Electrical Energy Conversion System for Pumping Airborne Wind Energy

Jeroen Stuyts
Wouter Vandermeulen

Table of Contents

- Introduction
- Powering the plane
- Electrical system design
- Testing the drives
- Trajectory reoptimization
- Conclusion

Electrical Energy Conversion System for Pumping Airborne Wind Energy

- Introduction
- Powering the plane
- Electrical system design
- Testing the drives
- Trajectory reoptimization
- Conclusion

Airborne wind energy

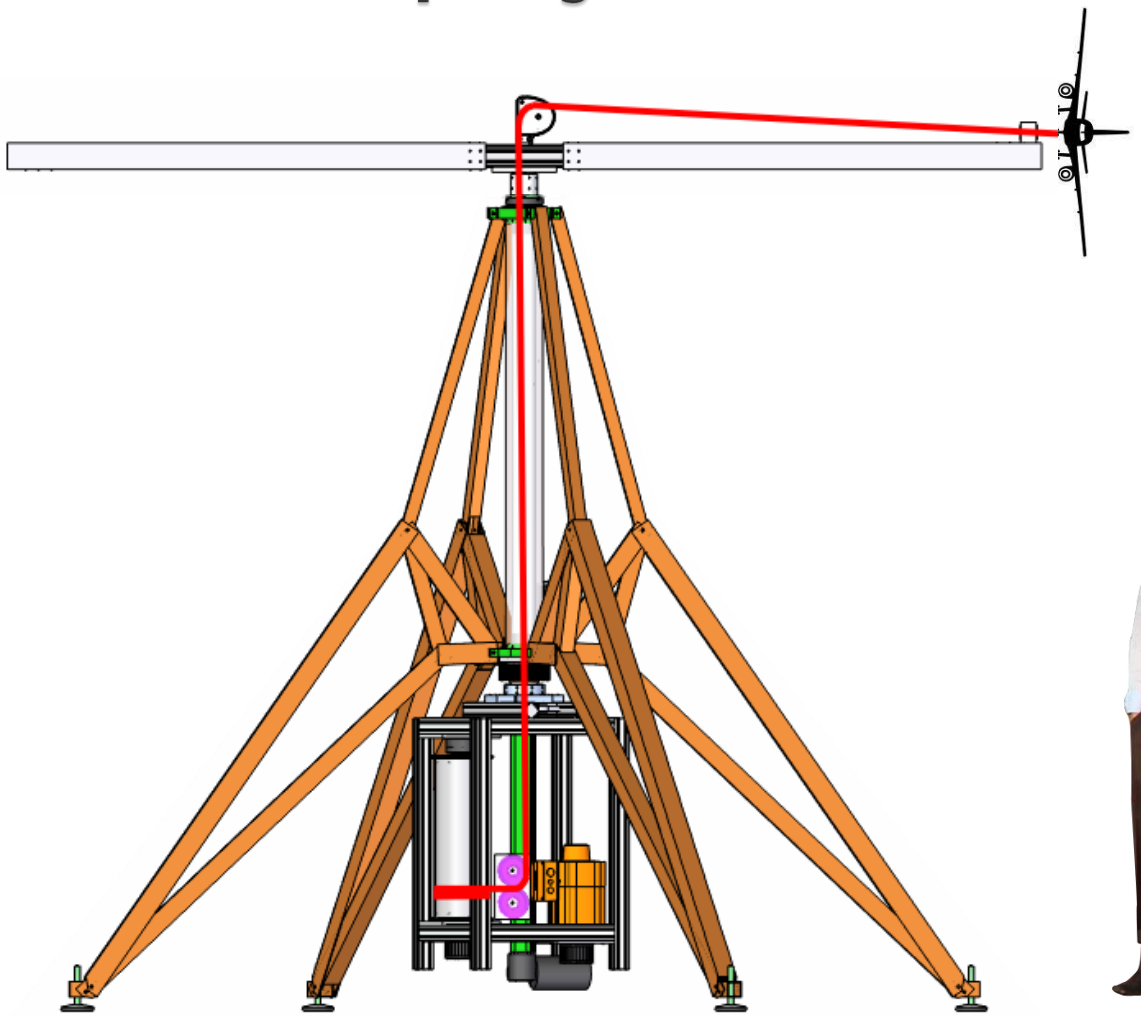
- Wind energy through
  - Flying object
  - High altitude
  - Cheap construction

Makani Power

SkySails

Simulated example

The HIGHWIND project



Introduction

Original goal of the thesis

- Designing, selecting, purchasing and testing
  - Power electronics for the winch motor
  - Power electronics for the carousel motor
  - A petrol powered generator

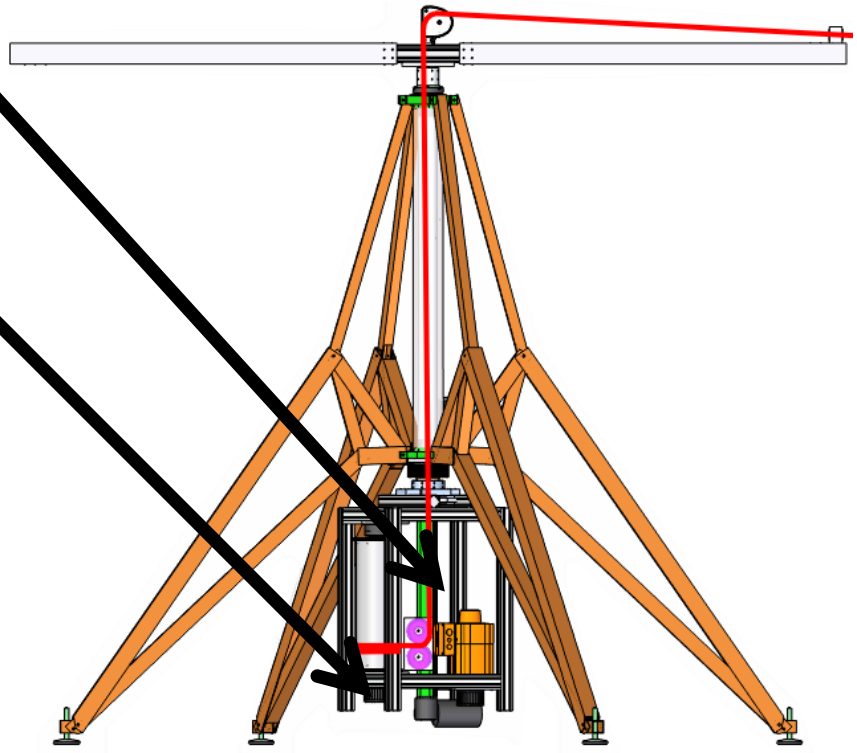
Has evolved in

- Designing, selecting, purchasing and testing
  - Carousel drive
  - Winch drive
  - Plane power electronics
  - Overall electrical system

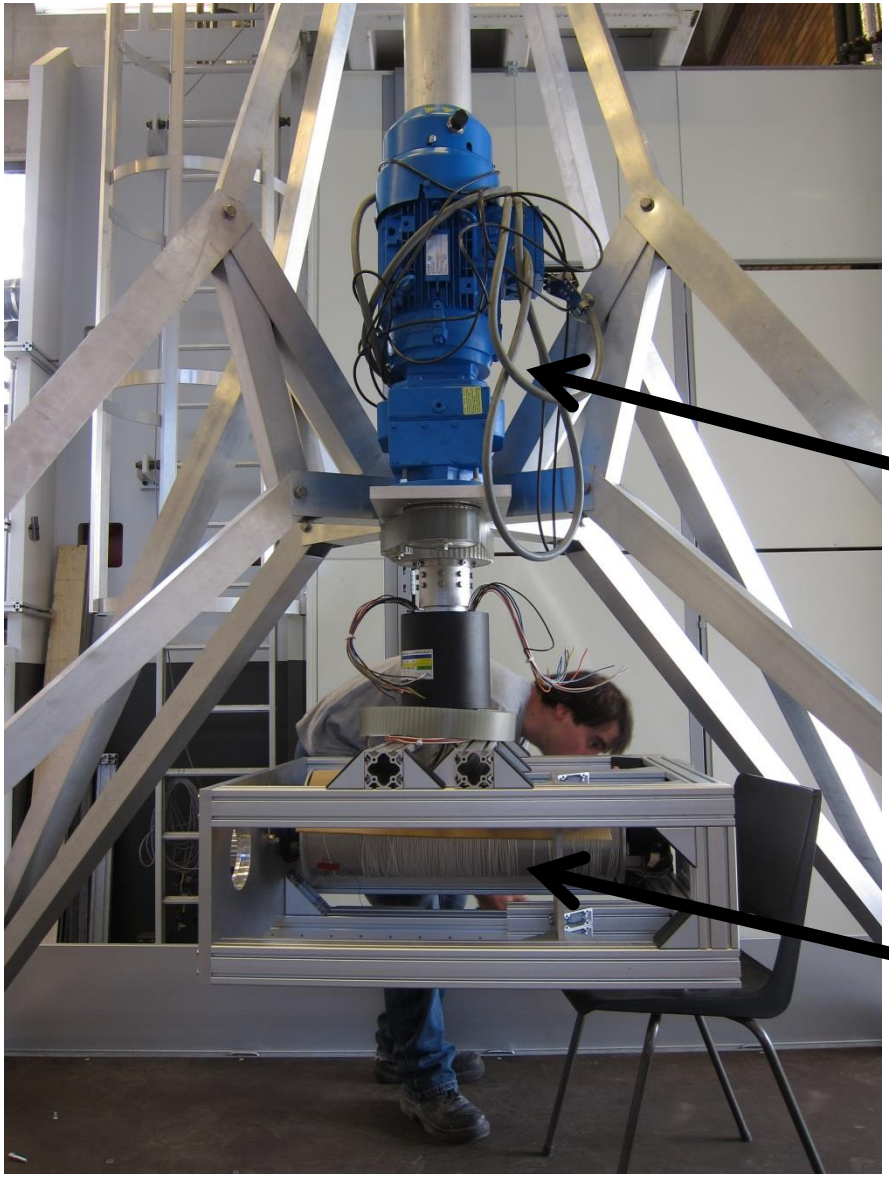
- Stuyts, J., Horn, G., Vandermeulen, W., Driesen, J., & Diehl, M. (2015). Effect of the Electrical Energy Conversion on Optimal Cycles for Pumping Airborne Wind Energy. *IEEE Transactions on Sustainable Energy*, *5* (1), 2-11. doi:10.1109/TSTE.2014.2349071
- Stuyts, J., Geebelen, K., Vandermeulen, W., Driesen, J., & Diehl, M. (2015). Electrical Energy Conversion System for an Experimental Pumping Airborne Wind Energy Set-up. *IEEE Transactions on Energy Conversion*. under review

Important terminology

- Drive = motor + motor controller / convertor
- Winch motor
  - Controls the tether
  - Generates power
- Carousel motor
  - Rotates the carousel
  - Required for launching



Introduction



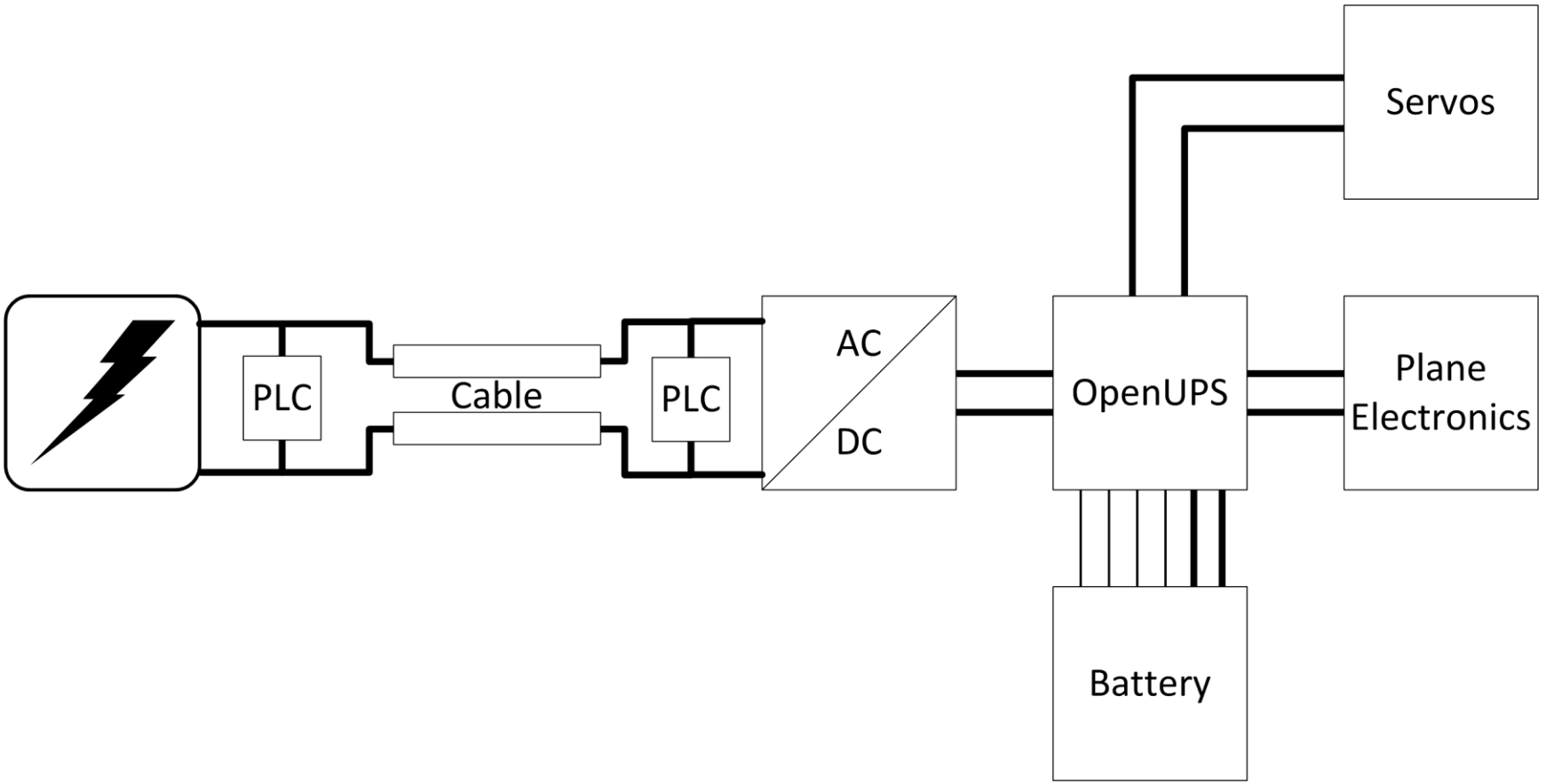
Electrical Energy Conversion System for Pumping Airborne Wind Energy

- Introduction
- Powering the plane
- Electrical system design
- Testing the drives
- Trajectory reoptimization
- Conclusion

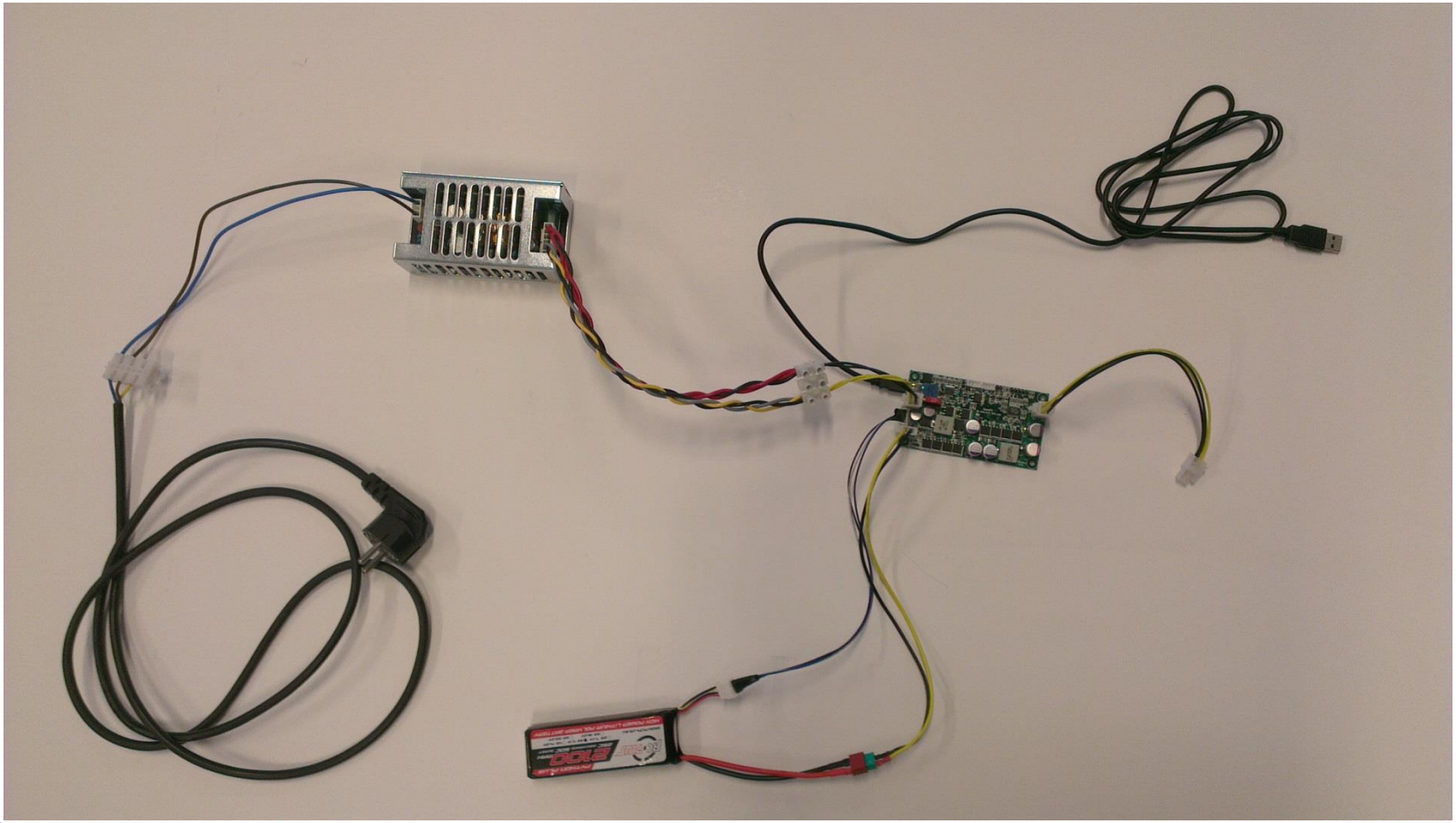
Electrical design

- Power for onboard electronics
- Power for servos
- AC connection
  - Power connection
  - PLC (power line communication)
- Onboard battery
  - Back-up
  - Tether cut possible

System procurement



System procurement



Electrical Energy Conversion System for Pumping Airborne Wind Energy

- Introduction
- Powering the plane
- Electrical system design
- Testing the drives
- Trajectory reoptimization
- Conclusion

Winch motor

- $T_{nom} = 80\ \mathrm{Nm}$
- $n_{nom} = 1000\ rpm$
- $P_{nom} = 8\ kW$

- Fast response time
- Lightweight
- Holding torque
- Encoder

→Permanent magnet synchronous machine

Carousel motor

- $T_{nom} = 400\ Nm$
- $n_{nom} = 100\ rpm$
- $P_{nom} = 4\ kW$

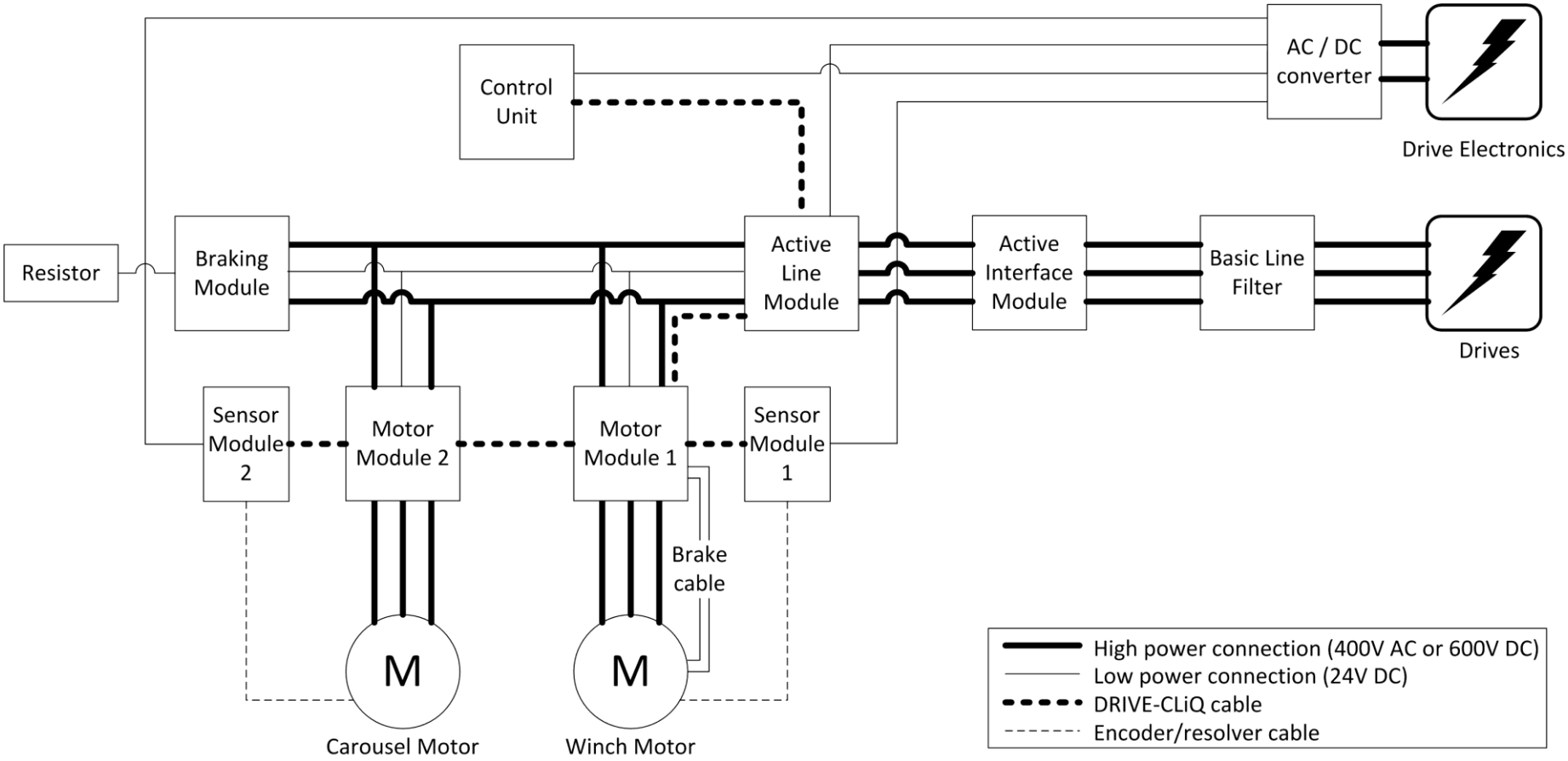
- Simple
- Robust
- Encoder

→**Induction machine**

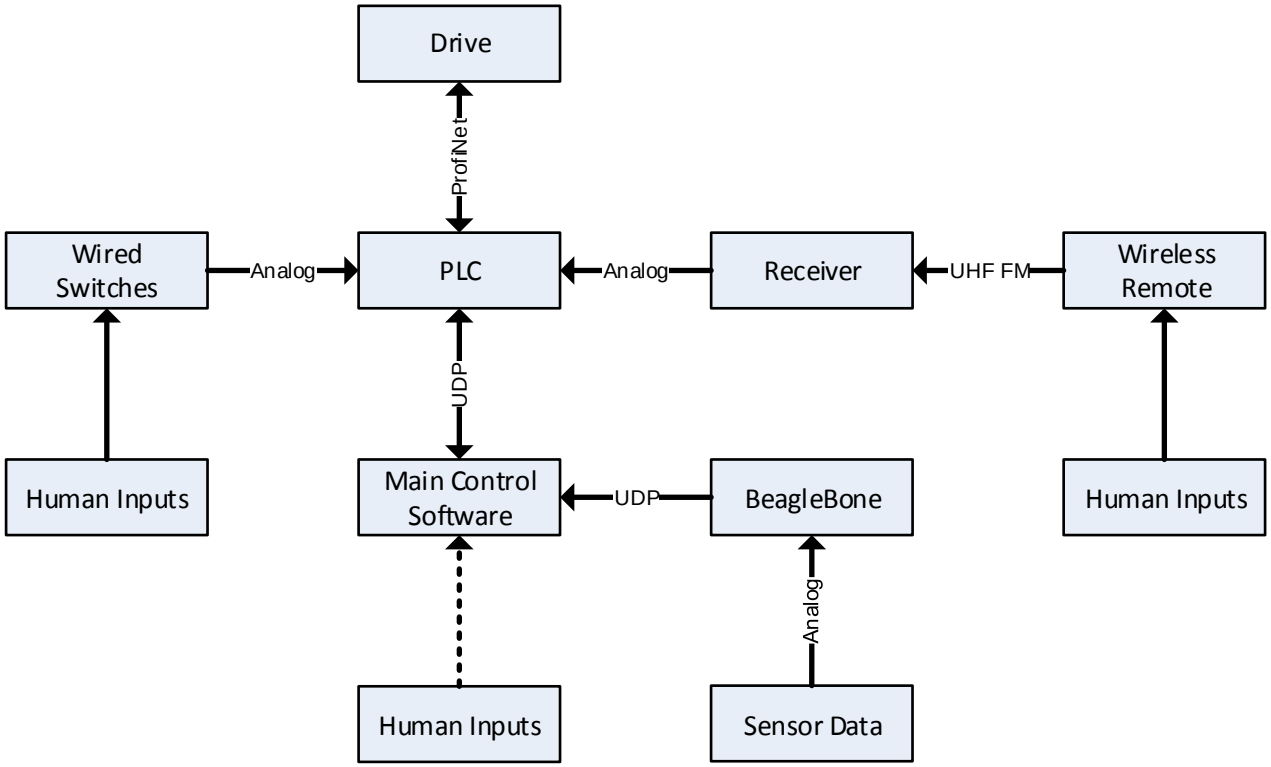
Other requirements

- Weather proofing
- Grid connection
- Sliprings

Drives

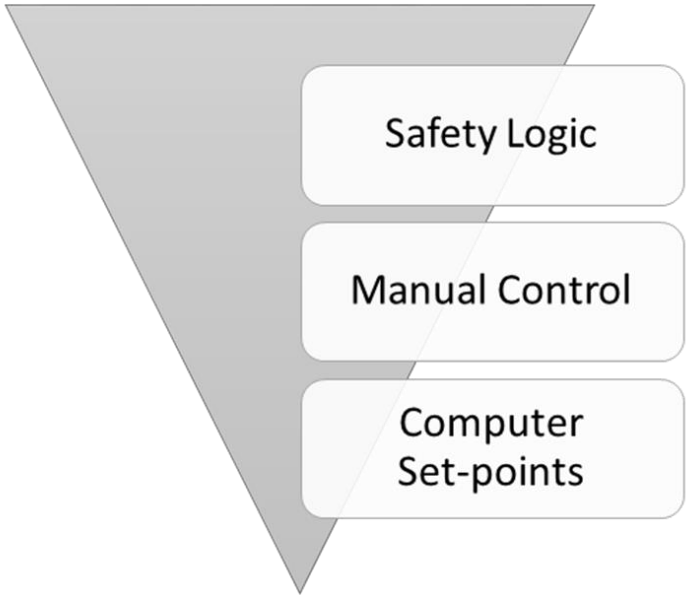

AC / DC converter
Drive Electronics
Control Unit
Resistor
Braking Module
Active Line Module
Active Interface Module
Basic Line Filter
Drives
Sensor Module 2
Motor Module 2
Motor Module 1
Sensor Module 1
Brake cable
M
M
Carousel Motor
Winch Motor
High power connection (400V AC or 600V DC)
Low power connection (24V DC)
DRIVE-CLiQ cable
Encoder/resolver cable

Communication diagram

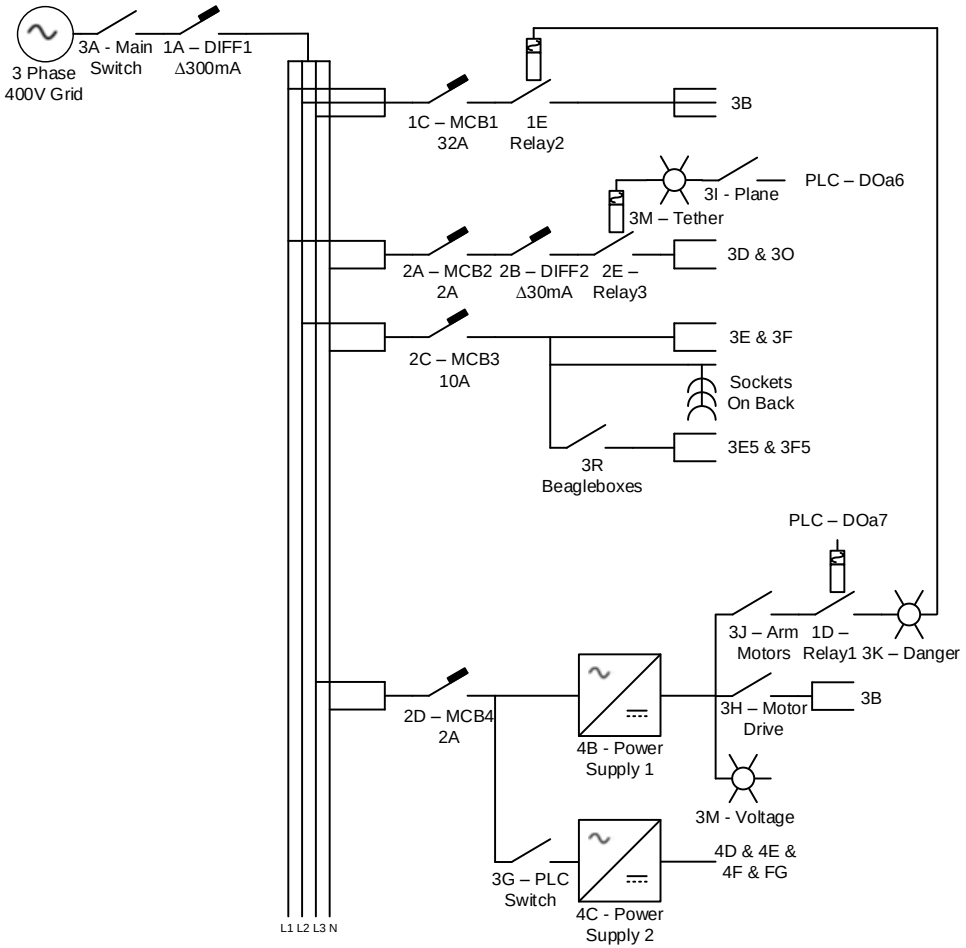


Safety

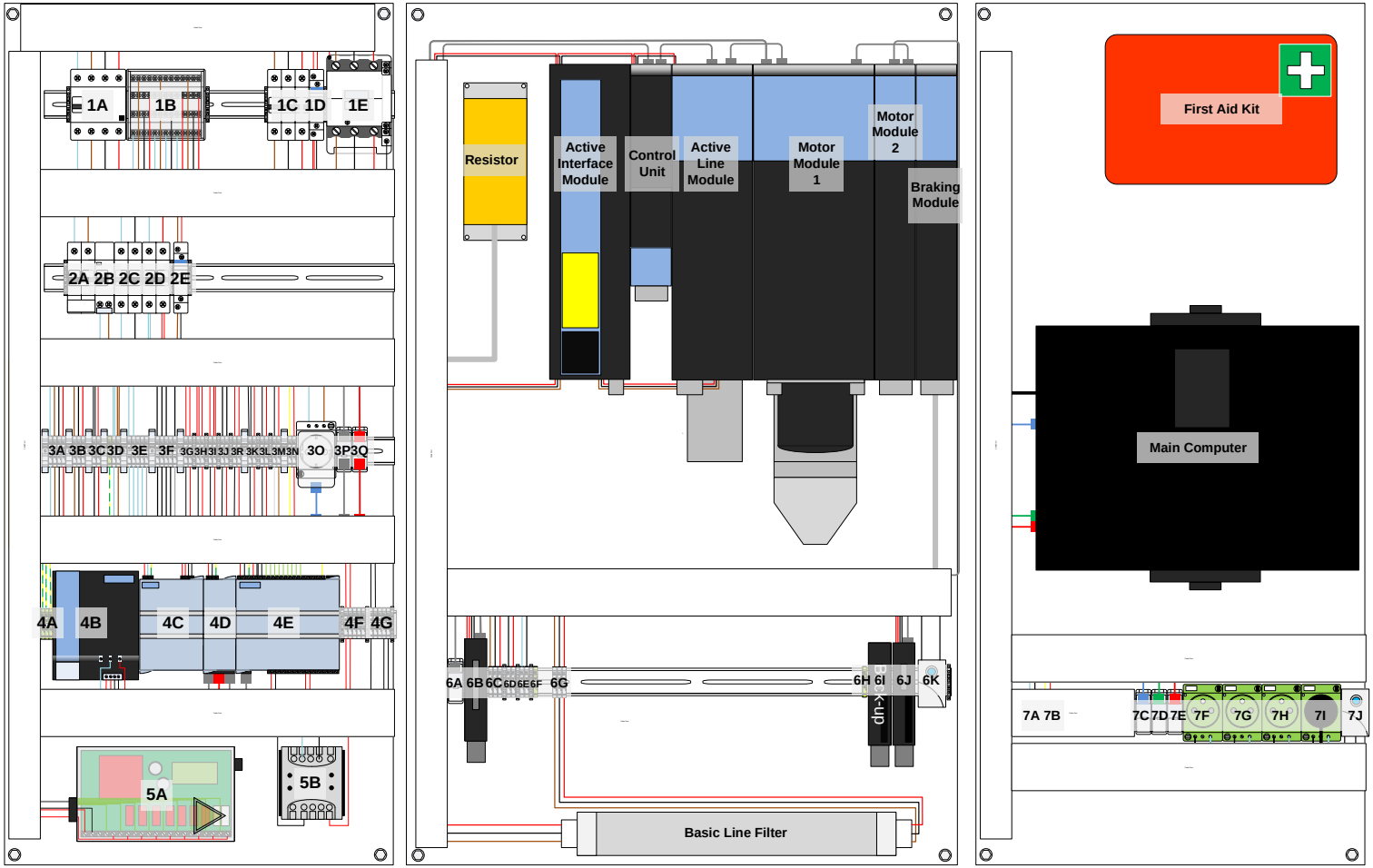
- Mechanical safety
  - Don’t be near!
- Operational safety
  - Intentional procedure
  - Emergency switches
- Electrical safety
  - RCDs
  - MCDs



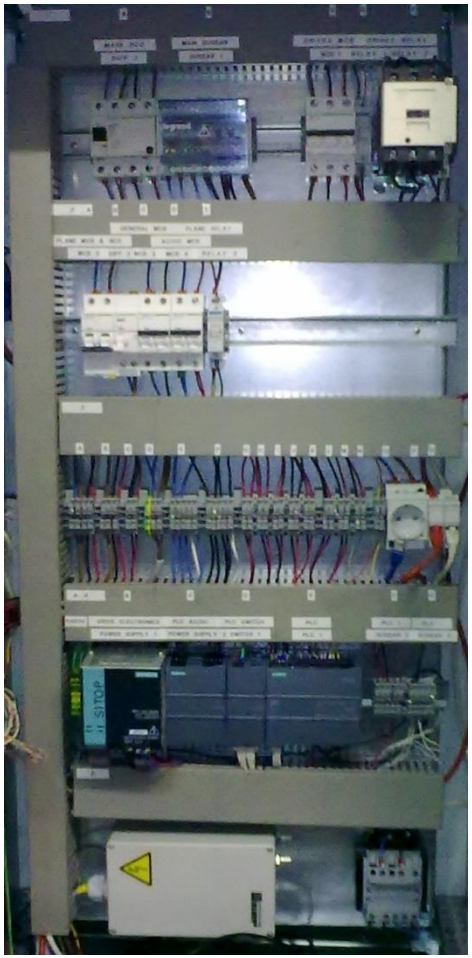
Overlaying architecture



Result


1A
1B
1C 1D
1E
2A 2B 2C 2D 2E
3A 3B 3C 3D 3E 3F 3G 3H 3I 3J 3R 3K 3L 3M 3N 3O 3P 3Q
4A 4B 4C 4D 4E 4F 4G
5A
5B
Resistor
Active Interface Module
Control Unit
Active Line Module
Motor Module 1
Motor Module 2
Braking Module
6A 6B 6C 6D 6E 6F 6G
6H 6I 6J 6K
dn-> up
Basic Line Filter
First Aid Kit
Main Computer
7A 7B
7C 7D 7E 7F 7G 7H 7I 7J

Result



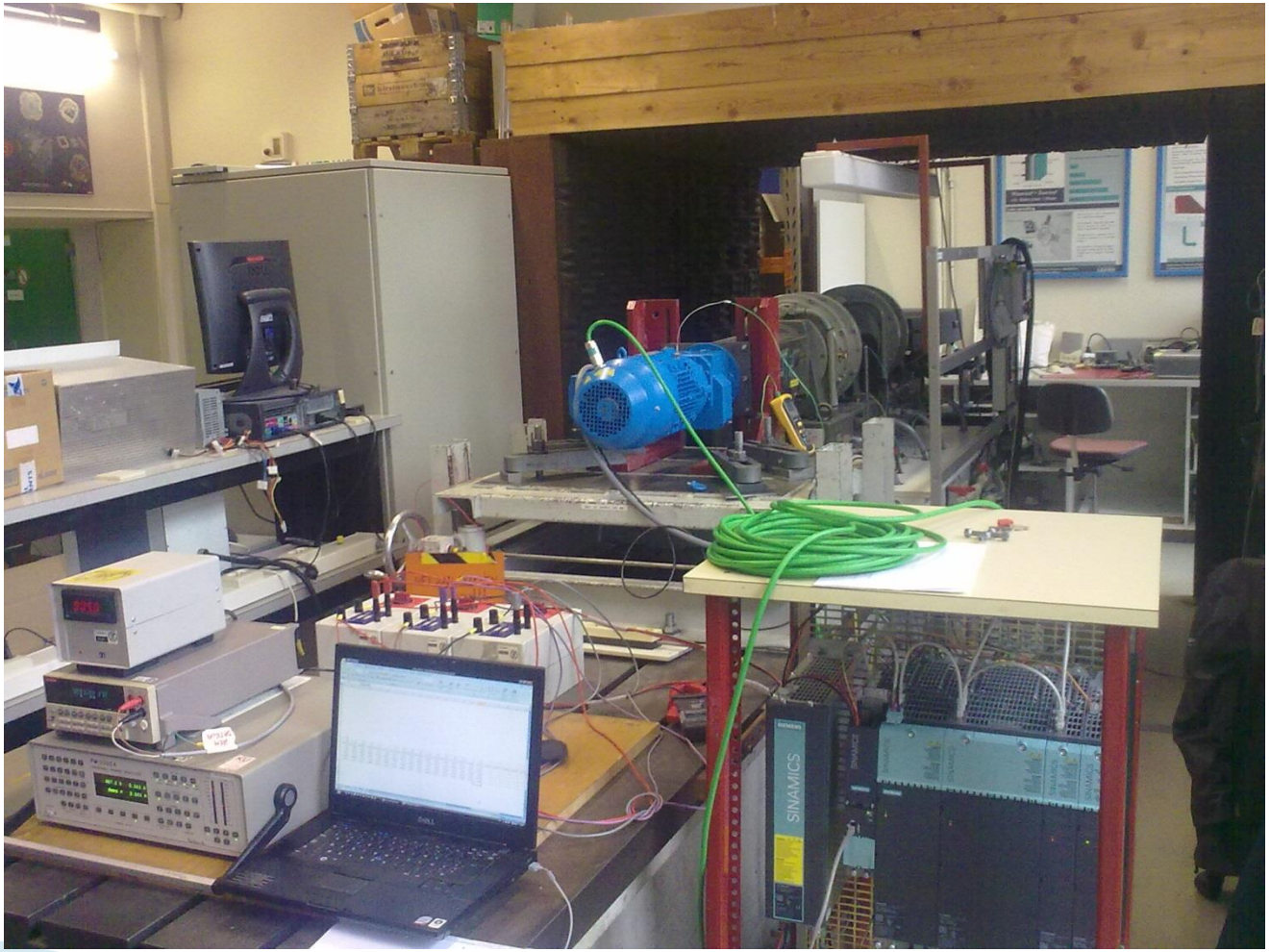

SIEMENS
SINAMICS
SINAMICS
SINAMICS
SINAMICS
SINAMICS
SINAMICS
CAROUSEL MOTOR
WINCH MOTOR


Erste Hilfe
BRAIN

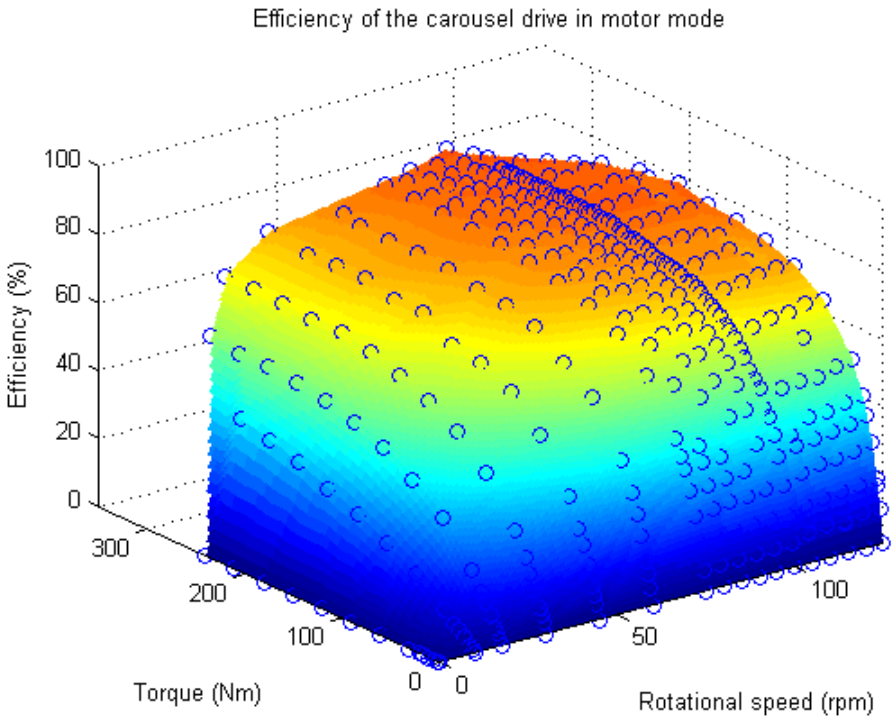
Electrical Energy Conversion System for Pumping Airborne Wind Energy

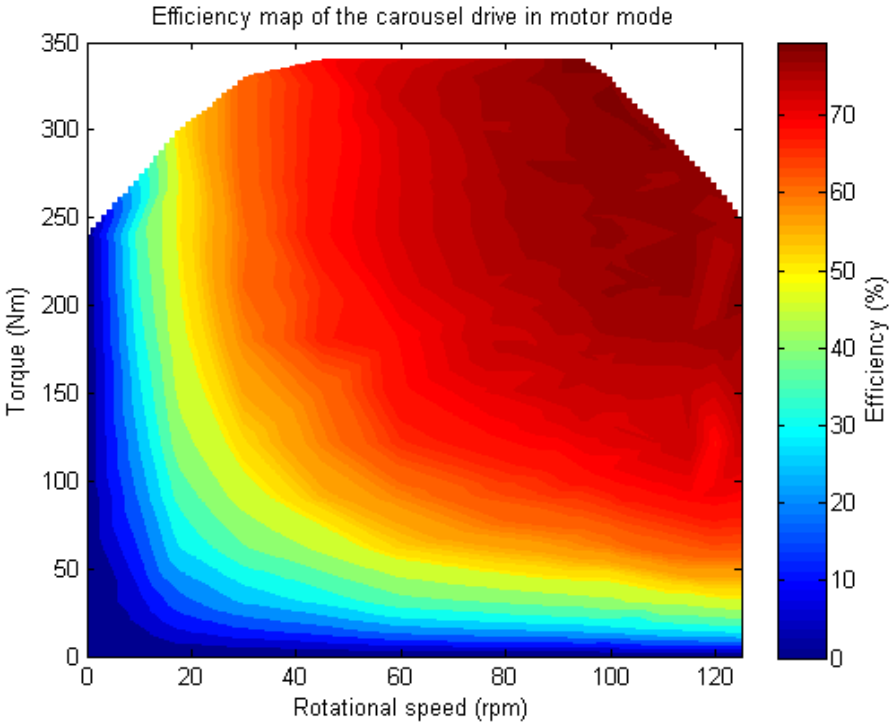
- Introduction
- Powering the plane
- Electrical system design
- Testing the drives
- Trajectory reoptimization
- Conclusion

Carousel drive – motor mode

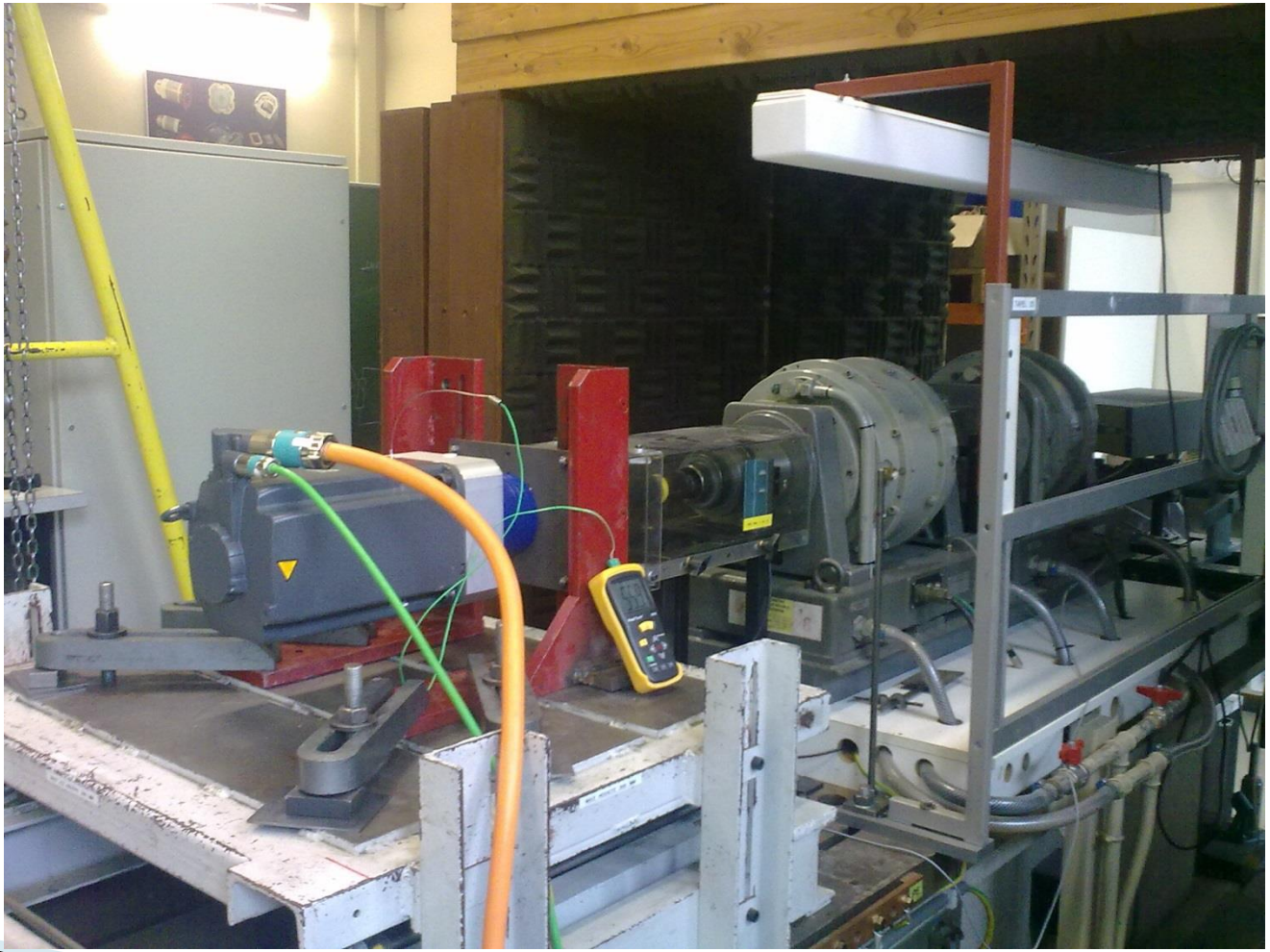


Carousel drive – motor mode

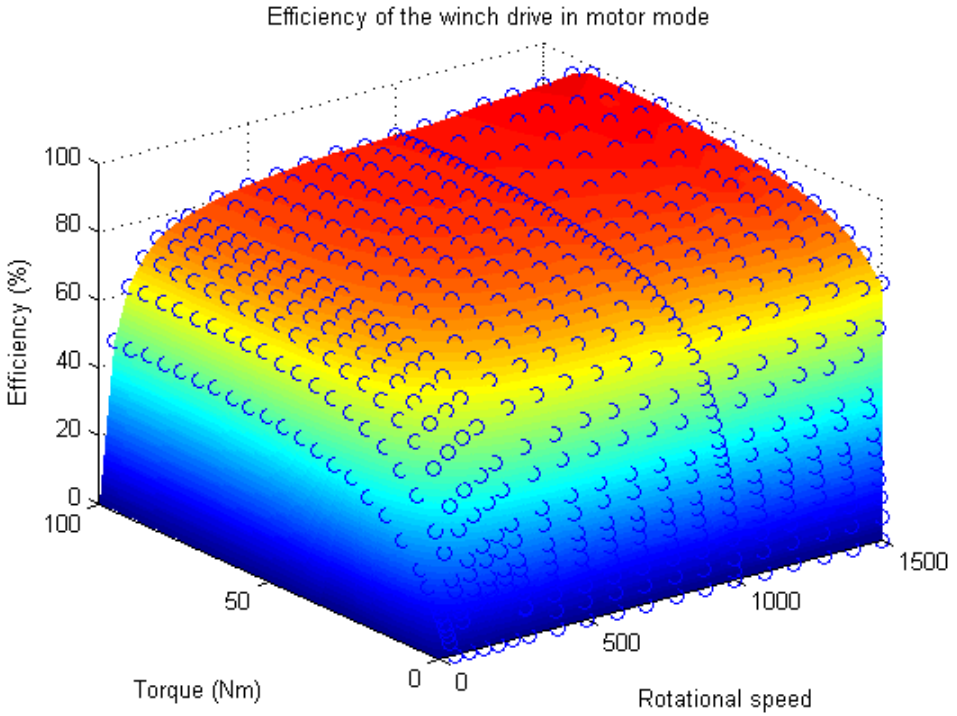


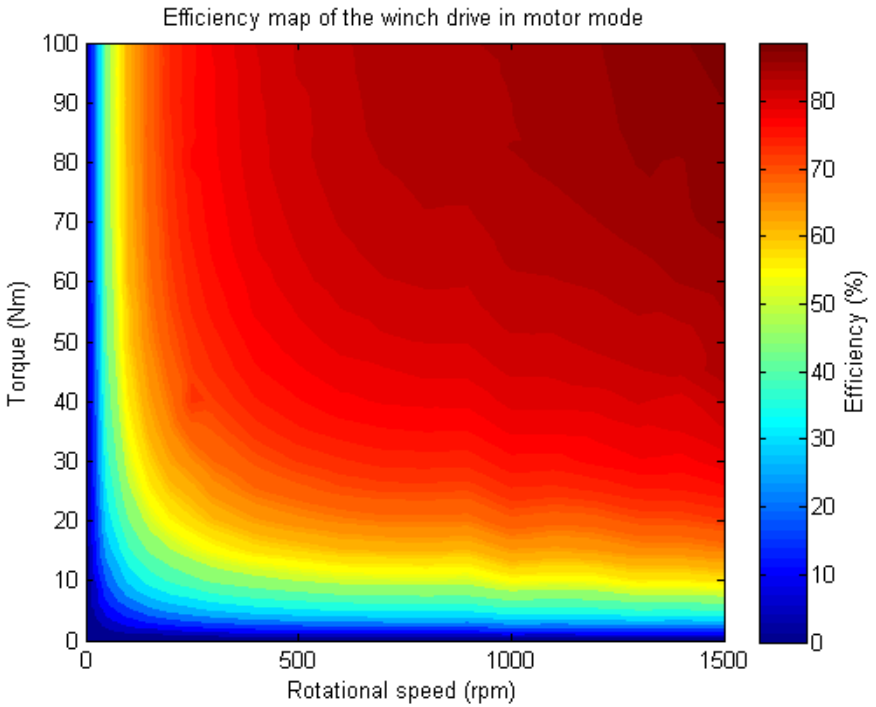


Winch drive – motor mode

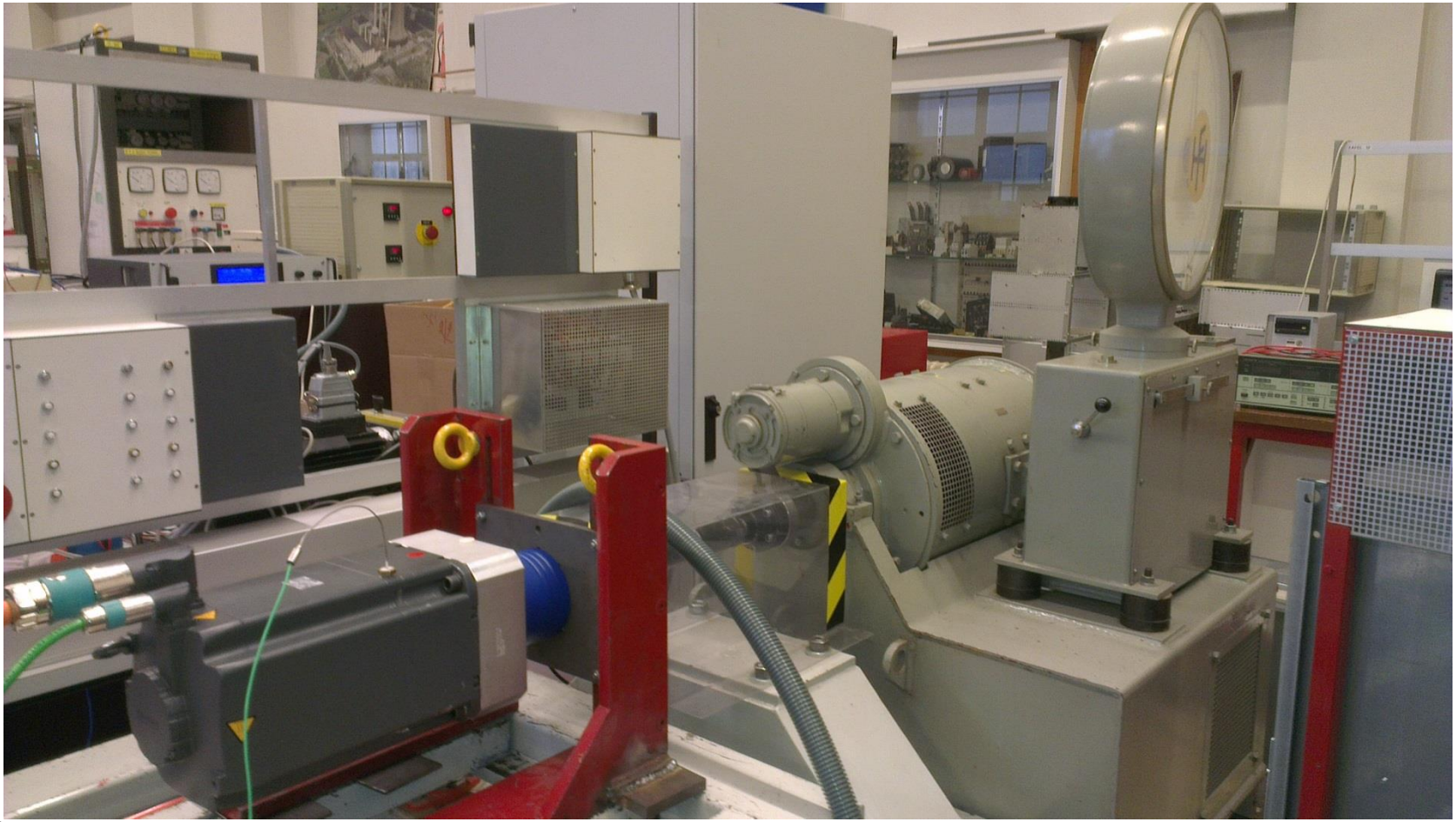


Winch drive – motor mode

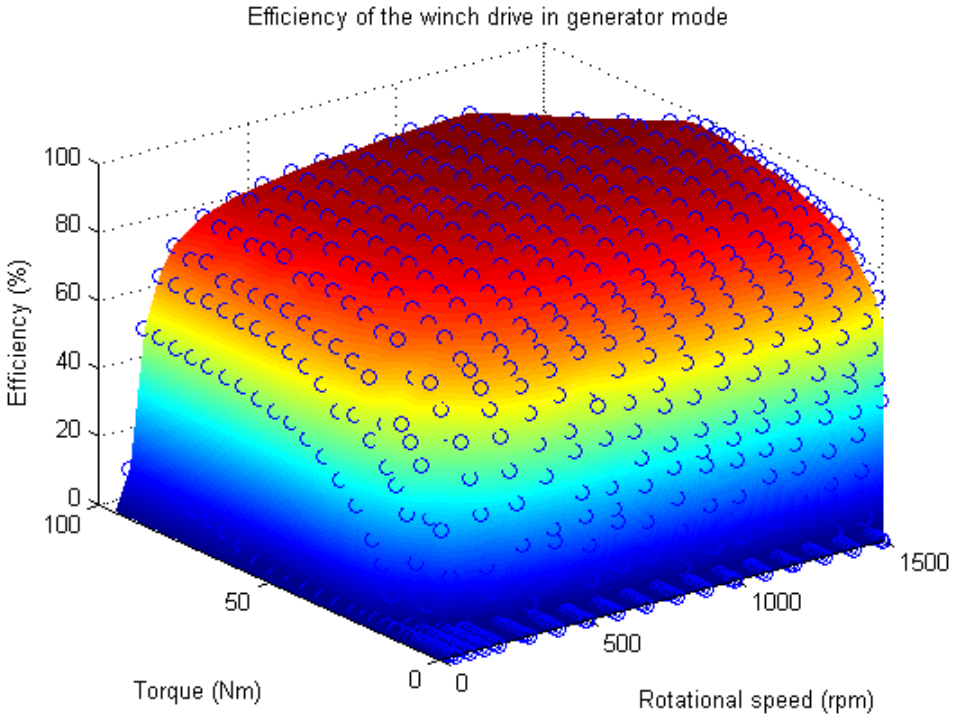


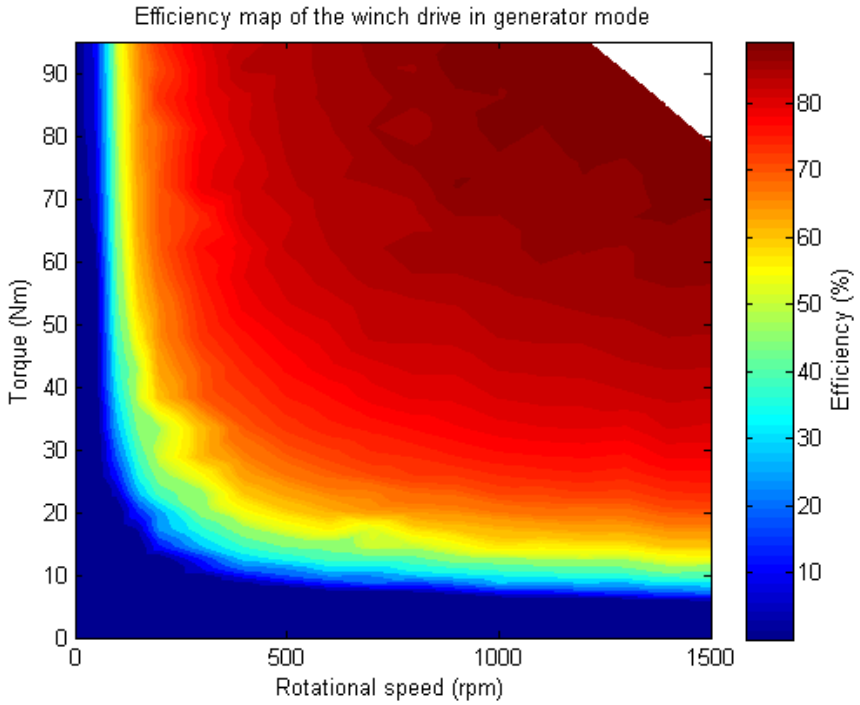


Winch drive – generator mode



Winch drive – generator mode





Electrical Energy Conversion System for Pumping Airborne Wind Energy

- Introduction
- Powering the plane
- Electrical system design
- Testing the drives
- Trajectory reoptimization
- Conclusion

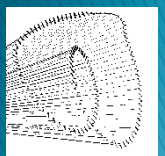
Effect of drive properties on the optimal trajectory

- Adding drive efficiency
- Adding motor constraints
- Comparing results:

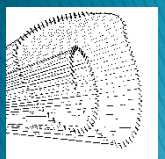
Before	After
Optimized trajectory for mechanical energy	Optimized trajectory for electrical energy

Modeling $P_{elec} = f(P_{mech})$

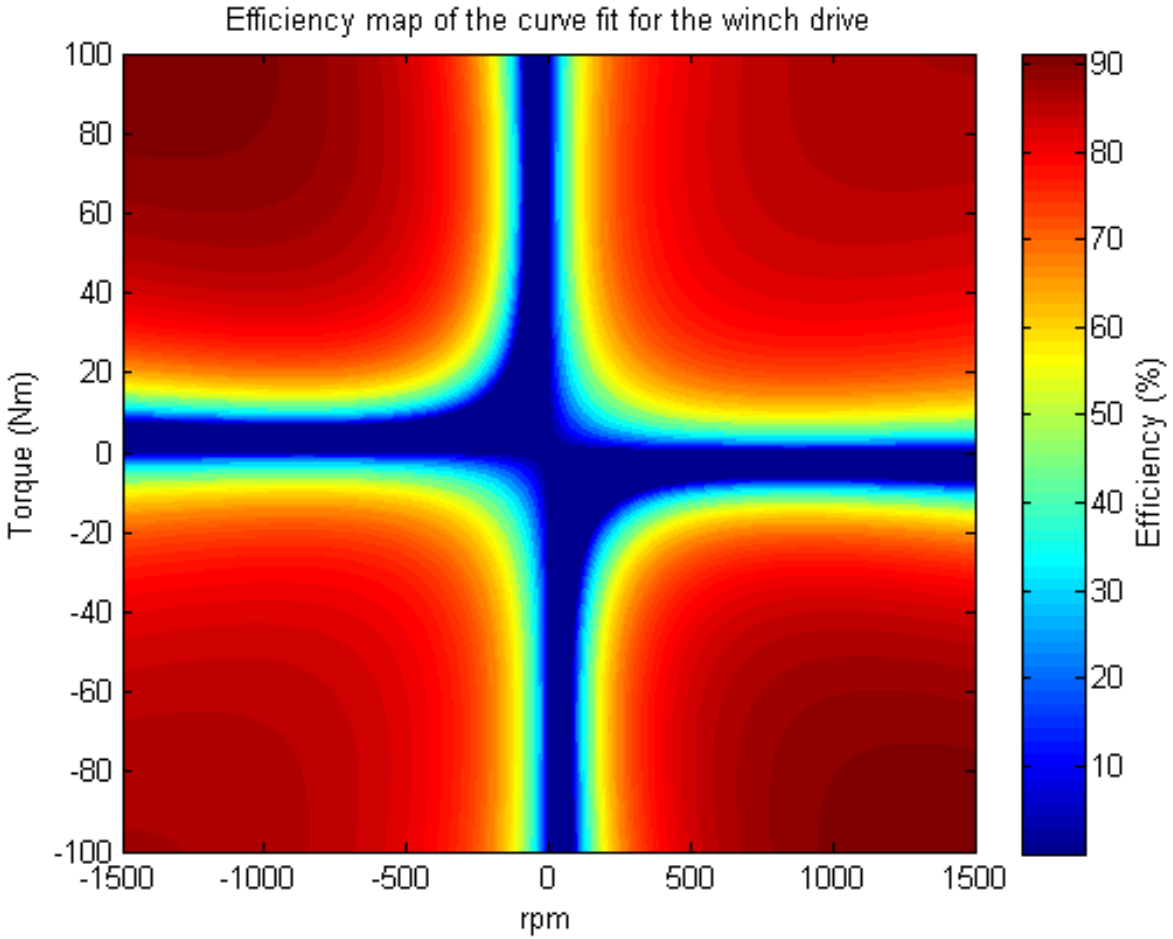
- Smooth curve required
- Power loss calculation
- Least squares solution for measurements
- $P_{elec} = [a_0 \quad a_1 \quad a_2 \quad a_3] \cdot \begin{bmatrix} 1 \\ \omega_{mech}^2 \\ \mathrm{T}_{mech}^2 \\ \omega_{\mathrm{mech}} \cdot \mathrm{T}_{mech} \end{bmatrix}$



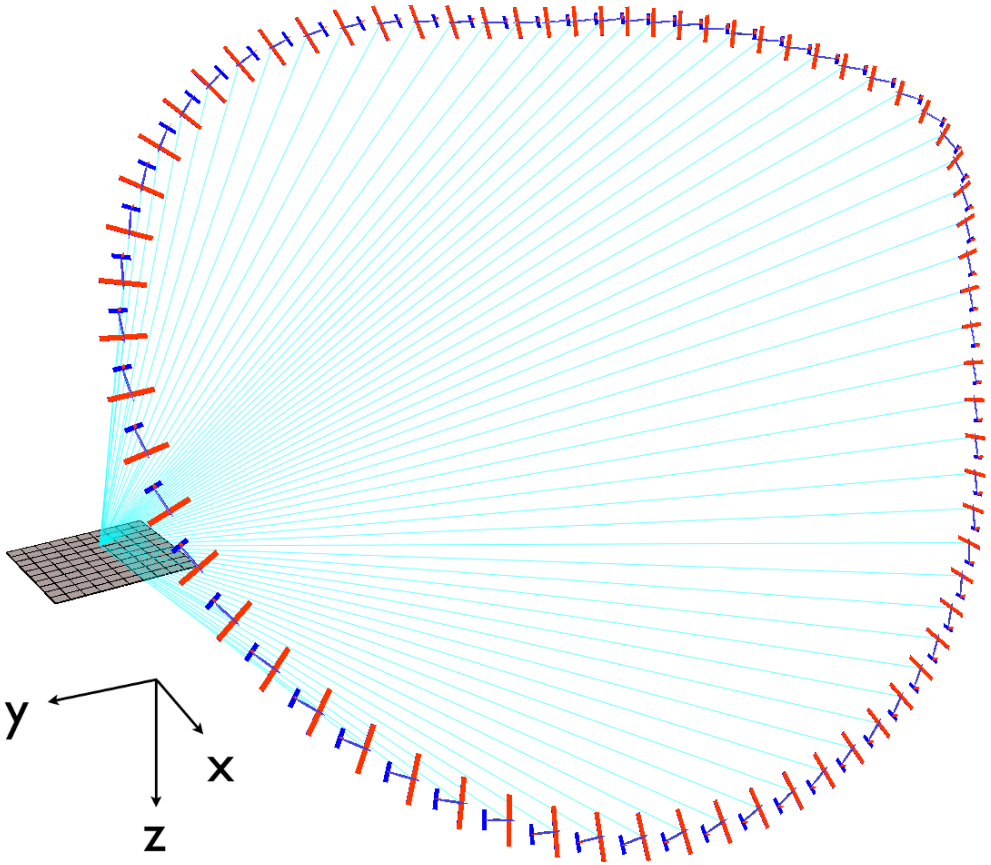
Curve fit results



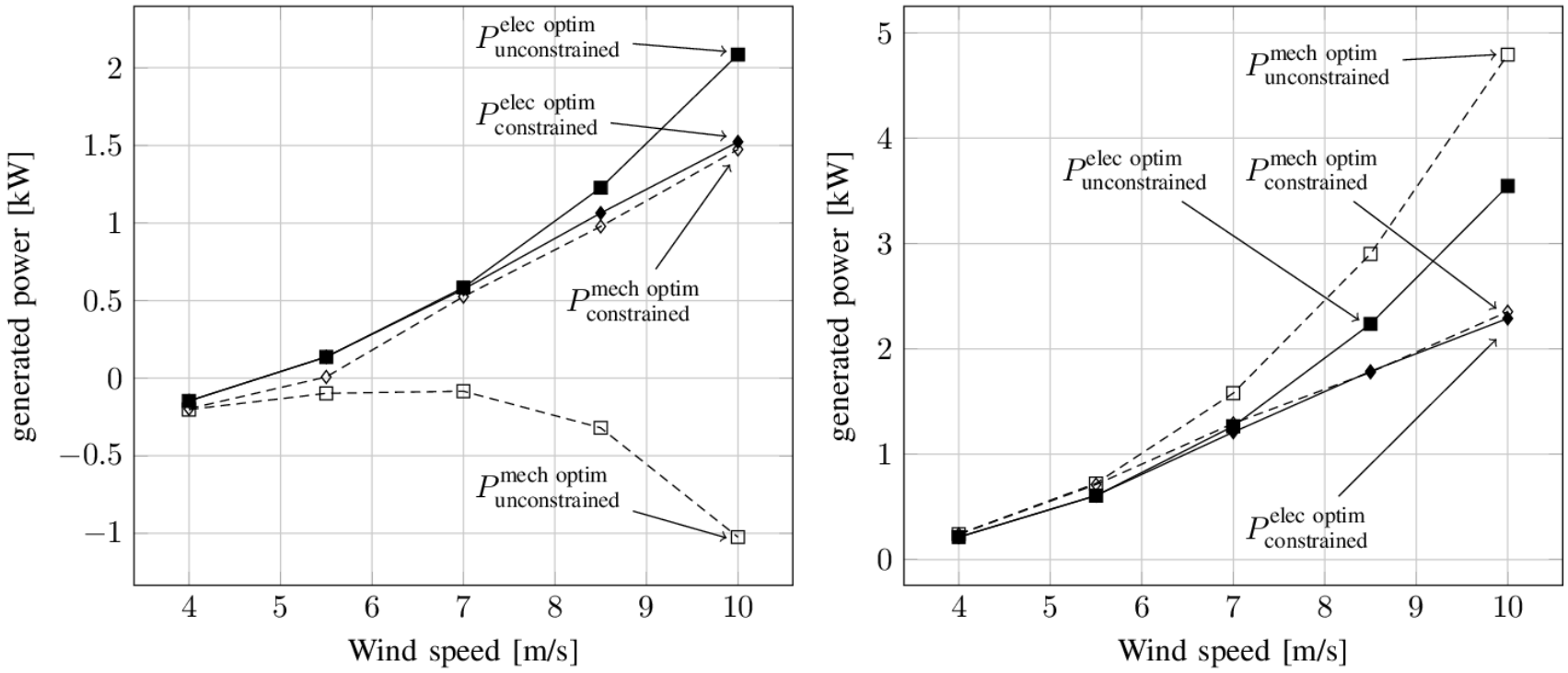
Curve fit results



Trajectory



Drive efficiency changes optimal energy output



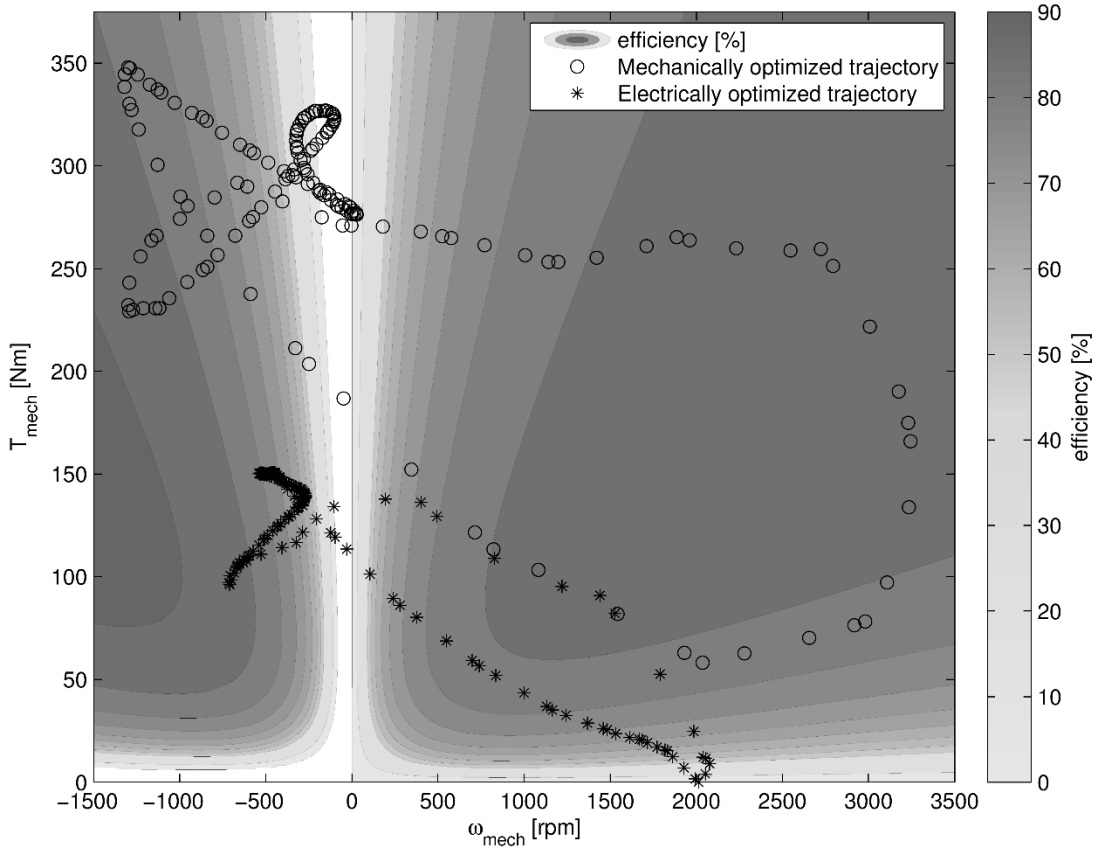
(a) Electrical powers

(b) Mechanical powers

Fig. 8. Optimization results for all scenarios, sorted by electrical (a) and mechanical (b) generated power; sub- and superscripts are used here (and only here) to indicate the scenario, elec/mech optim indicates an electrically or mechanically optimized scenario, (un)constrained indicates an (un)constrained scenario; the data can be found in Table II .

Drive efficiency changes optimal energy output

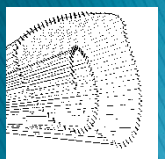
At high wind speed (10m/s) without constraints → trend



$$1\ kW_{consumed} \rightarrow 2\ kW_{generated}$$

Conclusions

- Optimizing with drive efficiency
  - Enables higher electrical output power
  - Enables a wider operating range
- Consider drive dimensioning

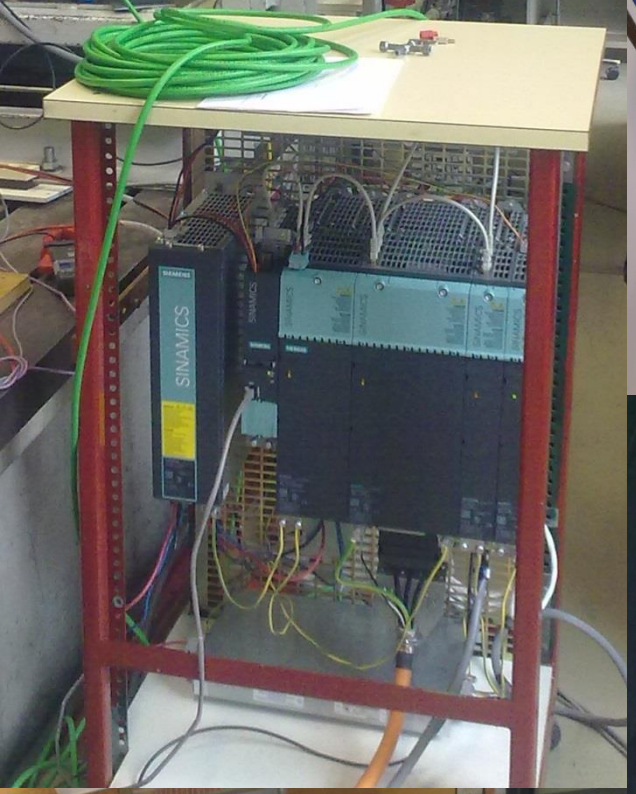


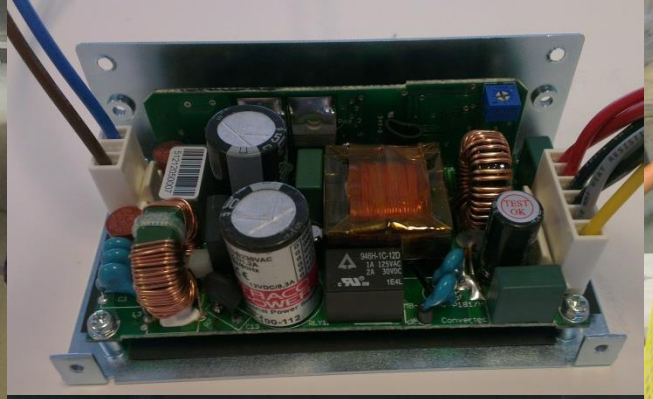
Electrical Energy Conversion System for Pumping Airborne Wind Energy

- Introduction
- Powering the plane
- Electrical system design
- Testing the drives
- Trajectory reoptimization
- Conclusion

Conclusions

- Electrical system design
  - Dimensioning
  - Selecting drives
  - Electrical architecture
  - Safety
- Operation
  - Prioritize control
  - Safety


SIEMENS
SINAMICS


TEST OK