Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Conceptualization and Multi-Objective Optimization of the Electric System of an Airborne Wind Turbine

J. W. Kolar et al.

Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
www.pes.ee.ethz.ch

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Pareto-Optimal Design of Airborne Wind Turbine Power Electronics

J. W. Kolar, T. Friedli, F. Krismer, A. Looser, M. Schweizer, P. Steimer, J. Bevirt

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JOBY ENERGY

Swiss Federal Institute of Technology (ETH) Zurich
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www.pes.ee.ethz.ch

Outline

- ETH Zurich
- Power Electronic Systems Laboratory (PES)
- Out-of-the-Box Wind Turbine Concepts
  → Pumping Power Kites
  → Airborne Wind Turbines
- Feasibility of AWT Electrical System
  → Electrical System Structure
  → Multi-Objective Optimization (Weight vs. Efficiency)
  → Controls Aspects
- Summary

Profile of ETH Zurich Dept. of ITET Power Electronic Systems Lab

Departments of ETH Zurich

ARCH	Architecture
BAUG	Civil, Environmental and Geomatics Eng.
BIOL	Biology
BSSE	Biosystems
CHAB	Chemistry and Applied Biosciences
ERDW	Earth Sciences
GESS	Humanities, Social and Political Sciences
HEST	Health Sciences, Technology
INFK	Computer Science
ITET	Information Technology and Electrical Eng.
MATH	Mathematics
MATL	Materials Science
MAVT	Mechanical and Process Engineering
MTEC	Management, Technology and Economy
PHYS	Physics
USYS	Environmental Systems Sciences

21 Nobel Prizes
413 Professors
6240 T&R Staff

2 Campuses
136 Labs
35% Int. Students
90 Nationalities
36 Languages

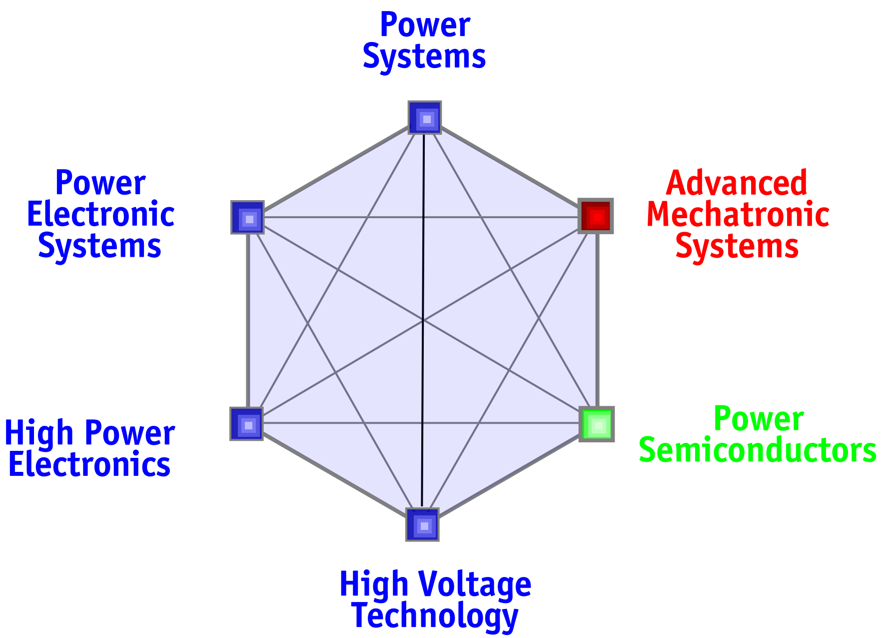
150th Anniv. in 2005

Students ETH in total

18’000 B.Sc.+M.Sc.-Students
3’900 Doctoral Students

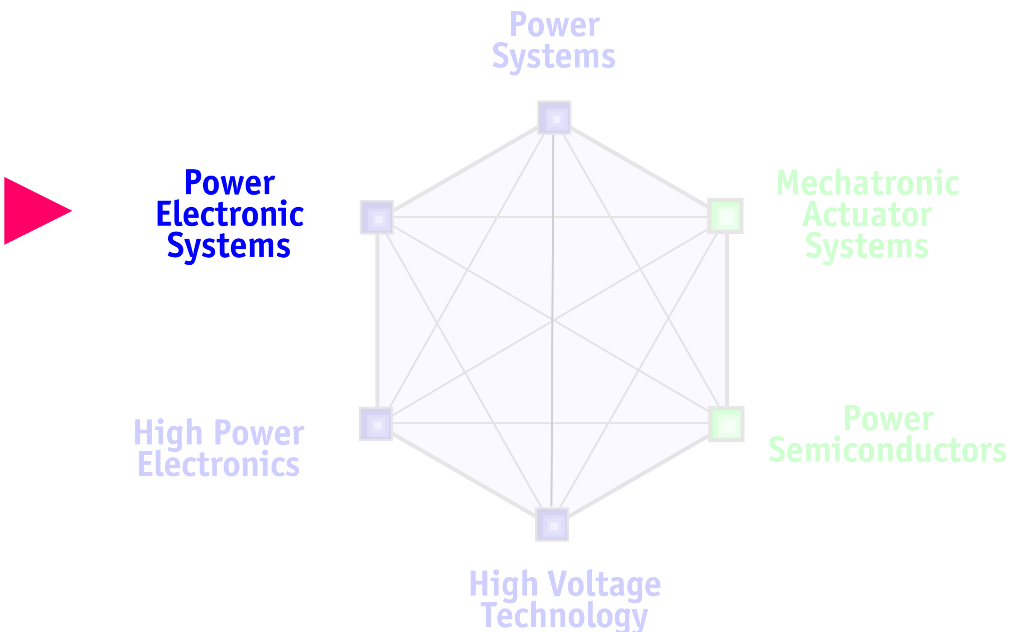
Research in EE @ D-ITET

Energy Research Cluster @ D-ITET



- Balance of Fundamental and Application Oriented Research

Energy Research Cluster @ D-ITET



- Balance of Fundamental and Application Oriented Research

Power Electronic Systems Laboratory

Power Electronic Systems Laboratory
Johann W. Kolar

Industry Relations
R. Coccia / B. Seiler

AC-DC Converter	AC-AC Converter	DC-DC Converter	DC-AC Converter	Pulsed Power	Multi-Domain Modeling	Mega-Speed Drives	Magnetic Levitation
F. Krismer		**J. Mühlethaler**	**D. Bortis**		**A. Müsing**		
F. Vancu R. Bosshard S. Schroth Ch. Marxgut	M. Schweizer N. Widmer	T. Andersen D. Boillat U. Badstübner M. Kasper St. Waffler G. Ortiz	Y. Lobsiger B. Wrzecionko R. Burkart H. Uemura	T. Soeiro	F. Giezendanner I. Kovacevic A. Stupar	T. Baumgartner A. Looser A. Tüysüz	M. Steinert T. Reichert B. Warberger C. Zingerli F. Zürcher

Secretariat
M. Kohn

Administration
P. Albrecht / P. Maurantonio

Computer Systems
C. Stucki

Electronics Laboratory
P. Seitz

28 Ph.D. Students
4 Post Docs

ECPE Competence Centre

EPSMA

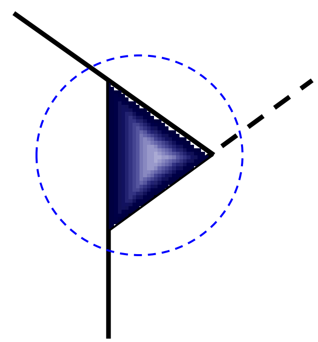
Leading Univ. in Europe

PES Research Scope

Power Electronics

Cross-Departmental

Mechanical Eng., e.g. Turbomachinery, Robotics
Microsystems
Medical Systems
Economics / Society



Actuators / EL. Machines

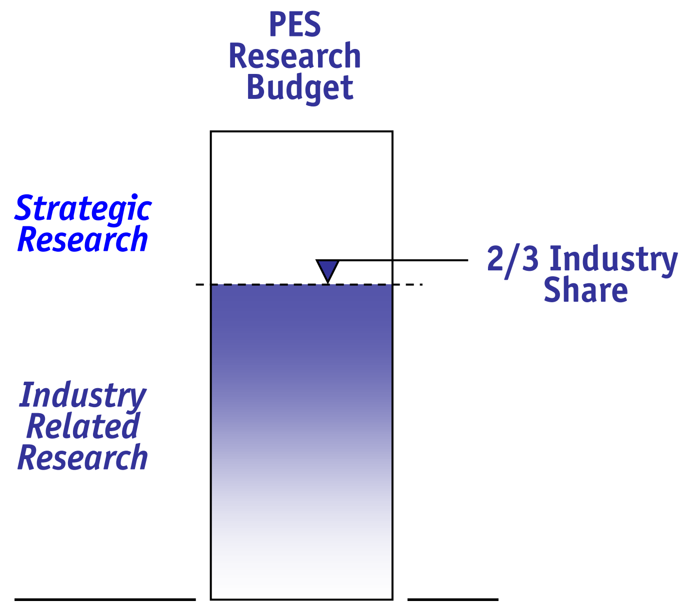
- *Micro-Scale Energy Systems*
- *Wearable Power*
- *Exoskeletons / Artificial Muscles*
- *Environmental Systems*
- *Pulsed Power*

Industry Collaboration

▶ Core Application Areas

- Automotive Systems
- More-Electric Aircraft
- Renewable Energy
- Semiconductor Process Technology
- Medical Systems
- Industry Automation
- Etc.

▶ *16 International Industry Partners*

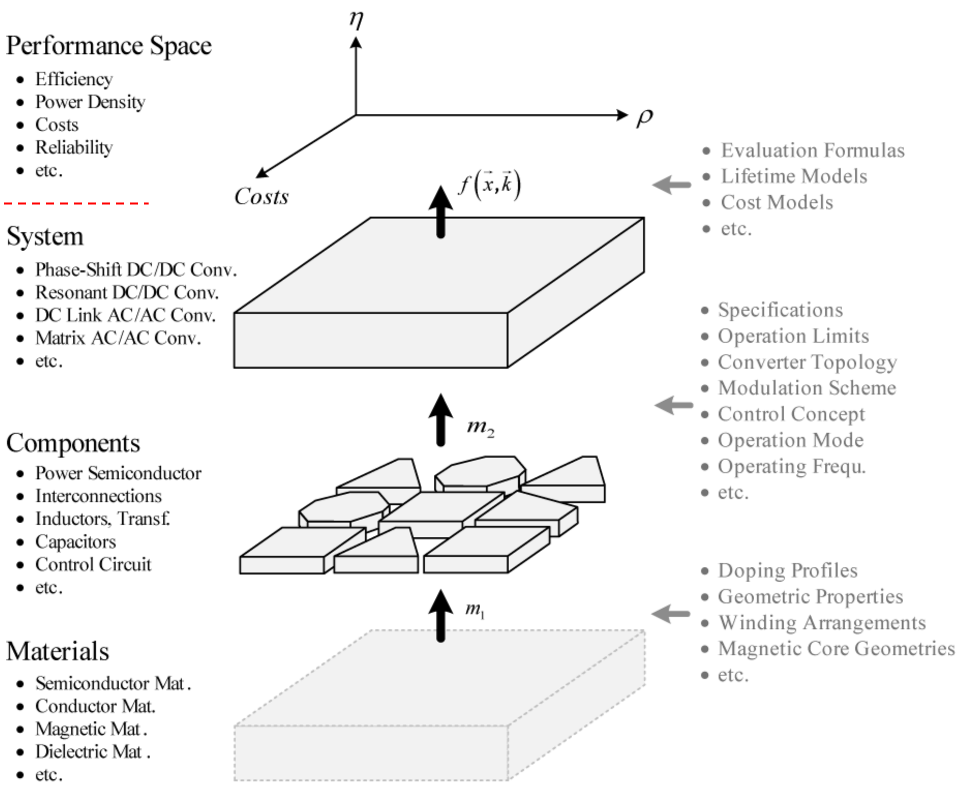


General Research Approach

Abstraction of Power Converter Design

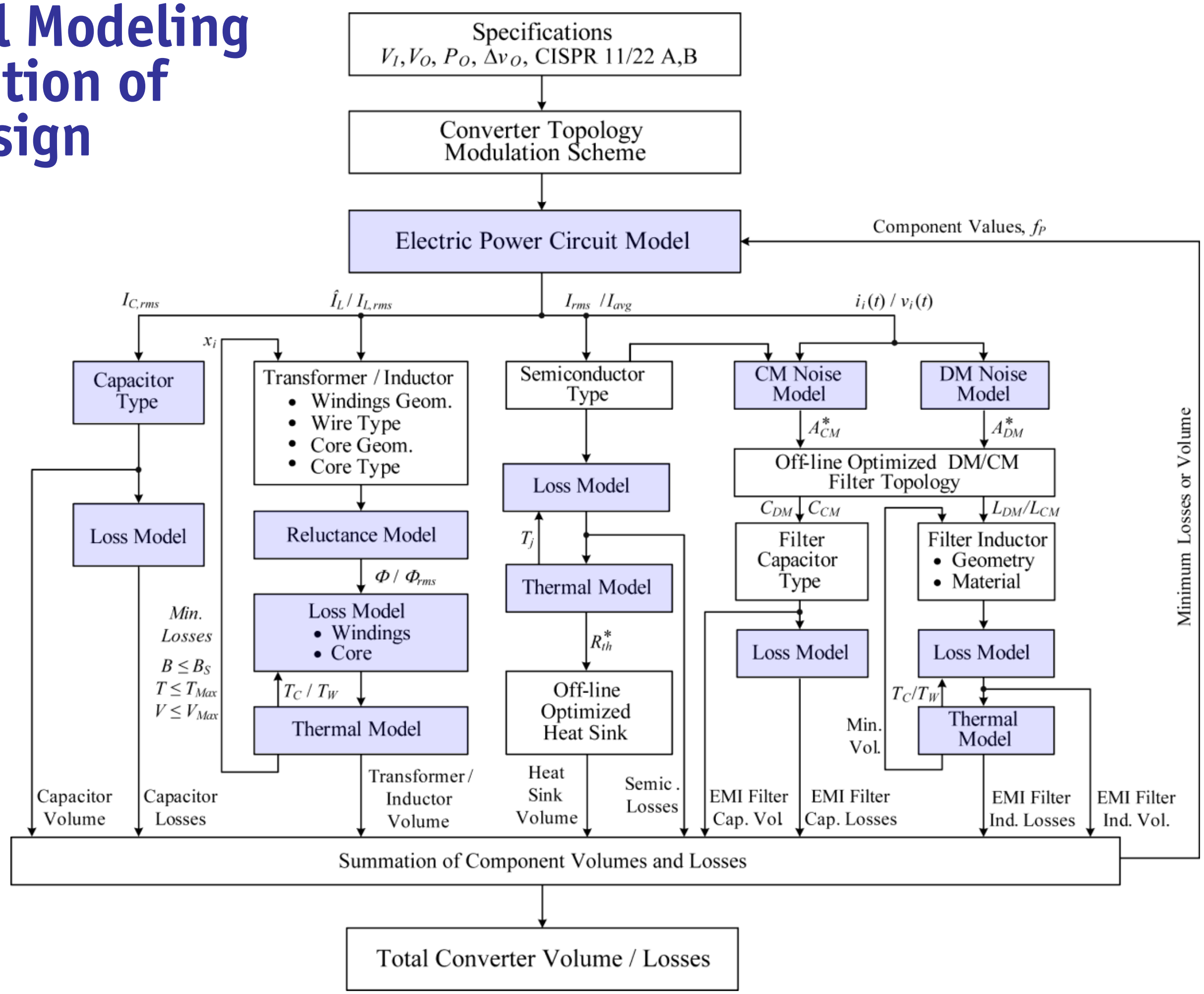
Performance Space

Design Space



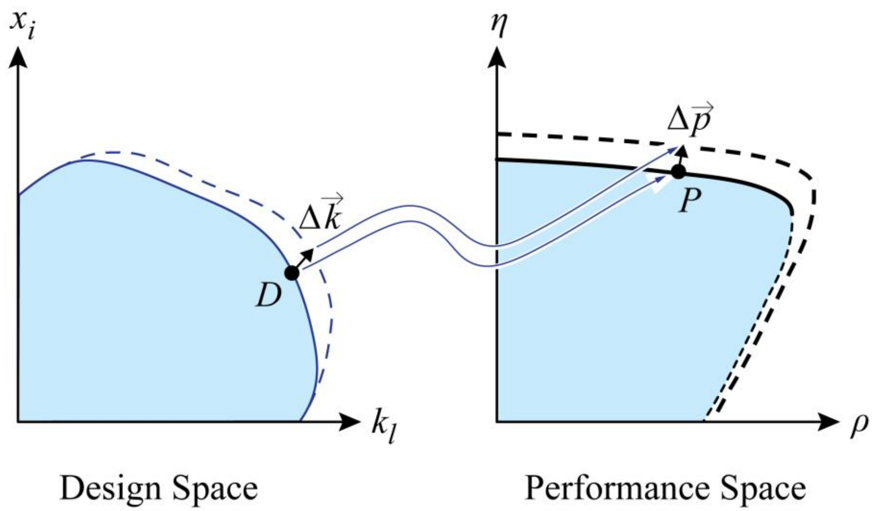
- Mapping of *Design Space* into System *Performance Space*

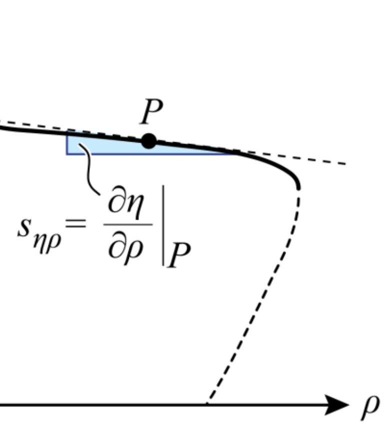
Mathematical Modeling and Optimization of Converter Design



Technology Sensitivity Analysis Based on η-ρ-Pareto Front

- ► Sensitivity to Technology Advancements
- ► Trade-off Analysis

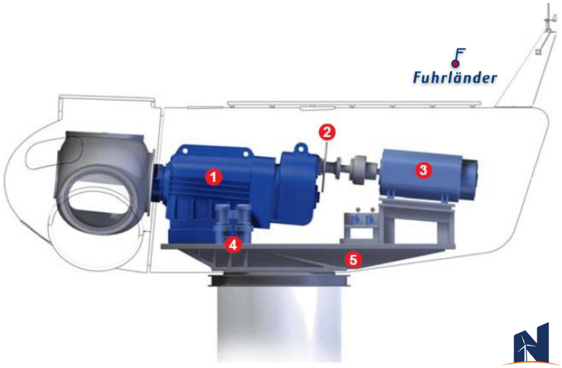




"Out-of-the-Box"
Wind Turbine Concepts

Power Kite & *Ground-Based* EE-Generation
Power Kite & *On-Board* EE-Generation

Conventional 100kW Wind Turbine



▶ Characteristics

- Tower 35m/18 tons
- Rotor 21m / 2.3tons
- Nacelle 4.4 tons

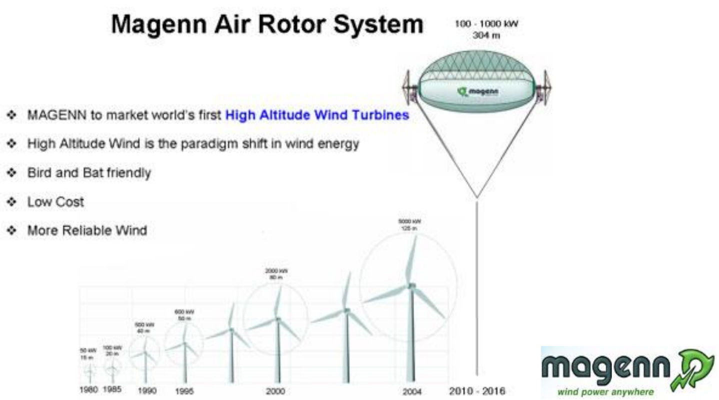
▼

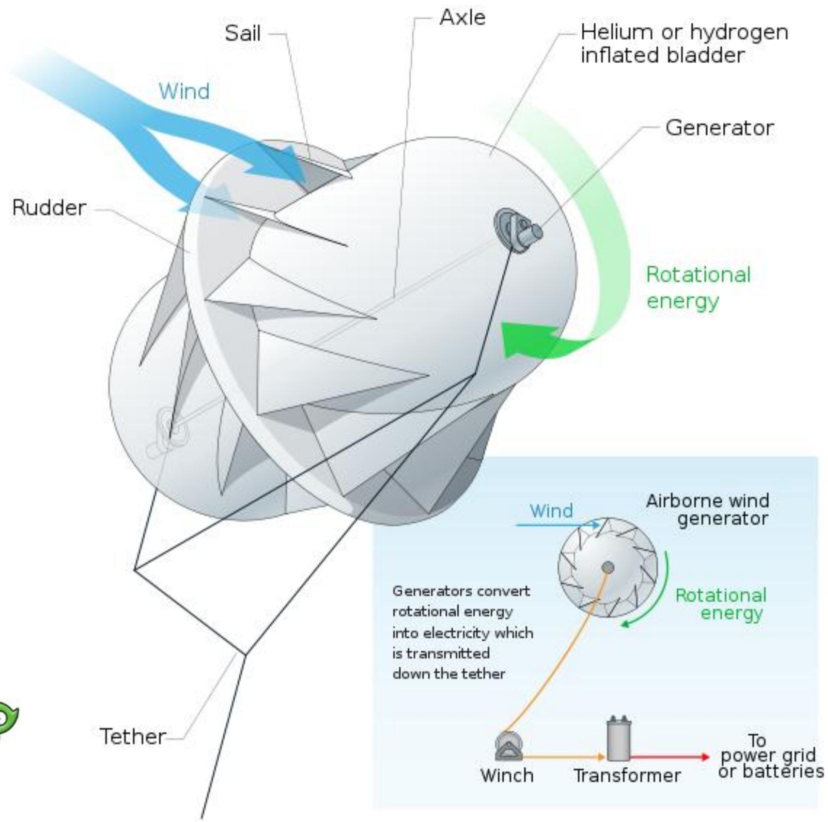
$$v_{\mathrm{W}}(h) = v_{\mathrm{W}}^{*}\left(\frac{h}{h^{*}}\right)^{\alpha_{\mathrm{H}}}$$

■ Large Fraction of Mechanically Supporting Parts / High Costs

Air Rotor Wind Generator

- Helium or Hydrogen Inflated
- Magnus Effect - Additional Lift





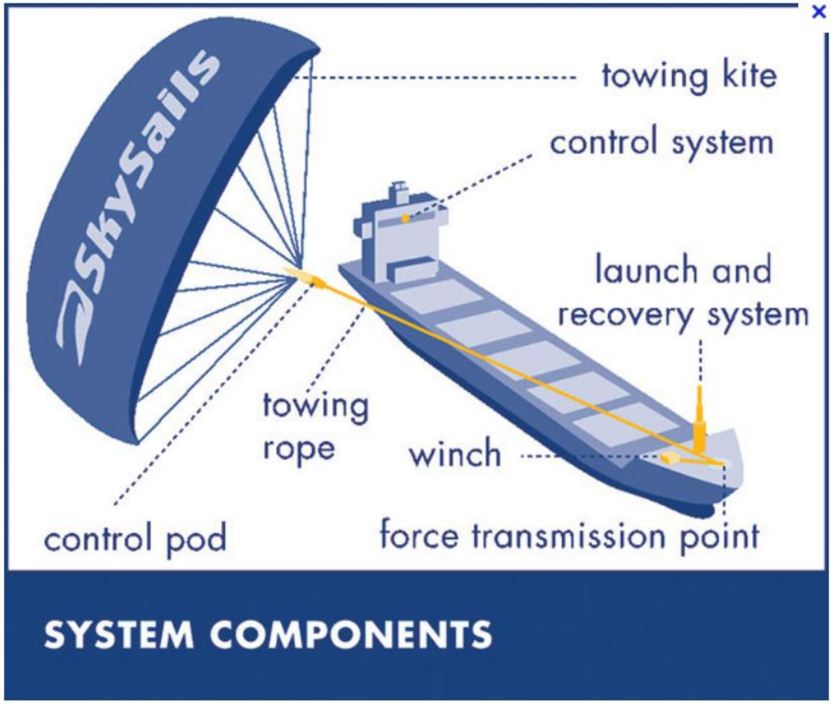
Revolutionize Wind Power Generation Using Kites / Tethered Airfoils

[2] M. Loyd, 1980

- Wing Tips / Highest Speed Regions are the Main Power Generating Parts of a Wind Turbine

SkySails → Support Ship Propulsion by Large Towing Kite

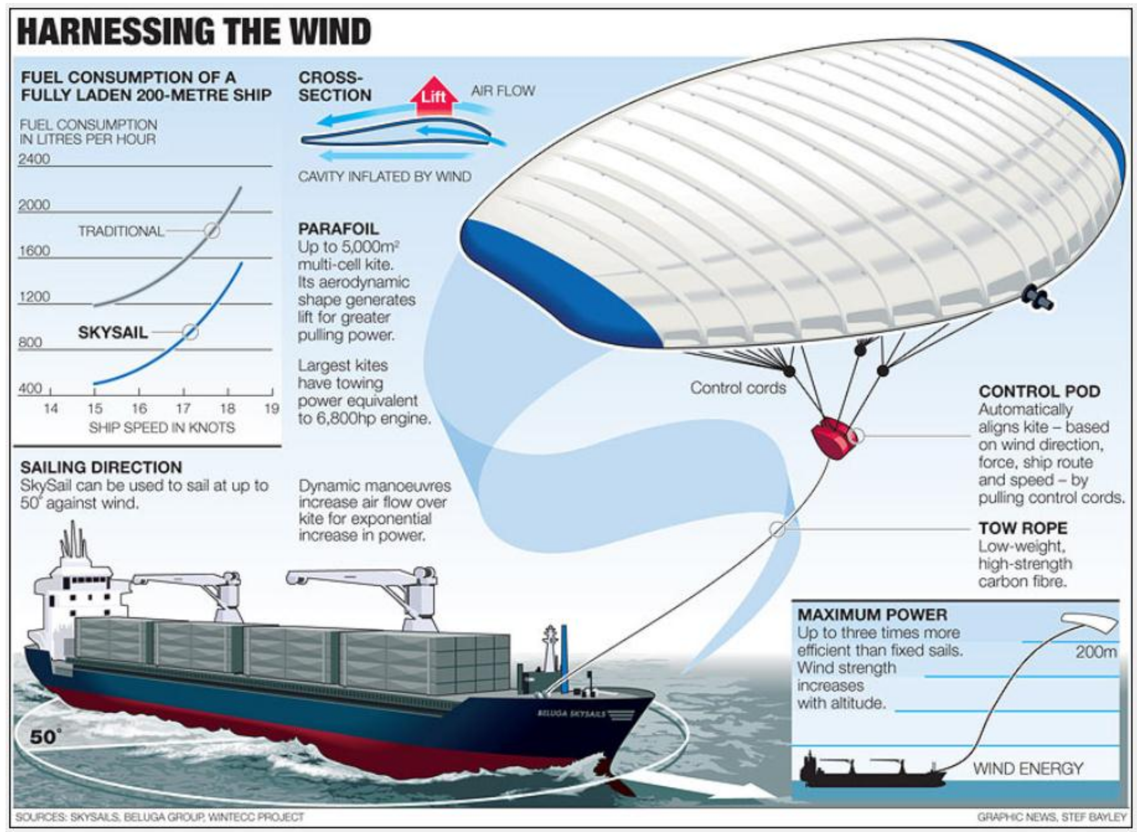
- 98% of All International Goods Carried via Sea
- 98% of All Cargo Vessels Powered by Diesel Engines

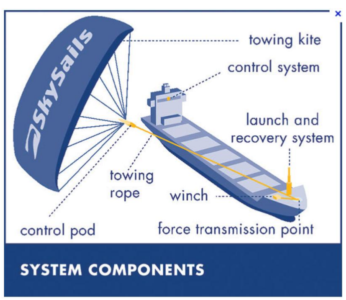


- Sails up to 5000m^2
- Filled with Compressed Air
- Adjustable Height of 500m
- Autopilot Force Control
- Sail Stored in Compact Form

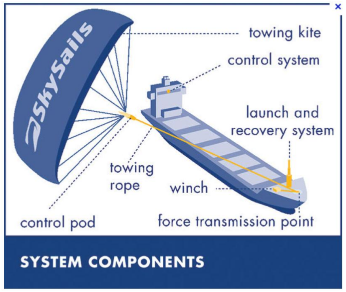
- 320m^2 → 2MW Prop. Power

SkySails → Support Ship Propulsion by Large Towing Kite





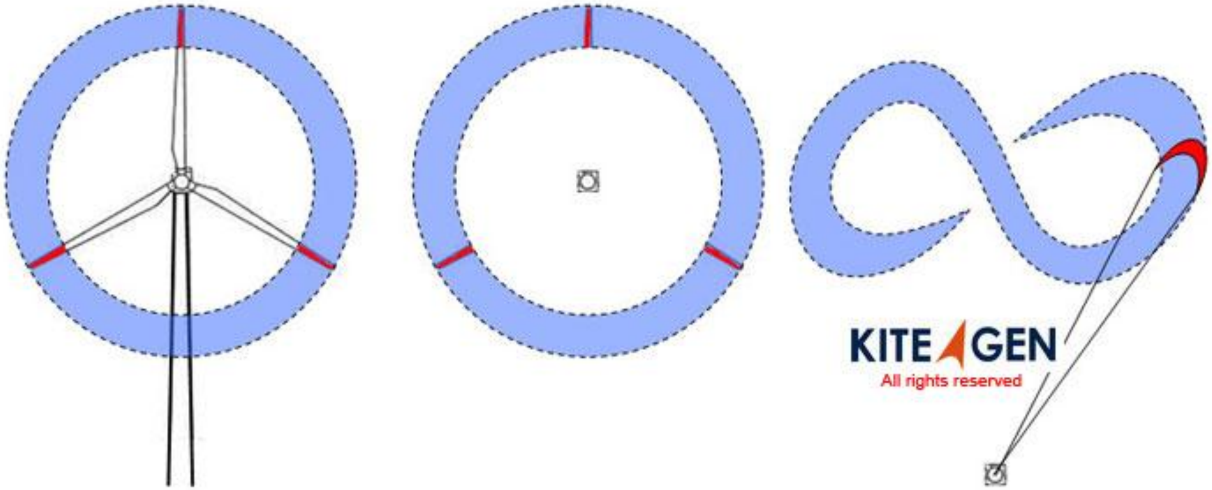
SkySails → Support Ship Propulsion by Large Towing Kite



Controlled Power Kites for Capturing Wind Power

- Replace Blades by Power Kites
- Minimum Base Foundation etc. Required
- Operative Height Adjustable to Wind Conditions

M. Loyd, 1980

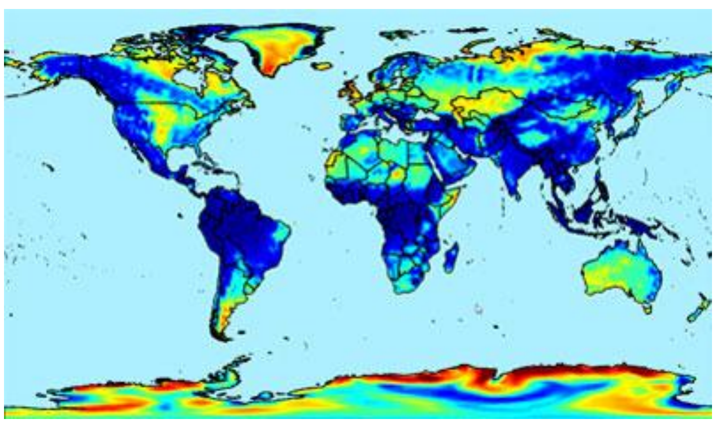


- Wing Tips / Highest Speed Regions are the Main Power Generating Parts of a Wind Turbine

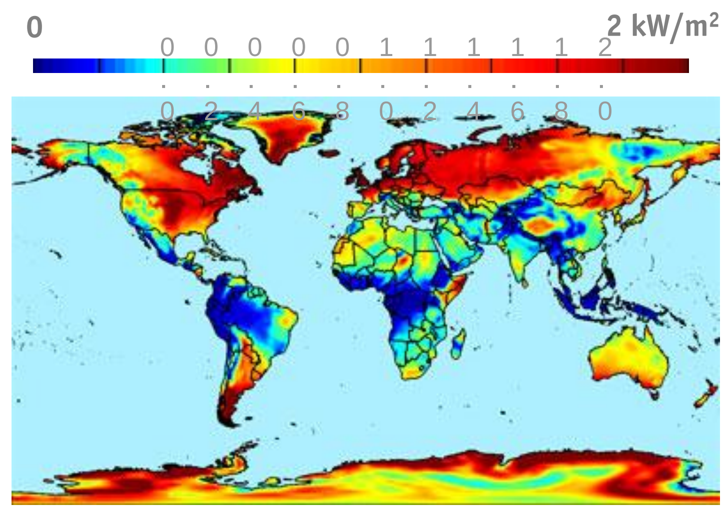
Controlled Power Kites for Capturing Wind Power

- Wind at High Altitudes is Faster and More Consistent
- Operate Kites at High Altitudes or Even in the Jet Stream

Source: JOBY ENERGY



120m



700m

Controlled Power Kites for Capturing Wind Power

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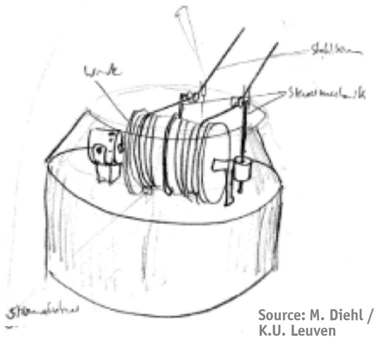
Pumping Power Kites



Source: M. Diehl /
K.U. Leuven

Ground-Based EE-Generation

Basics of Power Kites

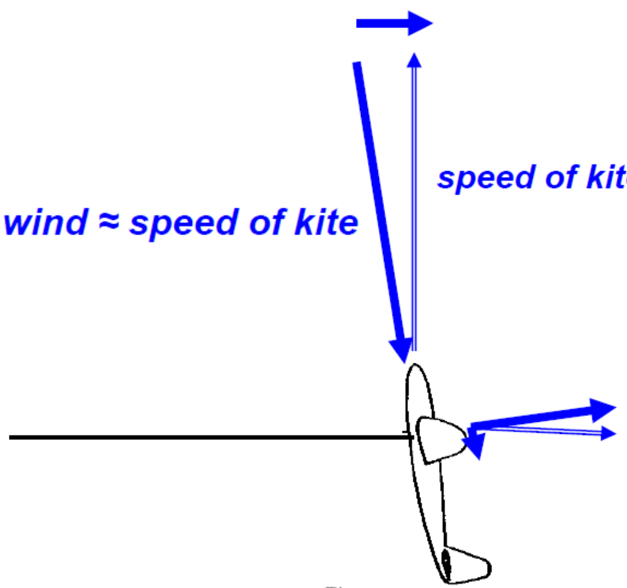
- Kite´s Aerodynamic Surface Converts Wind Energy into Kite Motion

real wind w

Source: M. Diehl / K.U. Leuven

speed of kite v

- *effective wind ≈ speed of kite*



Force

$$F_L = \frac{1}{2}\rho A C_\mathrm{L} v^2$$

- Generated Force Could be Converted into Useful Power by Pulling a Load / Driving Turbines via a Tether

Kite moves $\frac{C_\mathrm{L}}{C_\mathrm{D}}$ *x faster than real wind!*

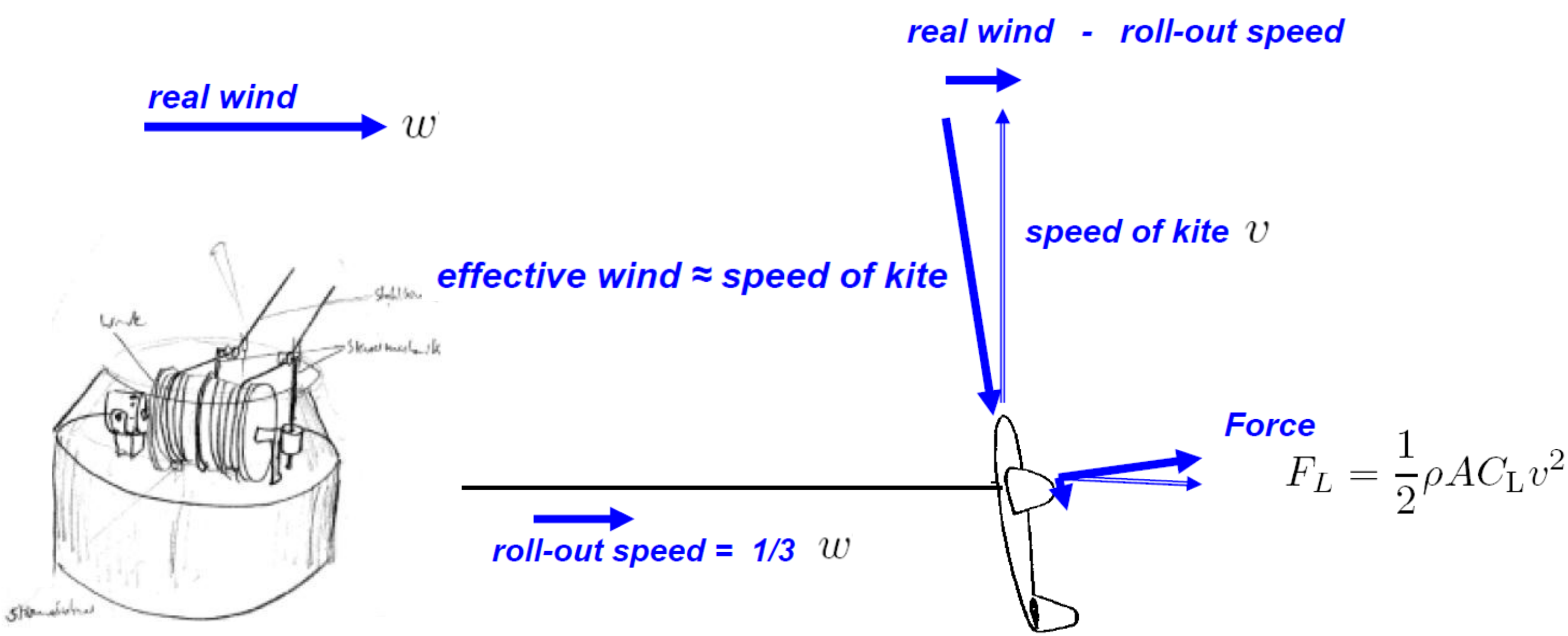
Pumping Power Kites

- **Maximum Power**

$$P = \frac{2}{27}\,\rho\,A\,w^3\,C_\mathrm{L}\left(\frac{C_\mathrm{L}}{C_\mathrm{D}}\right)^2$$

M. Loyd, 1980

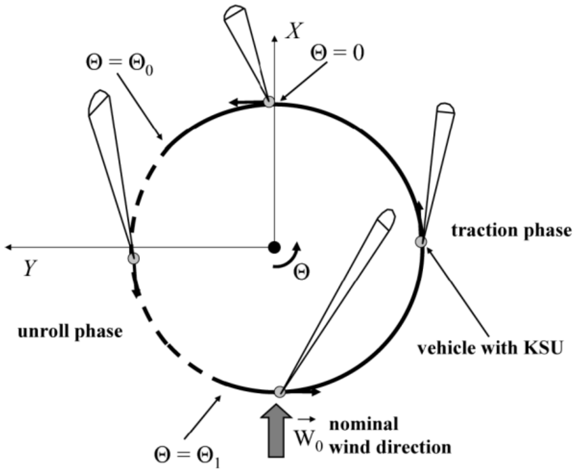
Source: M. Diehl / K.U. Leuven

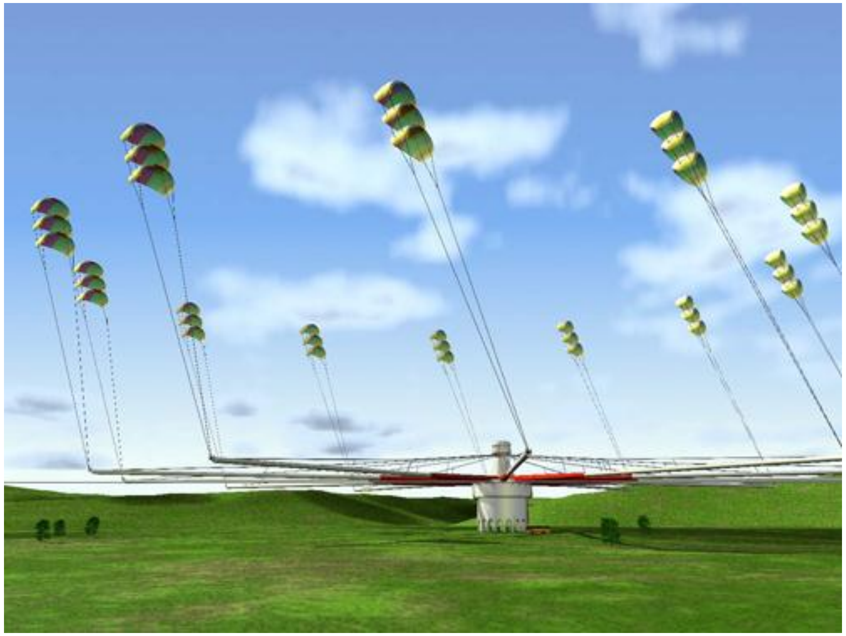


Pumping Power Kites for Capturing High Altitude Wind Power

- ▶ Lower Electricity Production Costs than Current Wind Farms
- ▶ Generate up to 250 MW/km^2, vs. the Current 3 MW/km^2
- ▶ Research at the POLITECNICO DI TORINO

KITE GEN





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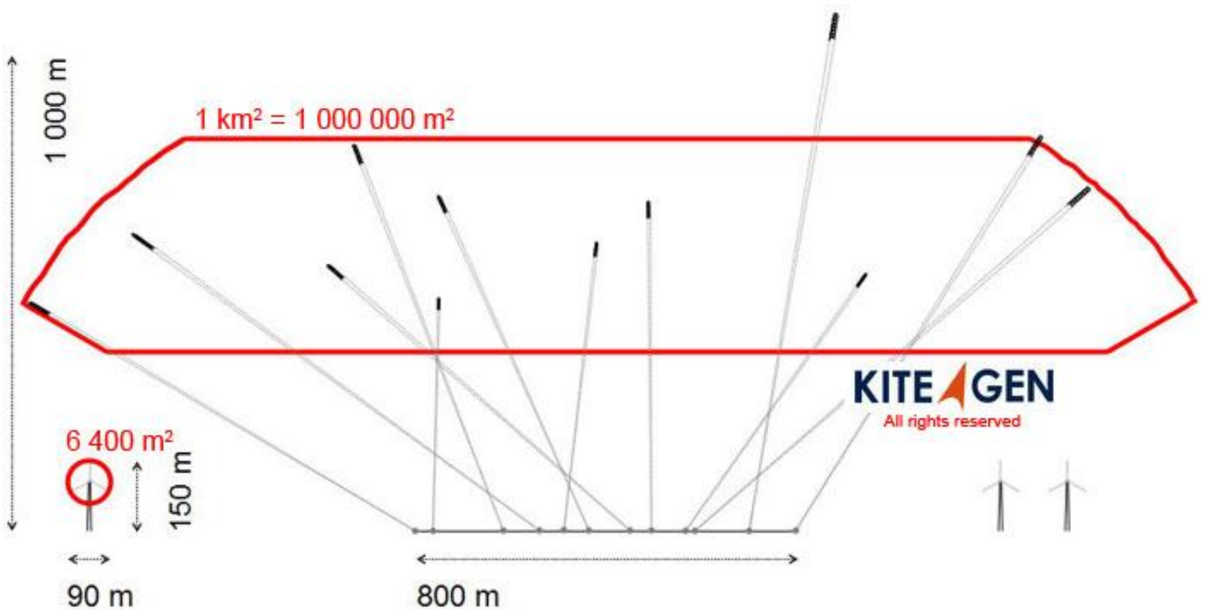
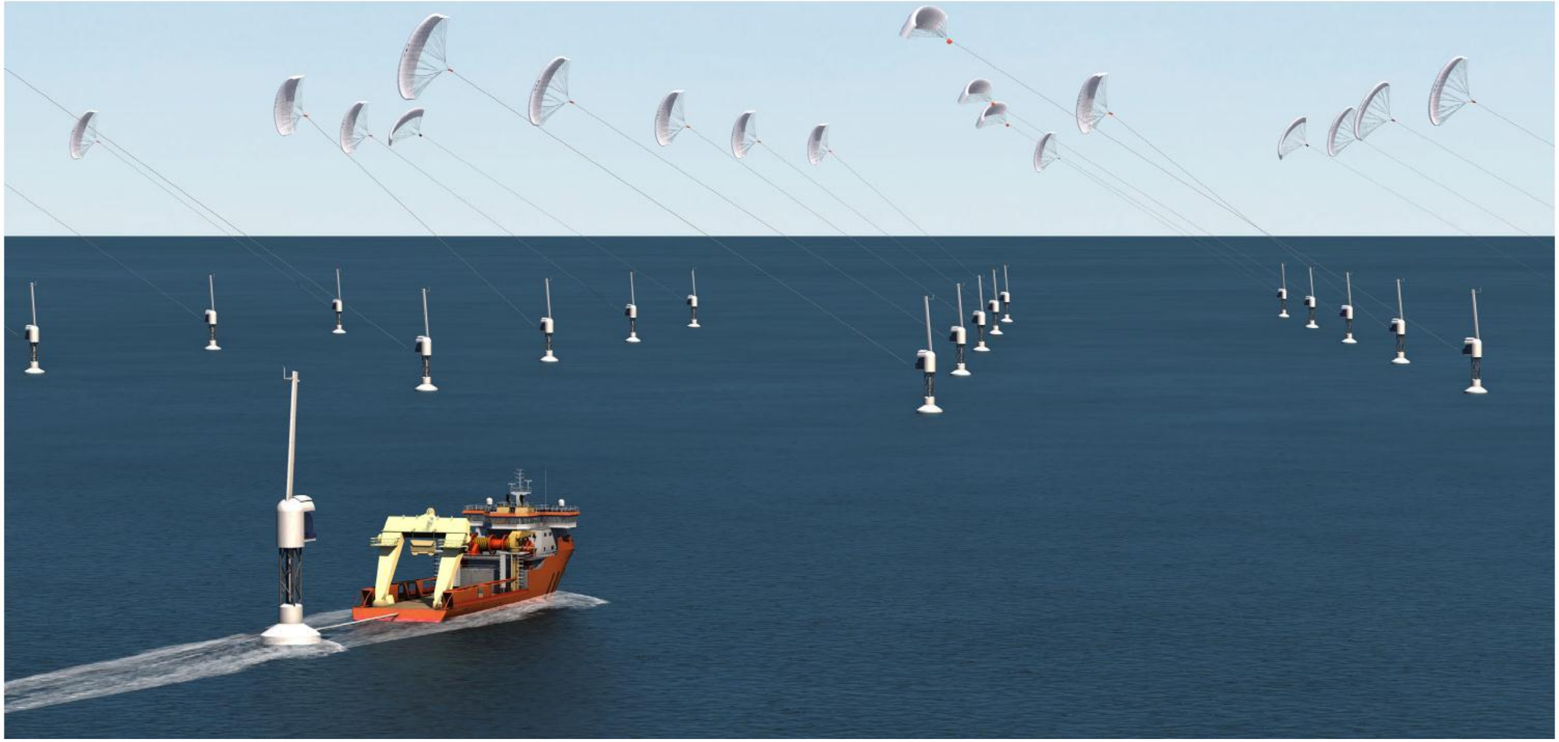


Carousel Configuration

Offshore Pumping Power Kites

- Operated at Altitudes of 200…800m
- Conventional Offshore Location or Floating Platforms



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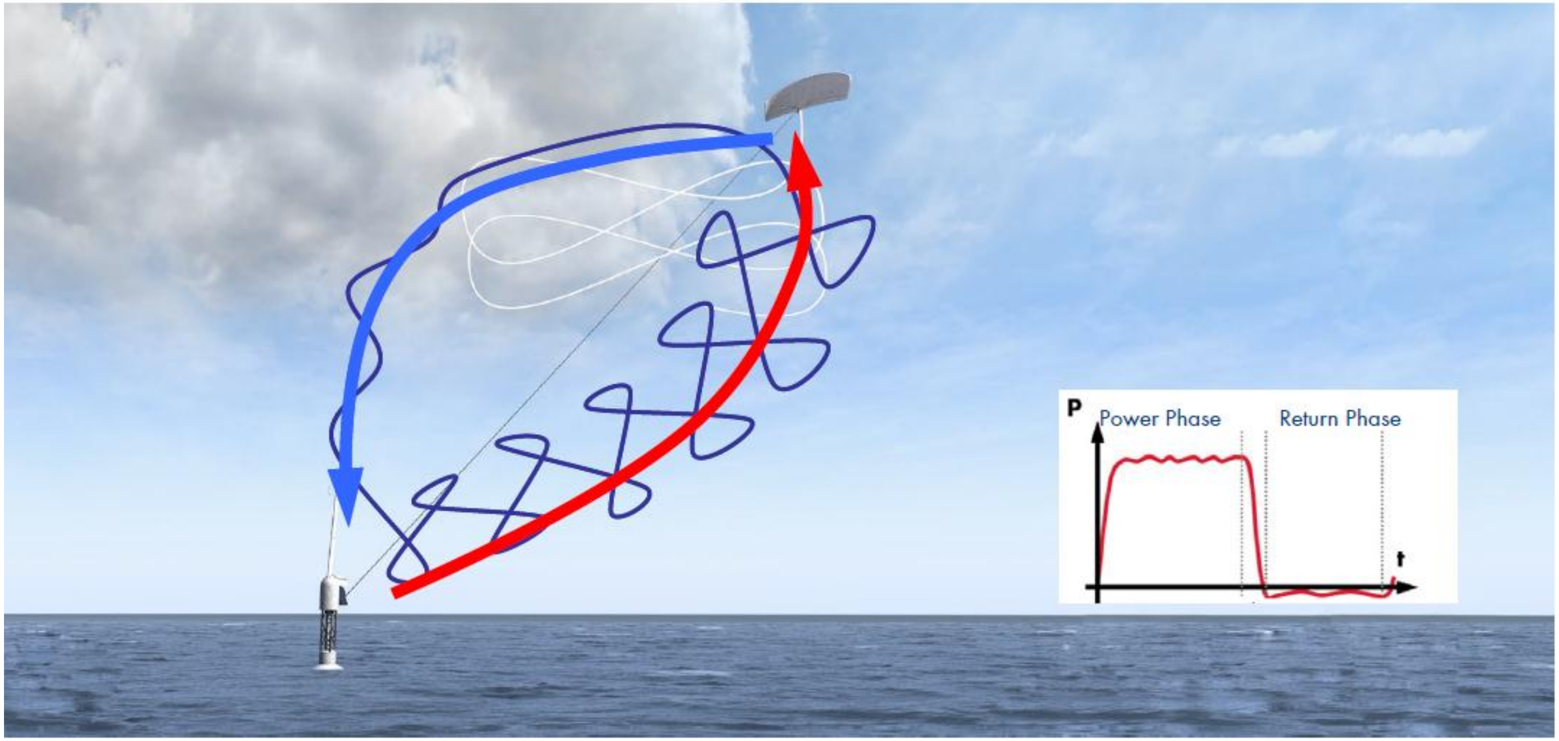
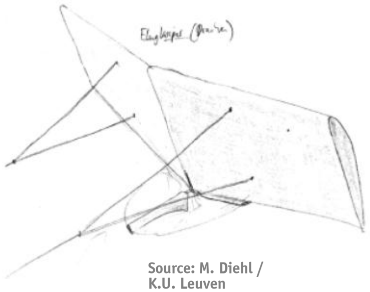
SkySails POWER



Airborne Wind Turbine



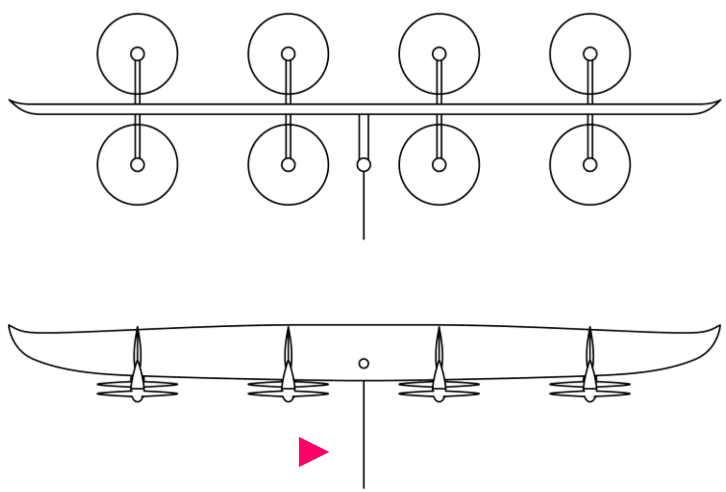
Source: M. Diehl / K.U. Leuven

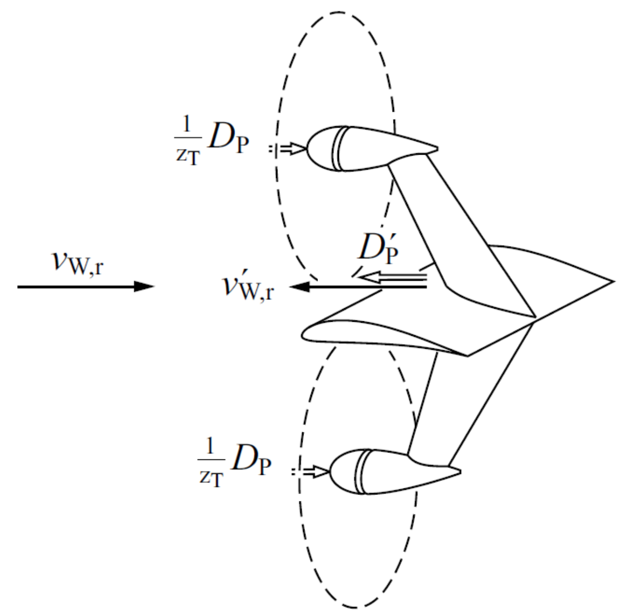
On-Board EE-Generation

Alternative Concept – Airborne Wind Turbine

- Power Kite Equipped with Turbine / Generator / Power Electronics
- Power Transmitted to Ground Electrically

M. Loyd, 1980





Alternative Concept – Airborne Wind Turbine

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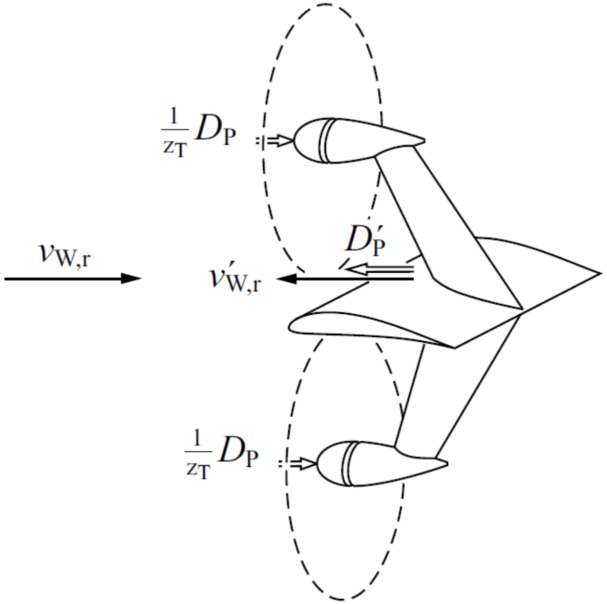
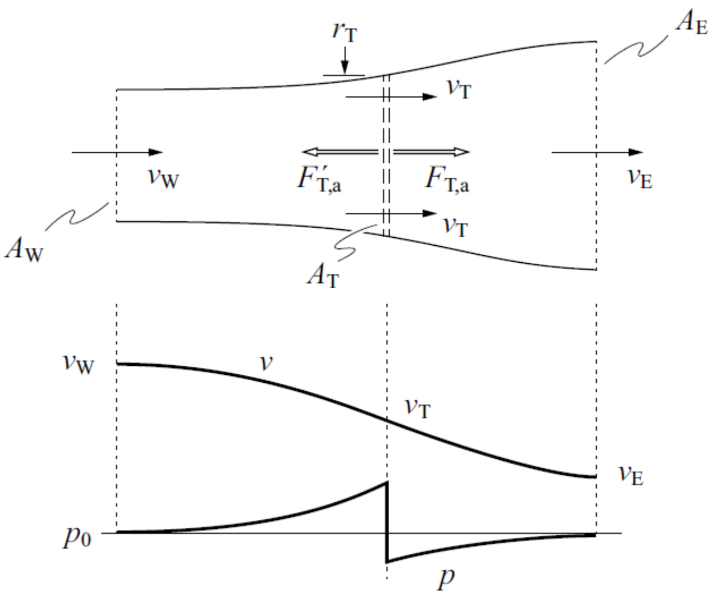


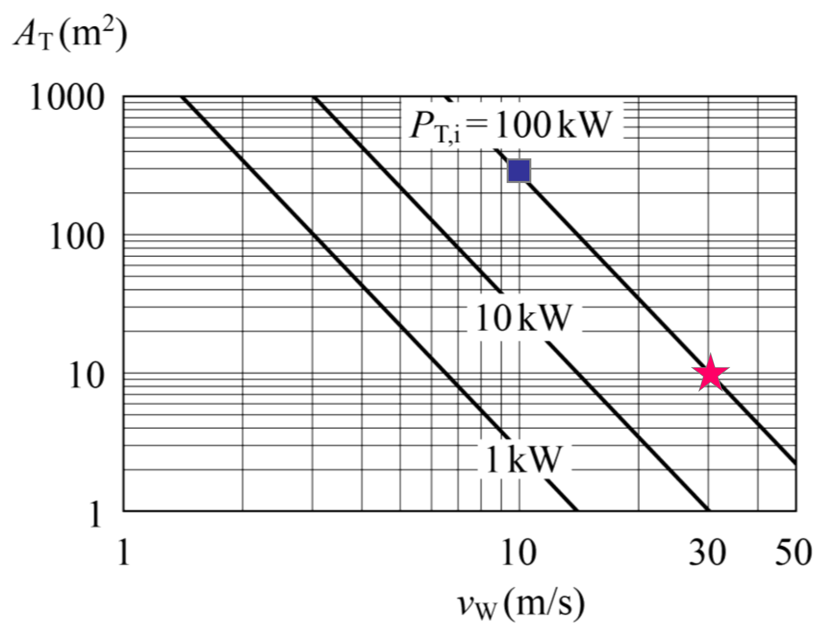
Basic Physics of Wind Turbines

- **Maximum Achievable acc. to Lanchester / Betz**
- **High Crosswind Kite Speed → Very Small Turbine Area**

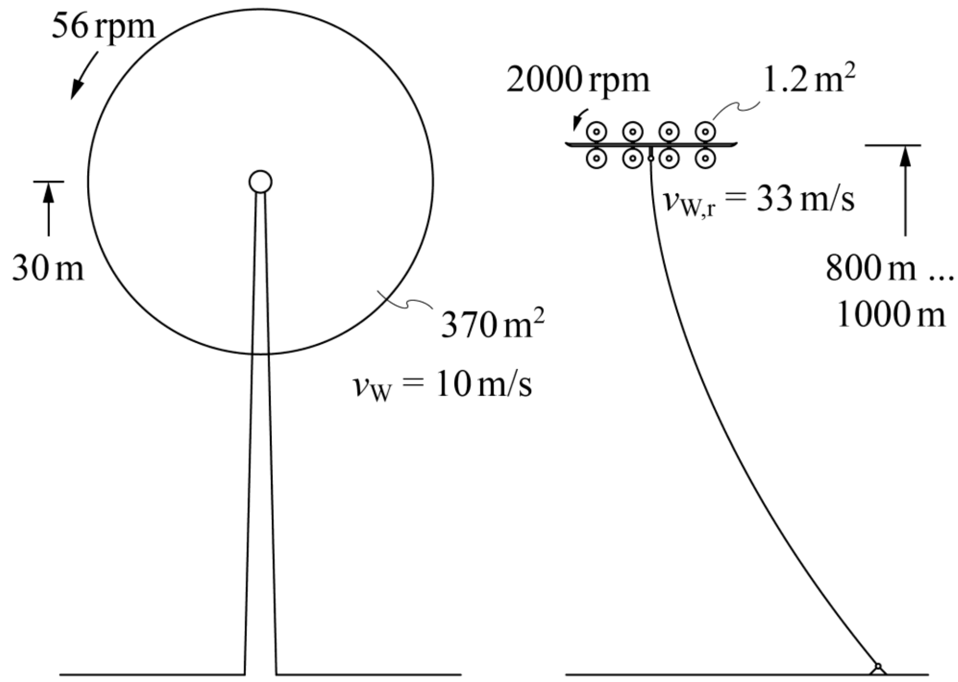
$$P_{\mathrm{T,i}} = c_{\mathrm{P,i}} \frac{1}{2} \rho A_{\mathrm{T}} v_{\mathrm{W}}^{3}$$

$$c_{\mathrm{P,i}} = \frac{16}{27} \approx 0.59$$





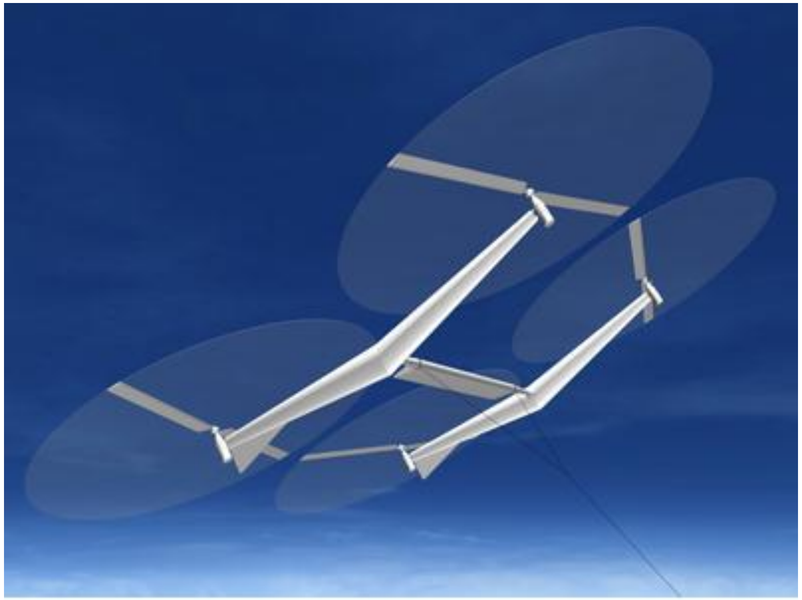
Comparison of Conventional / Airborne Wind Turbine



- Numerical Values Given for 100kW Rated Power

SkyWindPower AWT Concept

- ▶ Tethered Rotorcraft – Quadrupole Rotor Arrangement
- ▶ Inclined Rotors Generate Lift & Force Rotation / Electricity Generation



SKY WINDPOWER

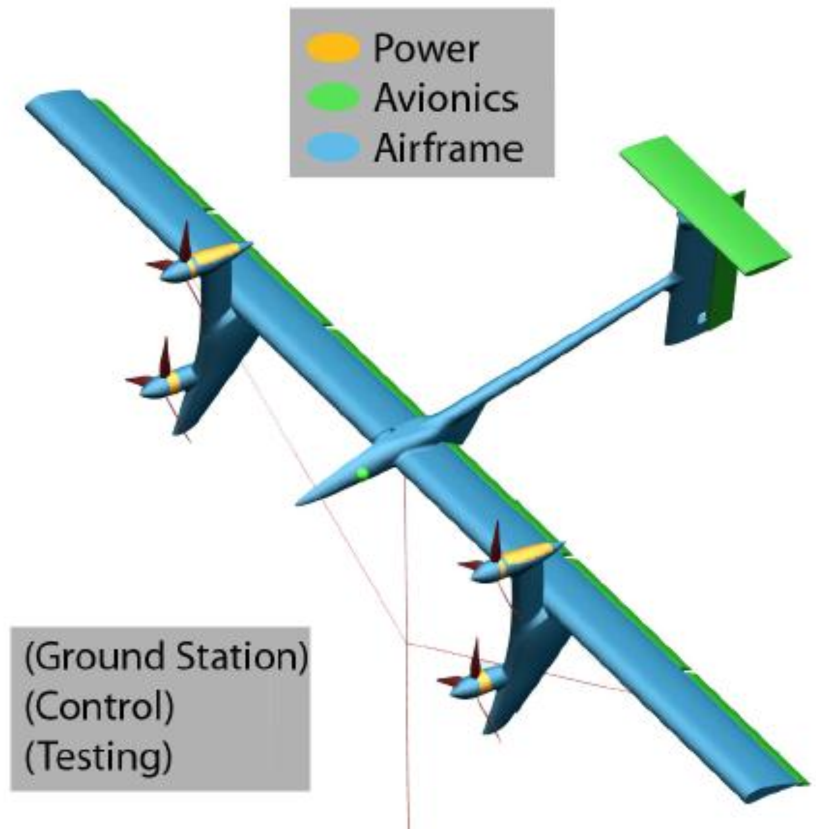
Artist´s Drawing of
240kW / 10m Rotor System

- Named as One of the 50 Top Inventions in 2008 by TIME Magazine

JOBY ENERGY AWT Concept

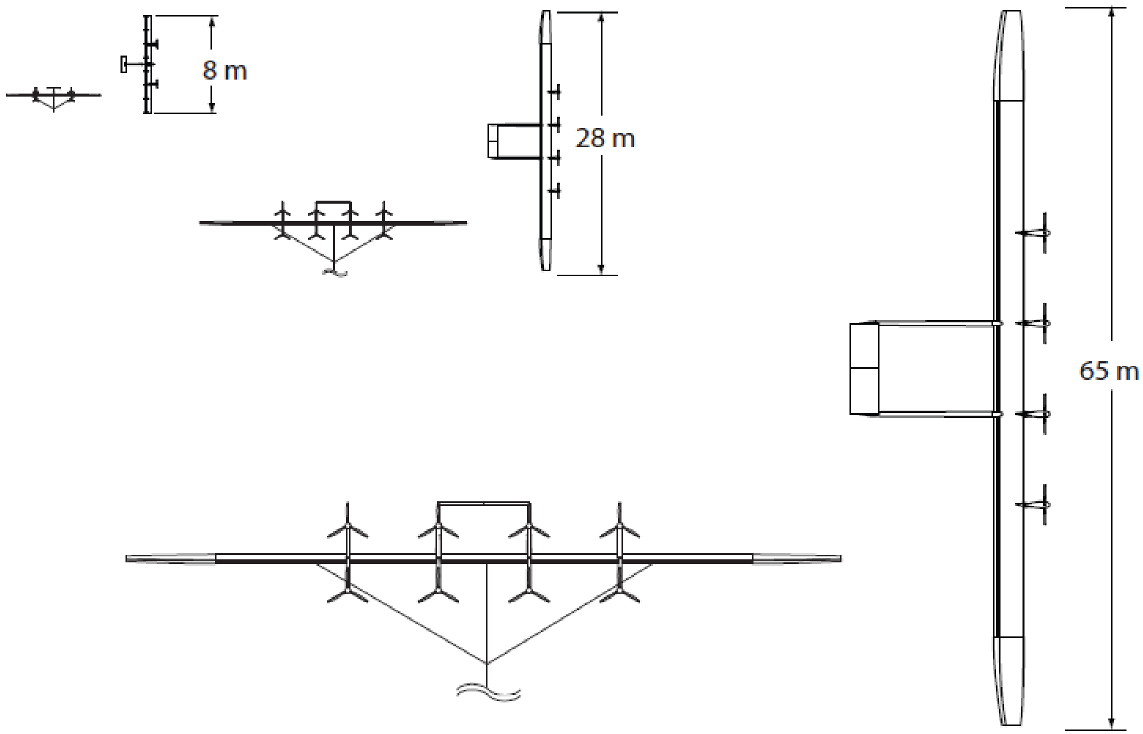
- ► Reinforced Tether Transfers MV-Electricity to Ground
- ► Composite Tether also Provides Mechanical Connection to Ground

MAKANI POWER AWT Concept



MAKANI POWER Demonstration Plan

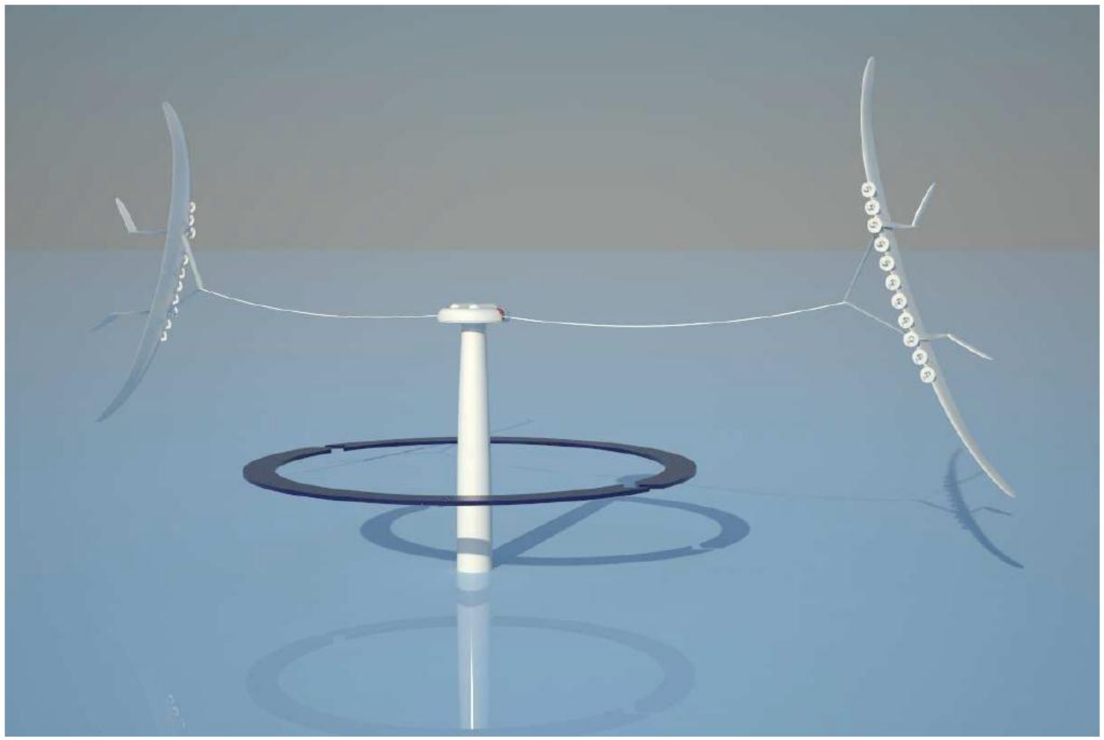
W7	M600	M5
30 KW	600 kW	5 MW



MAKANI POWER

Flight Mode - Parked

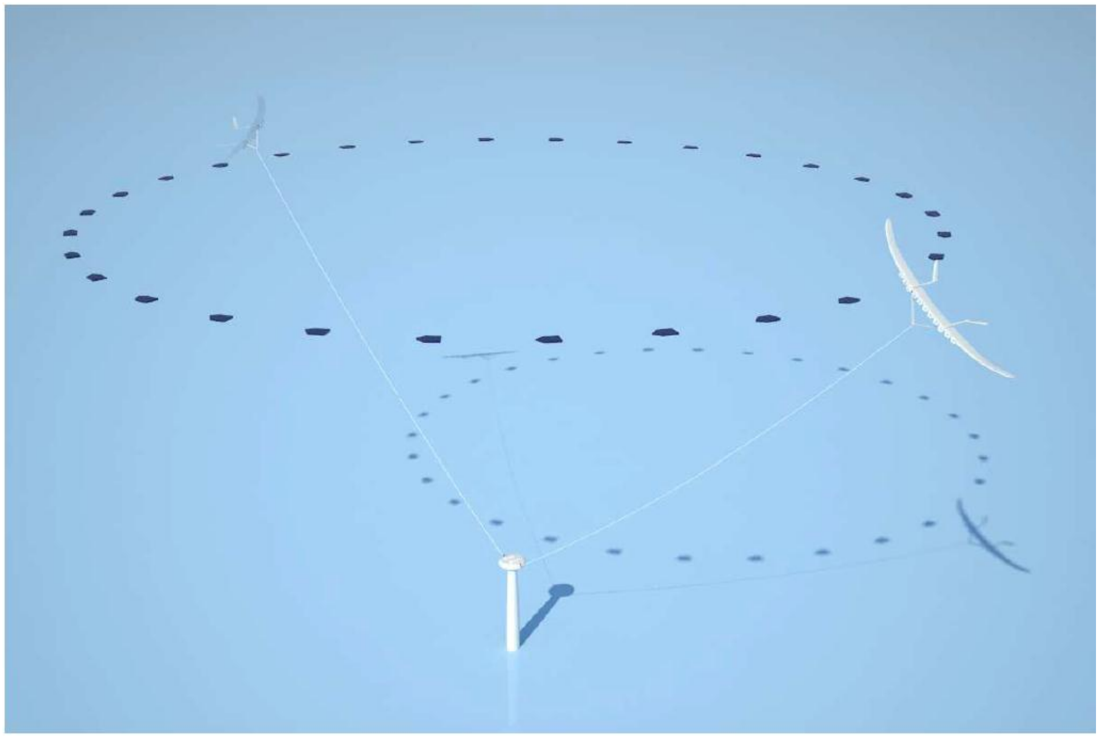
Future Prospects



Source: M. Diehl / K.U. Leuven

- Example for Thinking "Out-of-the-Box" !

Future Prospects



Source: M. Diehl /
K.U. Leuven

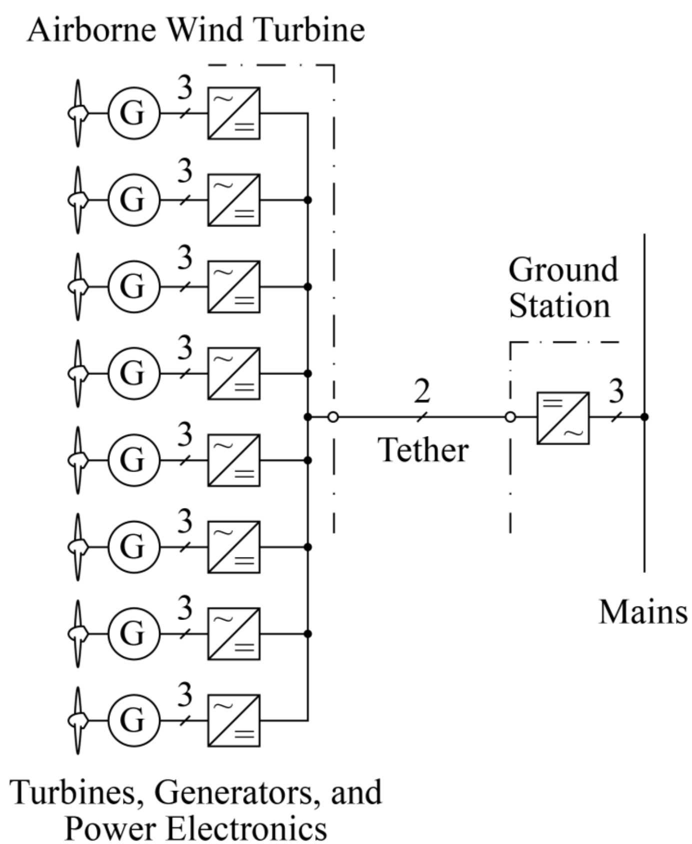
■ Example for Thinking "Out-of-the-Box" !

Technical Feasibility of AWT Electrical System

- AWT Electrical System Structure
- Multi-Objective Optimization (*Weight vs. Efficiency*)
- Controls Aspects

AWT Basic Electrical System Structure

▶ Rated Power	100kW
▶ Operating Height	800...1000m
▶ Ambient Temp.	40°C
▶ Power Flow	Motor & Generator



■ El. System Target Weight	100kg
■ Efficiency (incl. Tether)	90%
■ Turbine /Motor	2000/3000rpm

Design of Electrical Power System

- Clarify Practical Feasibility of AWT Concept
- Clarify Weight/Efficiency Trade-off / Multi-Objective Optimization / PARETO-Front

Tether Design

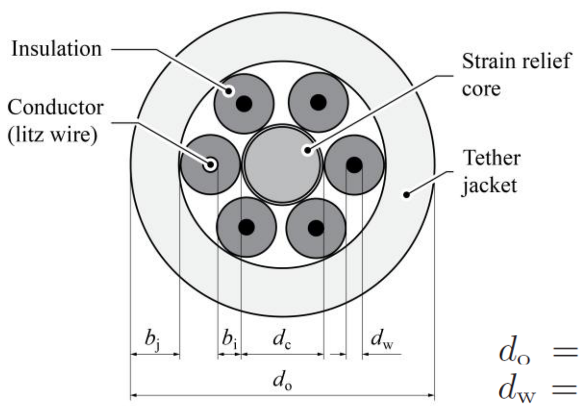
DC Voltage Level
η-γ-PARETO Front

Tether DC Transmission Voltage Level

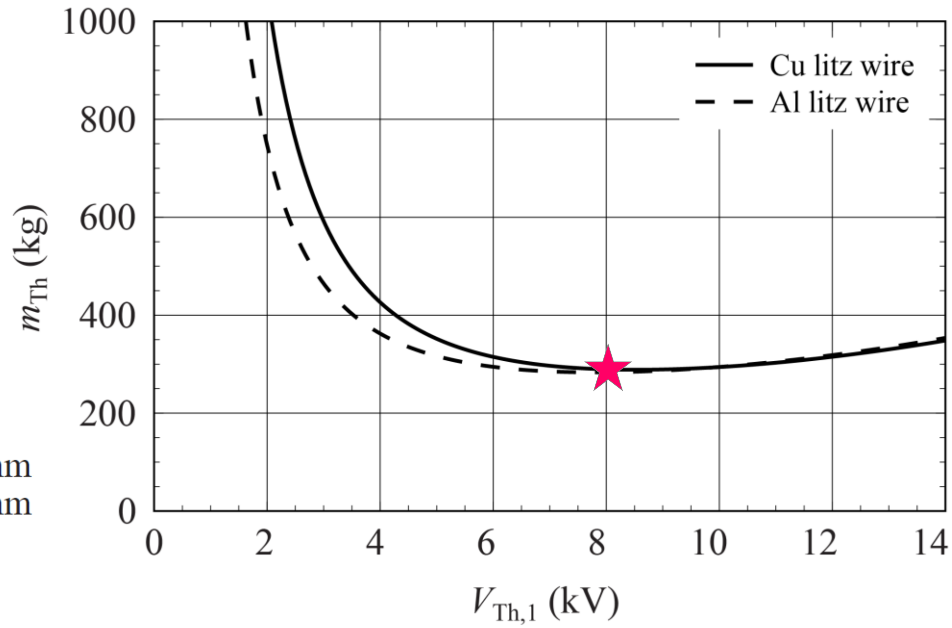
- $P_{th,1}$ = 100kW / l_{th} = 1000m
- Strain Relief Core – Kevlar (F_{th} = 70kN, d=5mm)
- Cu or Al Helical Conductors - ½ U_{th} Isolated
- Outer Protection Jacket (3mm)

$$\eta_{Th} = 98.5\%$$

$$b_i = 0.0144\frac{mm}{kV^2} \cdot V_i^2 + 0.1694\frac{mm}{kV} \cdot V_i + 0.40\,mm$$

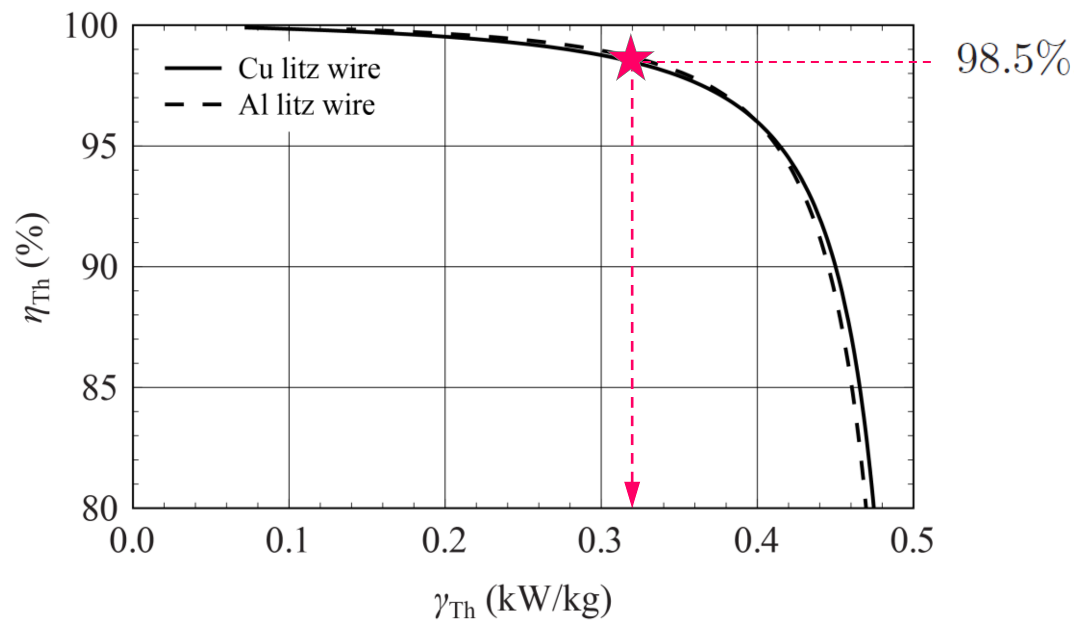


$$d_o = 19\,mm$$
$$d_w = 1.5\,mm$$



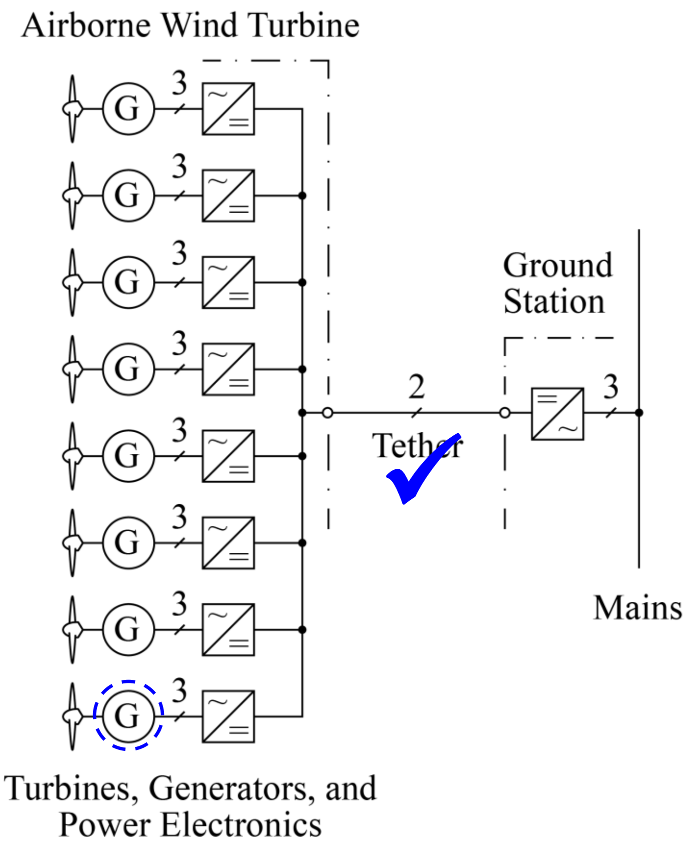
Tether η-γ-PARETO Front

► Tether Voltage $V_{th,1}$ = 8kV



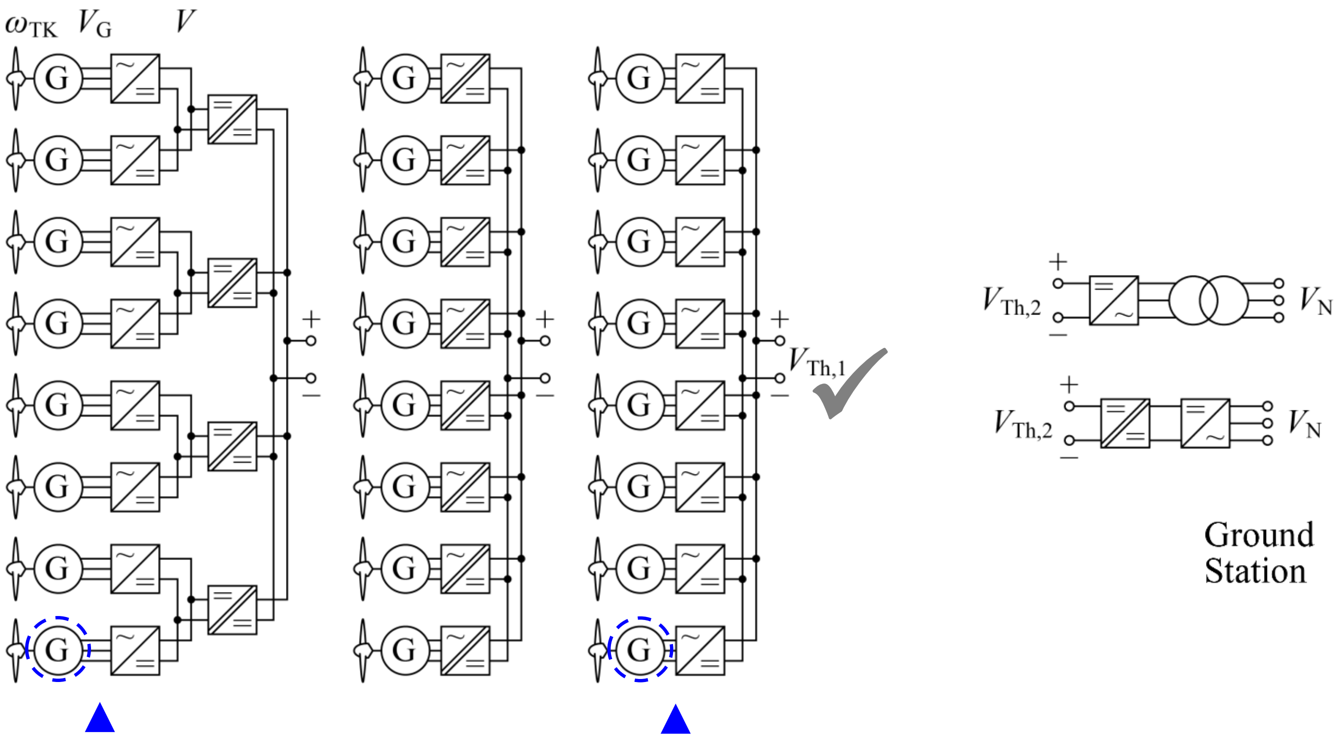
- **Total Weight of Tether: 320kg**

System Overview



Possible AWT Electrical System Structures

- Low-Voltage or Medium-Voltage Generators / Power Electronics
- Decision Based on Weight/Efficiency/Complexity



Generator / Motor Design

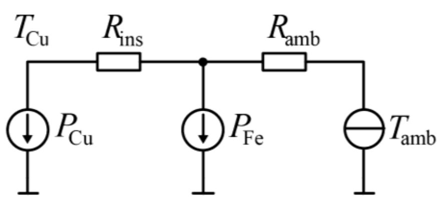
Dimensions
Number of Pole Pairs
η-γ-PARETO Front

Generator / Motor η-γ-PARETO Front

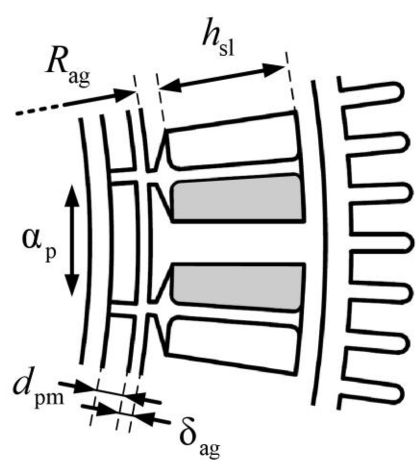
► Medium Voltage vs. Low Voltage Machine $V_{th,1}$ = 8kV

- PMSM – Radial Flux – Internal Rotor - Slotted Stator / Concentrated Windings – Air Cooling
- Analytical EM and Thermal Models for Weight / Efficiency Optimization
- P = 16kW / 2000rpm

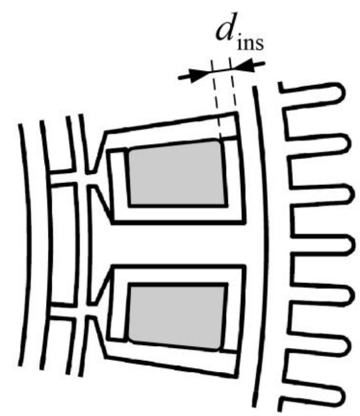
$$\eta_{mot} = \frac{P_{mech}}{P_{mech} + P_v}$$



Thermal Model



LV Machine



HV Machine

■ LVG: Diameter 17cm (excl. Cooling Fins) / Width 6.0cm / p = 20 / η = 95.4% / Weight 5.1kg

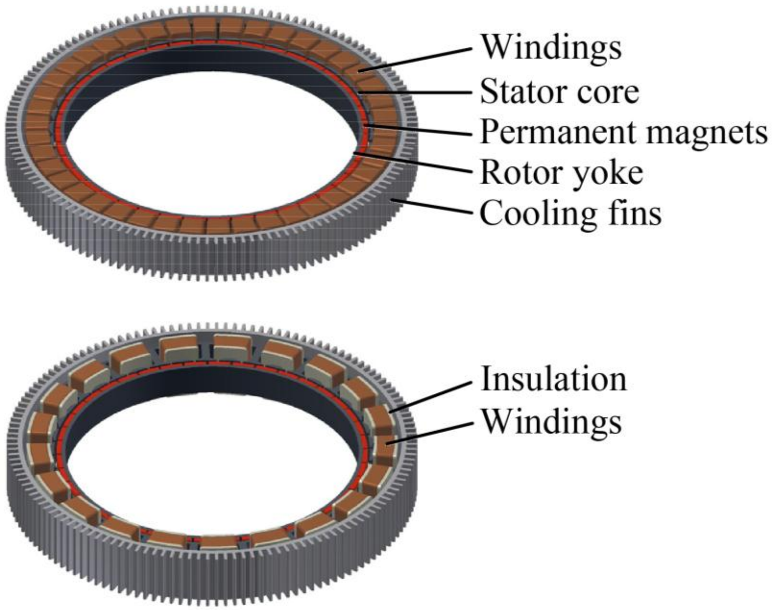
CAD Drawing of LV and MV Machine

► Fixed Parameters and Degrees of Freedom

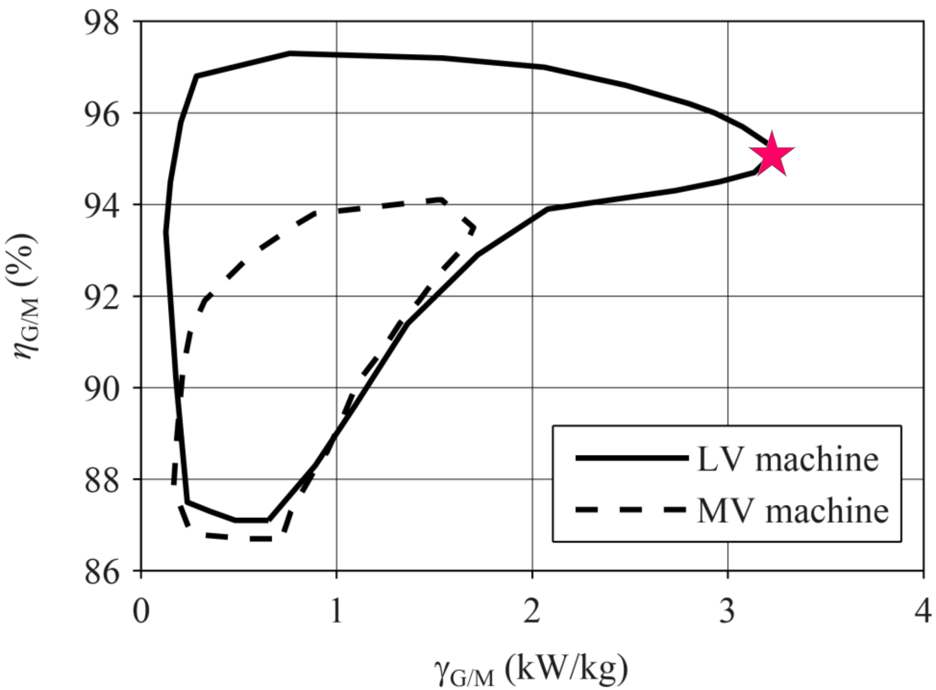
MACHINE OPTIMIZATION PARAMETERS AND FIXED PARAMETERS

Optimization parameters	Symbol	Range
Air-gap radius	R_{ag}	$50\dots250\,mm$
Active length	L	$10\dots60\,mm$
Slot depth	h_{sl}	$5\dots20\,mm$
Permanent magnet thickness	d_{pm}	$2\dots8\,mm$
Pole coverage factor	α_p	$0.8\dots1$
Number of pole pairs	p	$5\dots30$

Fixed parameters	Symbol	Value
Air gap	δ_{ag}	$1.5\,mm$
Copper filling factor	k_{Cu}	0.45
Permanent magnet remanence	B_{rem}	$1.3\,T$
Iron saturation flux density	B_{sat}	$2.2\,T$
Insulation thickness (MV machine only)	d_{ins}	$2\,mm$



Generator / Motor η-γ-PARETO Front



► **Selected Design**
$\eta =$ 95.4%
$\gamma =$ 3.1 kW/kg

- **Medium Voltage Machine Not Considered Further**

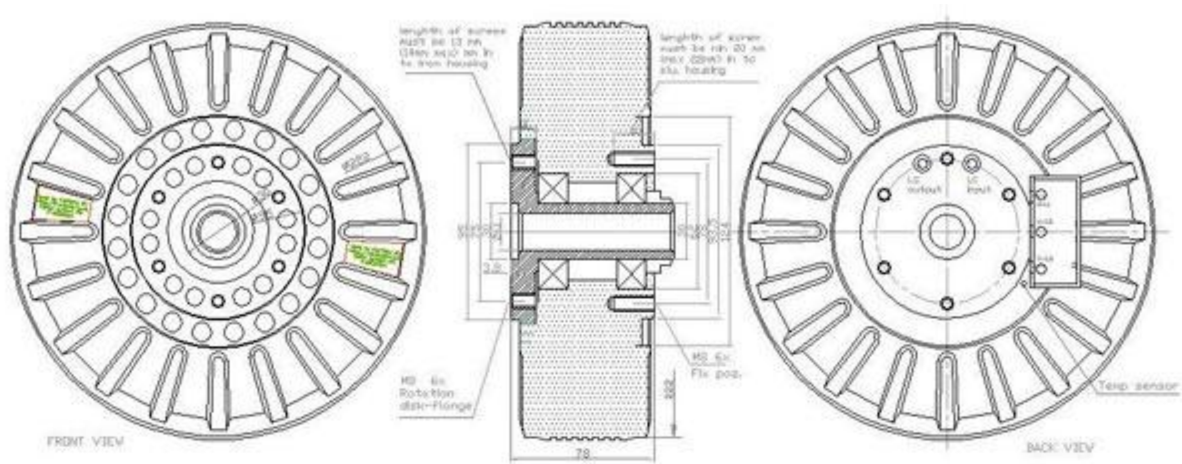
Comparison to Commercial Motors

- **Motors Employed for Electric Propulsion of Glider Airplane**

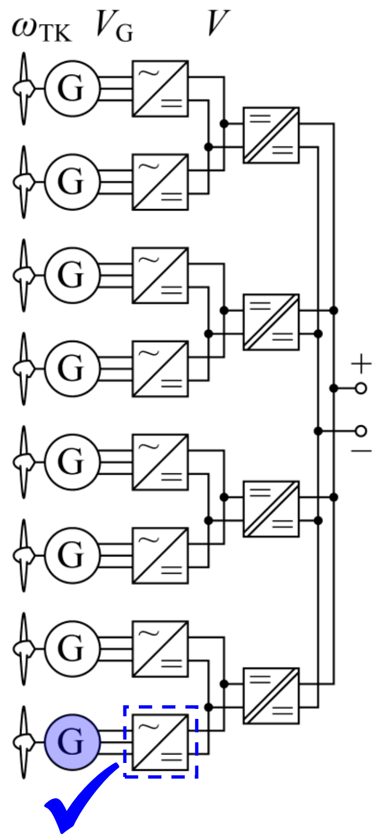
ENSTROJ
electric motor innovation
established in 1991

Power P = 10kW
Speed n = 2200rpm
Cooling v_L = 25m/s

- Diameter 22cm
  Width 8.6cm
  Weight 12kg
  Pole Pairs 10
  Efficiency 91%



System Overview



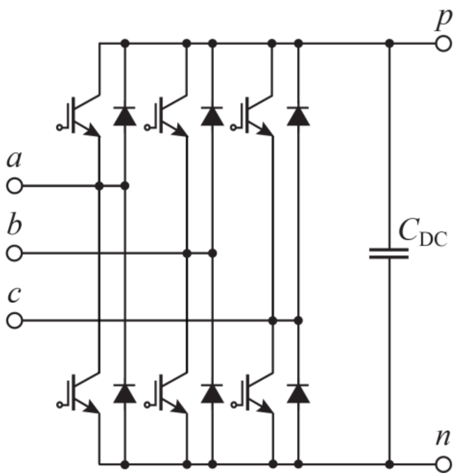
Rectifier / Inverter Design

Chip Area
Heatsink Volume
η-γ-PARETO Front

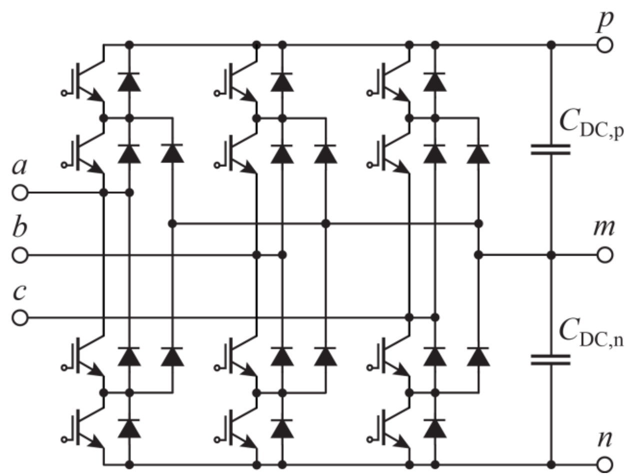
Rectifier / Inverter Design

► 2-Level or 3-Level Bidirectional Voltage Source Rectifier

- S = 19.3kVA
- V_{DC} = 750V
- $f_{S,min}$ = 24kHz
- T_J = 125°C
- Foil Capacitor DC Link



1200V T&FS Si IGBT4s /
1200V SiC Diodes

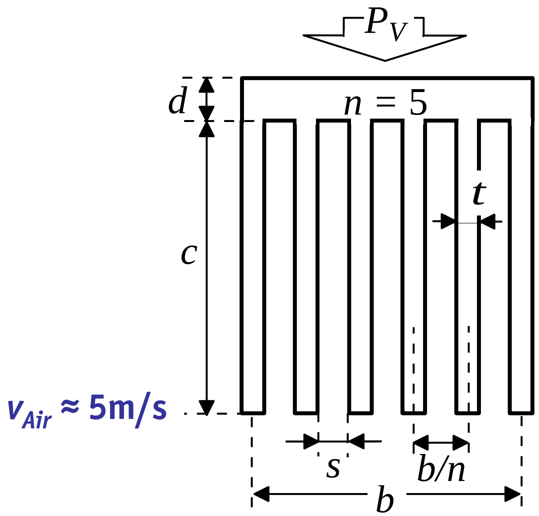


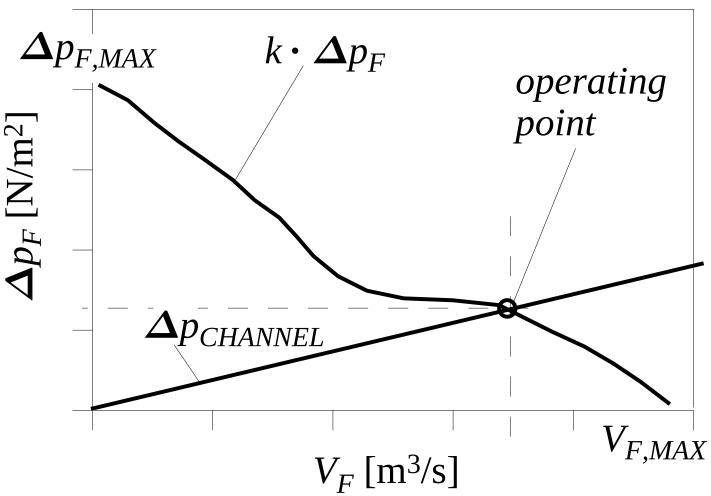
600V T&FS Si IGBT3s /
600V Si EmCon3 Diodes

■ Maximization of Heatsink Thermal Conductance / Weight (Volume) - Max. CSPI

Heatsink Optimization

▶ Maximize Thermal Conductance / Weight (Volume)

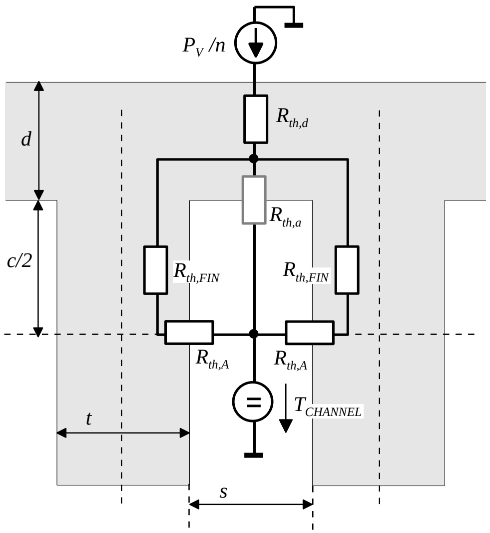


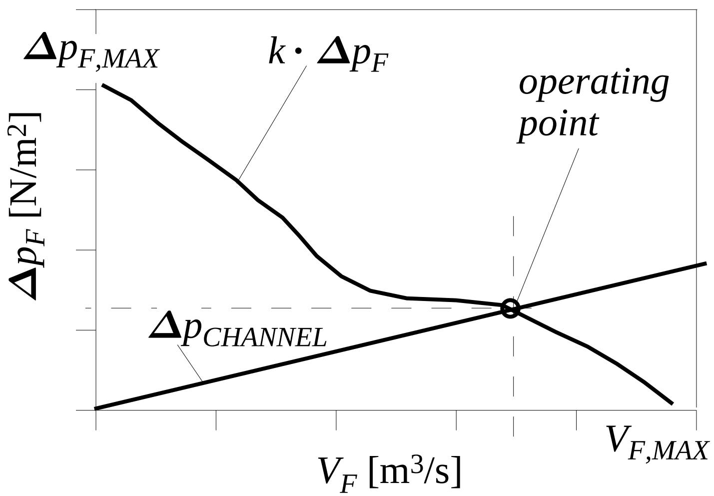


- Highest Performance Fan
- Fin Thickness / Channel Width Optimization

Heatsink Optimization

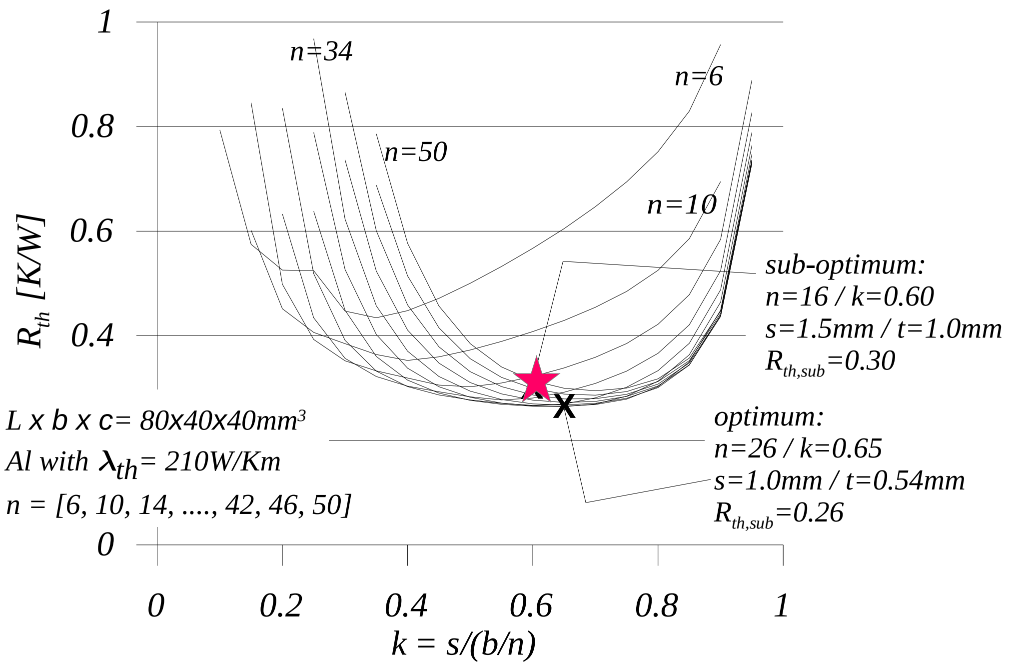
► Maximize Thermal Conductance / Weight (Volume)





- Highest Performance Fan
- Fin Thickness / Channel Width Optimization

Heatsink Optimization



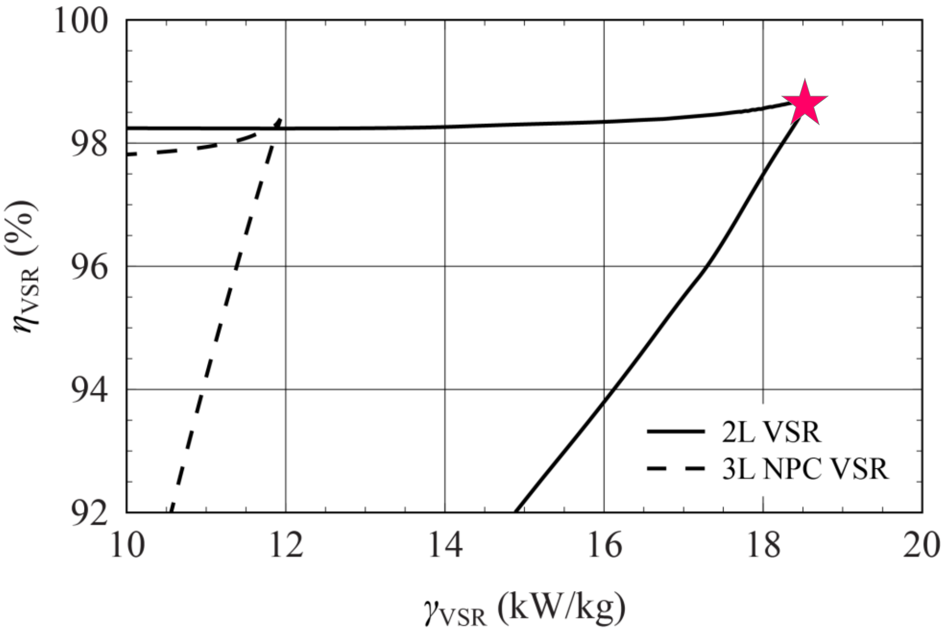
▶ **Optimum**

$$CSPI_{\mathrm{m}} = 15.0 \frac{\mathrm{W}}{\mathrm{K\,kg}}$$

- **Highest Performance Fan**
- **Fin Thickness / Channel Width Optimization**

Rectifier / Inverter η-γ-PARETO Front

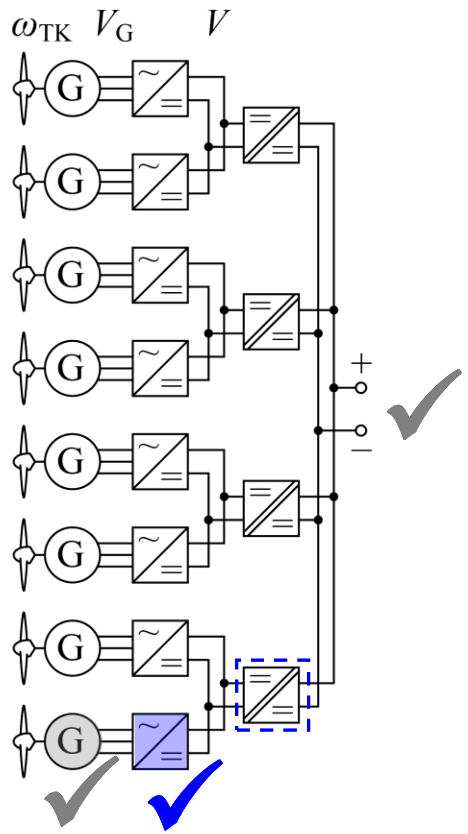
- Switching Frequency Range 24…70 kHz
- Heatsink Temperature Range 55…100 °C (T_{amb} = 40°C)



▶ Selected Design
η = 98.5%
γ = 19 kW/kg

■ 3-Level Topology Does Not Show a Benefit

System Overview



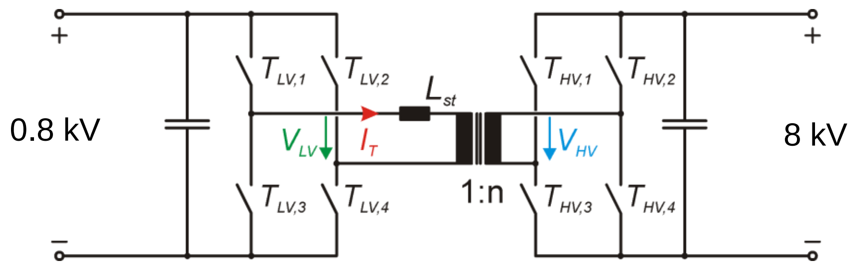
$8kV_{DC}/750V_{DC}$ DAB Converter Design

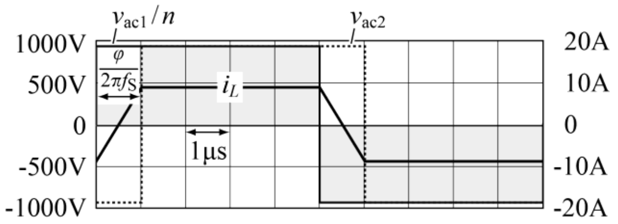
Switches / Topology
Transformer
η-γ-PARETO Front

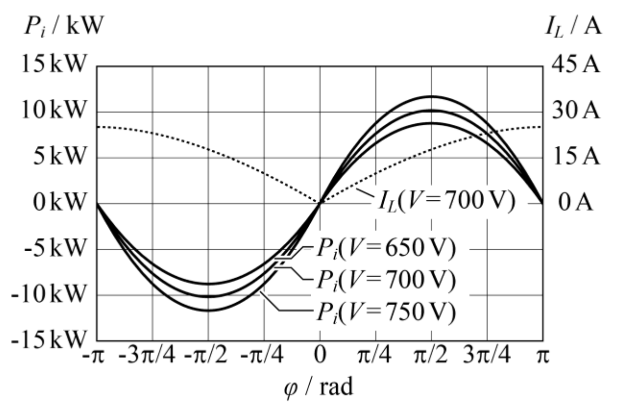
DC/DC Converter Topology

▶ **Bidirectional Energy Transfer - Dual Active Bridge**

- Weight ≤ 25kg
- f_S = 50...125kHz → $f_{S,m}$ = 100kHz
- Phase-Shift Control ($\varphi = \pi/4$)





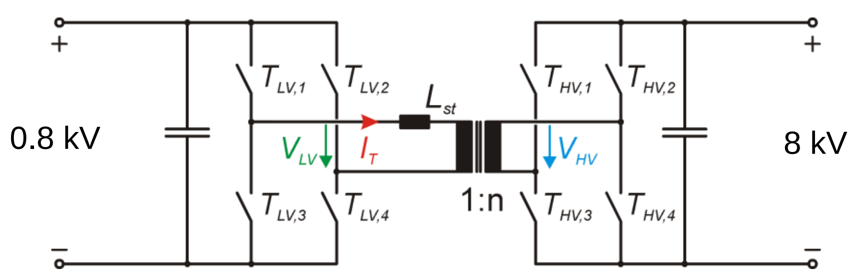


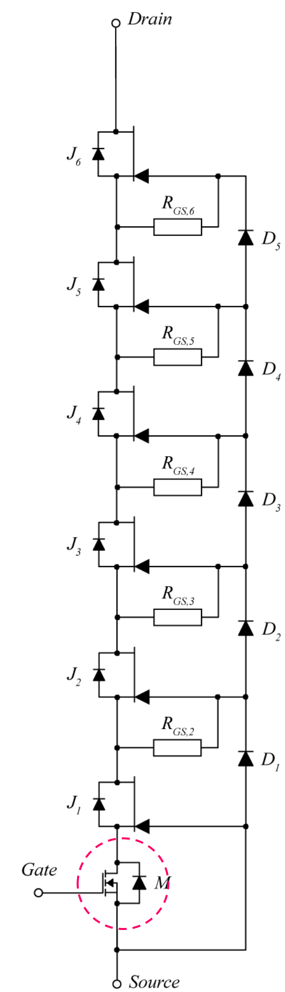
■ **Implementation of Electronic Switches - SiC**

DC/DC Converter Topology

▶ **Bidirectional Energy Transfer - Dual Active Bridge**

- Weight ≤ 25kg
- f_S = 50...125kHz → $f_{S,m}$ = 100kHz
- Phase-Shift Control (φ = $\pi/4$)

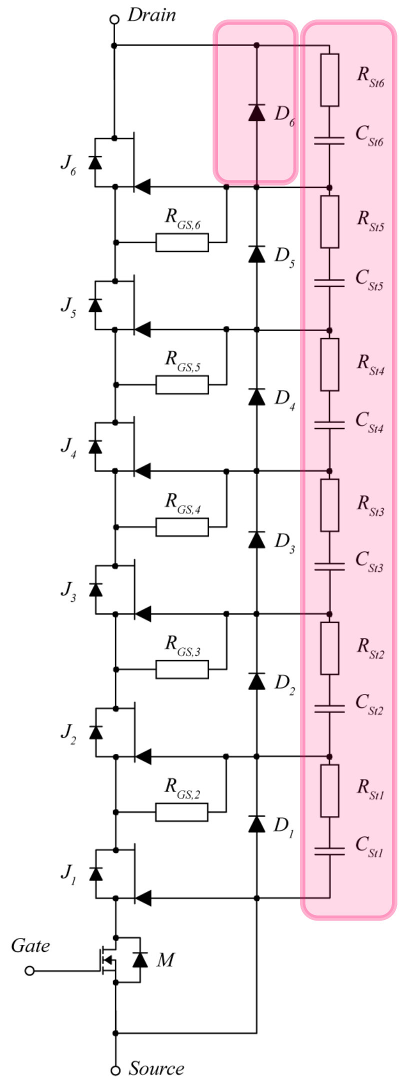


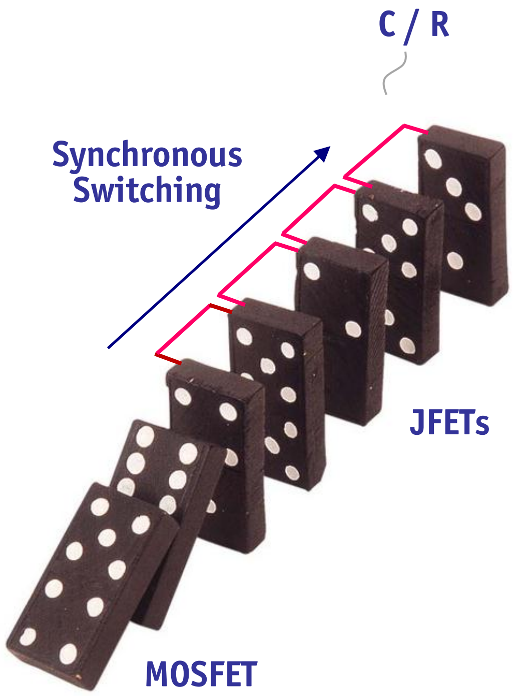


▶ **10kV Si/SiC SuperCascode Switch**

■ Implementation of Electronic Switches - SiC

Si/SiC Super Cascode Switch





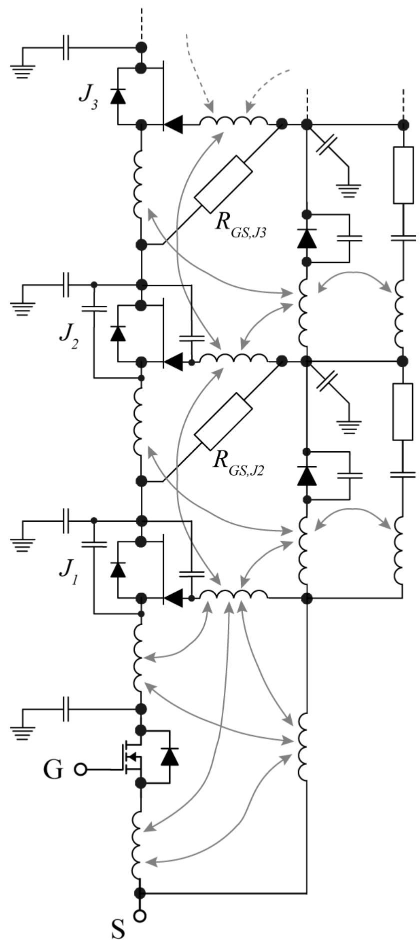
➔ HV-Switch Controllable via Si-MOSFET

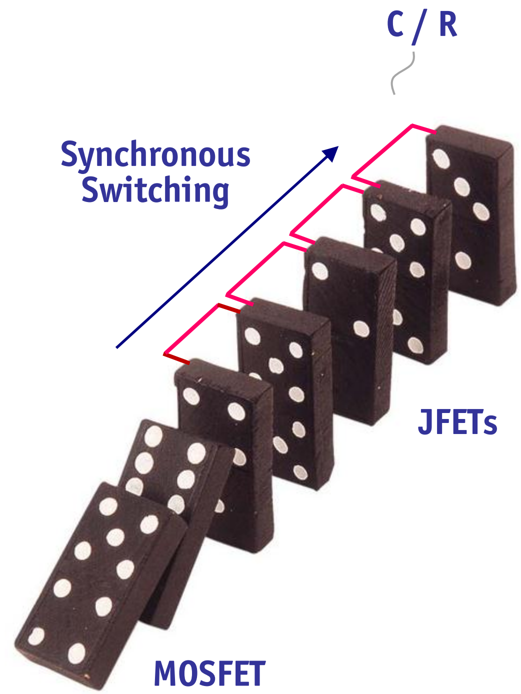
* 1 LV Si MOSFET
* 6 HV 1.7kV SiC JFETs
* Avalanche Rated Diodes

➔ Ultra Fast Switching
➔ Low Losses
➔ Parasitics

* Passive Elements for Simultaneous Turn-on and Turn-off
* Stabilization of Turn-off State Voltage Distribution

Si/SiC Super Cascode Switch





➔ HV-Switch Controllable via Si-MOSFET

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* Avalanche Rated Diodes

➔ Ultra Fast Switching

➔ Low Losses

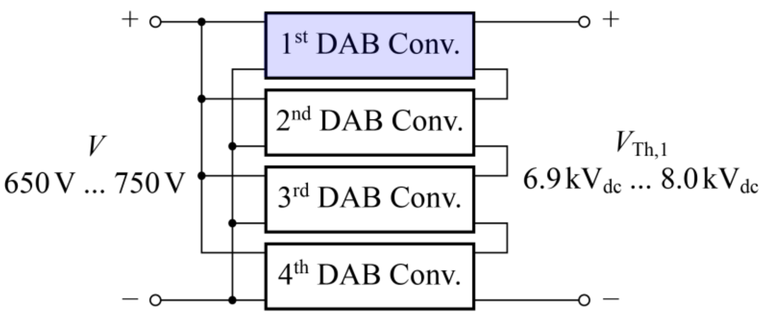
➔ Parasitics

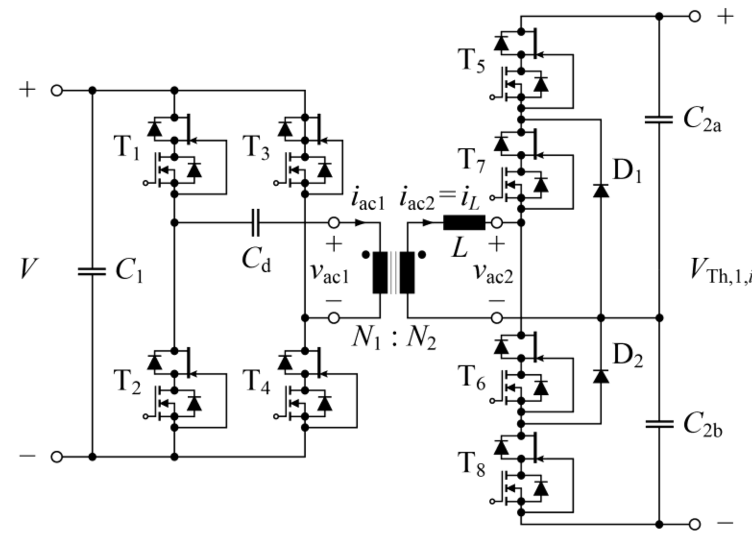
* Passive Elements for Simultaneous Turn-on and Turn-off
* Stabilization of Turn-off State Voltage Distribution

Selected Multi-Cell Converter Topology

► MV-Side Series-Connection / LV-Side Parallel-Connection

$P_i = 6.25kW$
$V_{th,1,i} = 2kV$

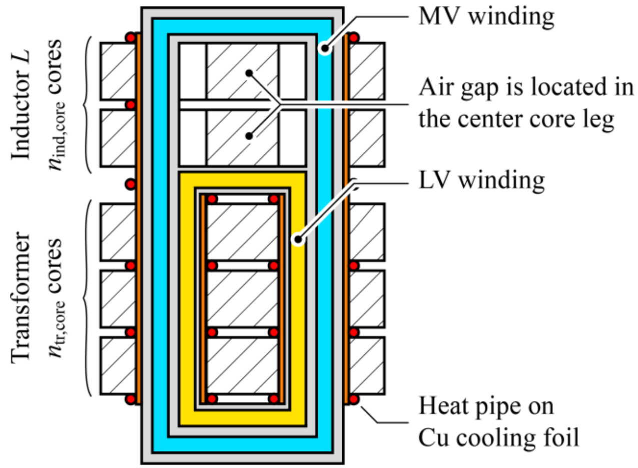


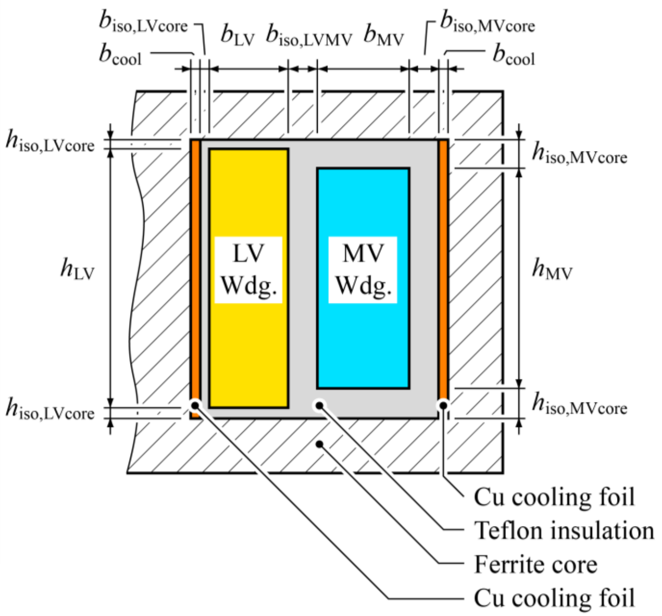


■ Winding Arrangement & Efficiency / Weight Optimization of Transformer

Transformer Design

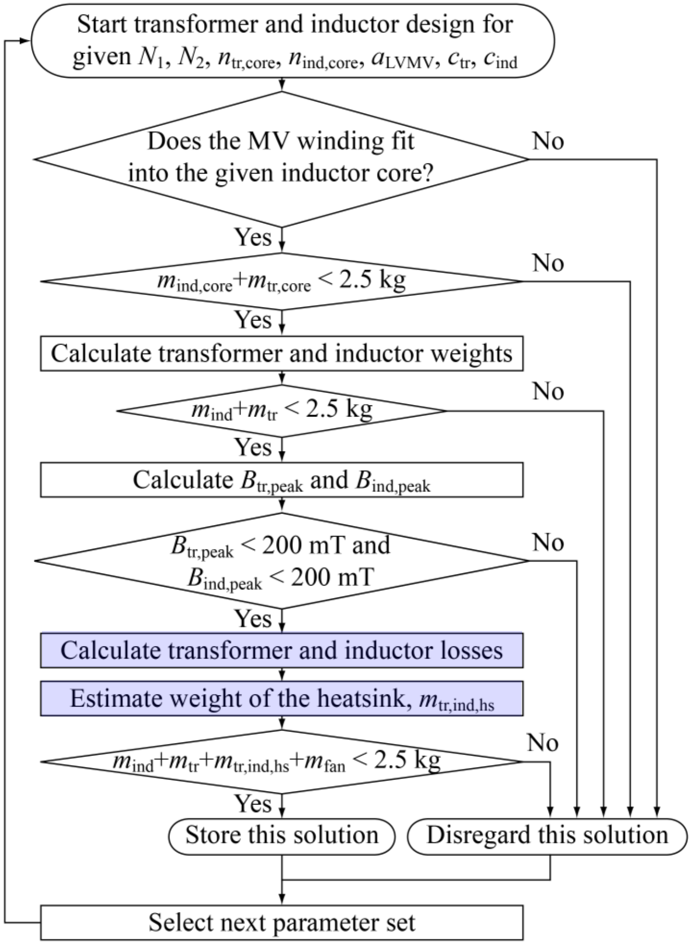
- ► MV-Winding Arranged Around Inductor Cores
- ► Cooling Provided by Heatpipes
- ► Stacked Cores - Scalable Arrangement





- ■ Optimization - Weight / Efficiency Trade-off

Transformer Optimization

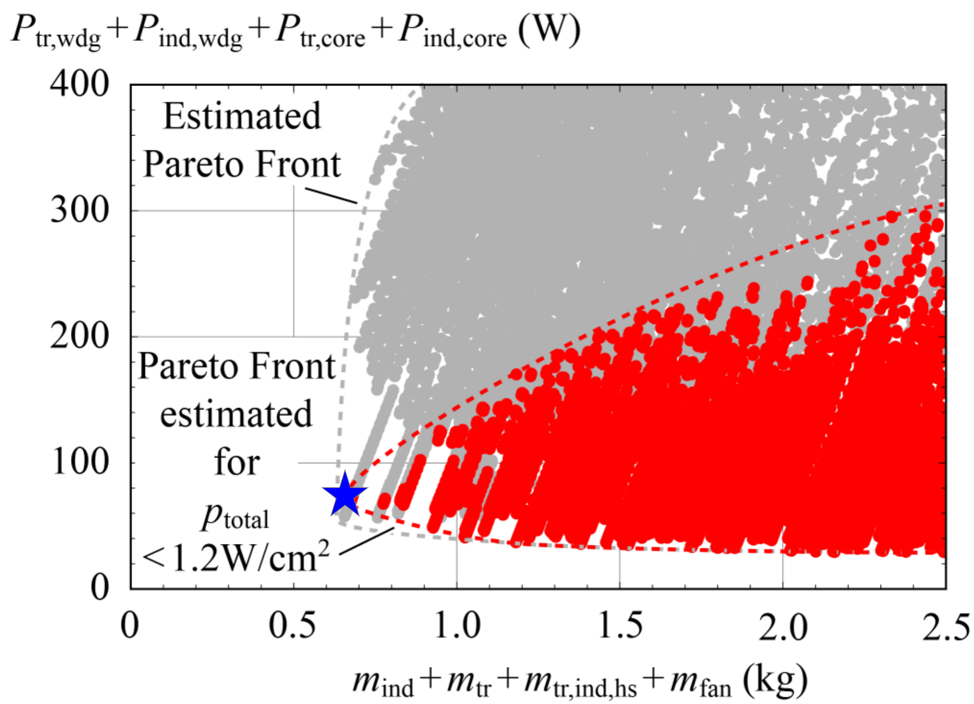


- **Degrees of Freedom / Parameter Ranges**

$$\begin{aligned}
\vec{N}_1 &= [5\ 6\ 7\ 8\ 9\ 10\ 11\ \ldots\ 39\ 40]^{\mathrm{T}},\\
\vec{N}_2 &= \mathrm{round}(\vec{N}_1 \cdot 1\,\mathrm{kV}/750\,\mathrm{V}),\\
\vec{n}_{\mathrm{tr,core}} &= [1\ 2\ 3\ 4\ 5\ 6\ 8\ 10\ 12\ 14\ 16\ 18\ 20]^{\mathrm{T}},\\
\vec{n}_{\mathrm{ind,core}} &= [1\ 2\ 3\ 4\ 5\ 7\ 10]^{\mathrm{T}},\\
\vec{a}_{\mathrm{LVMV}} &= [0.75\ 1.0\ 1.25]^{\mathrm{T}},\\
\vec{c}_{\mathrm{tr}} &= [\mathrm{E30/15/7}\quad \mathrm{E32/16/9}\quad \mathrm{E42/21/20}\quad \mathrm{E55/28/21}\\
&\quad\ \mathrm{E65/32/27}\ \mathrm{E70/33/32}\ \mathrm{UI93/76/30}\ \mathrm{UU93/76/30}]^{\mathrm{T}}\\
\vec{c}_{\mathrm{ind}} &= \vec{c}_{\mathrm{tr}}
\end{aligned}$$

Transformer η-γ-PARETO Front

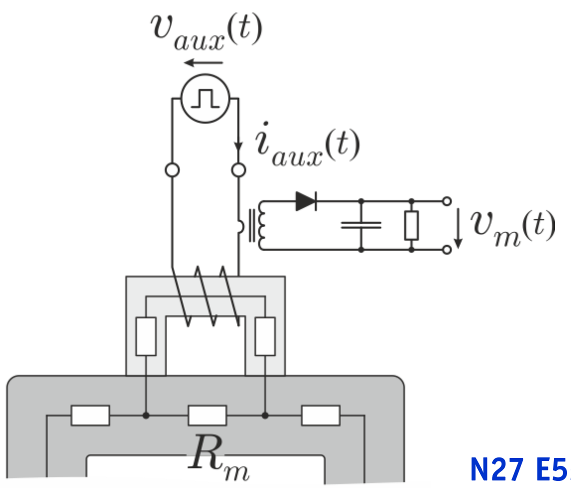
▶ **Selected Design**
η = 97%
γ = 4.5 kW/kg



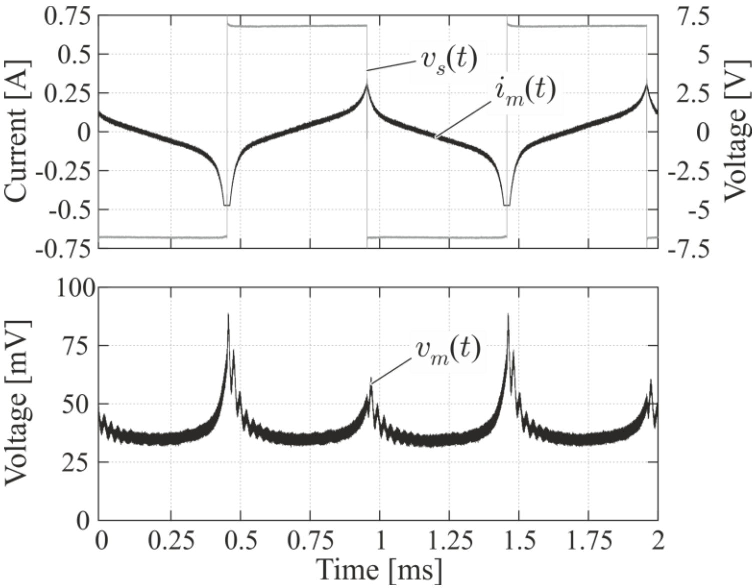
■ **Transformer Volt-Second Balancing - Series Capacitor or "Magnetic Ear" Control**

Transformer Volt-Second Balancing – "Magnetic Ear"

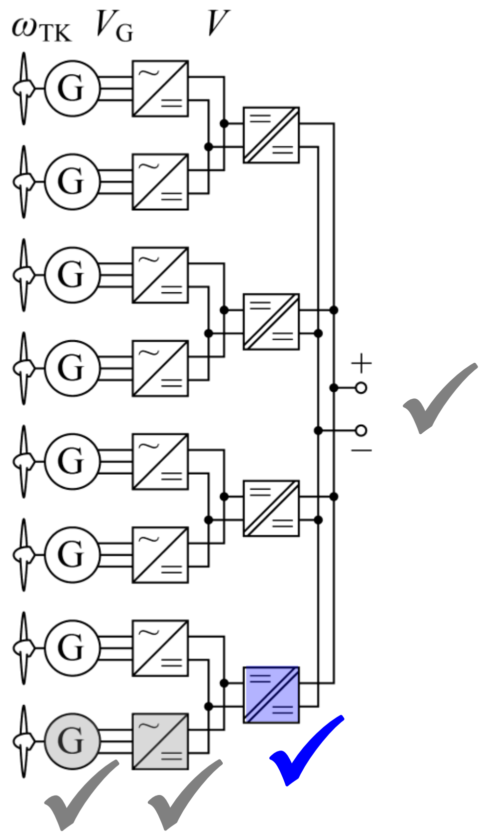
- Magnetic Ear Magnetized with 50% Duty Cycle Rectangular Voltage Winding
- Measured Aux. Current i_{aux} / Voltage v_m Indicates Flux Level
- Enables Closed-Loop Flux Control



N27 E55 Ferrite



System Overview

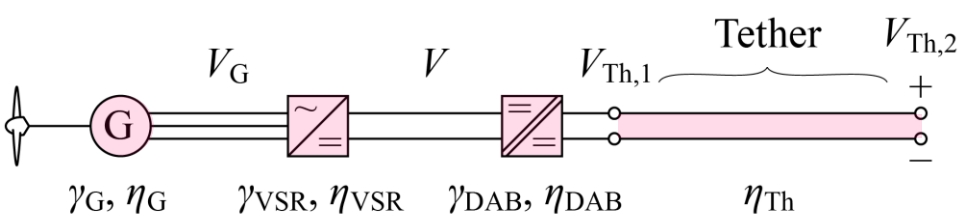


Overall System Consideration

Total Weight
Overall Efficiency
η-γ-PARETO Front

Determination of Overall System Performance

▶ **Consideration of the η-γ-Characteristics of the Partial Systems**



$$m_G = \frac{\frac{P_D}{P_R} P_{out}}{\eta_{VSR}\,\eta_{DAB}\,\eta_{Th}} \frac{1}{\gamma_G(\eta_G)}$$

$$m_{VSR} = \frac{\frac{P_D}{P_R} P_{out}}{\eta_{DAB}\,\eta_{Th}} \frac{1}{\gamma_{VSR}(\eta_{VSR})}$$

$$m_{DAB} = \frac{P_{out}/\eta_{Th}}{\gamma_{DAB}(\eta_{DAB})}$$

$$m = m_G + m_{VSR} + m_{DAB}$$

▶ **Overall η-γ-Characteristic**

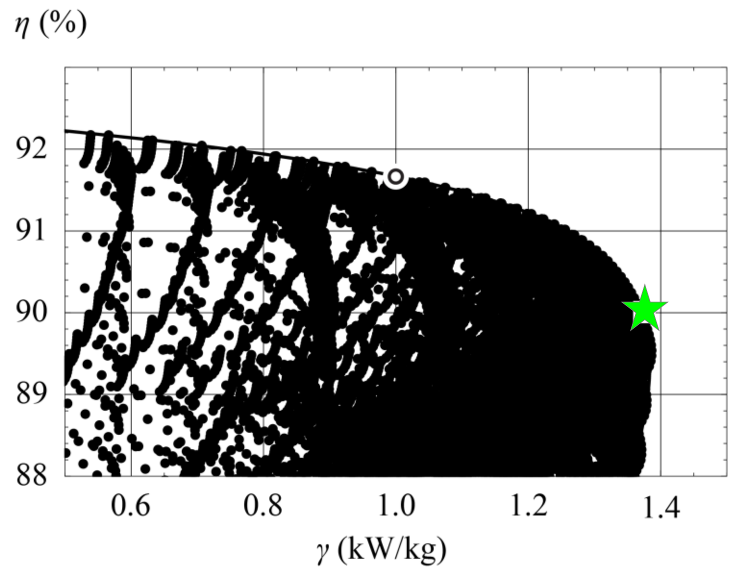
$$\gamma = \frac{P_{out}}{m}$$

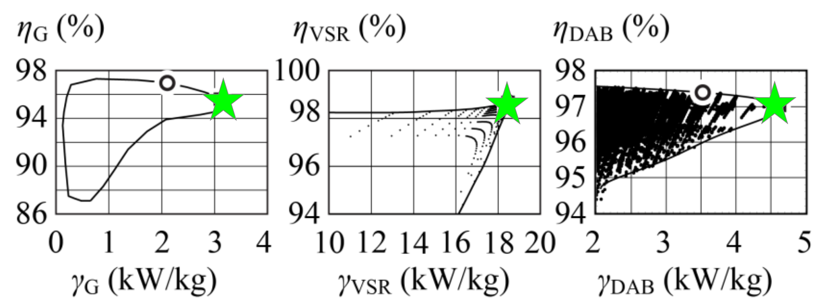
- **Efficiencies of the Partial Systems Need to be Taken into Account**
- **P_D/P_R = Overrating Ratio (8x16kW/100kW)**

Overall System Performance

EFFICIENCIES AND POWER-TO-WEIGHT RATIOS AT THE 2 DESIGN POINTS MARKED IN FIG. 24(A) (CALCULATED FOR NOMINAL OPERATION).

Total system	Generator, VSR, and DAB converter		
$\gamma = 1.37\,\mathrm{kW/kg}$ $\eta = 90.0\%$	Generator:	$\gamma_{G} = 3.11\,\mathrm{kW/kg}$,	$\eta_{G} = 95.4\%$
	VSR:	$\gamma_{VSR} = 18.3\,\mathrm{kW/kg}$,	$\eta_{VSR} = 98.6\%$
	DAB:	$\gamma_{DAB} = 4.60\,\mathrm{kW/kg}$,	$\eta_{DAB} = 97.1\%$
$\gamma = 1.00\,\mathrm{kW/kg}$ $\eta = 91.7\%$	Generator:	$\gamma_{G} = 2.14\,\mathrm{kW/kg}$,	$\eta_{G} = 96.9\%$
	VSR:	$\gamma_{VSR} = 18.3\,\mathrm{kW/kg}$,	$\eta_{VSR} = 98.6\%$
	DAB:	$\gamma_{DAB} = 3.53\,\mathrm{kW/kg}$,	$\eta_{DAB} = 97.4\%$





- **Final Step: System Control Consideration**

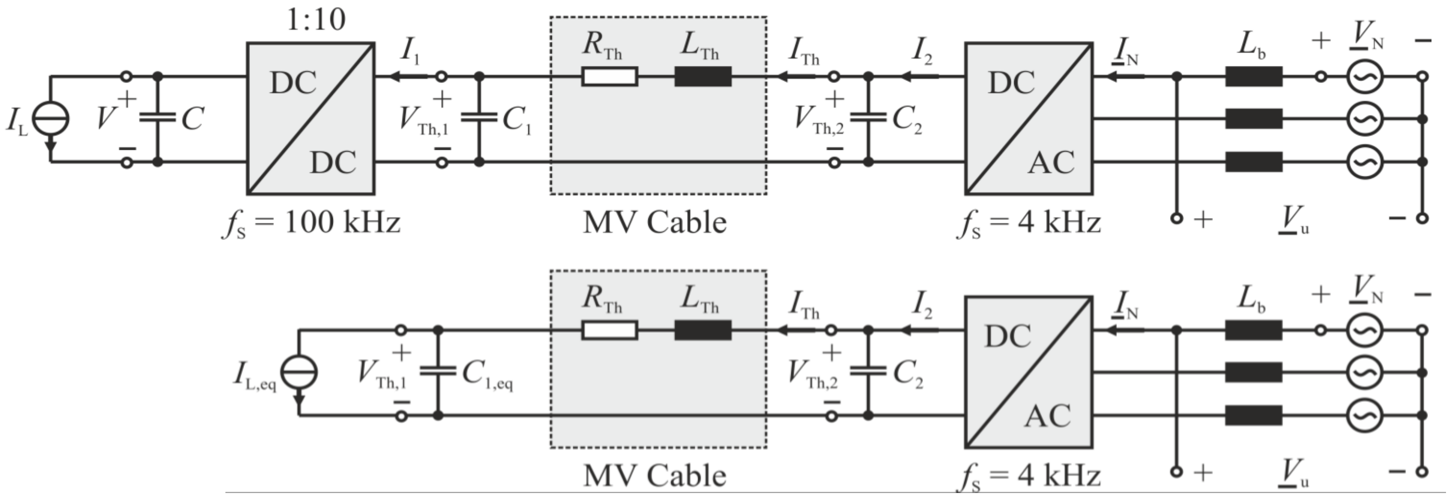
Electric System Control

Stability
Reference Response
Disturbance Response

System Control

- ▶ Control of Flight Trajectory / Max. Energy Generation
- ▶ Generator (Motor) Speed / Torque Control
- ▶ etc.

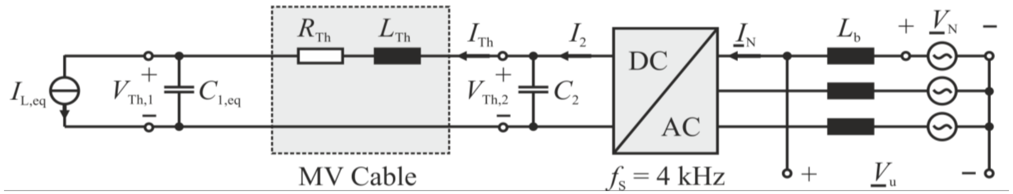
- ▶ Control of DC Voltage Levels is Mandatory !

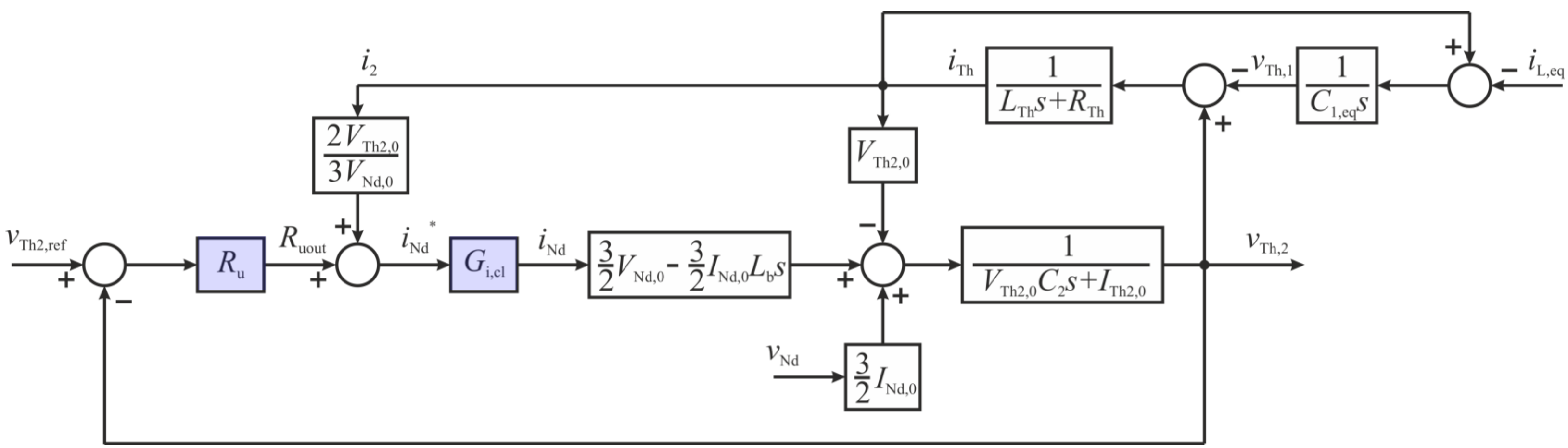


■ Simplified Control-Oriented Block Diagram of the Electric System

Control Block Diagram

- ▶ Ground Station Controls the Tether Voltage
- ▶ Control Objectives: LV DC Bus 650…750V; MV (Tether) < 8kV



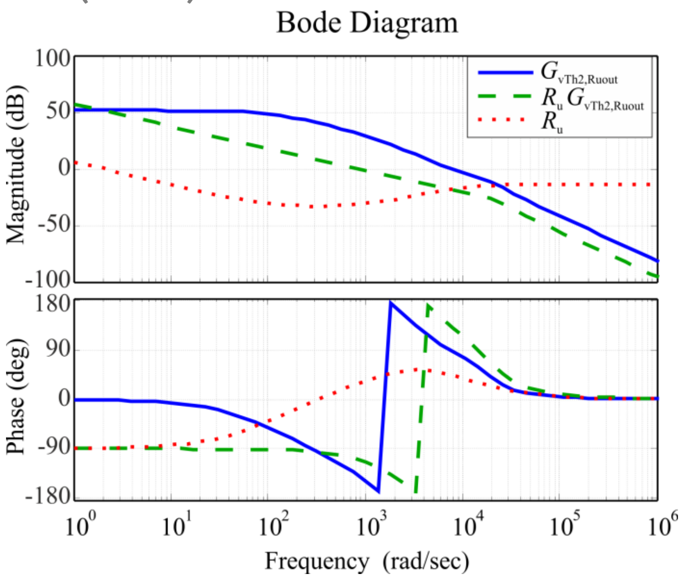


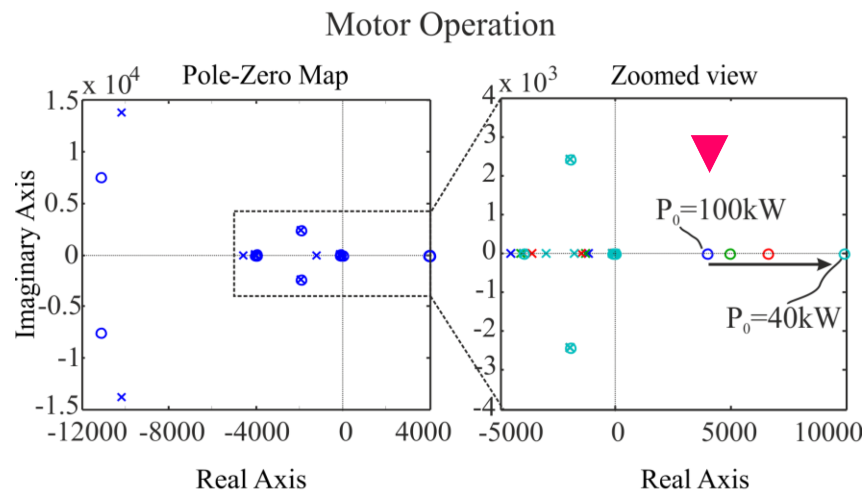
- ■ Only Tether Voltage at Ground Station is Measured (I_{Th} Feedforward)
- ■ Motor AND Generator Operation Must be Considered

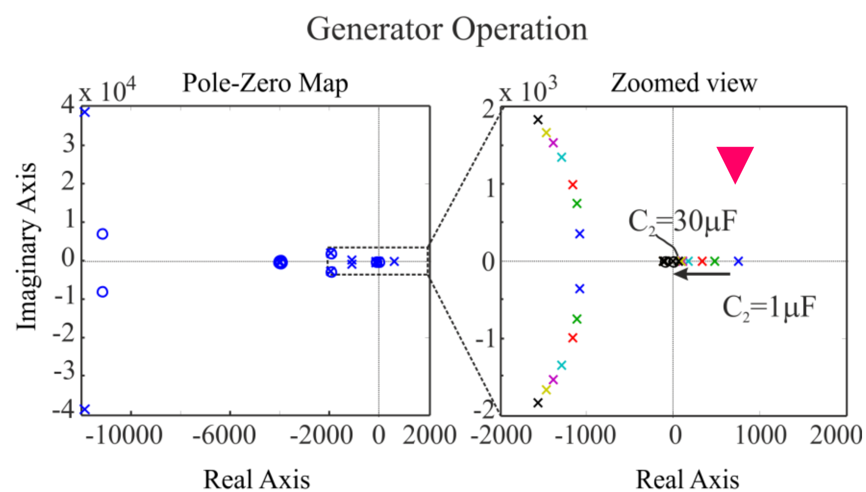
Tether Voltage Control Plant

$$G_{\mathrm{vTh2,Ruout}} = \left.\frac{v_{\mathrm{Th,2}}}{R_{\mathrm{uout}}}\right|_{v_{\mathrm{Nd}}=0,\, i_{\mathrm{L,eq}}=0}$$

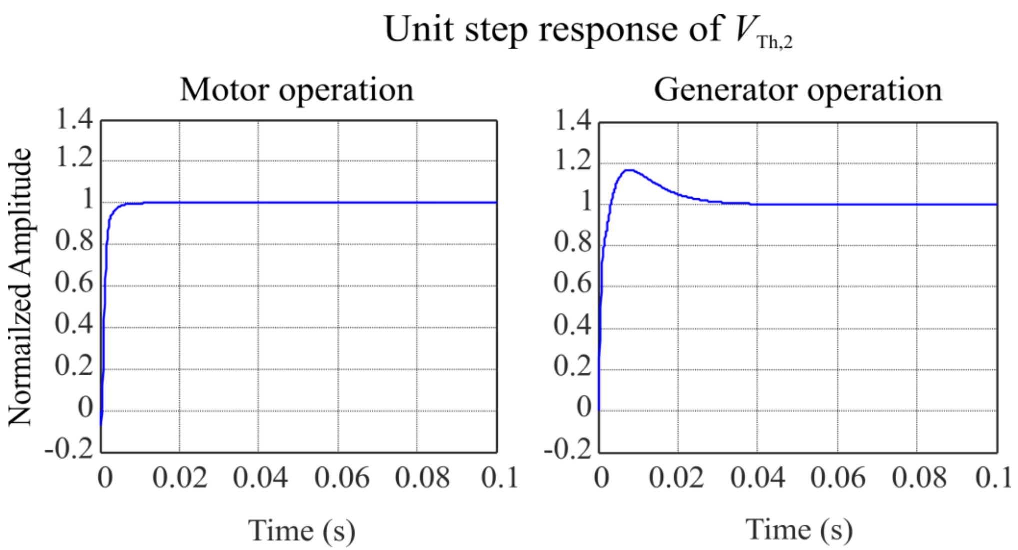
Motor Operation (100kW)





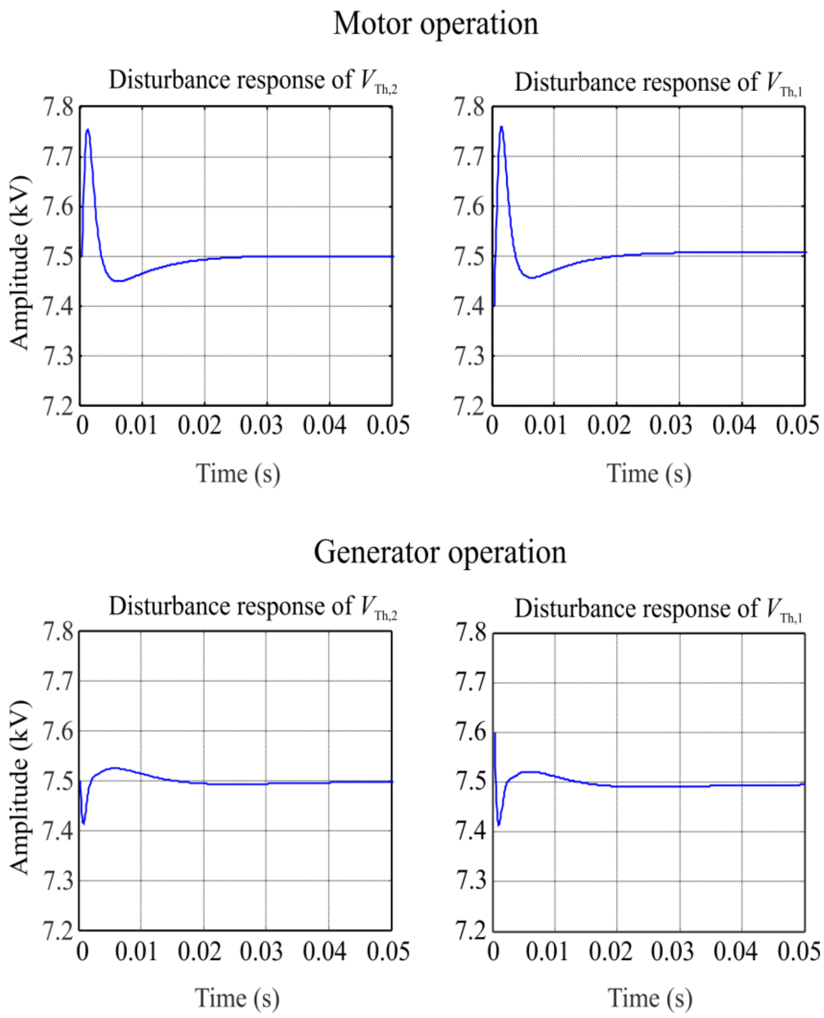


Voltage Control Reference Step Response



- Overshoot Could be Avoided with Reference Form Filter

Voltage Control
Disturbance Response



- Motor Operation 100kW → 0
- Gen. Operation —100kW → 0

Conclusions

- ▶ AWTs are Basically Technically Feasible
- ▶ AWTs Realization Combines Numerous Challenges
  - Aircraft Design
  - MVDC Transmission
  - MV/HF Power Electronics
  - etc.
- ▶ AWTs are a Highly Interesting Example for η-γ Trade-off Studies
- ▶ AWTs are Examples for Smart Pico Grids or MEA Power System Analysis
- ▶ AWTs is a Clear Example of Thinking "Out-of-the-Box" !


thinking
THE BOX

Questions ?