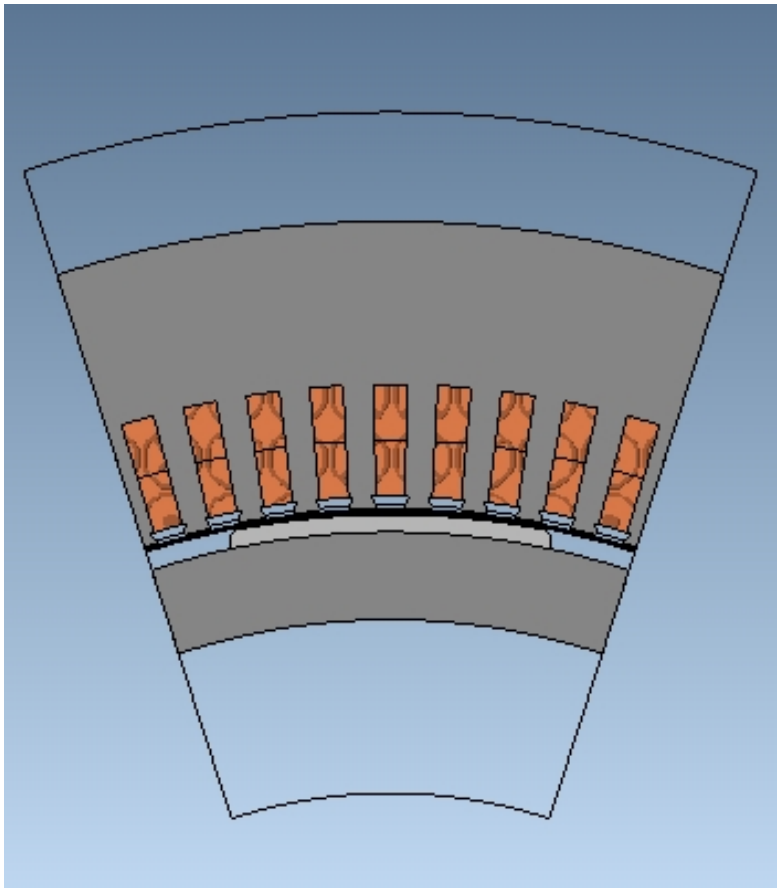
- Length: 1.0m
- Diameter: 0.64m
- Cost: 49.5k€
- Full load efficiency: 98.4%
- Estimated cost of energy: 0.26€/kWh



Results

Optimized for cost of energy

- Length: 0.8m
- Diameter: 0.78m
- Cost: 38.7k€
- Full load efficiency: 97.9%
- Estimated cost of energy: 0.25€/kWh



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Conclusion

The electromagnetic design of the generator is related to the cost of energy through several aspects:

- Losses
- Material cost
- Operational cost

Taking losses and material cost into consideration, optimal generator design for cost of energy has been demonstrated for PMSM wind turbine generators. The approach tends to yield a result between optimizing for efficiency and optimizing for cost reduction.

Conclusion

Acknowledgements

Thanks to DONG Energy for sponsoring the PhD project Wind Turbine Generators with Reduced Reliance on Rare Earth Metals.

Thank you!

Questions?