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Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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

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Pareto-Optimal Design of Airborne Wind Turbine Power Electronics

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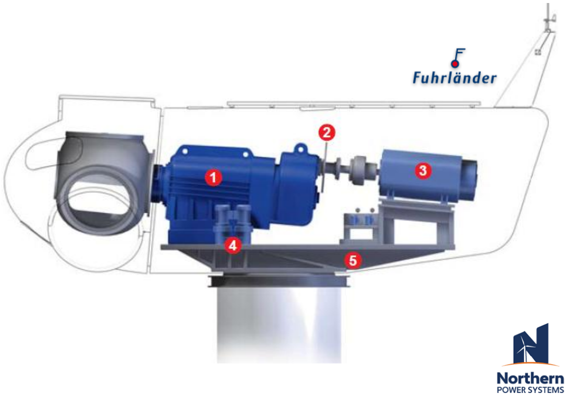
Outline

- Futuristic Wind Turbine Concepts
- Airborne Wind Turbine Electrical System
- Multi-Objective Optimization
- Controls Aspects
- Conclusions

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

Revolutionize Wind Power Generation Using Kites / Tethered Airfoils

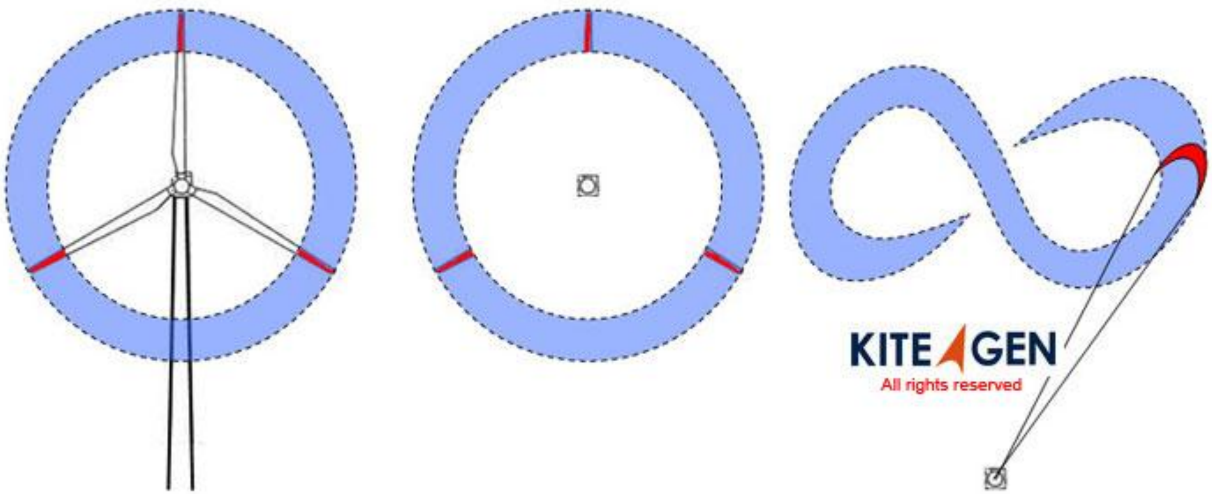
[2] M. Loyd, 1980

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

Controlled Power Kites for Capturing Wind Power

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

[2] M. Loyd, 1980

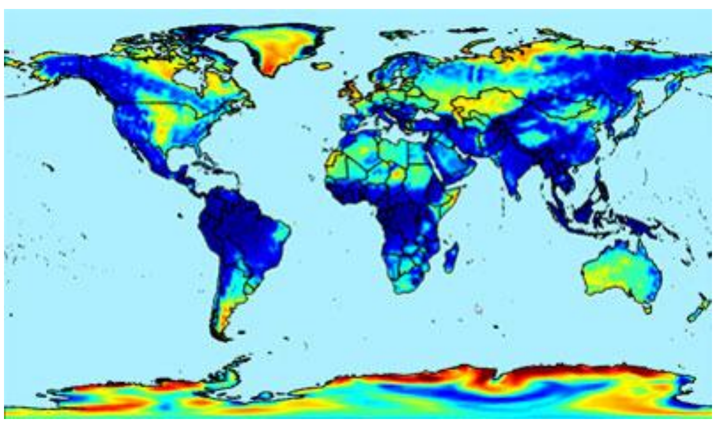


- Wing Tips / Highest Speed Regions are the Main Power Generating Parts of a Wind Turbine

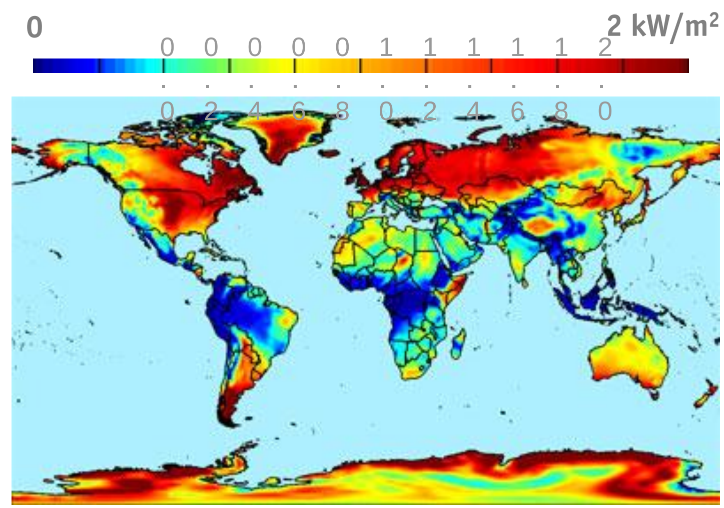
Controlled Power Kites for Capturing Wind Power

- 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

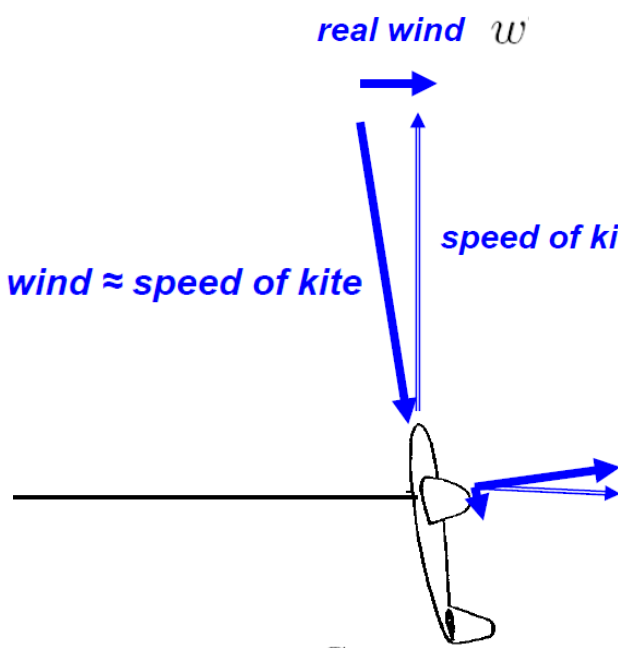
- Wind at High Altitudes is Faster and More Consistent
- Operate Kites at High Altitudes or Even in the Jet Stream

STANFORD UNIVERSITY

AIRBORNE 2010 WIND ENERGY CONFERENCE

Pumping Power Kites

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



Source: M. Diehl / K.U. Leuven

- *effective wind ≈ speed of kite*

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

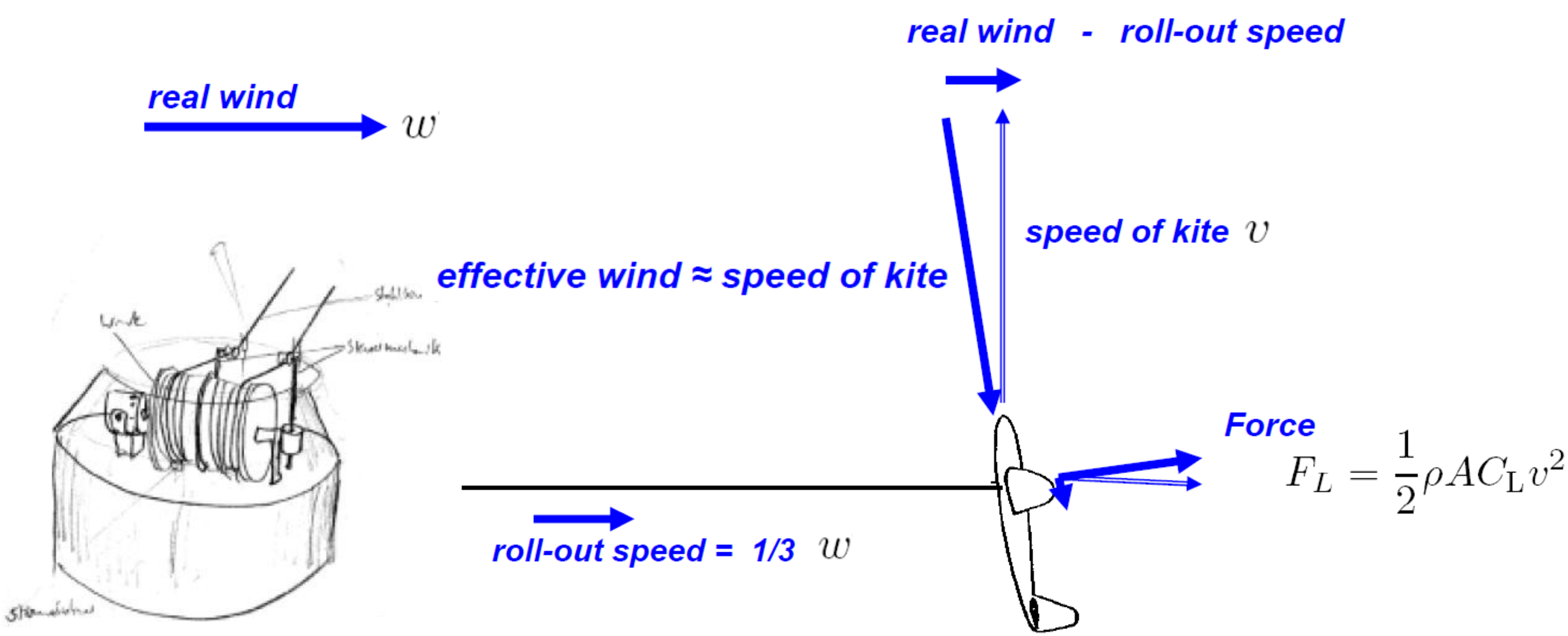
- Generated Force Could be Converted into Useful Power by Pulling a Load / Driving Turbines via a Tether

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

Pumping Power Kites

- **Maximum Power** $$P = \frac{2}{27}\,\rho\,A\,w^3\,C_\mathrm{L}\left(\frac{C_\mathrm{L}}{C_\mathrm{D}}\right)^2$$ [2] M. Loyd, 1980

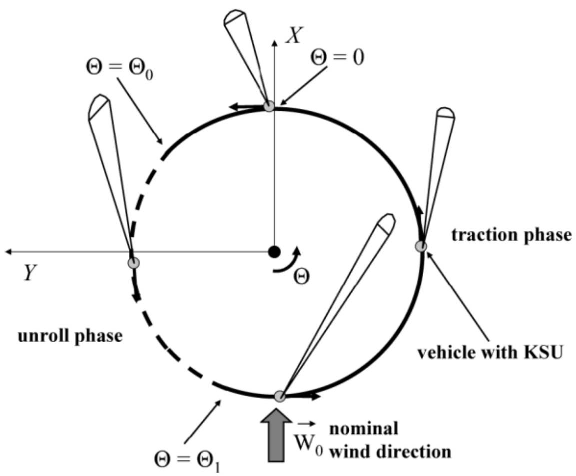
Source: M. Diehl / K.U. Leuven

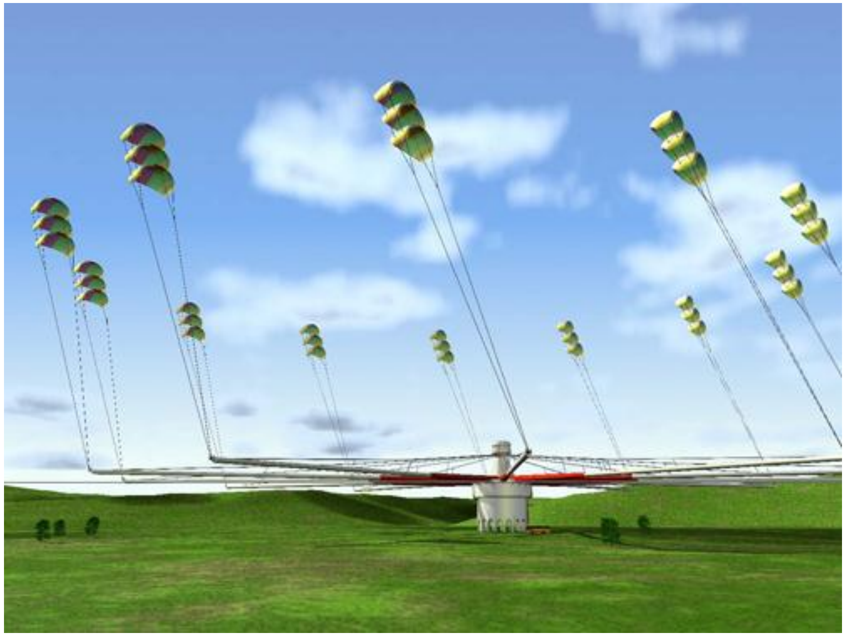


Pumping Power Kites for Capturing High Altitude Wind Power

- 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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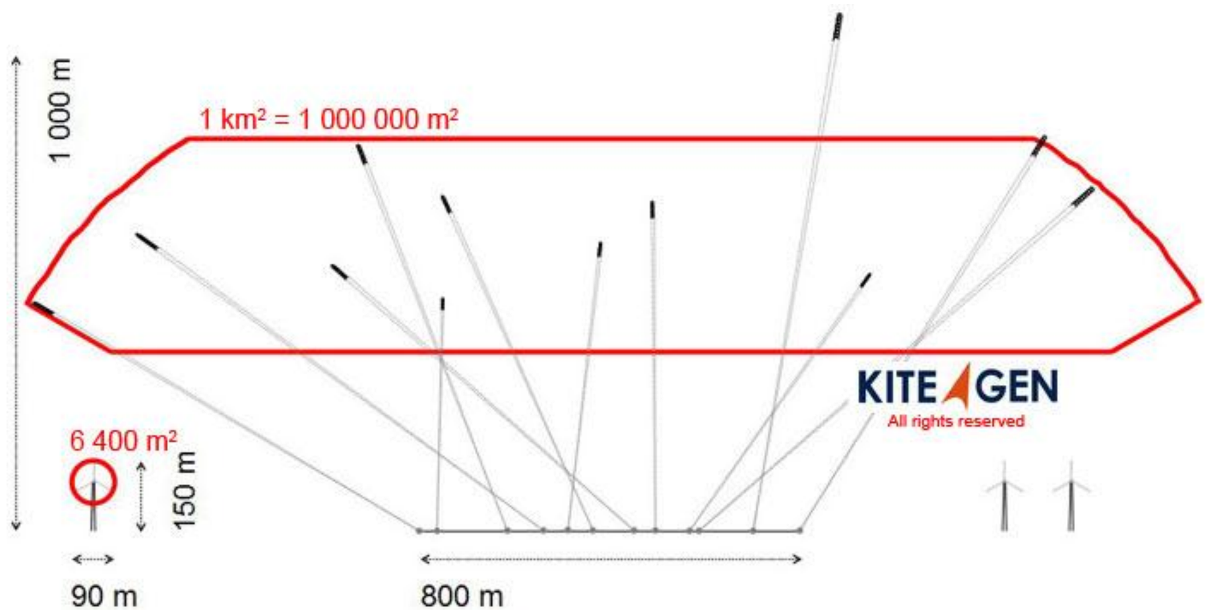
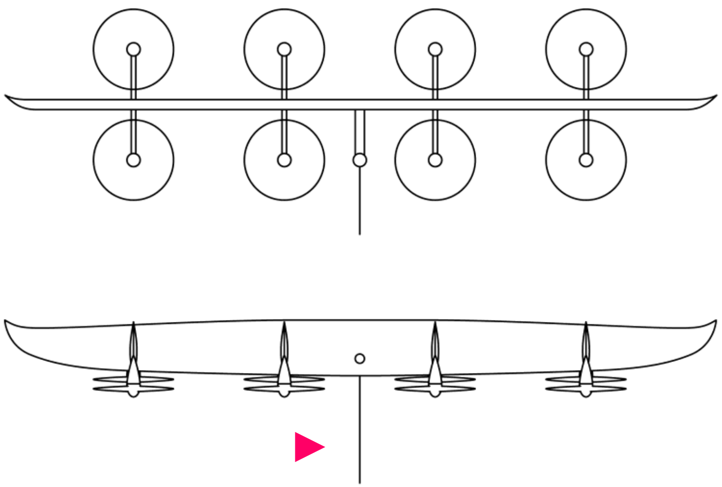


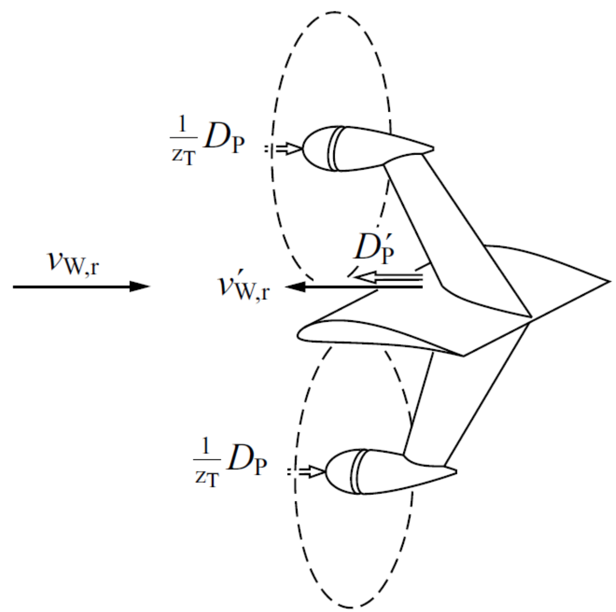
Carousel Configuration

Alternative Concept – Airborne Wind Turbine

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

[2] M. Loyd, 1980





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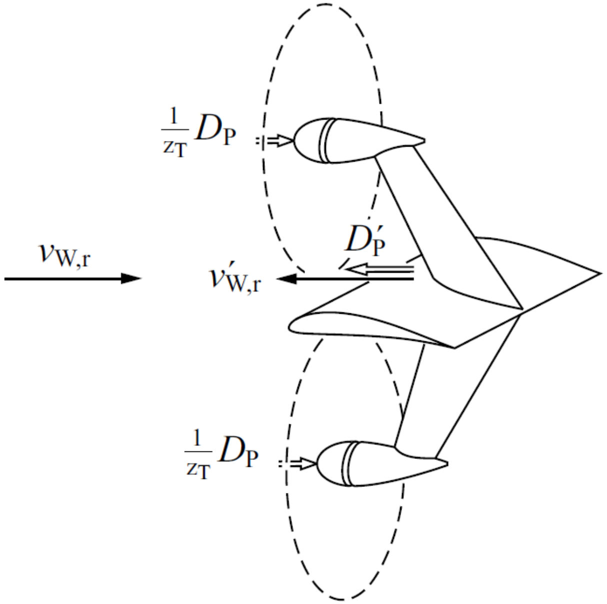
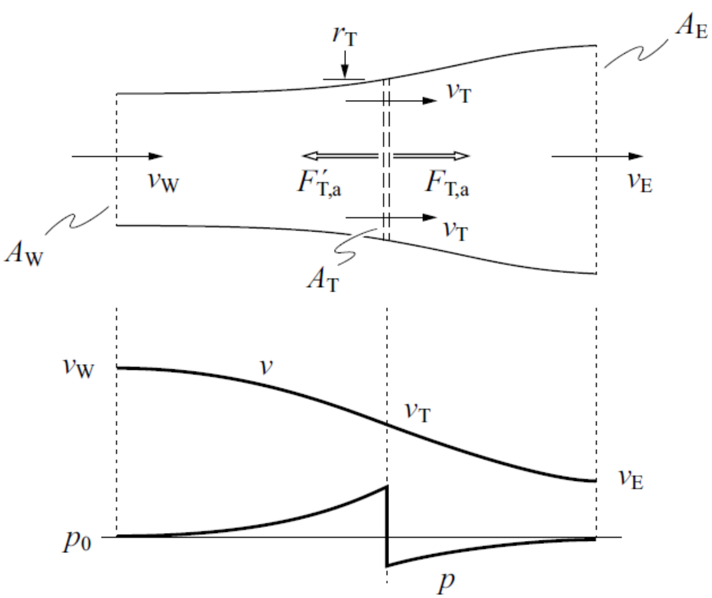


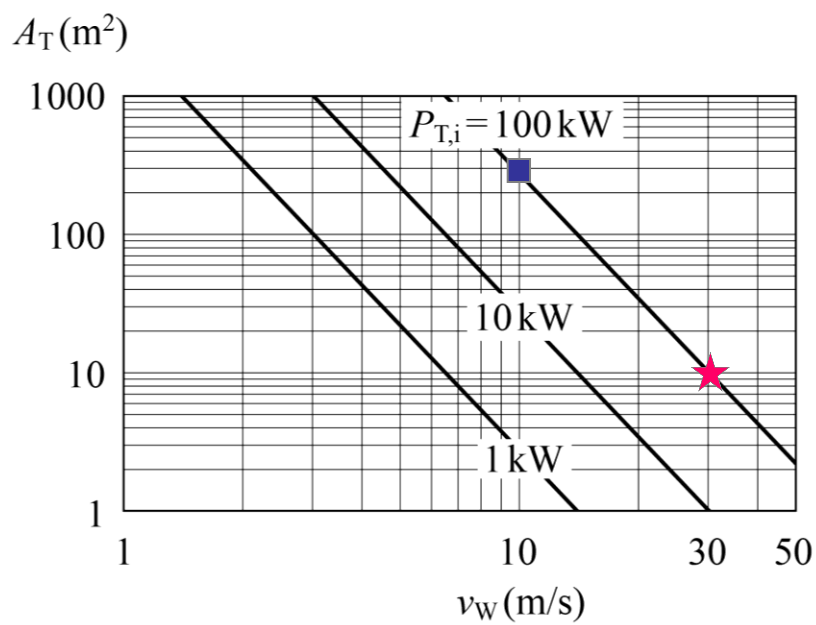
Basic Physics of Wind Turbines

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

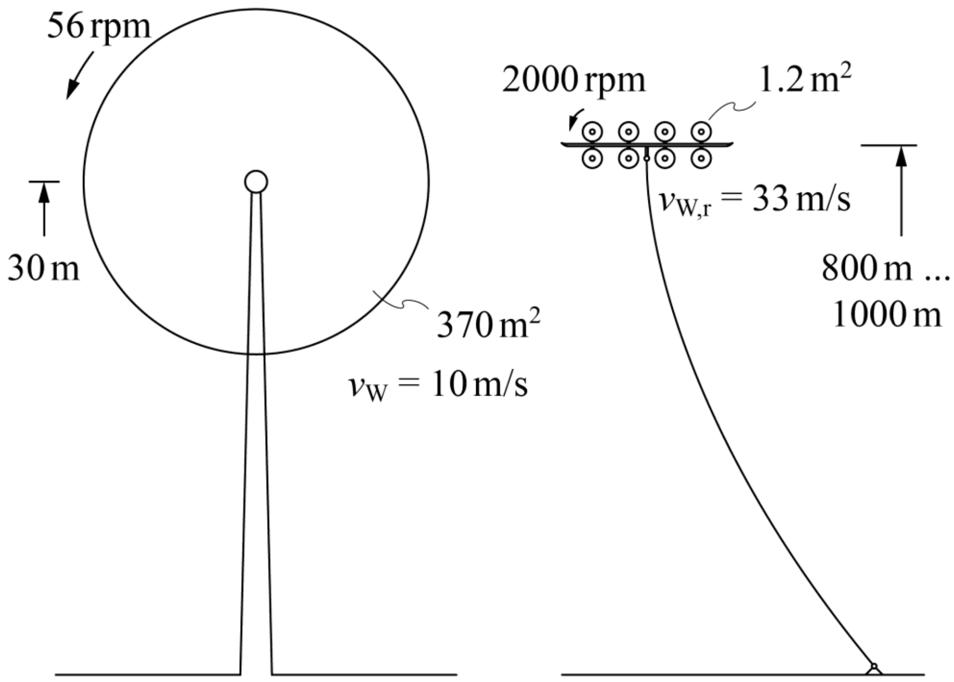
$$P_{\mathrm{T,i}} = c_{\mathrm{P,i}} \frac{1}{2} \rho A_{\mathrm{T}} v_{\mathrm{W}}^{3}$$

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





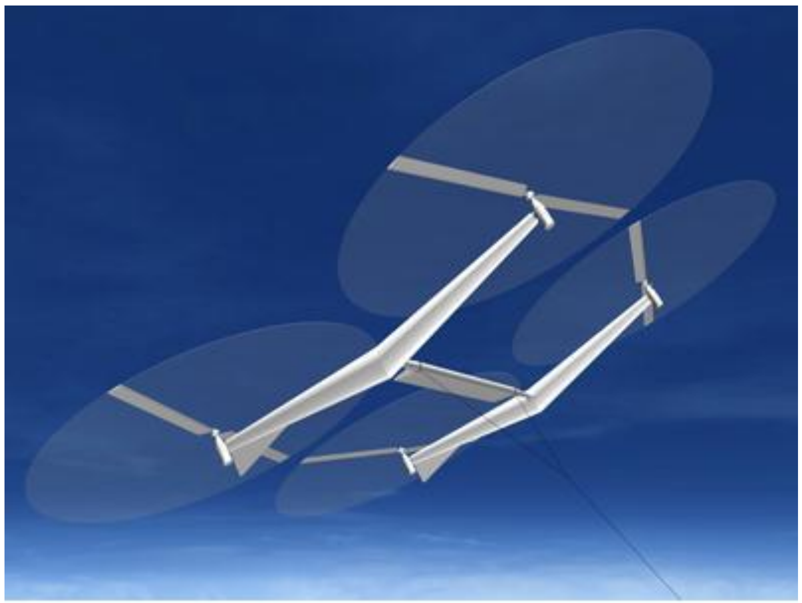
Comparison of Conventional / Airborne Wind Turbine



- Numerical Values Given for 100kW Rated Power

SkyWindPower AWT Concept

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



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

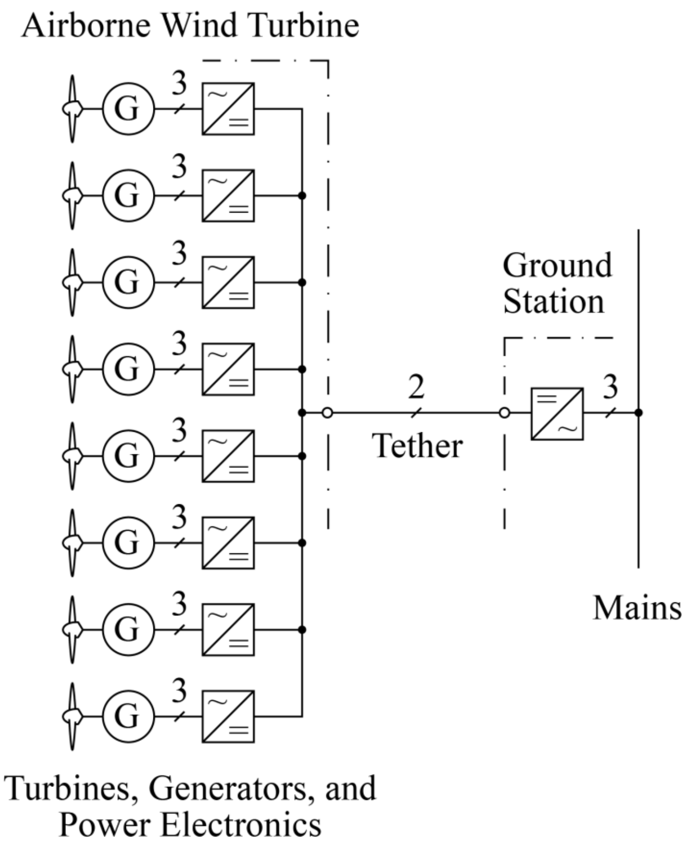
- Named as One of the 50 Top Inventions in 2008 by TIME Magazine

JOBY ENERGY AWT Concept

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

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

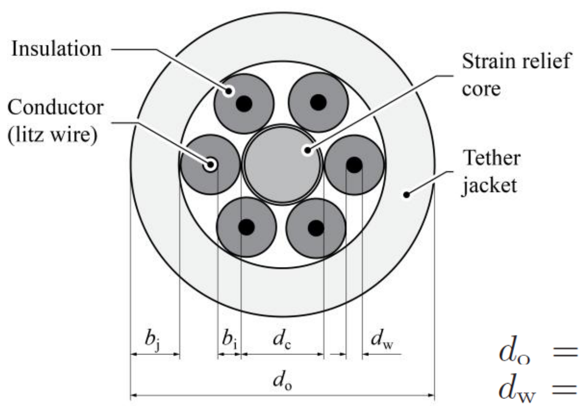
- Clarify Practical Feasibility of AWT Concept
- Clarify Weight/Efficiency Trade-off / Multi-Objective Optimization / Pareto-Front

Tether Design

DC Voltage Level
η-γ-Pareto Front

Tether DC Transmission Voltage Level

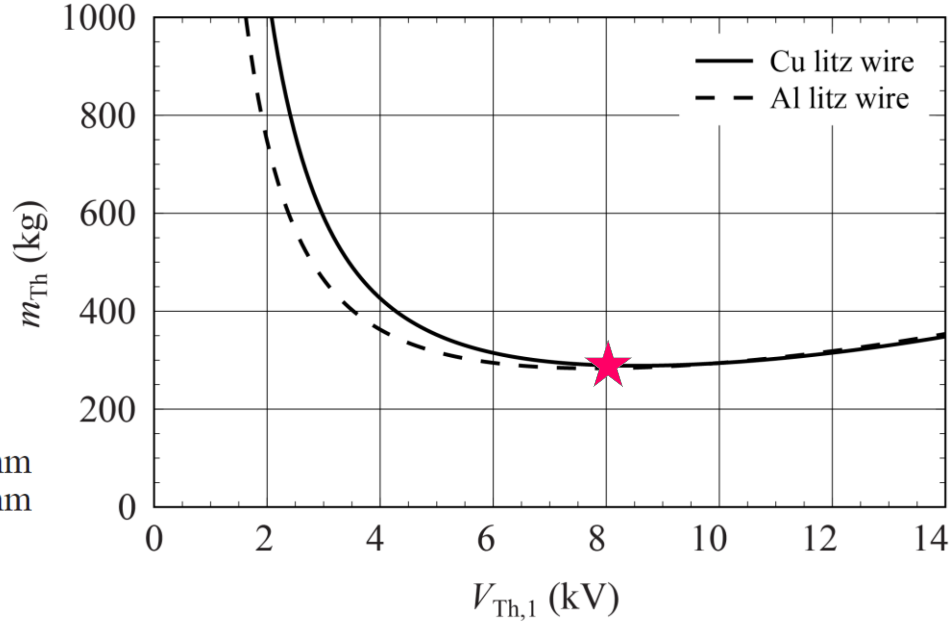
- $P_{th,1}$ = 100kW / l_{th} = 1000m
- Strain Relief Core – Kevlar (F_{th} = 70kN, d=5mm)
- Cu or Al Helical Conductors - ½ U_{th} Isolated
- Outer Protection Jacket (3mm)



$$d_o = 19\,\text{mm}$$
$$d_w = 1.5\,\text{mm}$$

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

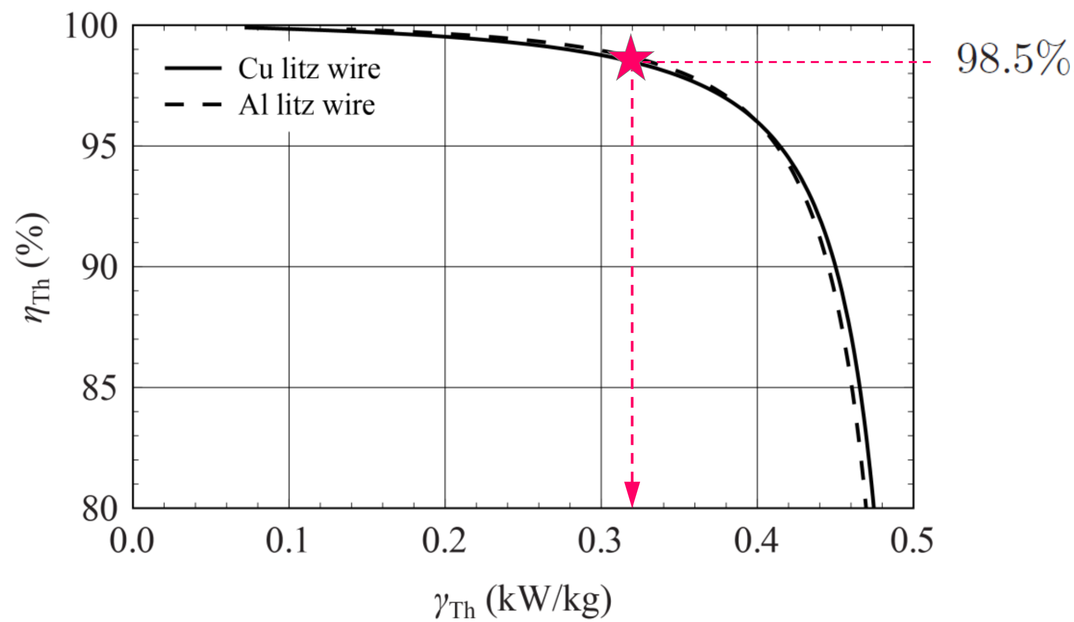
$$b_i = 0.0144\frac{\text{mm}}{\text{kV}^2}\cdot V_i^2 + 0.1694\frac{\text{mm}}{\text{kV}}\cdot V_i + 0.40\,\text{mm}$$



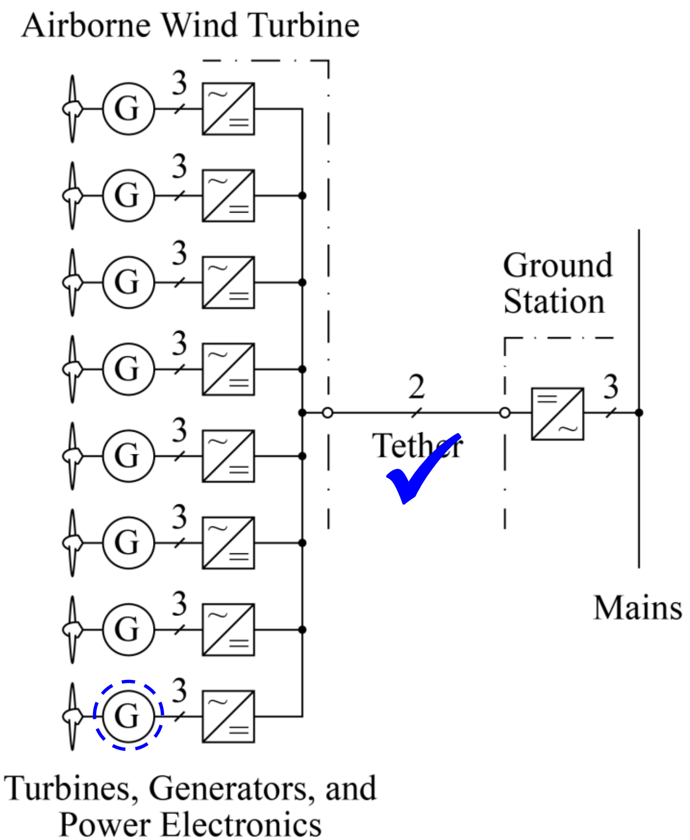
Tether η-γ-Pareto Front

▶ Tether Voltage $V_{th,1}$ = 8kV

■ Total Weight of Tether: 320kg

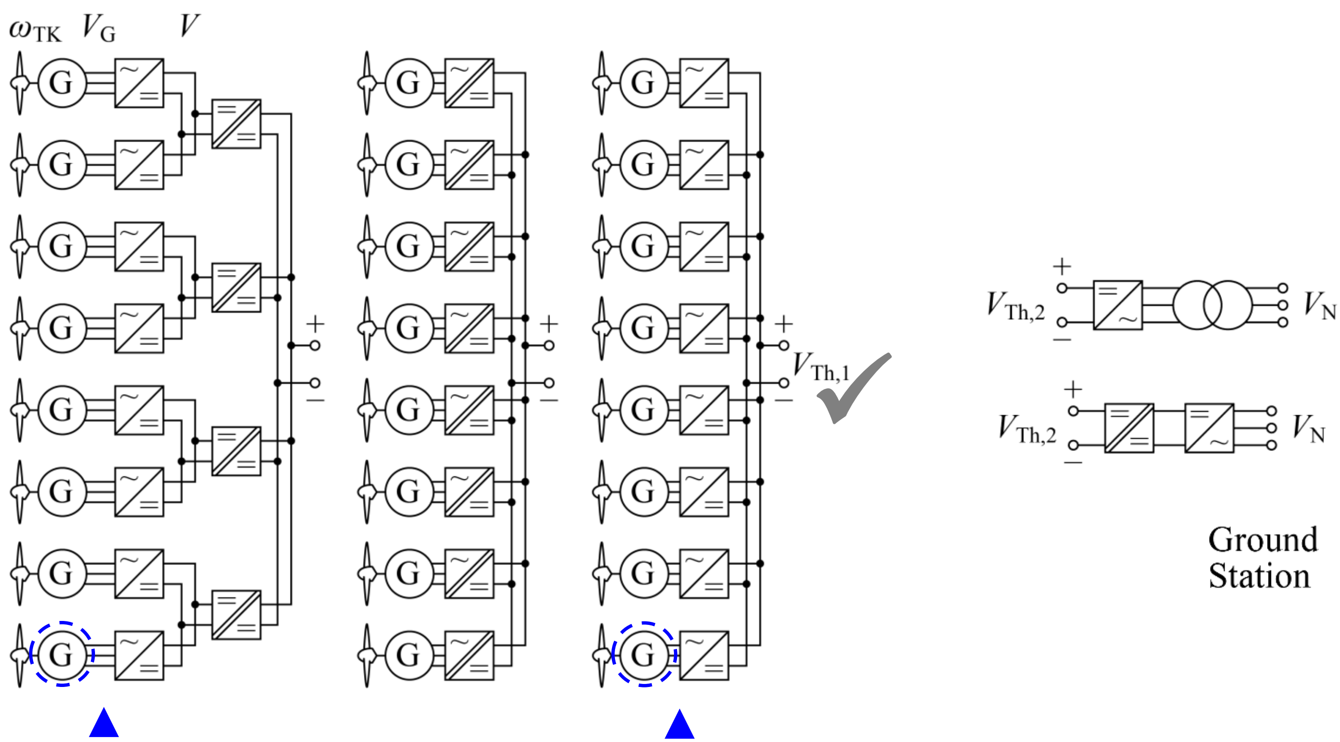


System Overview



Possible AWT Electrical System Structures

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



Generator / Motor Design

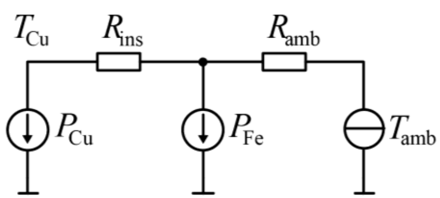
Dimensions
Number of Pole Pairs
η-γ-Pareto Front

Generator / Motor η-γ-Pareto Front

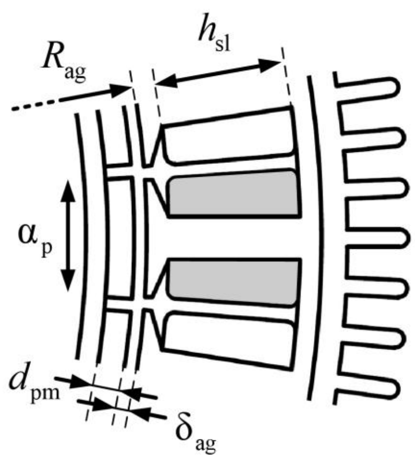
▶ **Medium Voltage vs. Low Voltage Machine** $V_{th,1}$ **= 8kV**

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

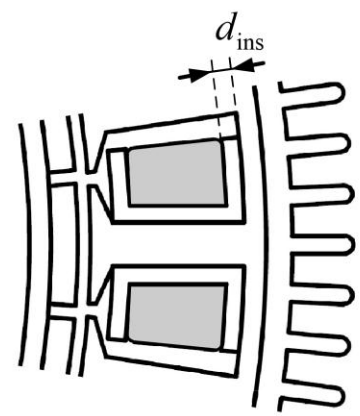
$$\eta_{mot} = \frac{P_{mech}}{P_{mech} + P_v}$$



Thermal Model



LV Machine



HV Machine

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

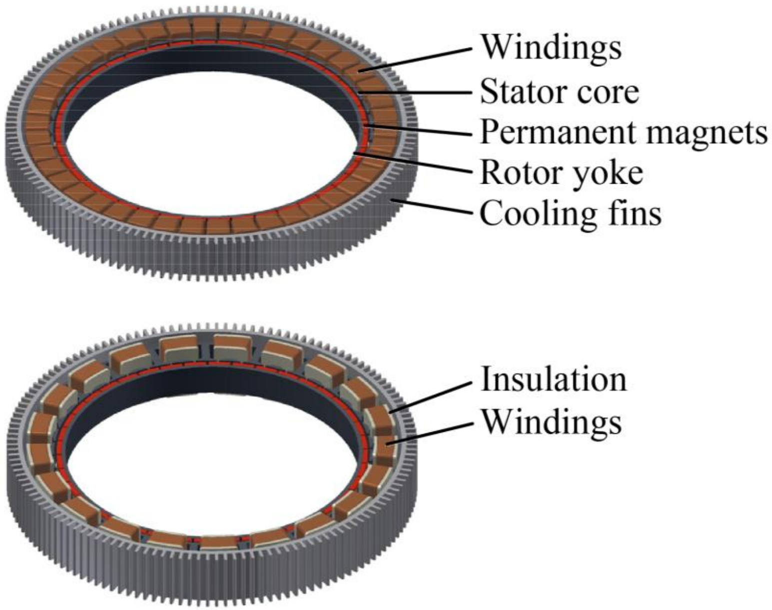
CAD Drawing of LV and MV Machine

▶ Fixed Parameters and Degrees of Freedom

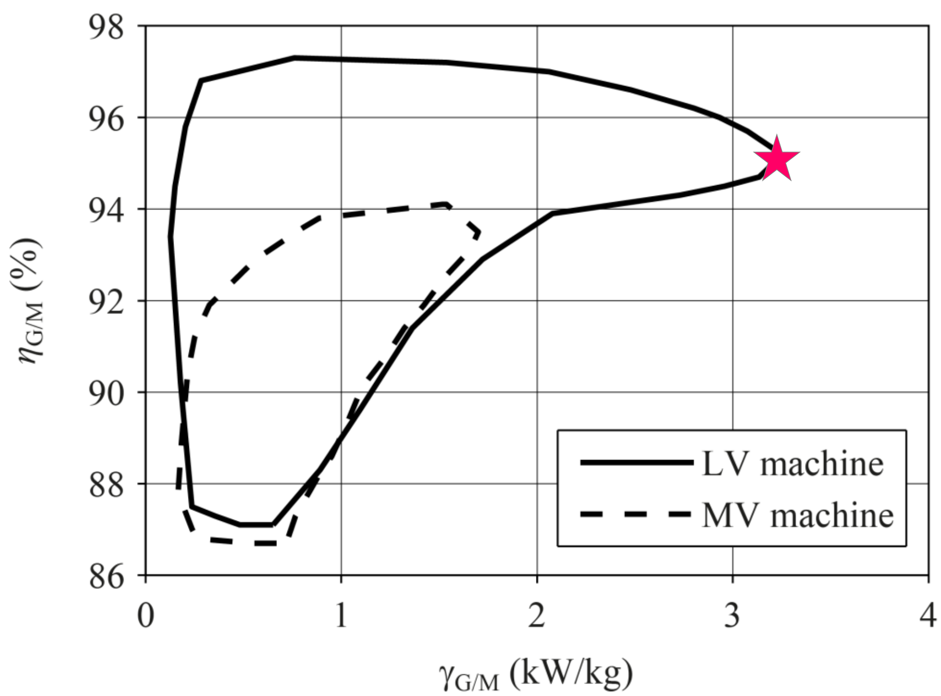
MACHINE OPTIMIZATION PARAMETERS AND FIXED PARAMETERS

Optimization parameters	Symbol	Range
Air-gap radius	R_{ag}	$50 \ldots 250\,\mathrm{mm}$
Active length	L	$10 \ldots 60\,\mathrm{mm}$
Slot depth	h_{sl}	$5 \ldots 20\,\mathrm{mm}$
Permanent magnet thickness	d_{pm}	$2 \ldots 8\,\mathrm{mm}$
Pole coverage factor	α_{p}	$0.8 \ldots 1$
Number of pole pairs	p	$5 \ldots 30$

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



Generator / Motor η-γ-Pareto Front



▶ **Selected Design**
η = 95.4%
γ = 3.1 kW/kg

■ **Medium Voltage Machine Not Considered Further**

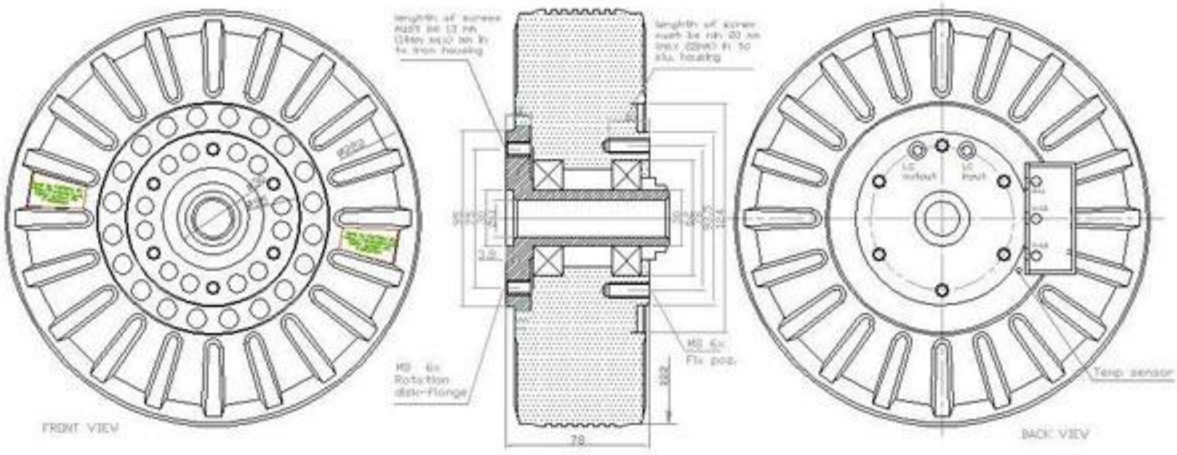
Comparison to Commercial Motors

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

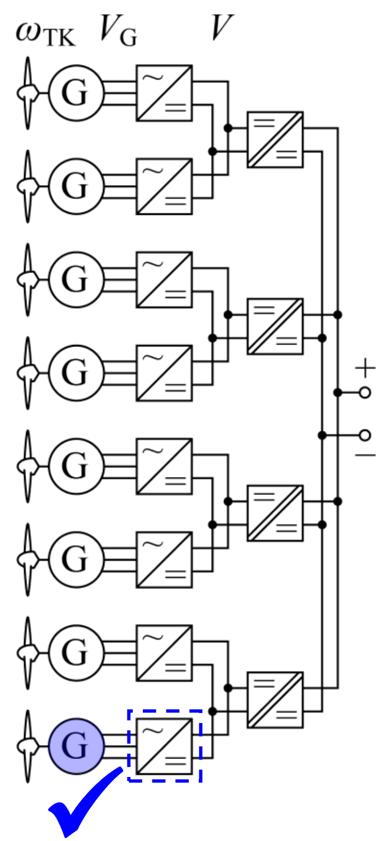
ENSTROJ
electric motor innovation
established in 1991

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



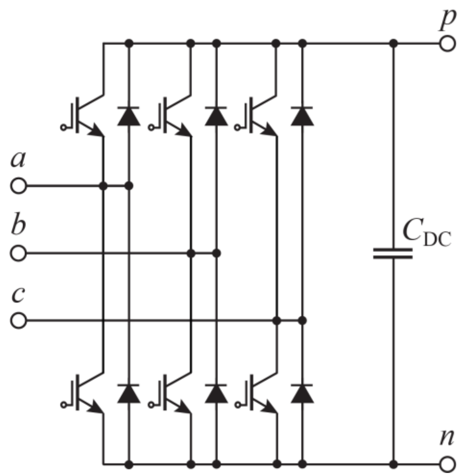
Rectifier / Inverter Design

Chip Area
Heatsink Volume
η-γ-Pareto Front

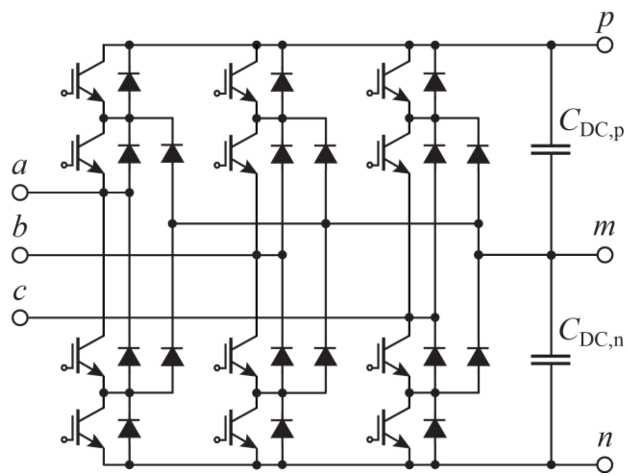
Rectifier / Inverter Design

► 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

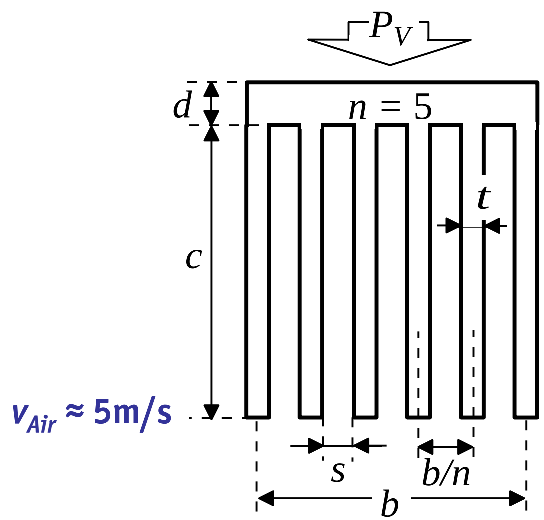


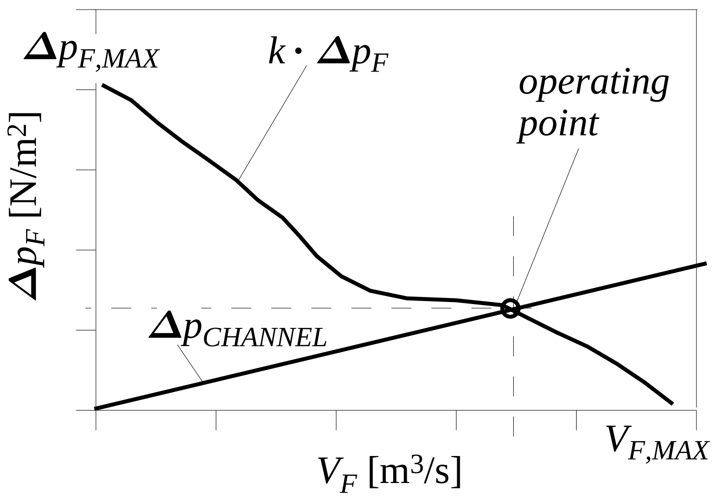
600V T&FS Si IGBT3s /
600V Si EmCon3 Diodes

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

Heatsink Optimization

▶ Maximize Thermal Conductance / Weight (Volume)

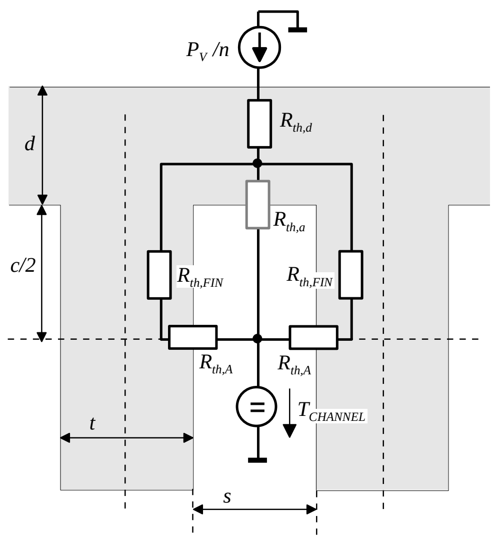


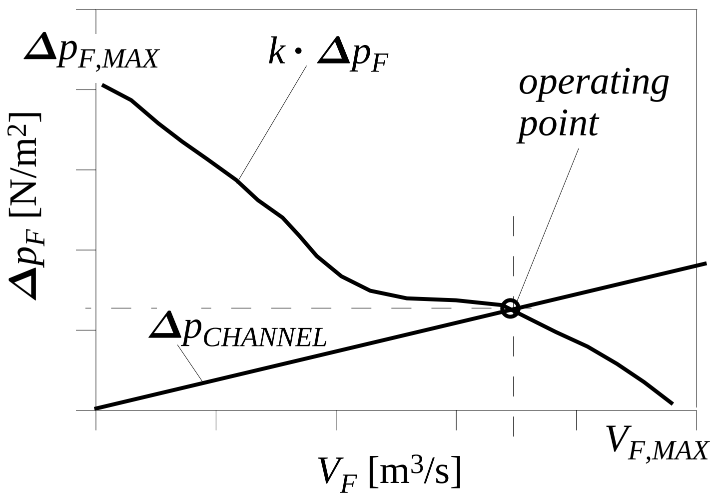


- Highest Performance Fan
- Fin Thickness / Channel Width Optimization

Heatsink Optimization

▶ **Maximize Thermal Conductance / Weight (Volume)**



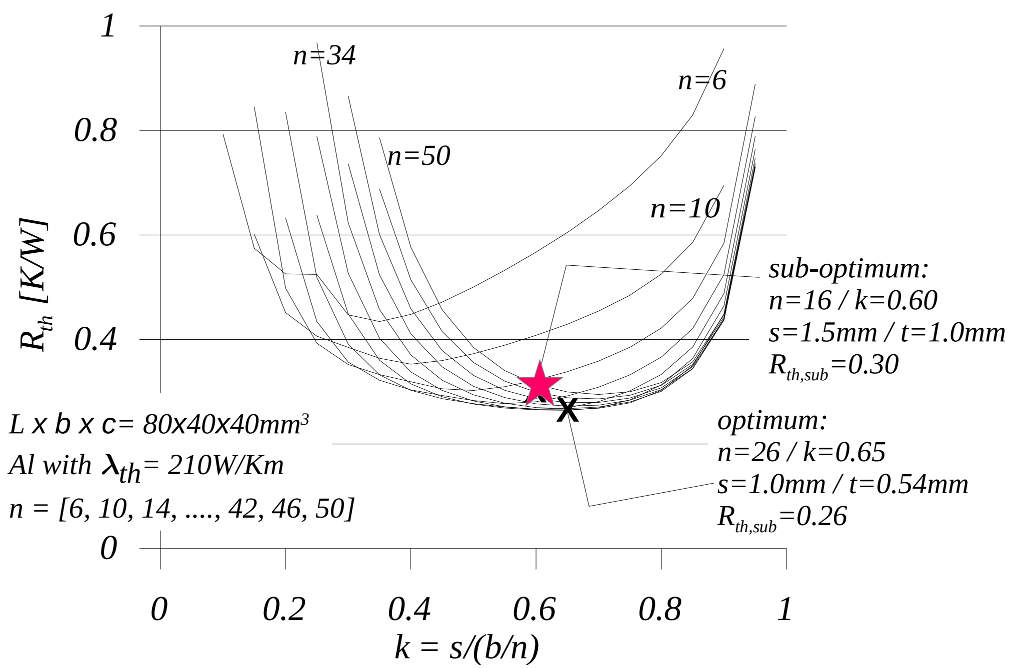


- Highest Performance Fan
- Fin Thickness / Channel Width Optimization

Heatsink Optimization

▶ **Optimum**

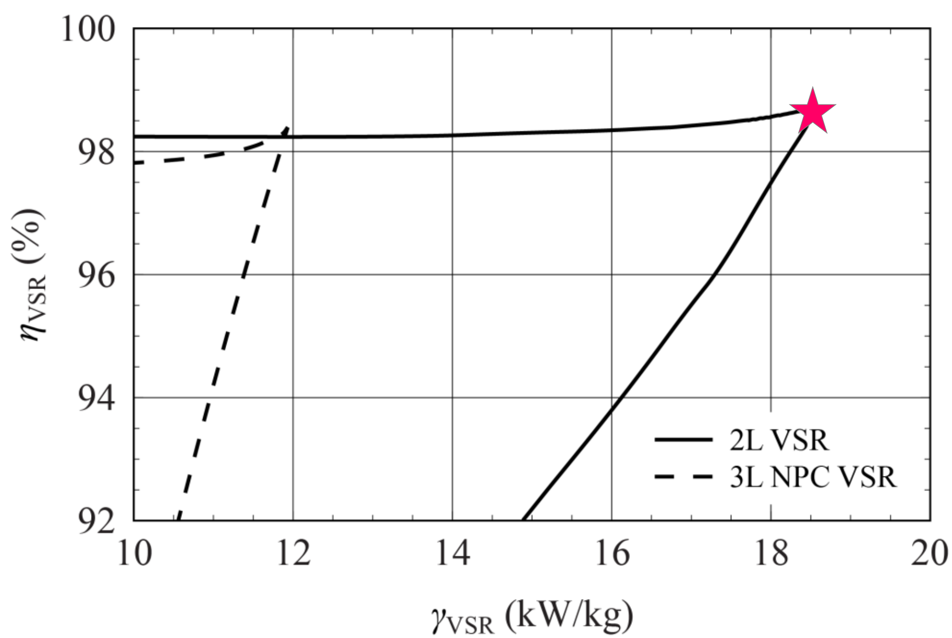
$$CSPI_{\mathrm{m}} = 15.0\frac{\mathrm{W}}{\mathrm{K\,kg}}$$



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

Rectifier / Inverter η-γ-Pareto Front

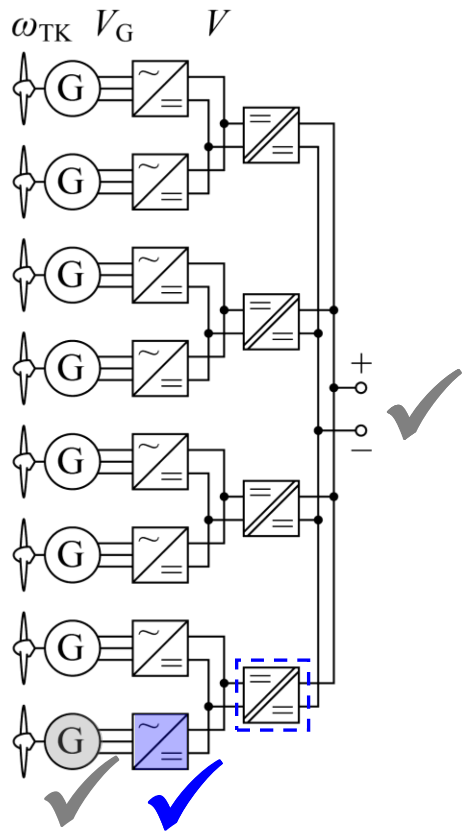
- Switching Frequency Range 24...70 kHz
- Heatsink Temperature Range 55...100 °C (T_{amb} = 40°C)



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

■ 3-Level Topology Does Not Show a Benefit

System Overview



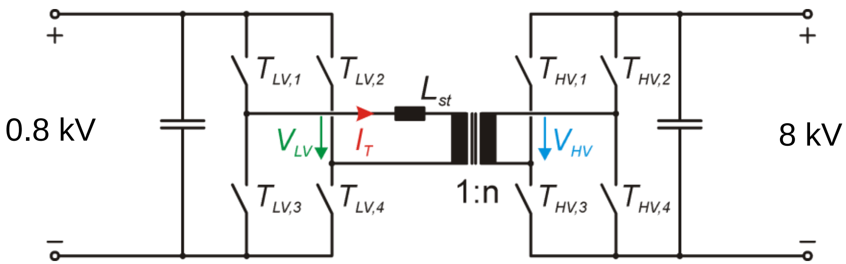
$8kV_{DC}/750V_{DC}$ DAB Converter Design

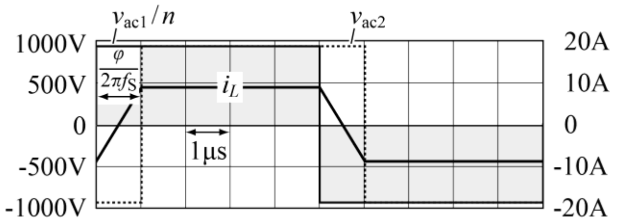
Switches / Topology
Transformer
η-γ-Pareto Front

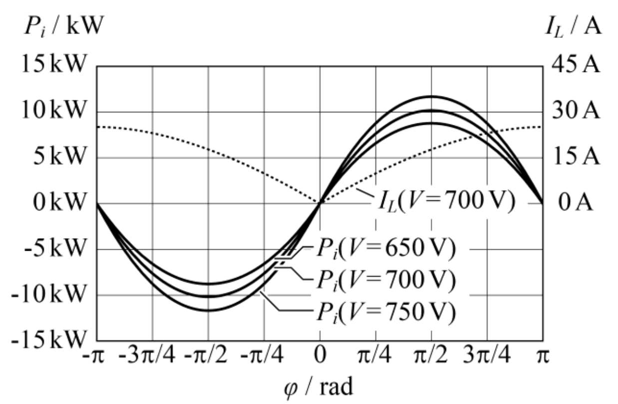
DC/DC Converter Topology

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

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







■ **Implementation of Electronic Switches - SiC**

DC/DC Converter Topology

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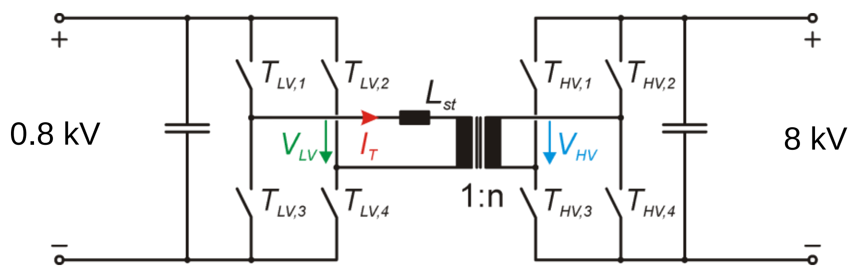
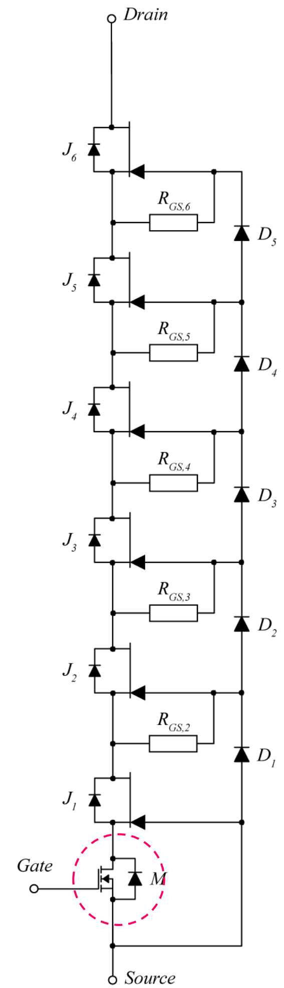


■ **Implementation of Electronic Switches - SiC**

► **10kV Si/SiC SuperCascode Switch**



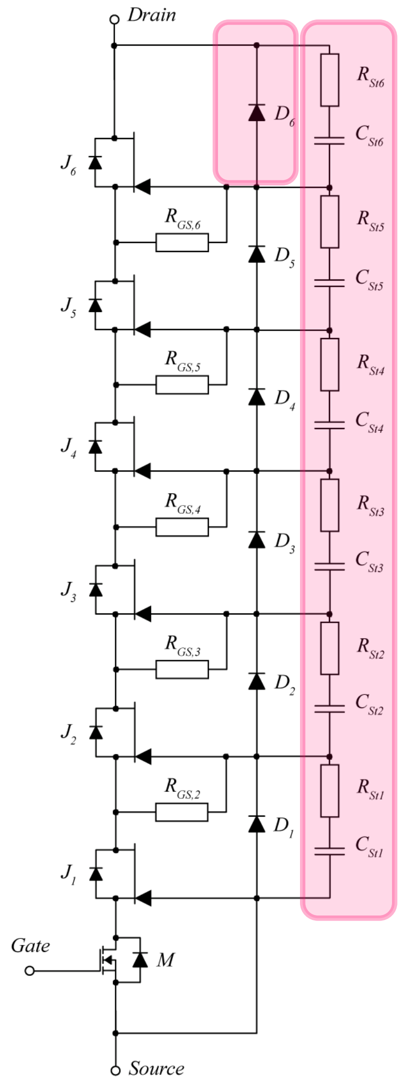
Si/SiC Super Cascode Switch

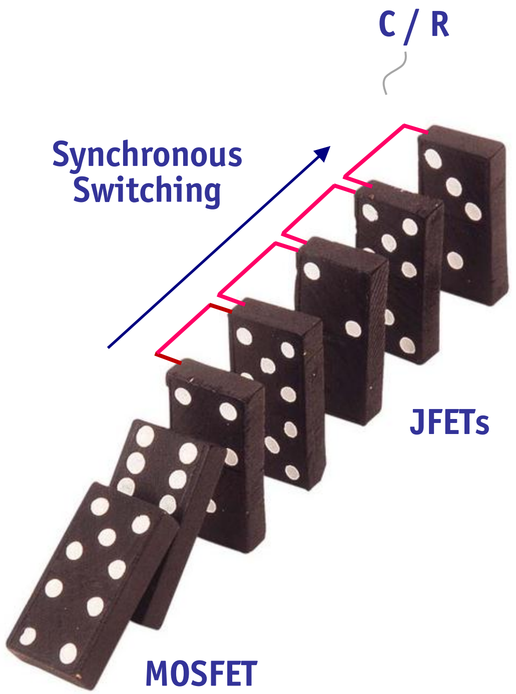
➔ HV-Switch Controllable via Si-MOSFET

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

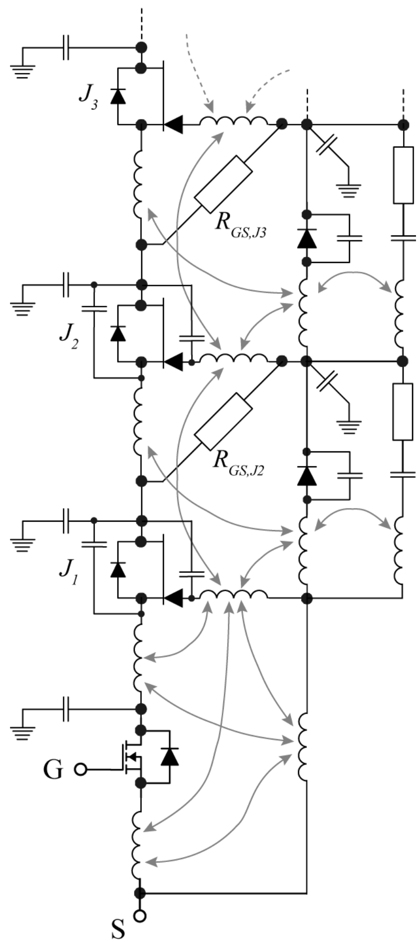
➔ Ultra Fast Switching
➔ Low Losses
➔ Parasitics

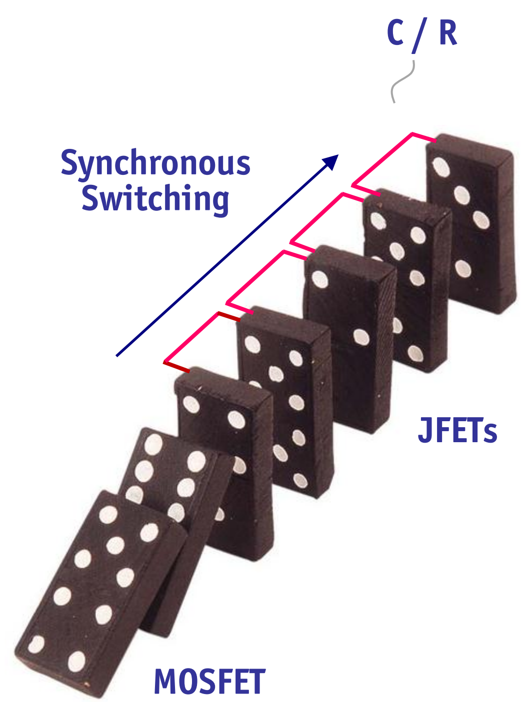
* Passive Elements for Simultaneous Turn-on and Turn-off
* Stabilization of Turn-off State Voltage Distribution





Si/SiC Super Cascode Switch





➔ HV-Switch Controllable via Si-MOSFET

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

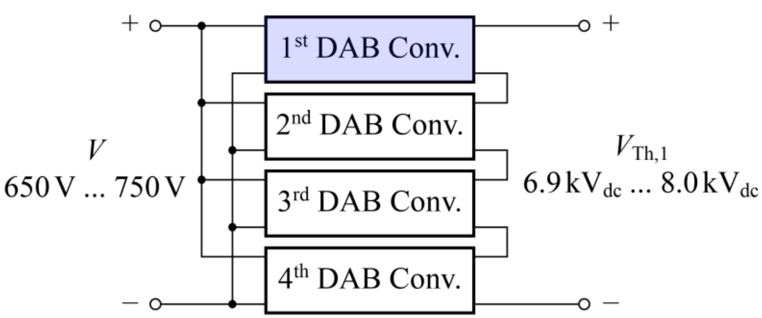
➔ Ultra Fast Switching
➔ Low Losses
➔ Parasitics

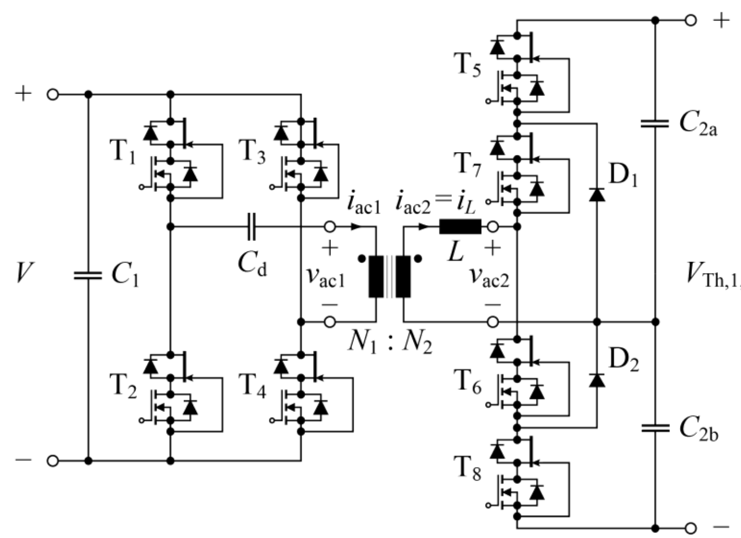
* Passive Elements for Simultaneous Turn-on and Turn-off
* Stabilization of Turn-off State Voltage Distribution

Selected Multi-Cell Converter Topology

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

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

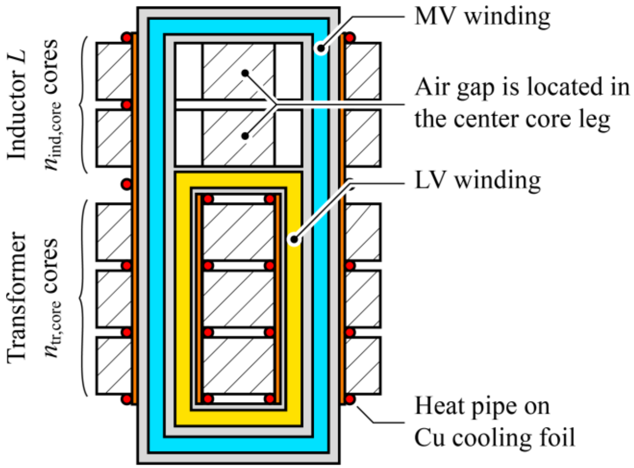


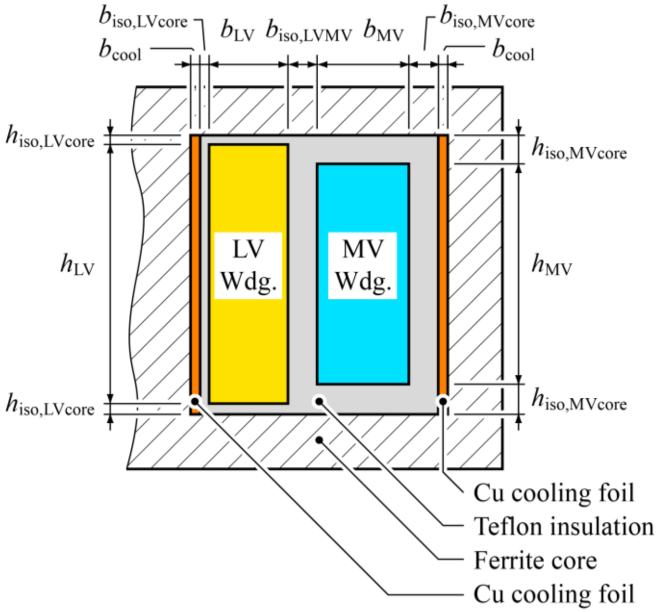


■ Winding Arrangement & Efficiency / Weight Optimization of Transformer

Transformer Design

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



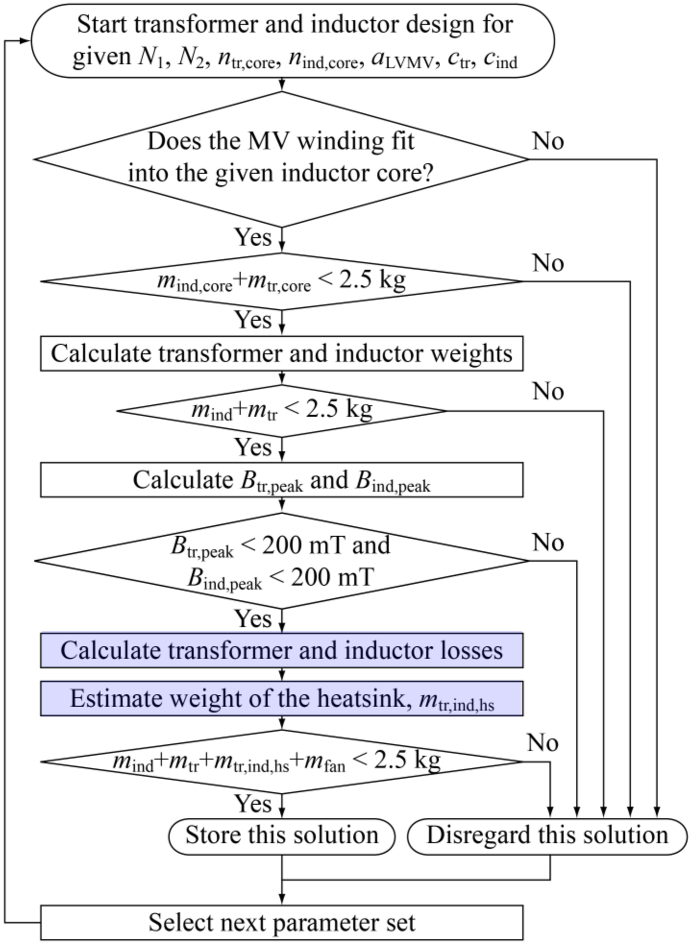


- ■ Optimization - Weight / Efficiency Trade-off

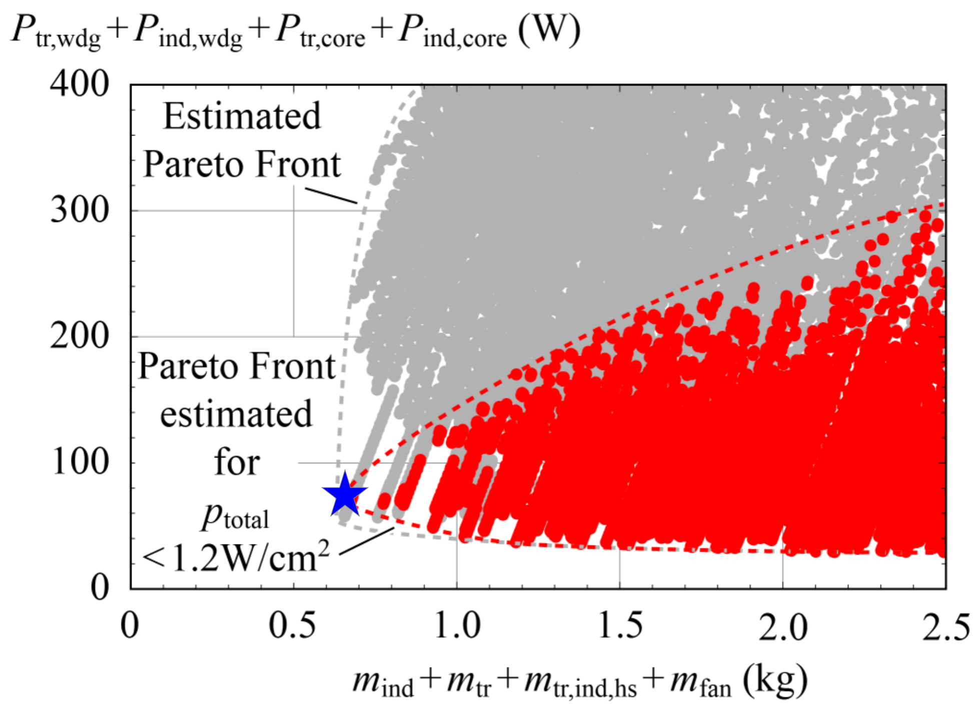
Transformer Optimization

- **Degrees of Freedom / Parameter Ranges**

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



Transformer η-γ-Pareto Front

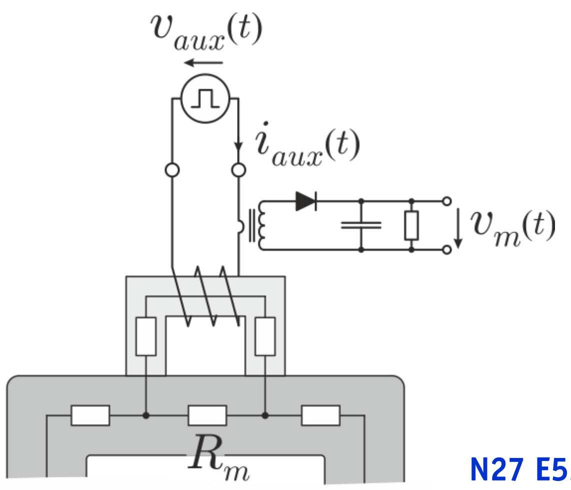


▶ **Selected Design**
η = 97%
γ = 4.5 kW/kg

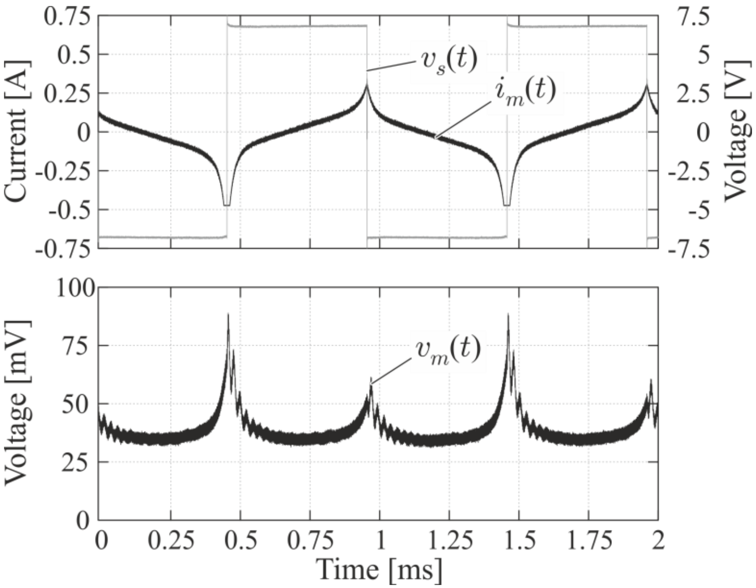
■ **Transformer Volt-Second Balancing - Series Capacitor or "Magnetic Ear" Control**

Transformer Volt-Second Balancing – “Magnetic Ear”

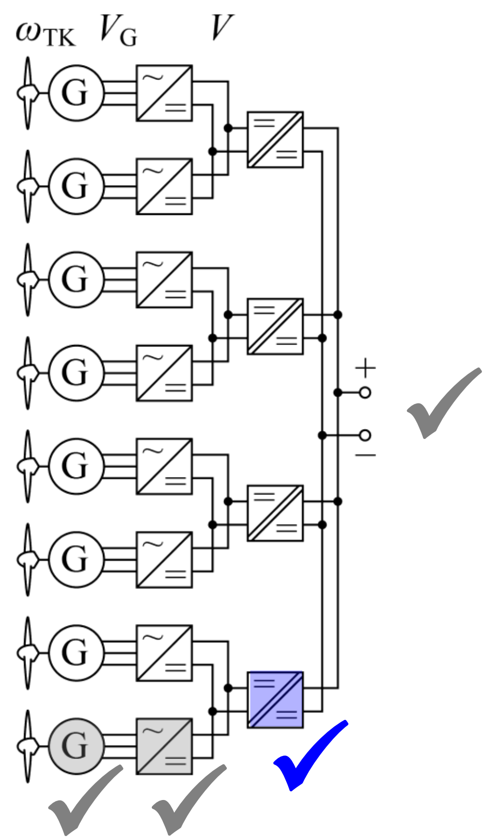
- Magnetic Ear Magnetized with 50% Duty Cycle Rectangular Voltage Winding
- Measured Aux. Current i_{aux} / Voltage v_m Indicates Flux Level
- Enables Closed-Loop Flux Control



N27 E55 Ferrite



System Overview

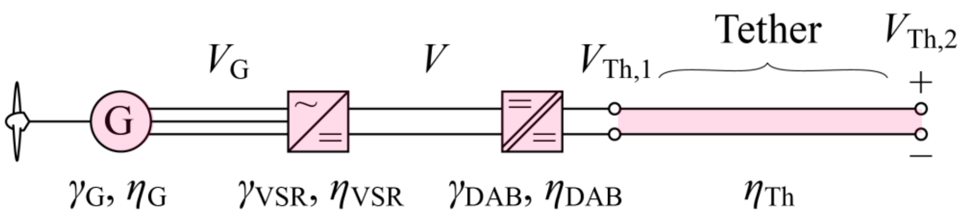


Overall System Consideration

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**

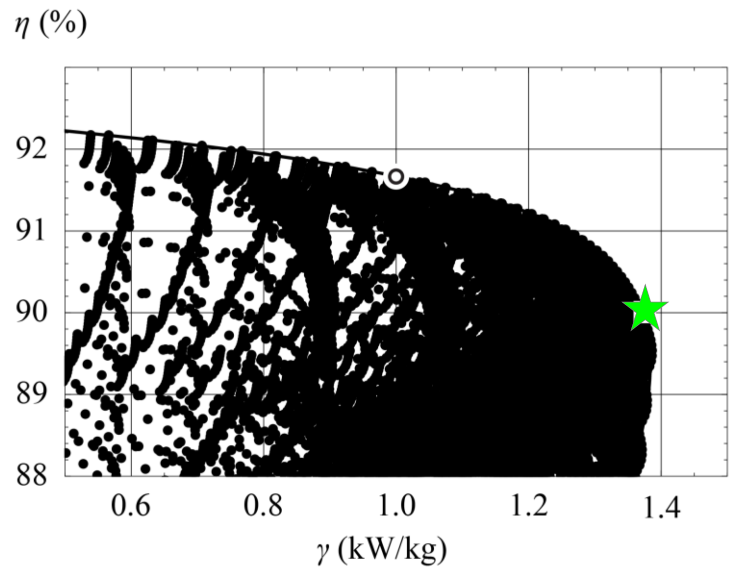
$$\gamma = \frac{P_{out}}{m}$$

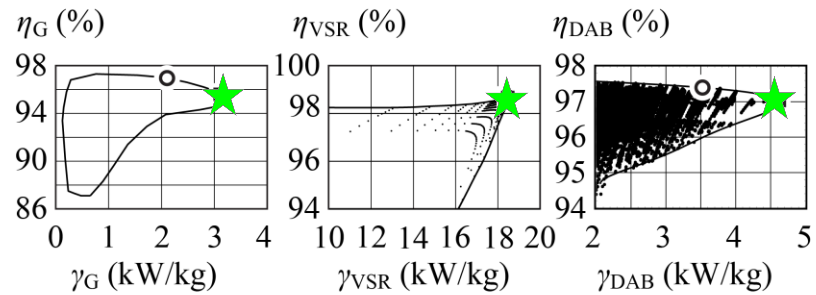
- **Efficiencies of the Partial Systems Need to be Taken into Account**
- **P_D/P_R = Overrating Ratio (8x16kW/100kW)**

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





- **Final Step: System Control Consideration**

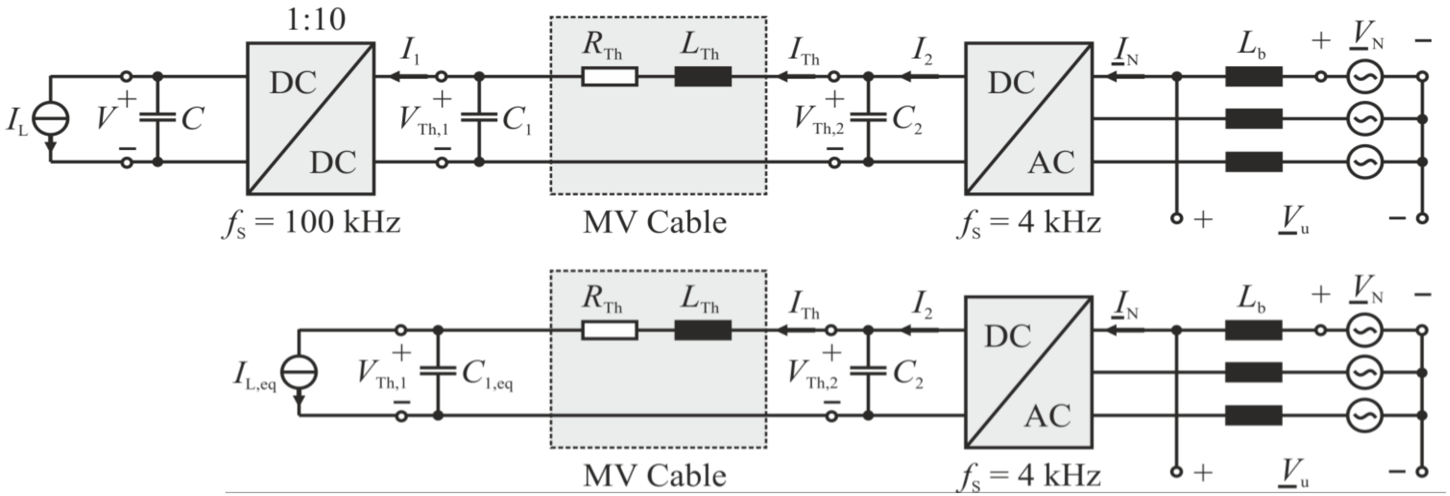
Electric System Control

Stability
Reference Response
Disturbance Response

System Control

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

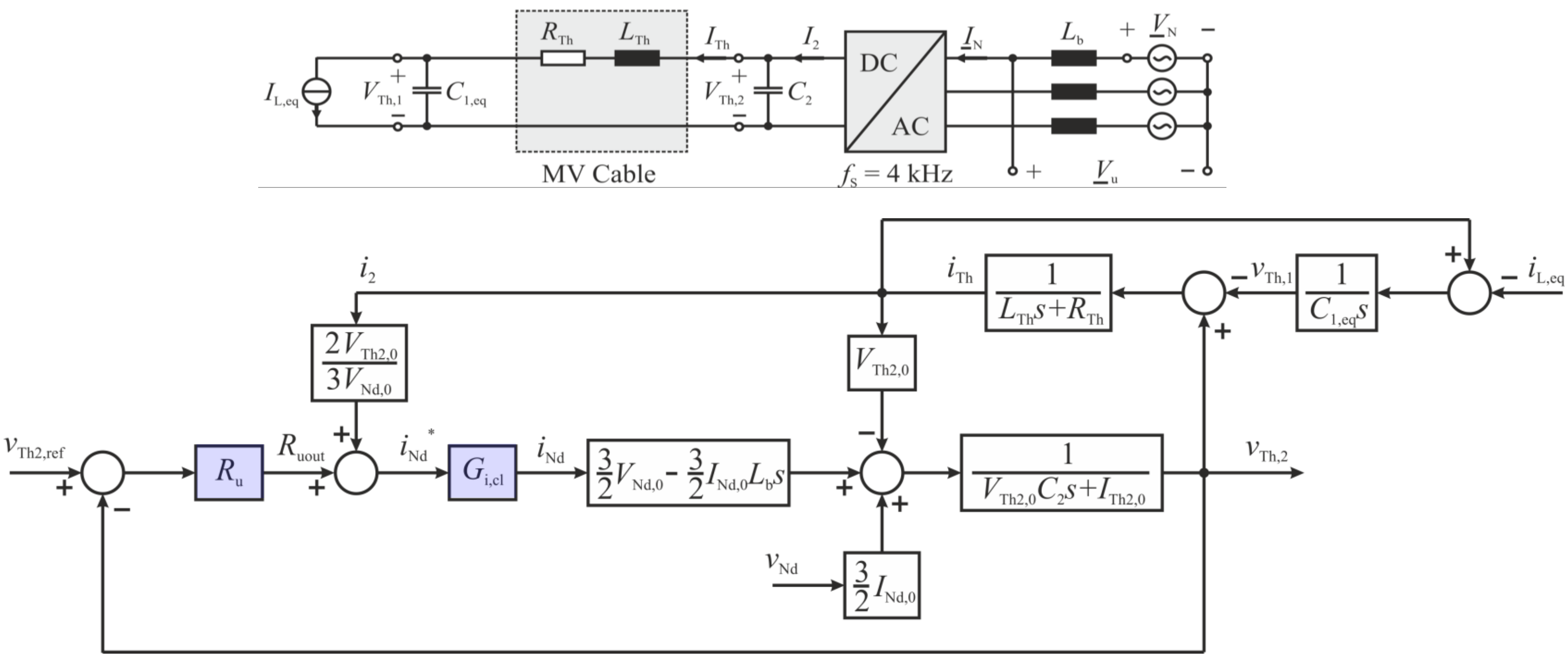
- ▶ Control of DC Voltage Levels is Mandatory !



■ 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**

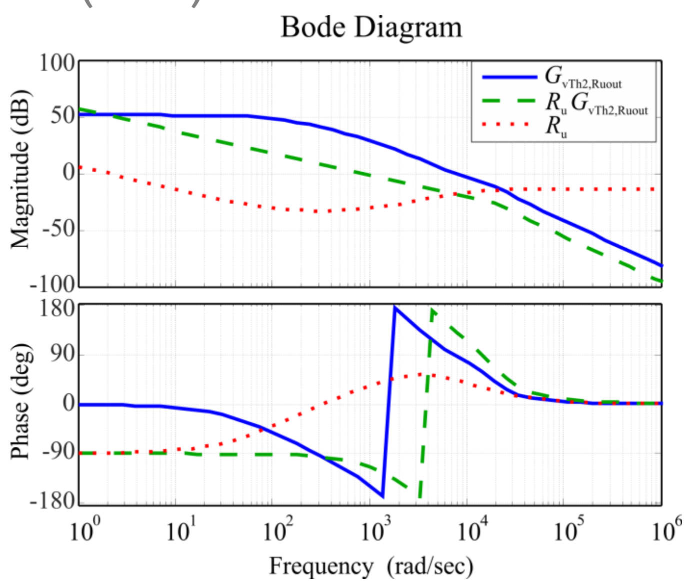


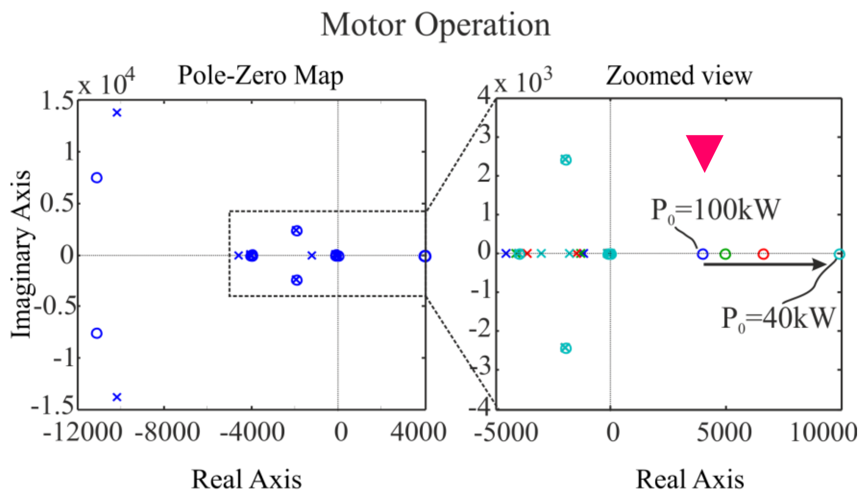
- ■ **Only Tether Voltage at Ground Station is Measured (I_{Th} Feedforward)**
- ■ **Motor AND Generator Operation Must be Considered**

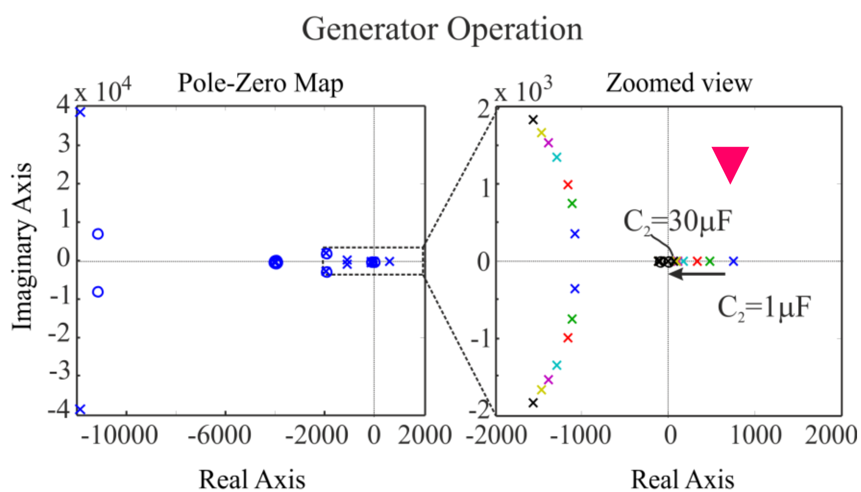
Tether Voltage Control Plant

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

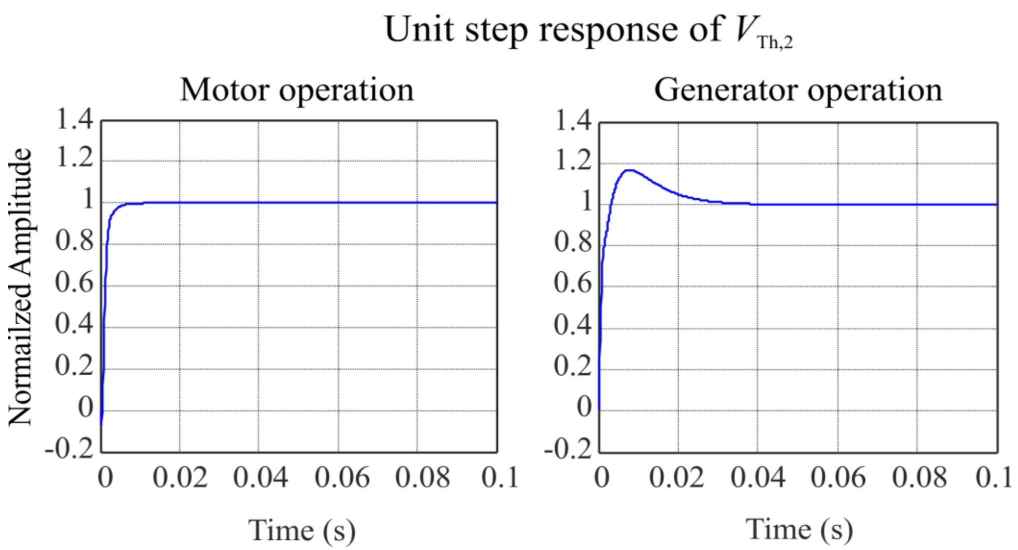
Motor Operation (100kW)





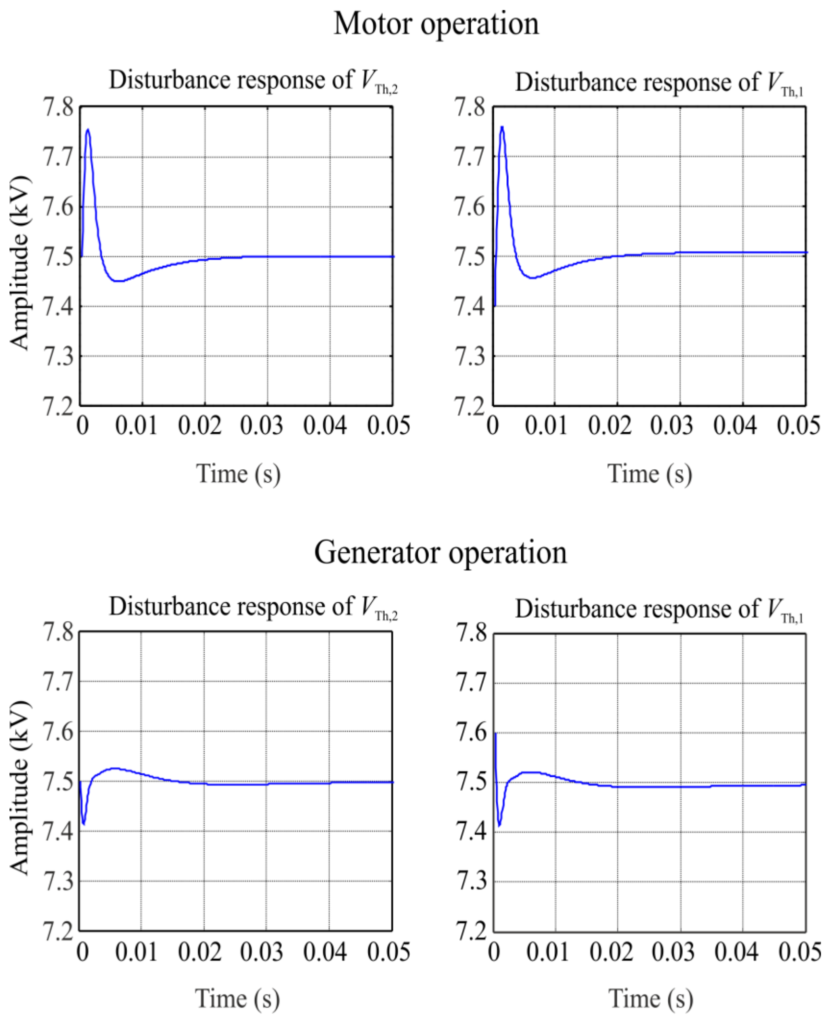


Voltage Control Reference Step Response



- **Overshoot Could be Avoided with Reference Form Filter**

Voltage Control Disturbance Response

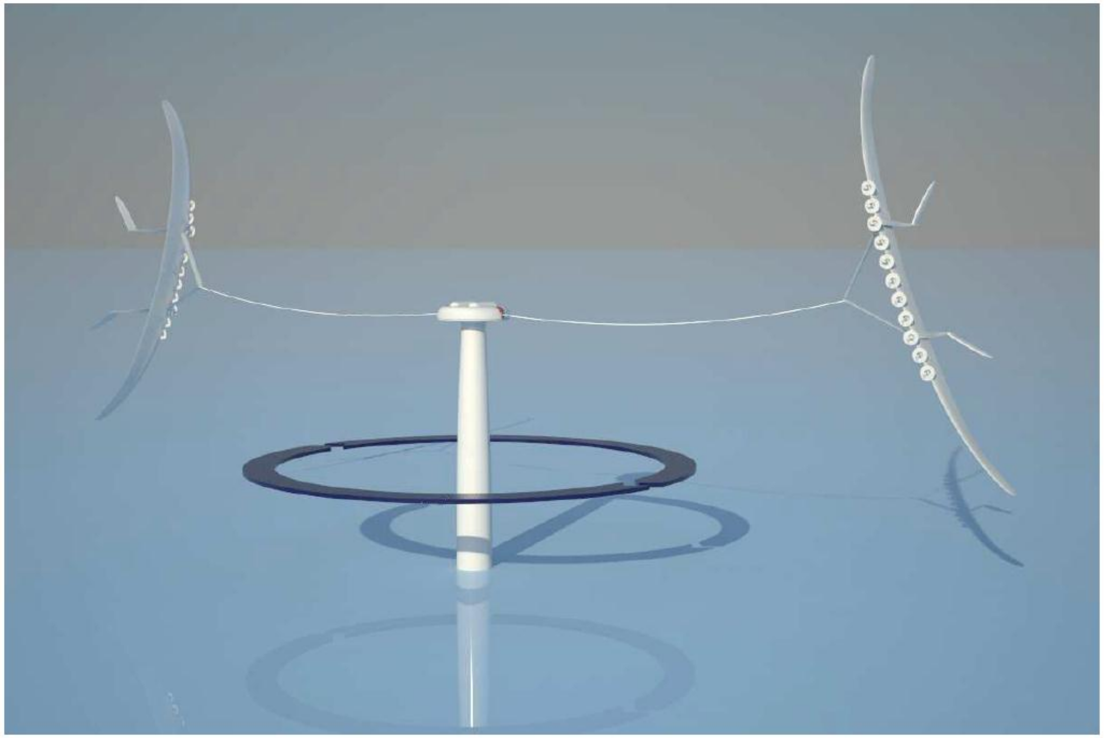


- Motor Operation 100kW → 0
- Gen. Operation —100kW → 0

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 Could Teach Students to Think "Out-of-the-Box"

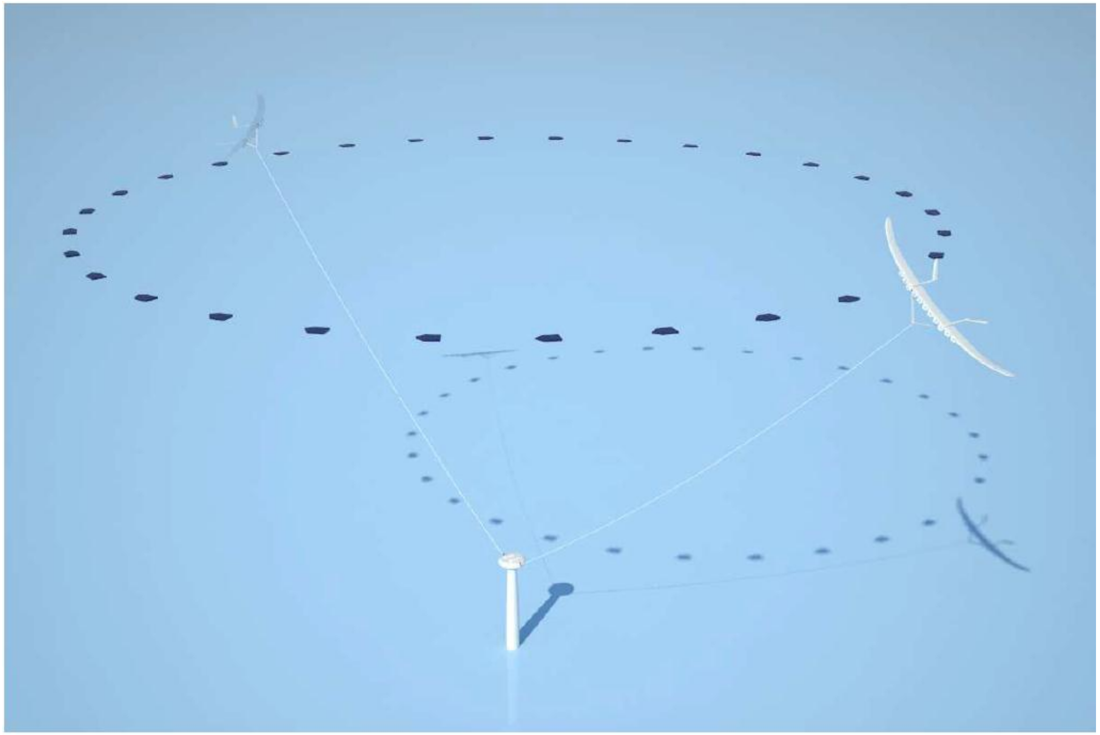
Future Prospects



Source: M. Diehl / K.U. Leuven

- Example for Students to Think "Out-of-the-Box" !

Future Prospects



Source: M. Diehl / K.U. Leuven

- Example for Students to Think “Out-of-the-Box” !

Thank You!

Questions ?