ELECTRICAL SYSTEM ARCHITECTURES FOR FUTURE (MORE) ELECTRIC AIRCRAFT

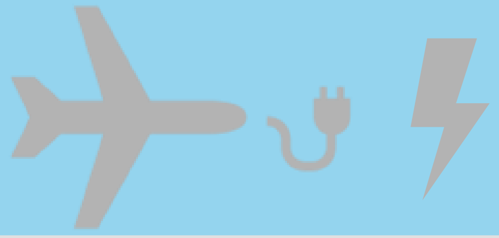
Dr.-Ing. Andrea Reindl, Institute of System Architectures in Aeronautics, DLR

DLR

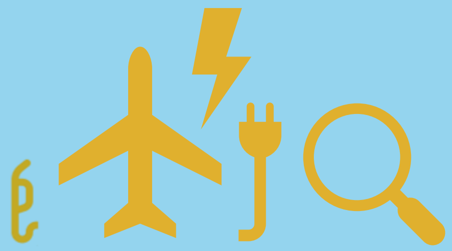

THE POWER
COMES FOM
THE SOCKET
More Electric Aircraft, All Eletric


THE POWER CAN'T COME FROM THE SOCKET
Electric Aircraft Need Real Power Solutions

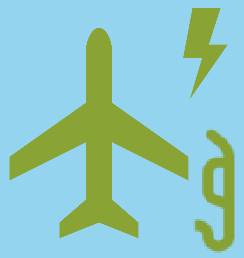
1. DESIGN STRATEGIES OF ELECTRICAL SYSTEM ARCHITECTURES AND MAIN CHALLENGES



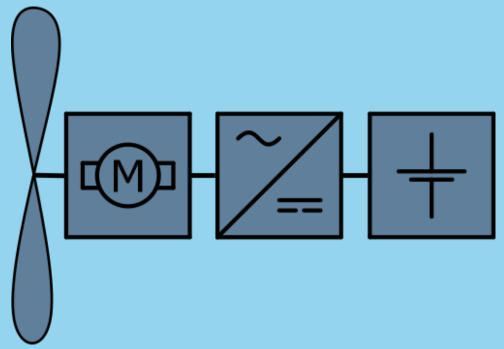
2. ELECTRICAL SYSTEM ARCHITECTURES FOR ALL ELECTRIC AIRCRAFT



3. ELECTRICAL SYSTEM ARCHITECTURES FOR MORE ELECTRIC AIRCRAFT



4. POWERTRAIN ARCHITECTURES

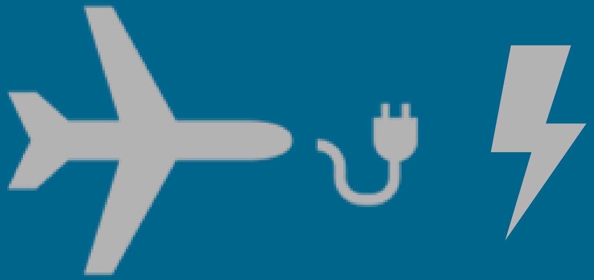


DESIGN STRATEGIES OF ELECTRICAL SYSTEM ARCHITECTURES AND MAIN CHALLENGES

Dr.-Ing. Andrea Reindl, Institute of System Architectures in Aeronautics, DLR

1. WHAT IS NEW COMPARED TO THE STATE-OF-THE-ART?

2. WHAT ARE THE CHALLENGES OF DESIGNING ELECTRICAL SYSTEMS?



3. HOW IS THE DESIGN PROCESS?

1. WHAT IS NEW COMPARED TO THE STATE-OF-THE-ART?

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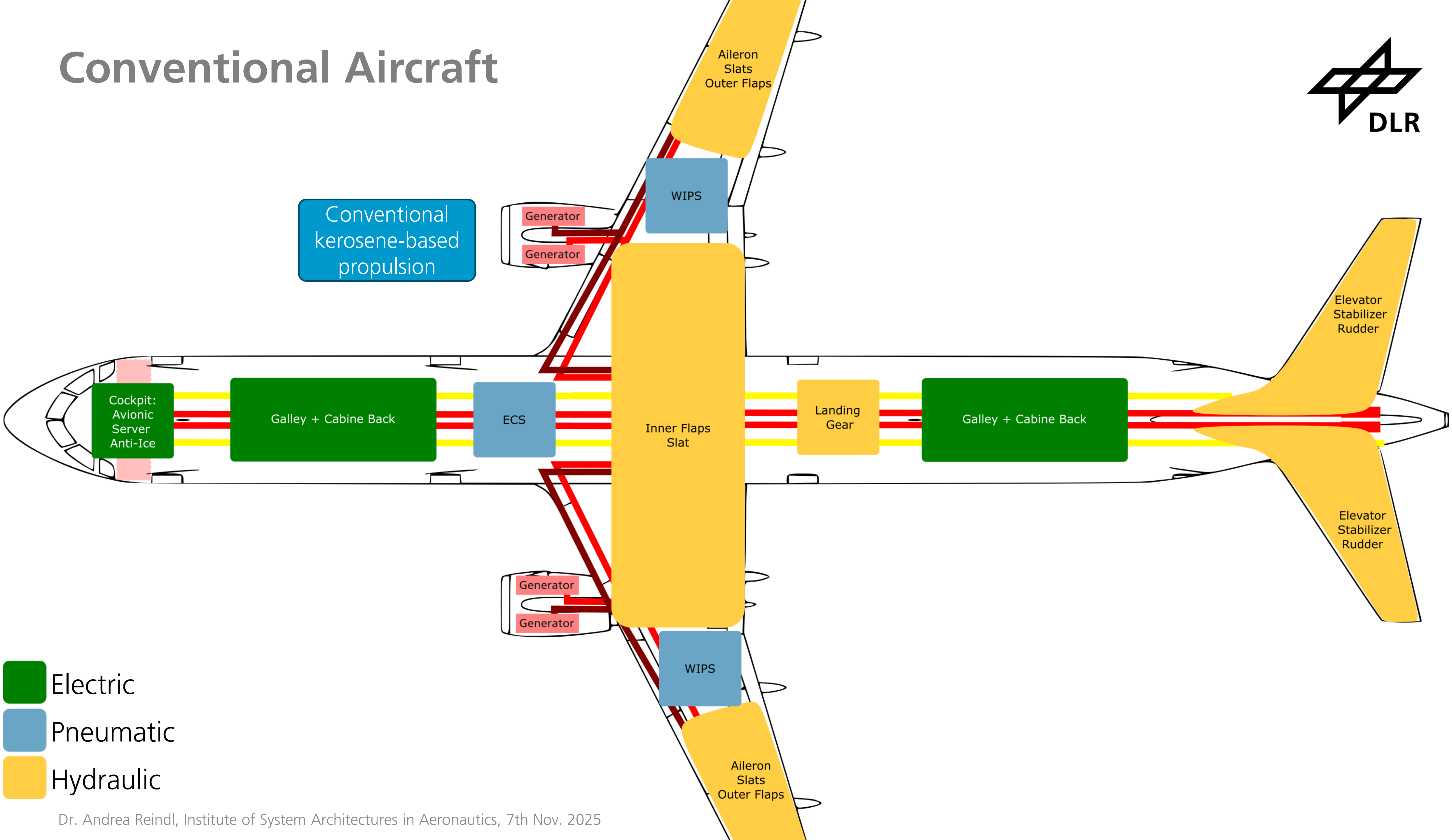
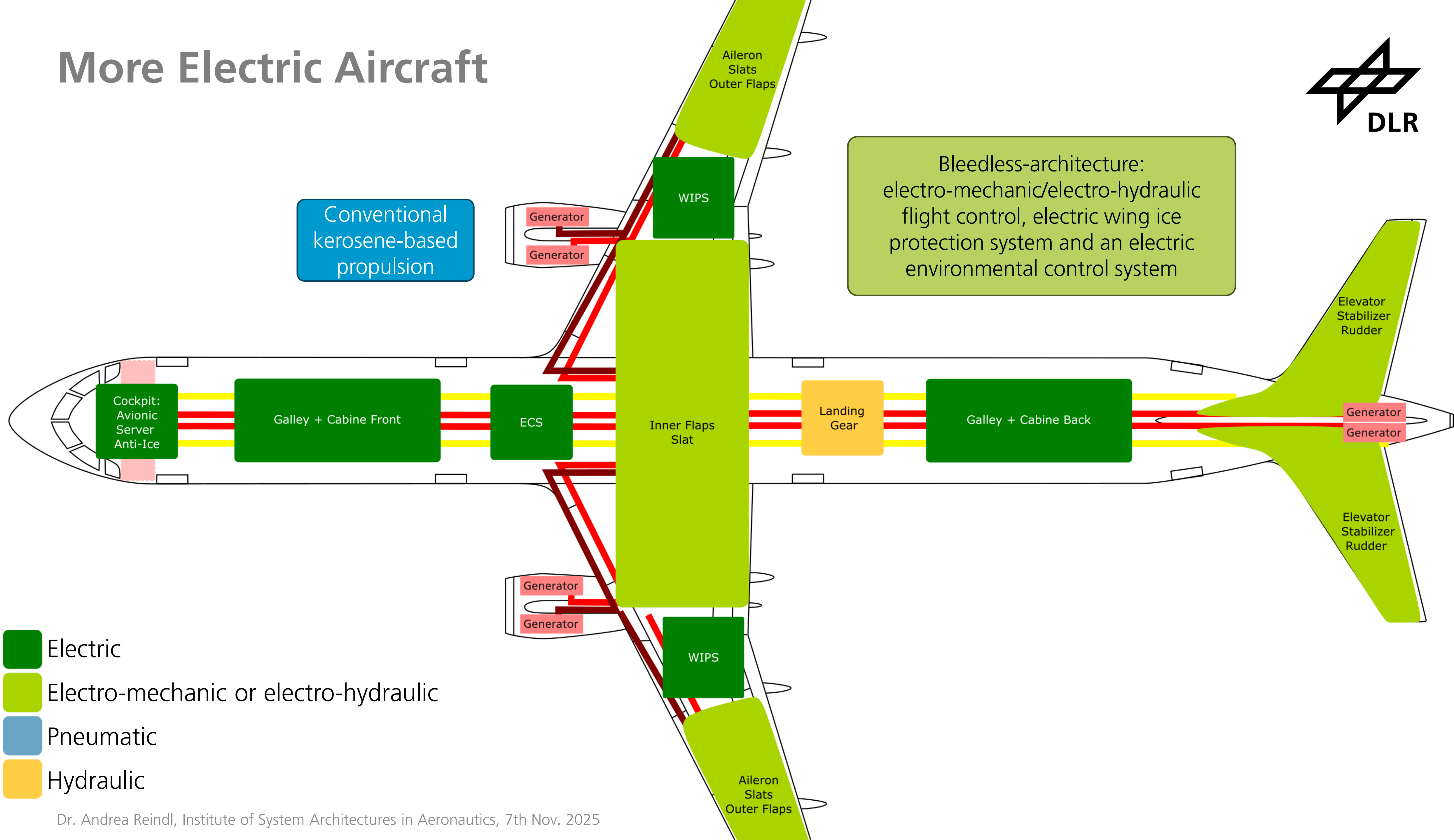
Conventional Aircraft

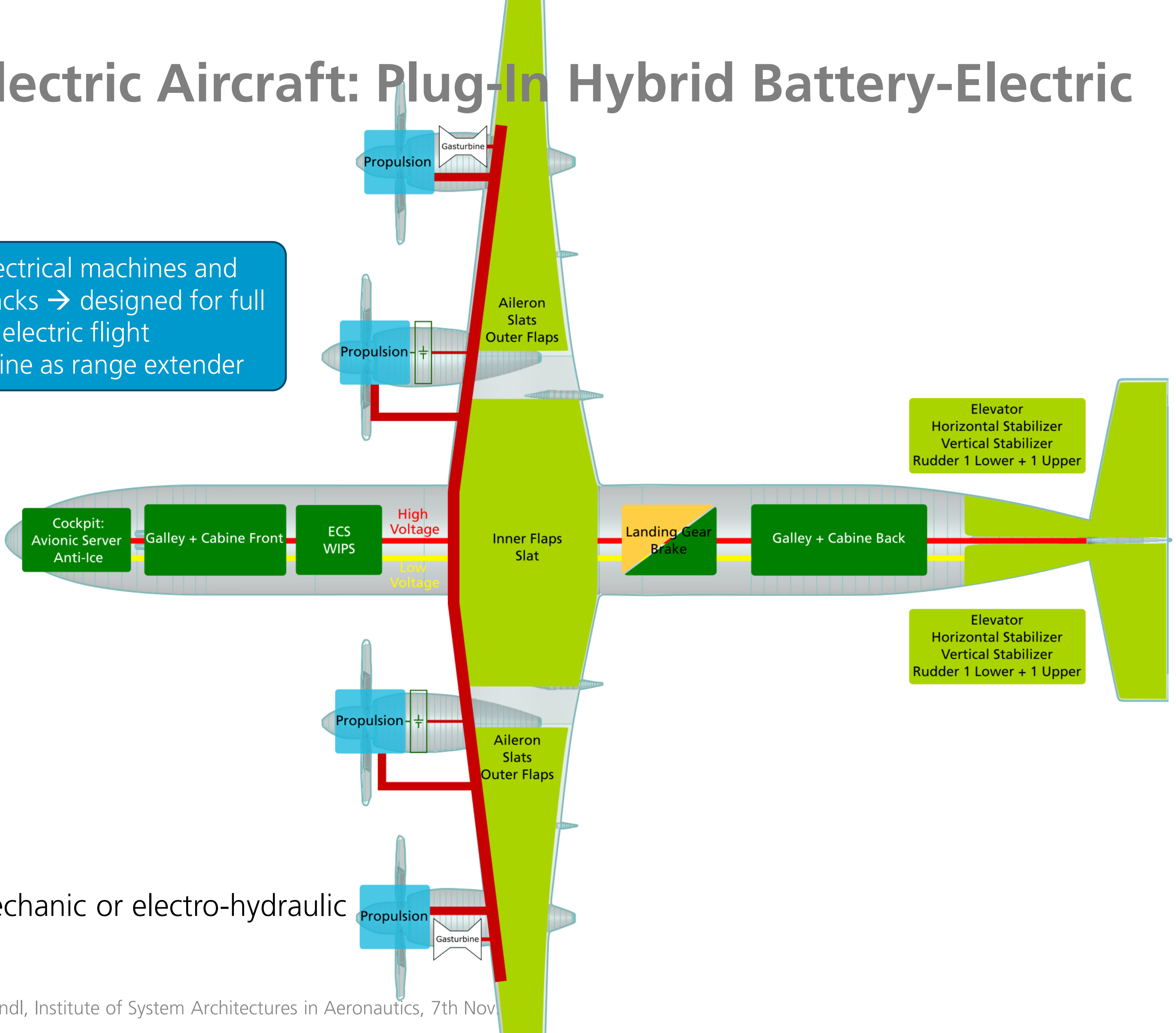


More Electric Aircraft



All Electric Aircraft: Plug-In Hybrid Battery-Electric

Four electrical machines and battery packs → designed for full electric flight
Gasturbine as range extender



Electric
Electro-mechanic or electro-hydraulic
Hydraulic

POWER RATING ELECTRICAL SYSTEM

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CONVENTIONAL

Type	A320	A321	A380
Maximum passenger capacity	180	220	853
Installed electrical power	~100 kW	~150 kW	~600-800 kW

MORE ELECTRIC AIRCRAFT

Type	A350	A321 (under research)	B787
Maximum passenger capacity	440	220	250
Installed electrical power	~1000 kW	~800 kW	~1000-1500 kW

POWER RATING ELECTRICAL SYSTEM

DLR

CONVENTIONAL

Type	A320	A321	A380
Maximum passenger capacity	180	220	853
Installed electrical power	~100 kW	~150 kW	~600-800 kW

MORE ELECTRIC AIRCRAFT

Type	A350	A321	under research	B787
Maximum passenger capacity	440	220		250
Installed electrical power	~1000-1400 kW	~800 kW		~1500 kW

ALL ELECTRIC AIRCRAFT

Type	EXACT PHEP	under research
Maximum passenger capacity	250	
Installed electrical power	~17.5 MW = 17500 kW	

Dr. Andrea Reindl, Institute of System Architectures in Aeronautics, 7th Nov. 2025

WEIGHT ELECTRICAL SYSTEM EXISTING AIRCRAFT

CONVENTIONAL

A320
~100 kW
Electric Generation: ~400 kg
Electric Distribution: ~1040 kg

A321
~150 kW
Electric Generation: ~400 kg
Electric Distribution: ~1200 kg

PHEP 250
~17.5 MW
Electric Generation: ?
Electric Distribution: ?

A321
~800 kW
Electric Generation: ?
Electric Distribution: ?

does not exist yet
under research

What are the (dis)advantages of DC compared to AC?

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Advantages

+ No synchronization
+ No reactive power
  → simpler control
  → smaller cable cross-section
+ Fewer transformers
+ Lower conversion losses
+ Lower wiring losses (3 phase AC→ 3 wires)
+ Batteries/fuel cells integration
+ Less stress to insulation and connectors
  - Same power → AC factor $\sqrt{2}$ higher
  - 12kV AC cable can be used for 60kV DC on ground
+ Power converters in DC girds only have approx. 50% volume of the ones in AC (due to transformers mainly)

Disadvantages

- No zero crossing → arcing
- Arc detection and resolution is very difficult
- Low inertia → fault protection
- Partial discharge
  + AC is more prone to partial discharge
  - **Partial discharge is more consistent in DC** (no extinction due to natural zero crossing)
  - Presence of polarity effect in DC, leads to more likelihood of PD at negative polarity
  - DC employes fast switching converter with high dV/dt, leads to more chances of PD (→ manage voltage change rate and insulation design)
- **DC systems need more creepage distance**
  - Electric field in DC is constant and unidirectional.
  - May promote electrolytic ion migration and surface discharges tracking.
  - Once conductive path forms, it keeps consistent current flow.

What are the (dis)advantages of DC compared to AC?

By way of comparison, the electrical on-board grid of a ship was converted from AC to DC, reducing its **volume** by **41%** and its **weight** by **56%**.

Source: Chang, G. Y. (2020). DC Bus Systems for Electrical Ships: Recent Advances and Analysis of a Real Case. *IEEE Electrification Magazine 8 (3)*, 28–39.

What is new in comparison to state-of-the-art electrical systems?

- **Increase** in **installed electrical power** through electrification of on-board and powertrain systems
- **Advances** in **power electronics** (SiC, GaN) and **battery** technology (safety, gravimetric and volumetric power and energy density)
- Increased **reliability** requirements of the electrical system due to electrification of **flight control**
- **Higher power classes** due to electrification of the powertrain
- Conversion from pure AC/hybrid AC and DC grids to **pure DC grids**

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3. HOW IS THE DESIGN PROCESS?

Challenges at System Level

Arc Detection Resolution

Galvanic Isolation vs. efficiency, volume, weight

Electro-magnetic Interference (EMI)

Fault Management in low intertia DC grids

Disconnection in DC Grids

Higher Voltages Benefits and Paschen's Curve

Partial Discharge

Electrical Wiring Sytem: Weight & fault impedance

Reliability and Multi-Source/ Non-similarity

Grounding in CFRP structures and its impact

Power Quality

Control Stability

Efficiency

Thermal Management

Power Density

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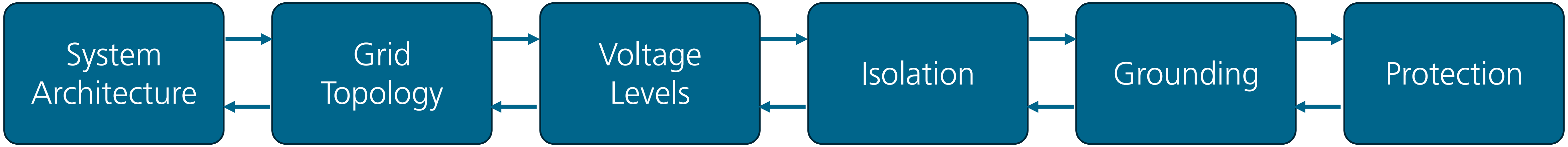
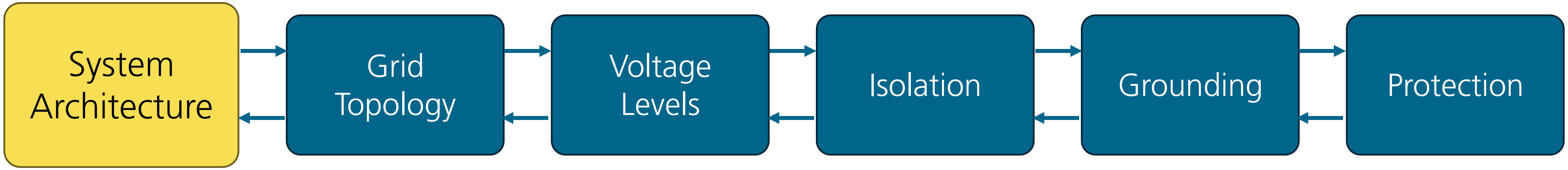
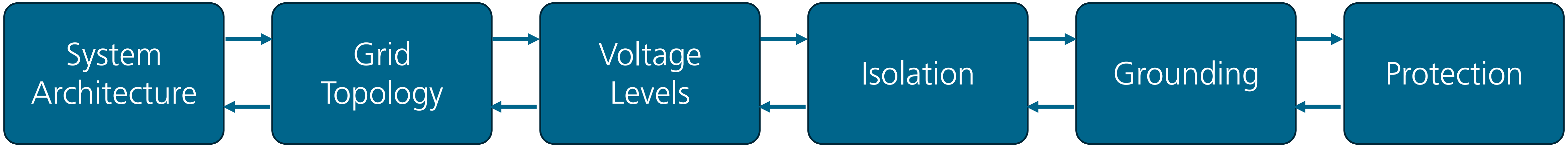
Electric System Design Process



Electric System Design Process



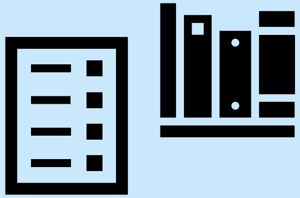
Electric System Design Process



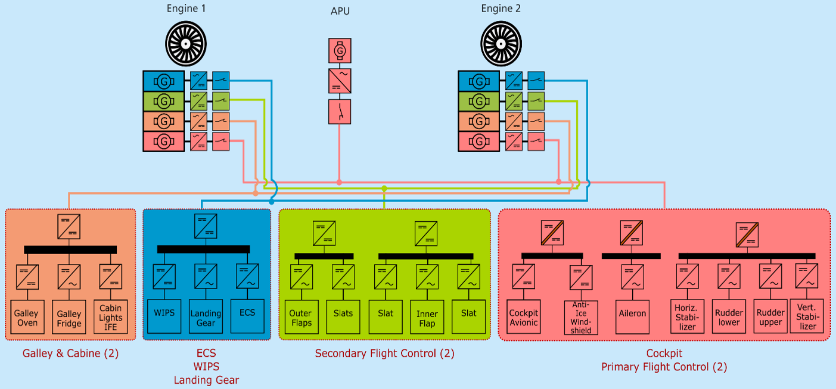
1. Constraints
   - voltage
   - current
   - power
2. Physical layer
   - define topology of DC/DC converter, inverter, rectifier
   - define grounding topology
3. Control layer
   - primary control
   - secondary control

Process

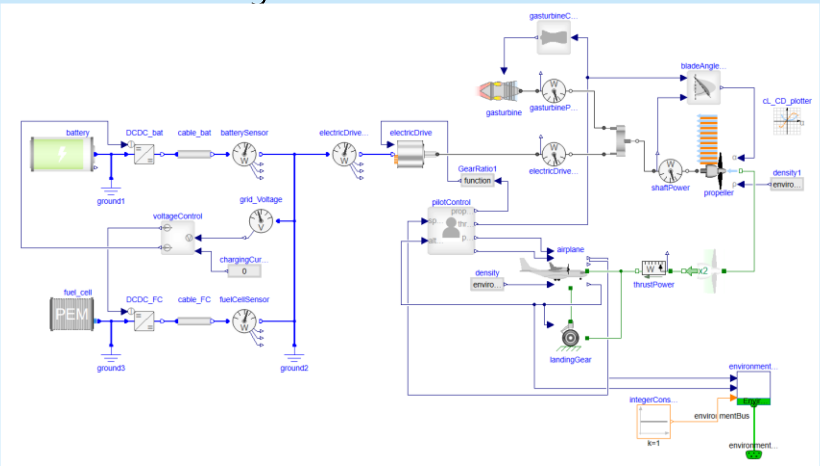
Definition of research objectives and requirements
Literature review and applicable standards (ISO 1440, MIL-STD-704E, DO-160,
CS.25 – Paragraph 1302 and following)



Architectural Design Decisions



Gate-to-gate Simulation - MODELICA

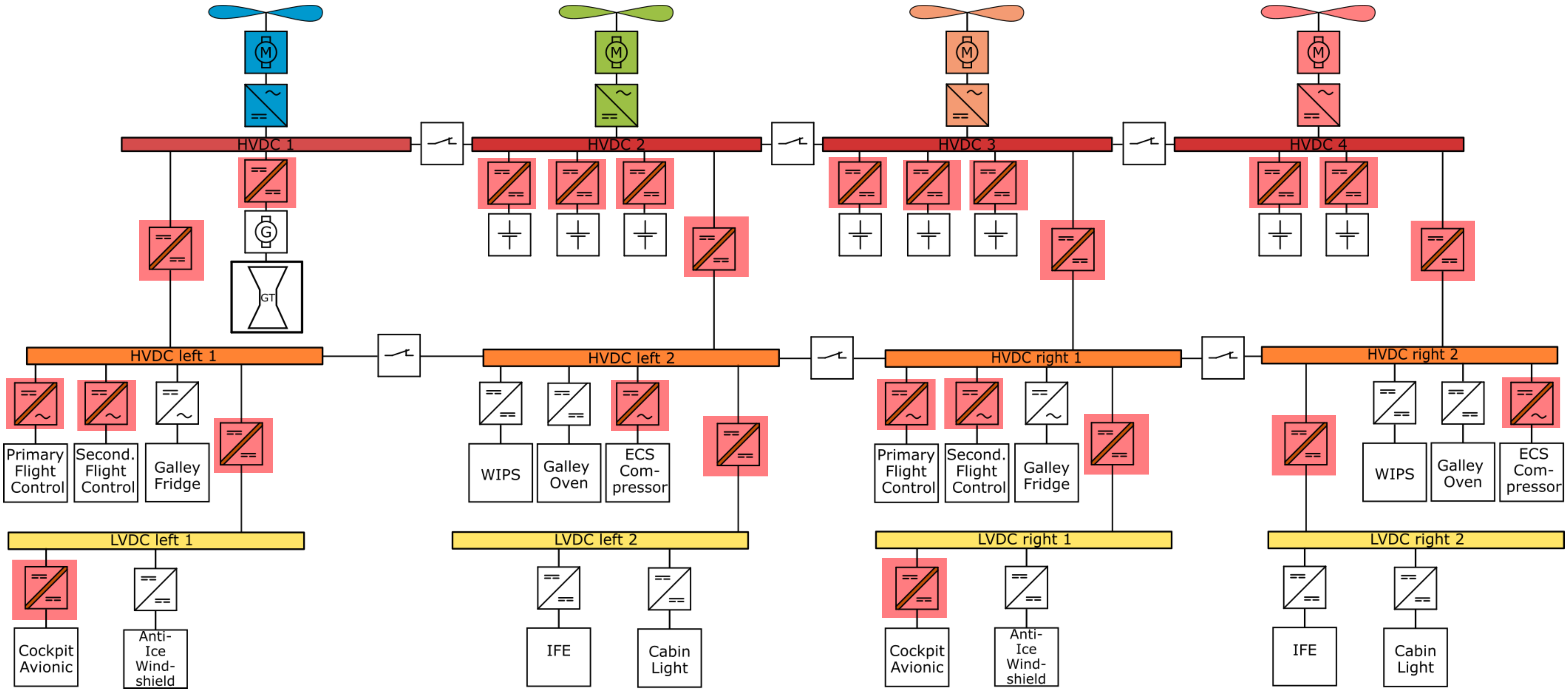


Validation of Selected Models DC Miniature Test Grid

Challenges at System Level

- **Arc** Detection Resolution
- **Partial Discharge**
- **Efficiency**
- **Galvanic Isolation vs. efficiency, volume, weight**
- **Electrical Wiring Sytem:** Weight & fault impedance
- **Electro-magnetic Interference (EMI)**
- **Reliability and Multi-Source/ Non-similarity**
- **Thermal Management**
- **Fault Management** in low intertia DC grids
- **Grounding** in CFRP structures and its impact
- **Disconnection** in DC Grids
- **Power Quality**
- **Power Density**
- **Higher Voltages** Benefits and Paschen's Curve
- **Control Stability**

Galvanic Isolation

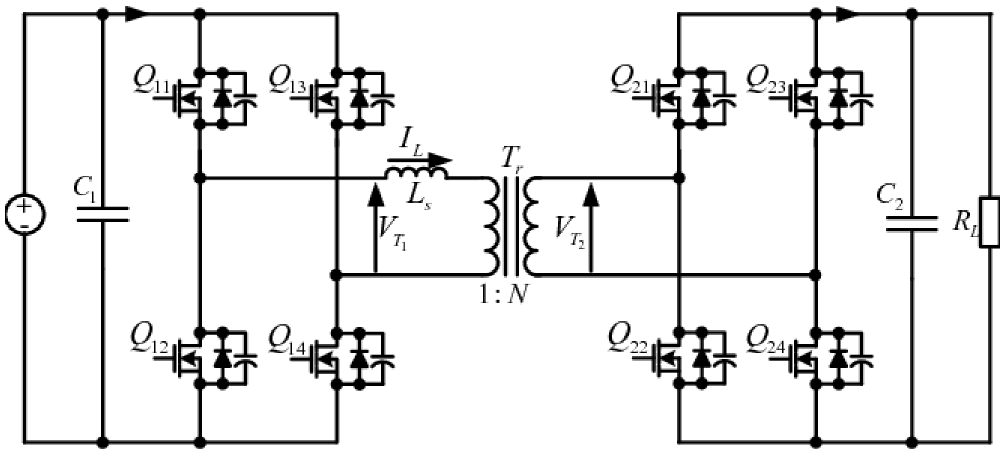


Galvanic Isolation

Isolated DC/DC Converter

+ Galvanic isolation / physical seperation between input and output side
+ Avoidance of ground loops
+ EMI and fault limitation
- Less efficiency
- Bulky transformers
- Reduced control dynamics

Dual Active Bridge



η = 98.5%

But: volume of transformer for **150 kW** power equals to 6 cola cans

Galvanic Isolation

- Electrical system architecture (number of sub-grids, loads per sub-grid) has a significant influence on where galvanic isolation is absolutely necessary.
- Ideally, there should be as few galvanic isolations as possible without compromising safety, as efficiency is still lower than with non-isolated systems and transformers are bulky.

Design Rule Electrical System Architecture

Define the number and type of sub-grid in such a way that galvanic isolation requirements are minimized:

- Divide the grid into electrically separate, isolated sub-grids (islanded DC microgrids)
- Separate safety-critical from non-safety-critical loads

Challenges at System Level

Arc Detection Resolution

Partial Discharge

Efficiency

Galvanic Isolation vs. efficiency, volume, weight

Electrical Wiring Sytem: Weight & fault impedance

Electro-magnetic Interference (EMI)

Reliability and Multi-Source/ Non-similarity

Thermal Management

Fault Management in low intertia DC grids

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Power Quality

Power Density

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Control Stability

Disconnection in DC Grids

- Disconnection in DC grids comes with a high risk of arcing, as there is no natural zero crossing.
- Fuse-based switches, which are heavy and bulky, often have to be used. In addition, they do not allow reconnection and must be replaced after a single activation.

Design Rule Electrical System Architecture

Separating the electrical system into islanded DC microgrids results in grids that are already separated from each other (fewer circuit breakers). Furthermore, it is advisable to combine solid-state circuit breakers (fast, no galvanic isolation) with additional mechanical circuit breakers (disconnector designed for the rated current load drastically reduces size).

Challenges at System Level

- **Arc** Detection Resolution
- **Galvanic Isolation vs. efficiency, volume, weight**
- **Electro-magnetic Interference (EMI)**
- **Fault Management** in low intertia DC grids
- **Disconnection in DC Grids**
- **Higher Voltages Benefits and Paschen's Curve**
- **Partial Discharge**
- **Electrical Wiring Sytem: Weight & fault impedance**
- **Reliability and Multi-Source/ Non-similarity**
- **Grounding** in CFRP structures and its impact
- **Power Quality**
- **Control Stability**
- **Efficiency**
- **Thermal Management**
- **Power Density**

EWIS: Voltage, Weight and Fault Impedance

Weight Comparison Wiring System Different Voltage Levels		
Voltage Level High Voltage	**Voltage Level Low Voltage**	**Connected Grid Wiring System**
800 V	28 V	Baseline 100%
1200 V	28 V	- 3%
800 V	48 V	- 23%
800 V	60 V	- 40%

EWIS: Voltage, Weight and Fault Impedance

Design Rule Electrical System Architecture

Reduce cable lengths as much as possible (beneficial for weight, EMI, filter size and fault impedance)
Check the optimal voltage levels for each sub-grid (increasing the voltage level does not necessarily result in the desired weight savings).

Challenges at System Level

- **Arc** Detection Resolution
- **Galvanic Isolation** vs. efficiency, volume, weight
- **Partial Discharge**
- **Electrical Wiring Sytem:** Weight & fault impedance
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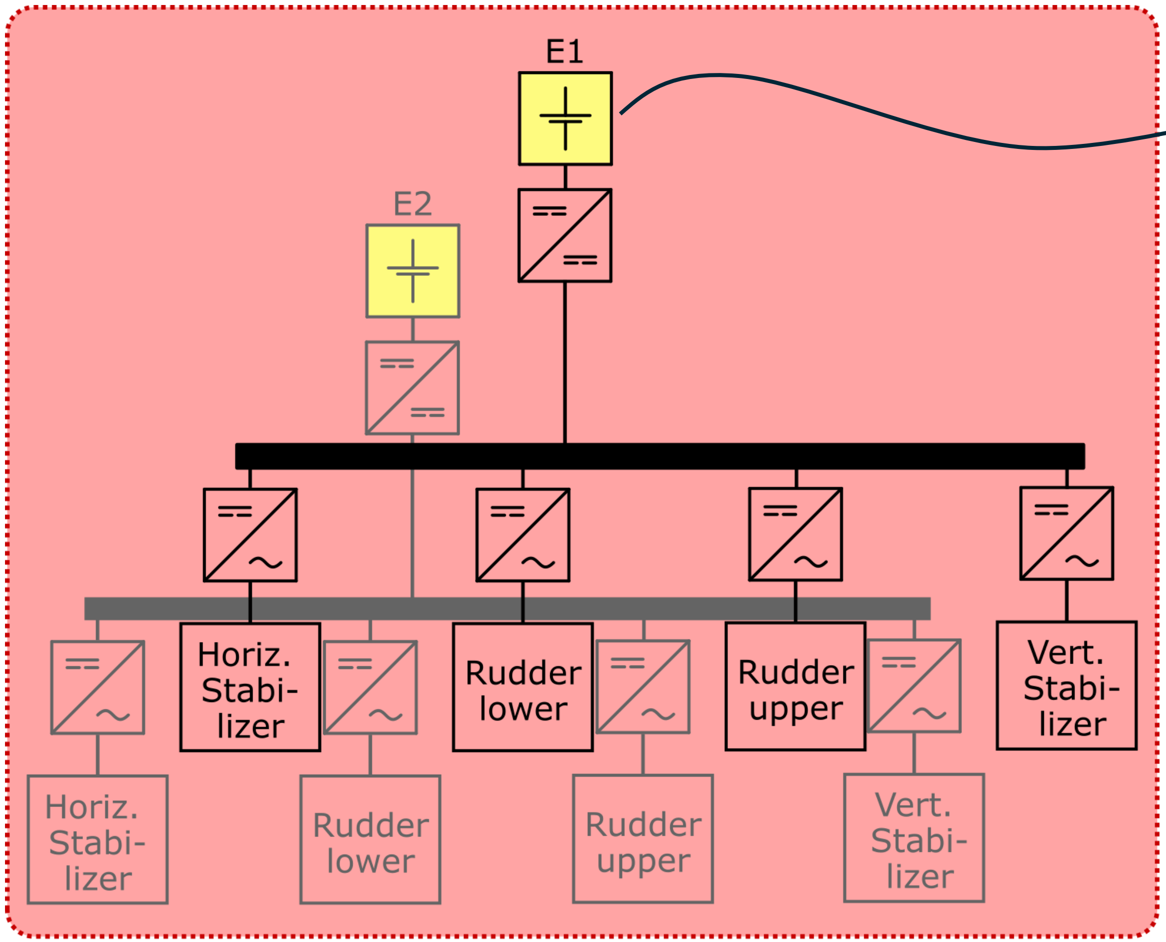
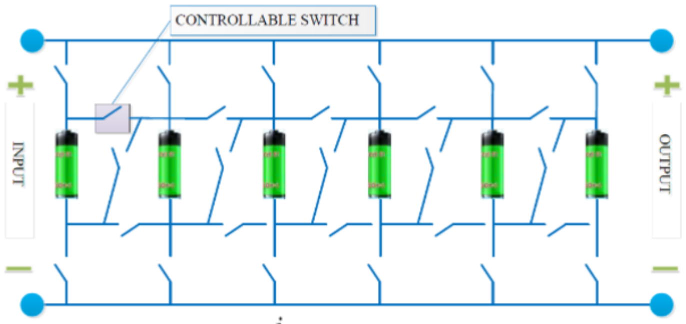
Flight Control System



Primary Flight Control Tail Plane

Redundancy at cell level:

- Reconfigurable batteries for DC output
- Battery-integrated modular multilevel converter



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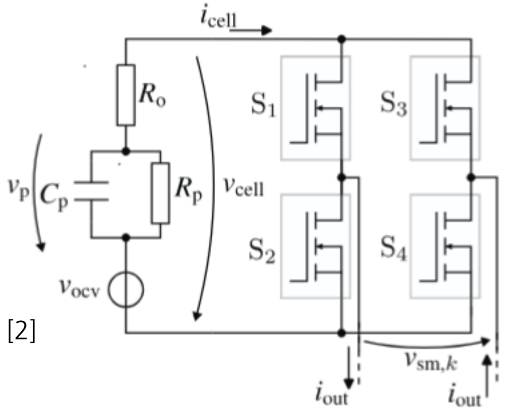

[2]

[1] S. Ci, N. Lin and D. Wu, "Reconfigurable Battery Techniques and Systems: A Survey," 2016.
[2] F. Hashemniya, A. Balachandran, E. Frisk and M. Krysander, "Structural Diagnosability Analysis of Switched and Modular Battery Packs," 2024.

Reliability and Multi- Source/ Non-similarity

Design Rule Electrical System Architecture

Take advantage of the modularity of the batteries and separate them electrically and with containment boxes.
Create redundancy at the cell/pack level and thus increase reliability.
Design the electrical grids inclusive power electronics and actuators redundantly.

Challenges

DLR

Arc
Detection Resolution

Galvanic Isolation
vs. efficiency, volume, weight

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in DC Grids

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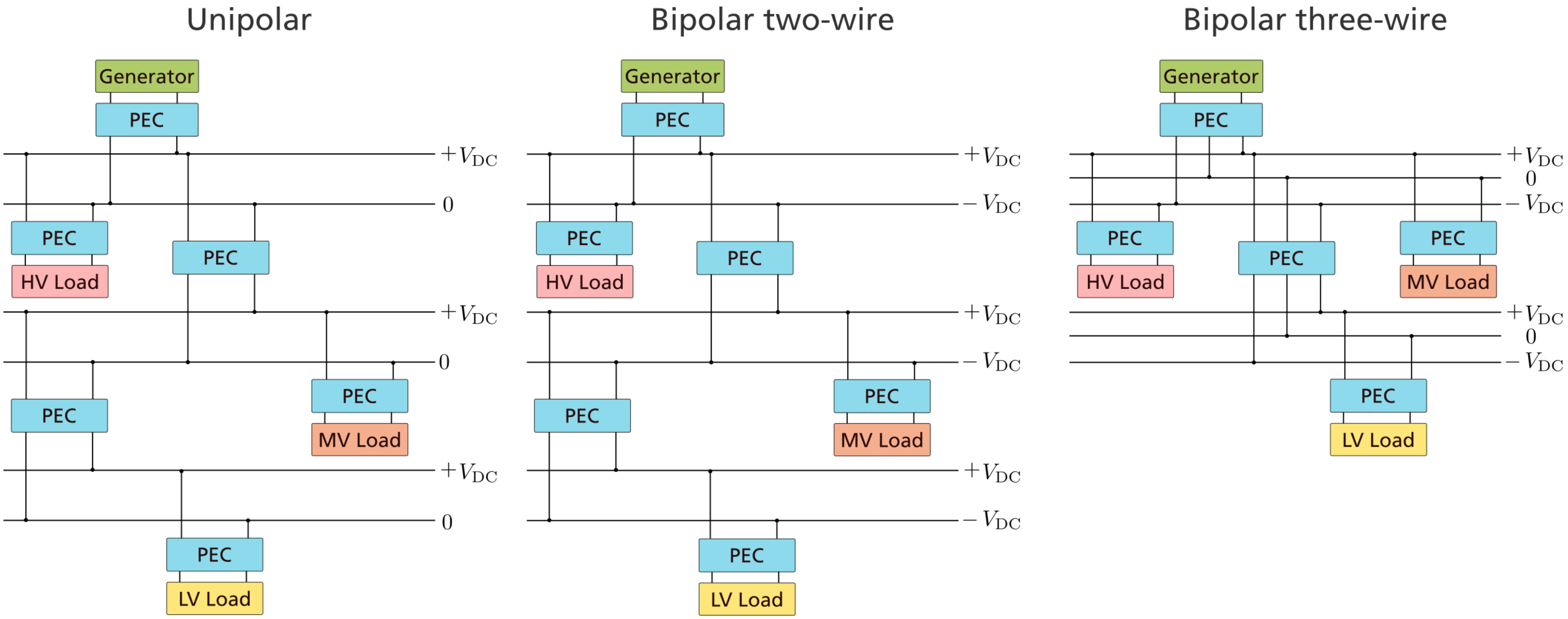
Benefits and Paschen's Curve

Control Stability

DC Grid Topology



DC Grid Topology

Criteria	Unipolar	Bipolar	
		2-wire	3-wire
Corona effect	↑ higher ion current slew rate (5.5 times faster) ion current density at the corona inception voltage: $10.474 \frac{A}{m^2}$ higher maximum electric field strength: $36.38 \frac{kV}{m}$	↓ ionization of air is stronger corona onset voltage is lower ion current density at the corona inception voltage: $-1.969 \frac{A}{m^2}$ →ion current density is better suppressed lower maximum electric field strength: $25.93 \frac{kV}{m}$	
First short-circuit current transient	↓ slower and lower current transients	↑ higher and faster current transients	
Pole-to-ground fault current	↓ depends on topology and grounding scheme slower and lower current transients ($0.32 \frac{kA}{ms}$)	↑ depends on topology and grounding scheme higher and faster current transients ($1.6 \frac{kA}{ms}$) higher fault current amplitude	
Overvoltage caused by short-circuit faults	↑ higher	↓ lower → Lower requirements for dielectric strength of the cable and higher equipment reliability	

Criteria	Unipolar	Bipolar	
		2-wire	3-wire
Weight	↓ lower	↓ two-wire: app. same as unipolar	↑ three-wire: higher due to additional line and balancing converters
Reliability	↓ lower	↓ lower	↑ operation under a single line fault
Safety	↓ lower → higher voltage differential to ground	↑ higher → lower voltage differential to ground reduces the risk of electric shock and arcing	
EMI	↑ higher higher voltages generate stronger electromagnetic fields, potentially disrupting other systems.	↓ lower symmetrical operation reduces electromagnetic interference	
Efficiency and Performance	↓ lower	↑ higher	
Implementation Effort	↓ simpler less complex circuits and reduced wiring effort	↑ more complex three-wire connectors increased cable volume → separation and insulation between the wires	

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Challenges

Arc Detection Resolution

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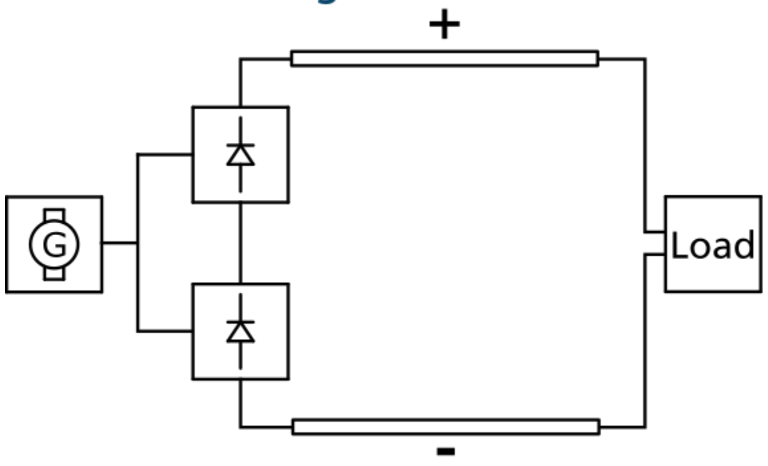
Grounding and Fault Detection

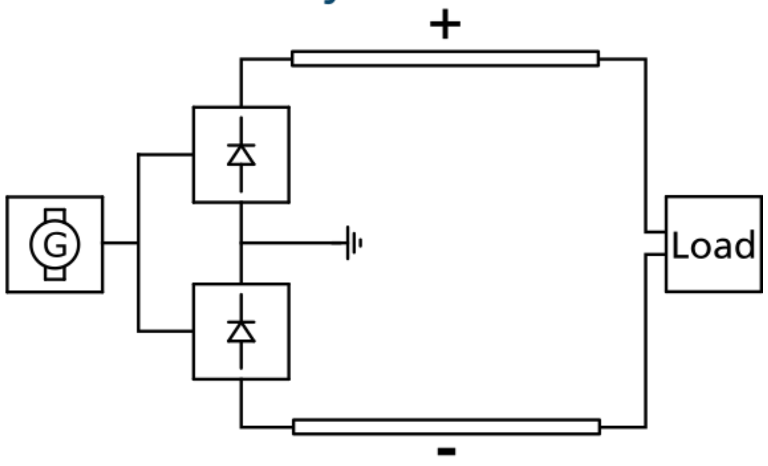
General: The voltage source converters consist of switches and diodes and they are the weakest part of the system. These components must be protected against fault currents. Thereby any approach **limiting both the magnitude and rate of rise of the fault current** are valuable as it provides more reaction time for the DC breakers. One approach is hereby to reduce the diode's fault current by changing the grounding arrangement. **Attention: too low currents are also not desired, as it makes it hard to detect distinct failures.**

Grounding Options

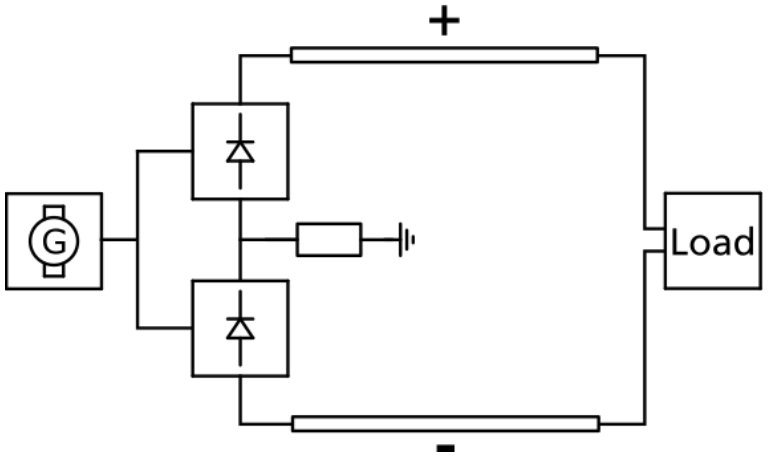
Ungrounded



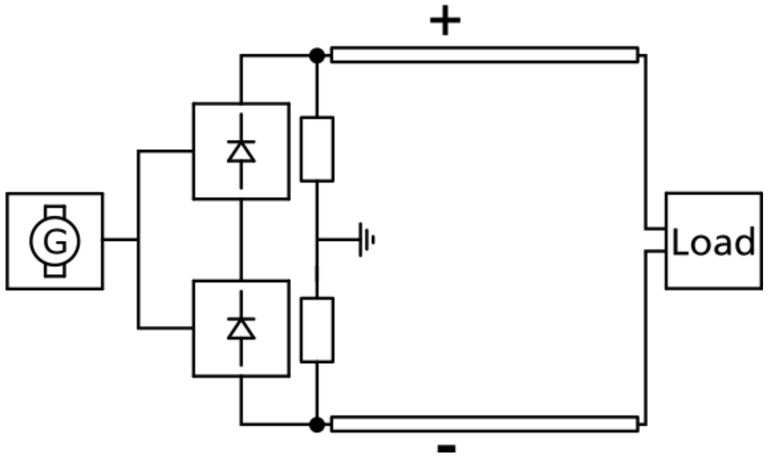
Solidly Grounded



Grounded via Resistor



Grounded via Resistors in Parallel

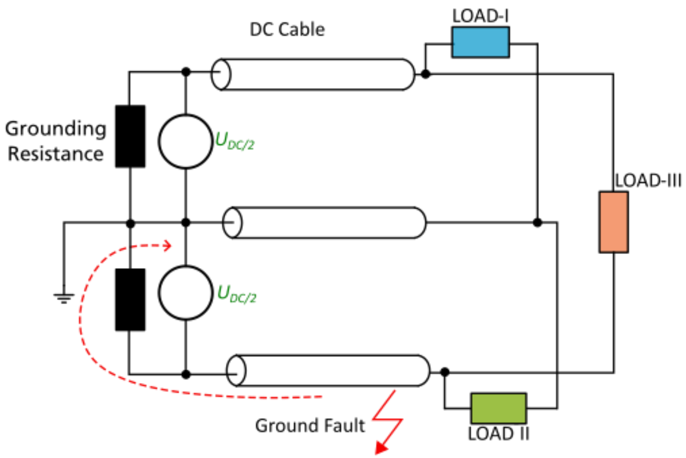


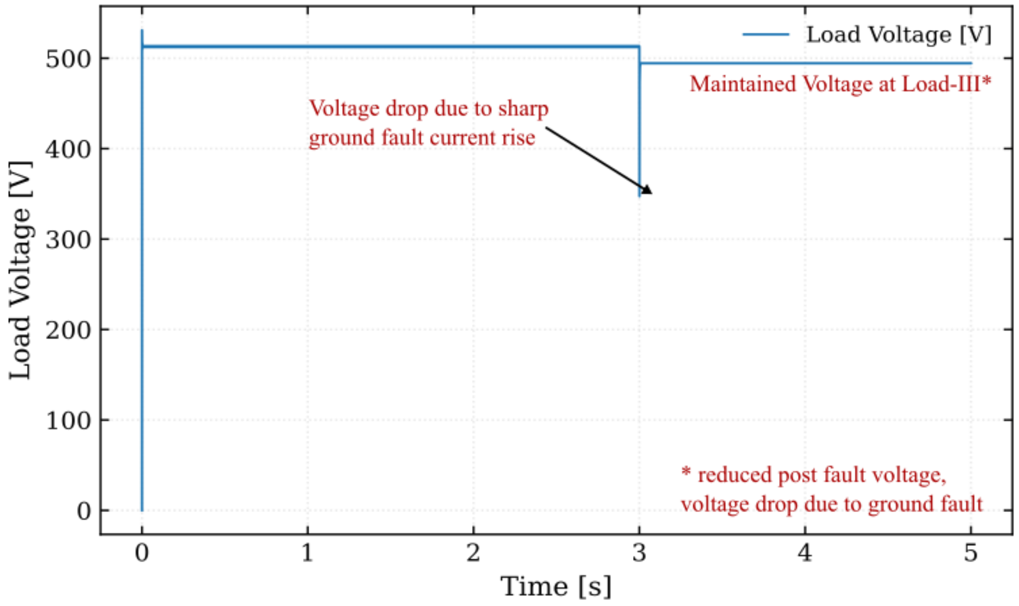
Grounding Options

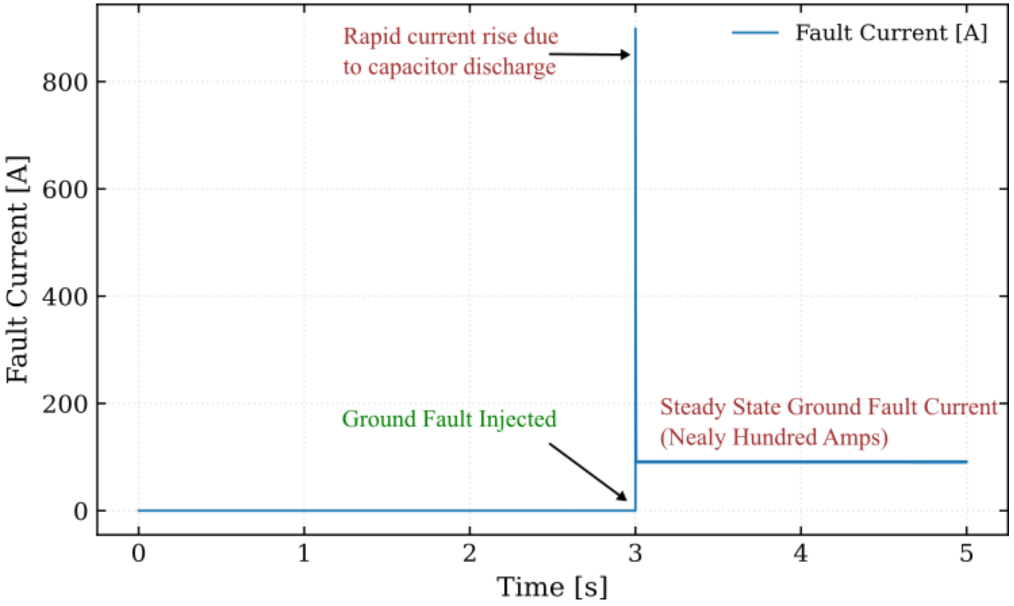
- **Neutral not grounded**: higher level of bus overvoltage, higher level of overcurrent
- **Neutral point directly grounded**: lower level of bus overvoltage, but even higher overcurrent
- **Grounding with resistor:** overvoltage and overcurrent is in between those of the neutral not grounded and the neutral point directly grounded, increase of grounding resistance → voltage of cables increases, current peak decreases
- **Grounding resistors in parallel:** compared with neutral grounded with resistor the overvoltage does not change, with the increase of neutral grounding resistance the current peak of the neutral point decreases, for high neutral grounding resistance the system overvoltage peak and overcurrent peak gradually approach the condition of the system neutral not grounded
- **Ungrounded and grounded with resistors in parallel:** advantage in fault current control, continuity of power supply; disadvantage in overvoltage control
- **Grounded mode:** opposite, advantage in overvoltage control; disadvantage regarding fault current control and continuity of power supply
- **Grounded with resistor:** combines both advantages of the previous points

→for the ship MVDC system a **grounded with resistors** between 400 Ω to 800 Ω → too low for aircraft

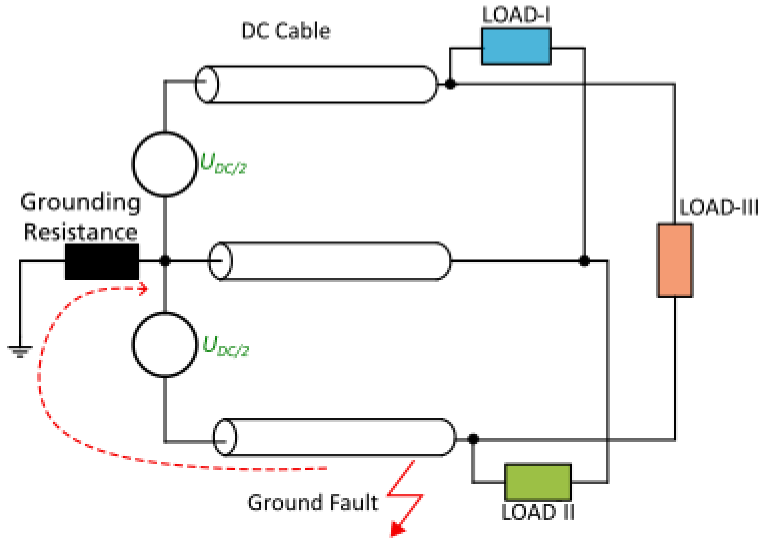
Grounded via Resistors in Parallel

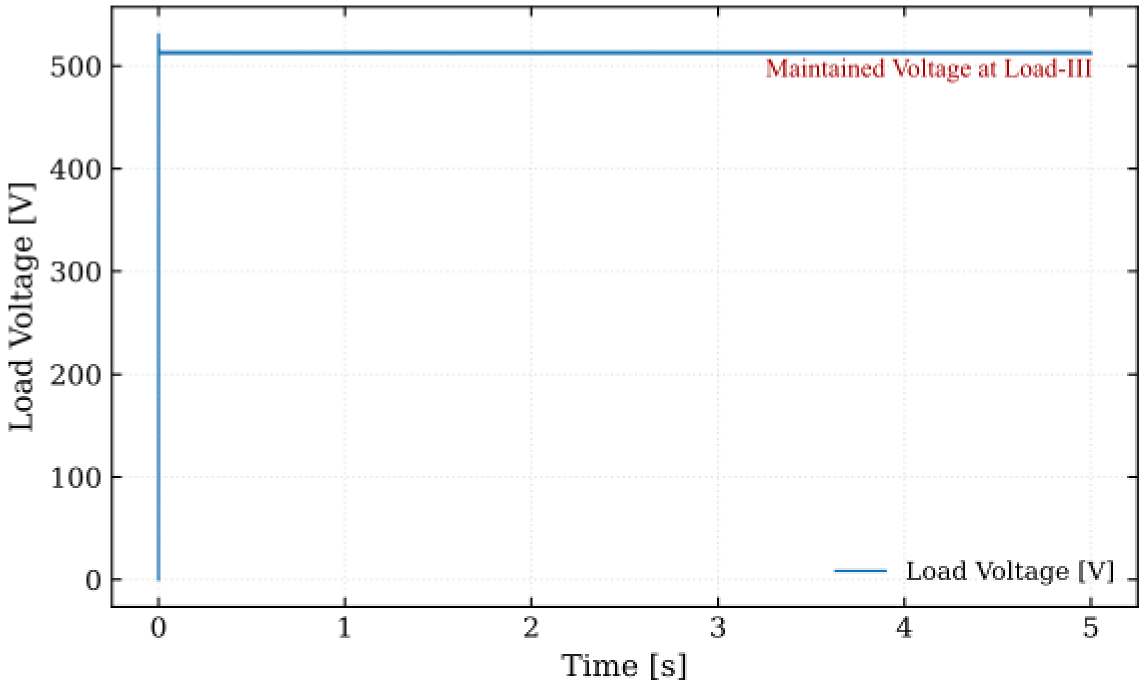


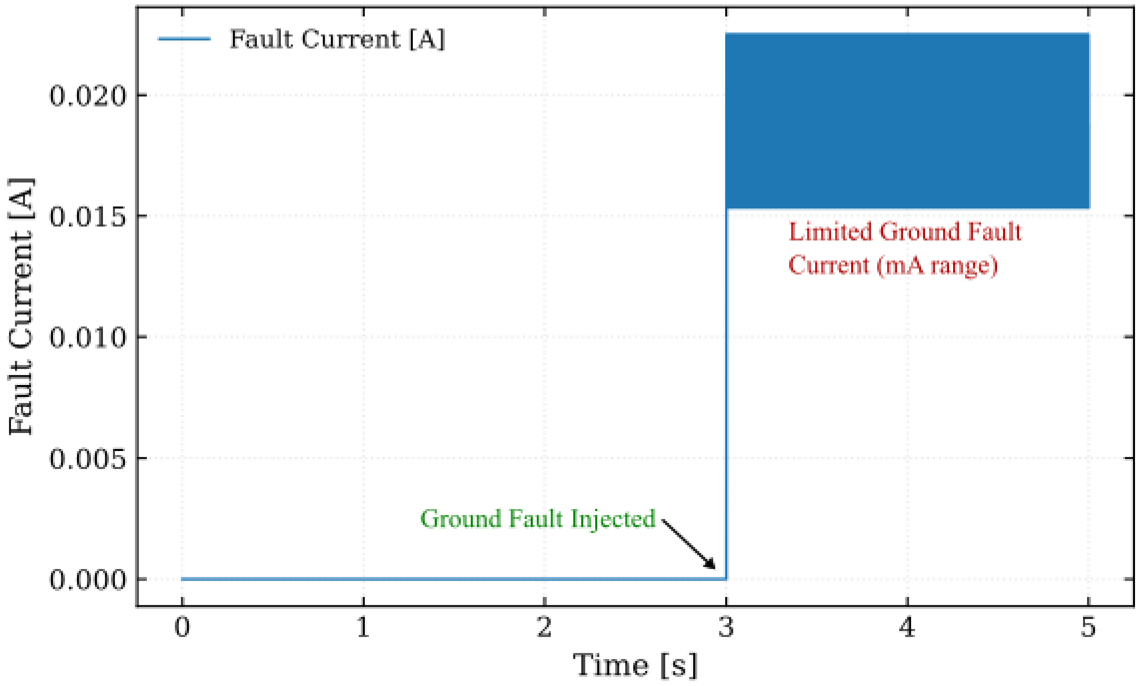




Grounded via Resistor







Challenges

- **Arc Detection Resolution**
- **Partial Discharge**
- **Efficiency**
- **Galvanic Isolation** vs. efficiency, volume, weight
- **Electrical Wiring Sytem:** Weight & fault impedance
- **Electro-magnetic Interference (EMI)**
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- **Power Density**
- **Higher Voltages** Benefits and Paschen's Curve
- **Control Stability**

Capacitors

Electrical System Architecture Level

In a system with many parallel-connected loads, many capacitors (output capacitors of power electronic converters) are connected in parallel with each other. This is advantageous for the stability of the DC link voltage. However, capacitors significantly determine the inertia, the fault behavior in the event of a short circuit (the more capacitors in parallel, the higher the fault current amplitude), and significantly drive the arc fault.
For improved fault management, reduce components connected in parallel and reduce output capacitor sizes.

Challenges at System Level

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Control Stability

Key Take-Away-Messages

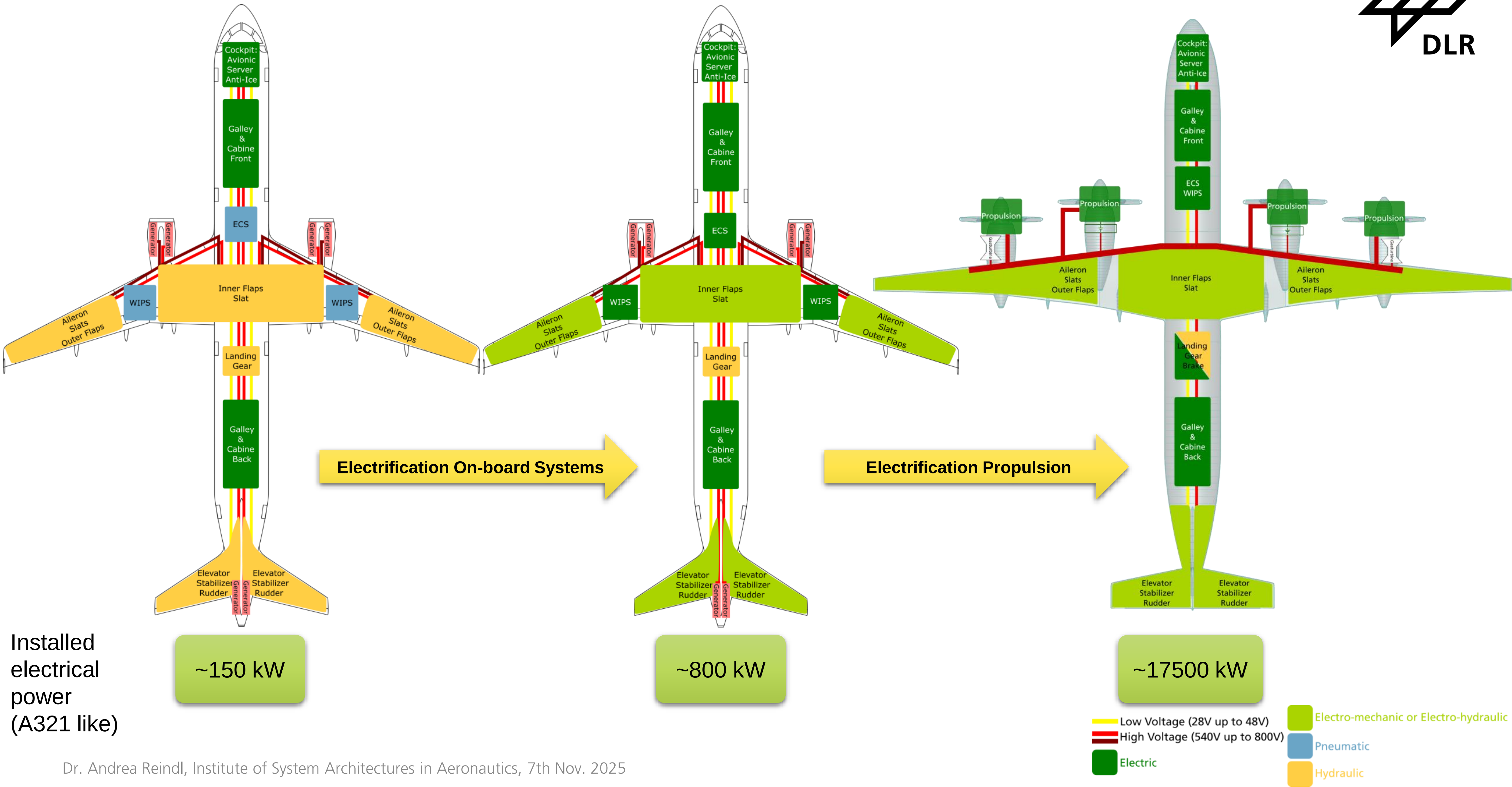
- Some challenges can already be addressed at the **architectural level**.
- Everything is **interconnected** and **influences** each other. Therefore, initial design decisions are required, followed by simulations and hardware validations.
- **Separation** helps to reduce **complexity**

ELECTRICAL SYSTEM ARCHITECTURES FOR FUTURE (MORE) ELECTRIC AIRCRAFT

Dr.-Ing. Andrea Reindl, Institute of System Architectures in Aeronautics, DLR

DLR

Conventional Aircraft | More Electric Aircraft | All Electric Aircraft



Research Questions

1. What is the impact of the electrical system at the Overall Aircraft Design (OAD)?
2. How can system architectures be designed to meet advanced requirements for fail-safety, reliability and availability?
3. Which control strategies are most effective in ensuring control stability while maximizing system availability?

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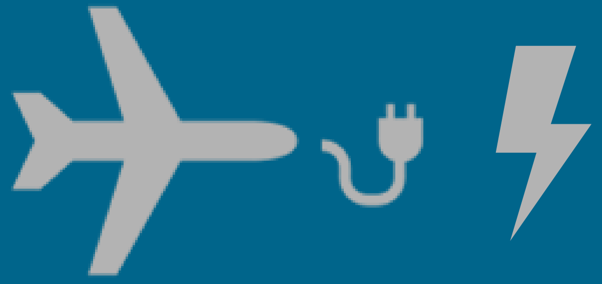
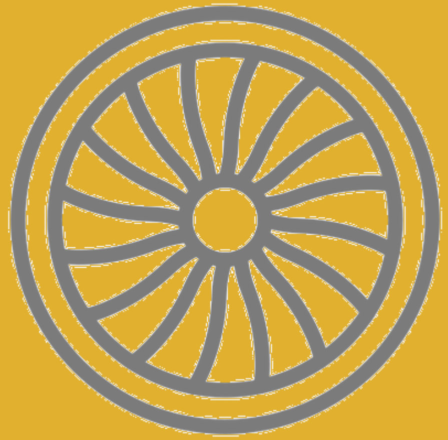
1. ALL ELECTRIC AIRCARFT ELECTRICAL SYSTEM



2. MORE ELECTRIC AIRCARFT ELECTRICAL SYSTEM

3. PROPULSION SYSTEM ARCHITECTURE



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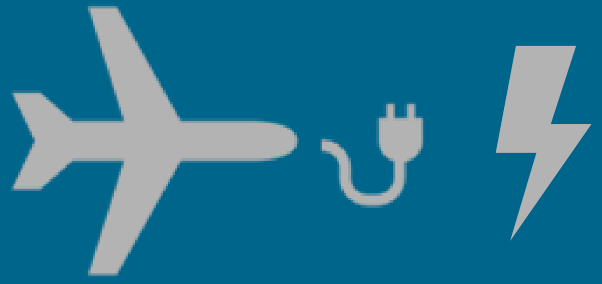

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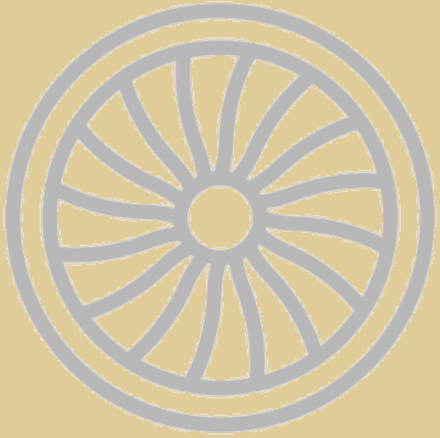


Method of Procedure

Analyze the **state of the art** and **map** it to the selected aircraft configuration

→ **Conventional Approach**

Focus on **new** aircraft configuration and the **technical innovations** and associated advantages for the system level

→ **Disruptive Approach**

Compare the **advantages** of the **conventional approach** with the **disadvantages** of the **disruptive approach** and derive a **hybrid** of both approaches.

→ **Intermediate Approach**

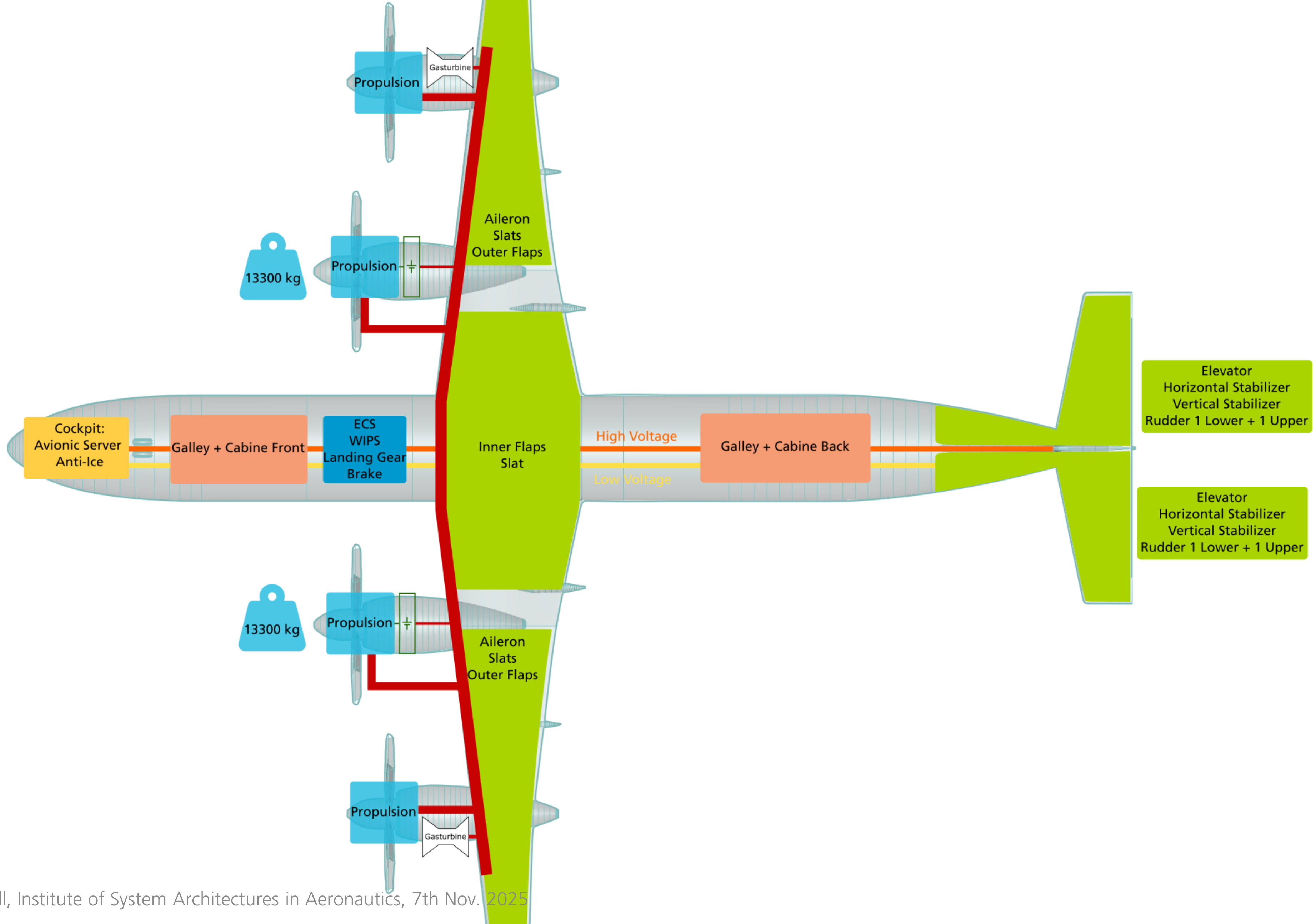
Method of Procedure

Analyze the **state of the art** and **map** it to the selected aircraft configuration

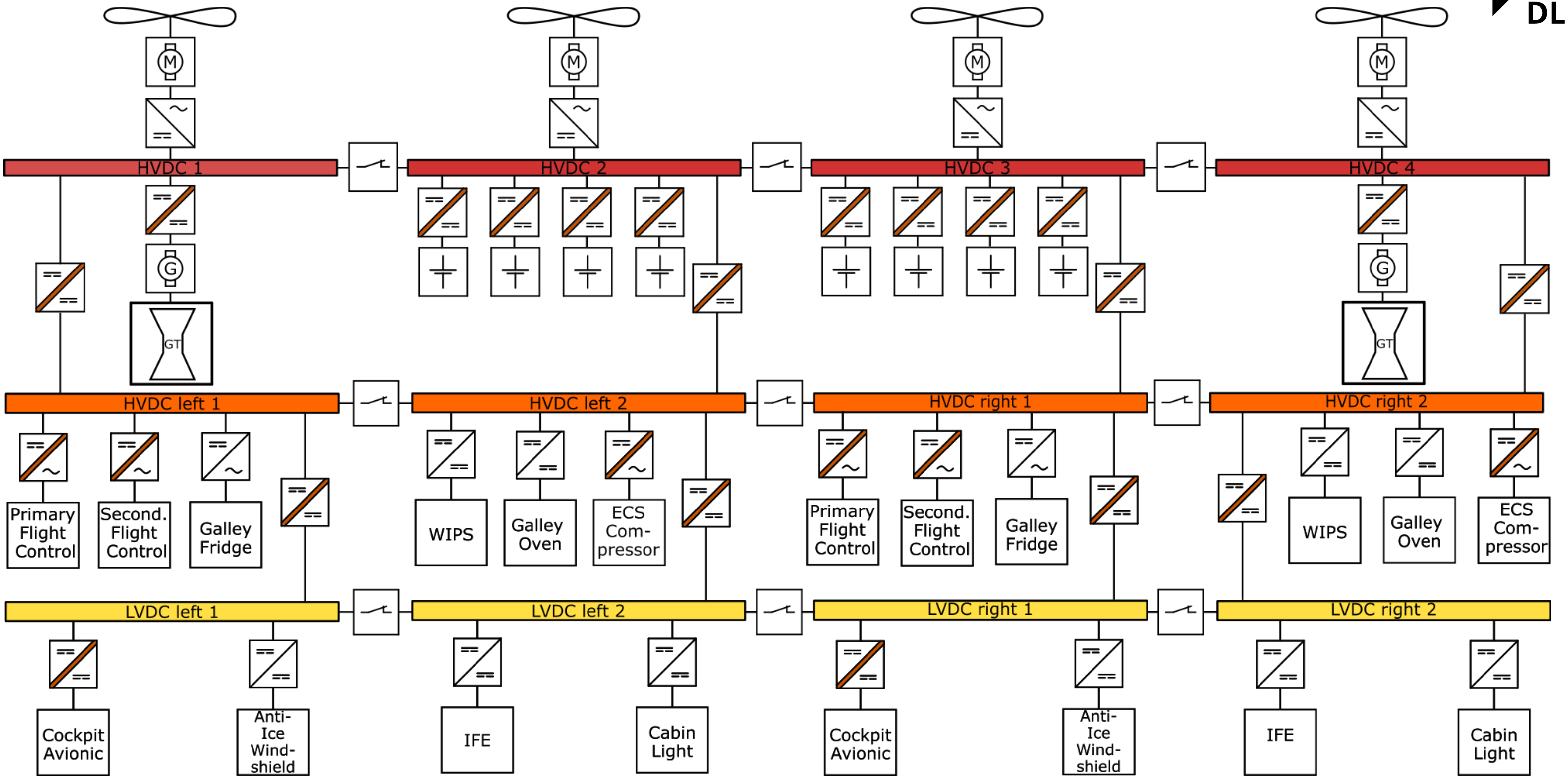
↓

Conventional Approach

All Electric Aircraft - Conventional Grid Architecture

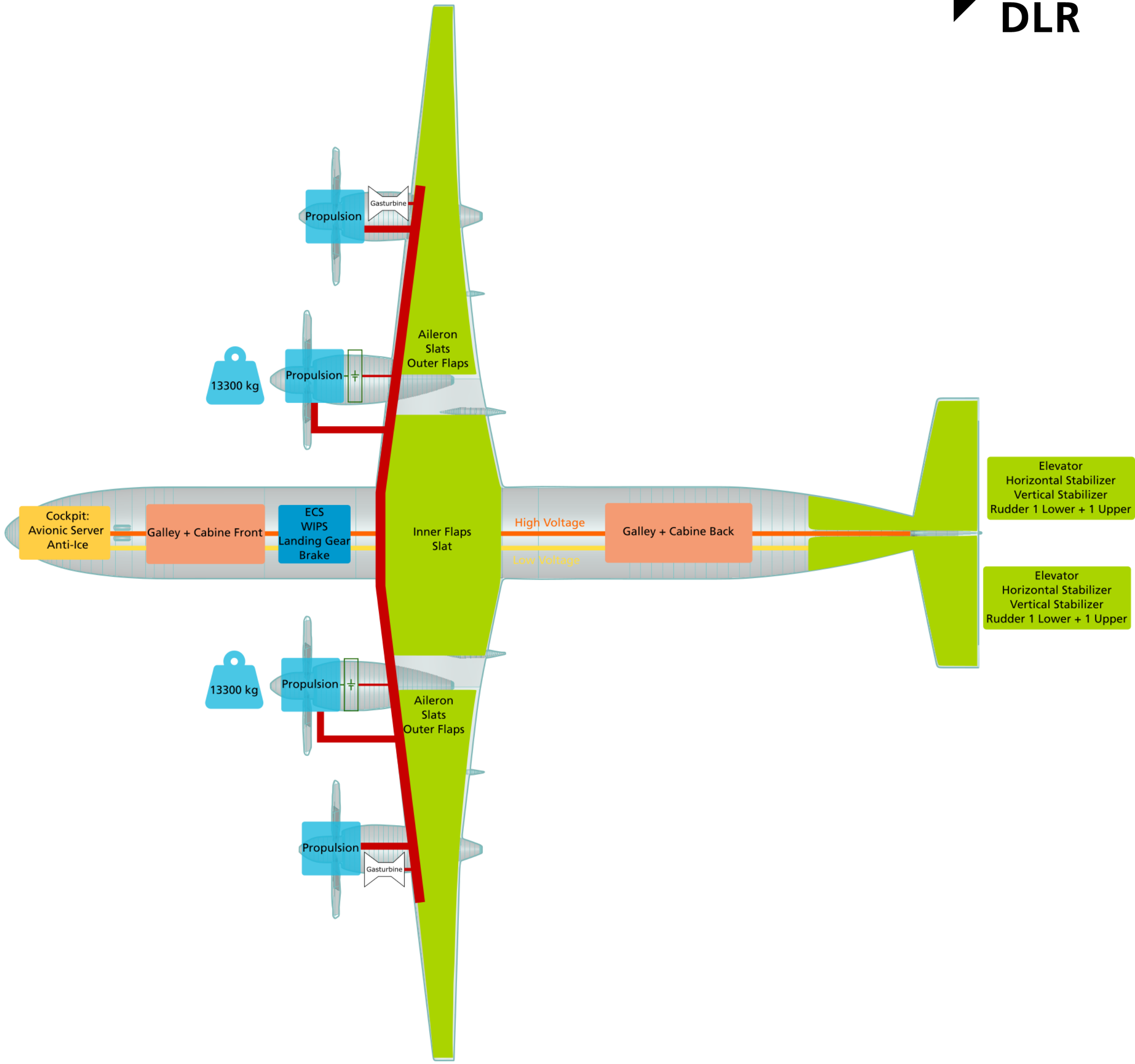


All Electric Aircraft – Conventional Grid Architecture



All Electric Aircraft - Conventional Approach: Connected Grid

- \+ Failure of one engine: available battery capacity is used to operate and overpower functional e-machines → availability
- \+ Failure of a single battery pack has little effect on the system
- \+ Batteries are placed in the narcelles: the fire load is separated from the remaining aircraft in case of a thermal runaway
- – Fault currents and line faults affect the entire system to some extent: complex protective mechanisms, bulky circuit breakers
- – Galvanic isolation is required at several points → heavy transformers, less efficiency
- – High voltage DC disconnection: risk of arcs is very high
- – Many components connected in parallel: high fault discharge currents



Method of Procedure

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Conventional Approach: Connected Grid

Method of Procedure

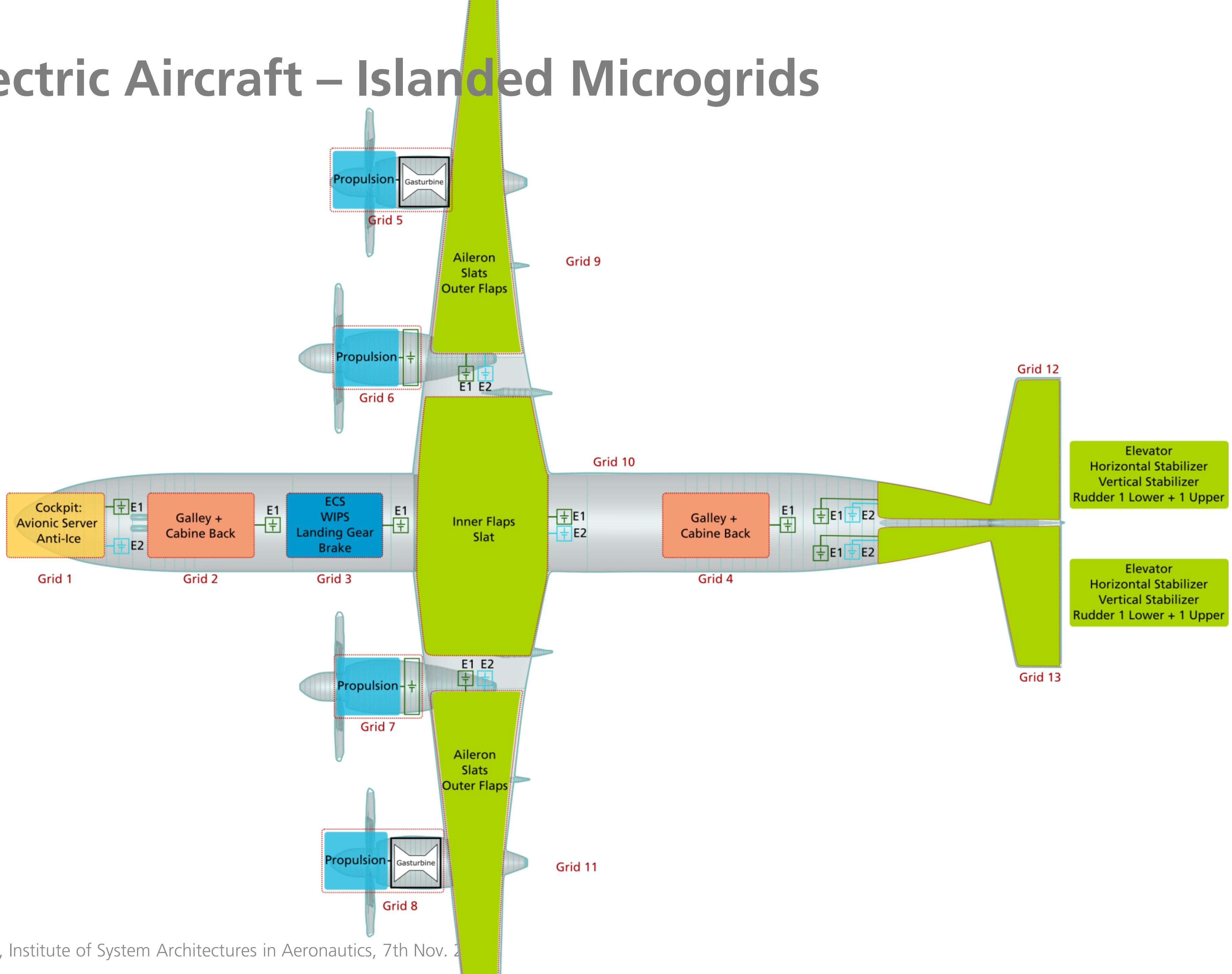
Analyze the **state of the art** and **map** it to the selected aircraft configuration

Focus on **new** aircraft configuration and the **technical innovations** and associated advantages for the system level

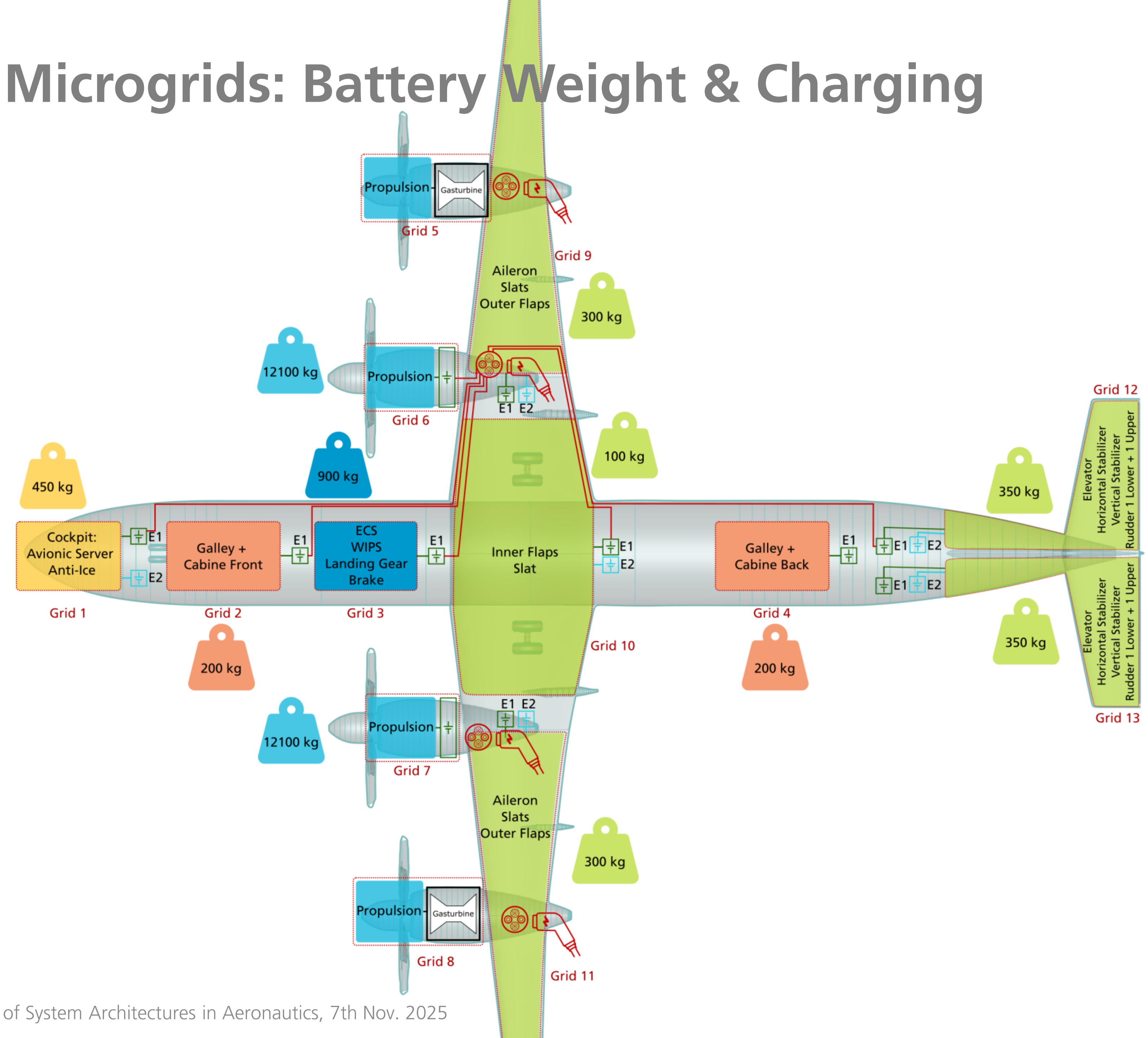
Conventional Approach: Connected Grid

Disruptive Approach

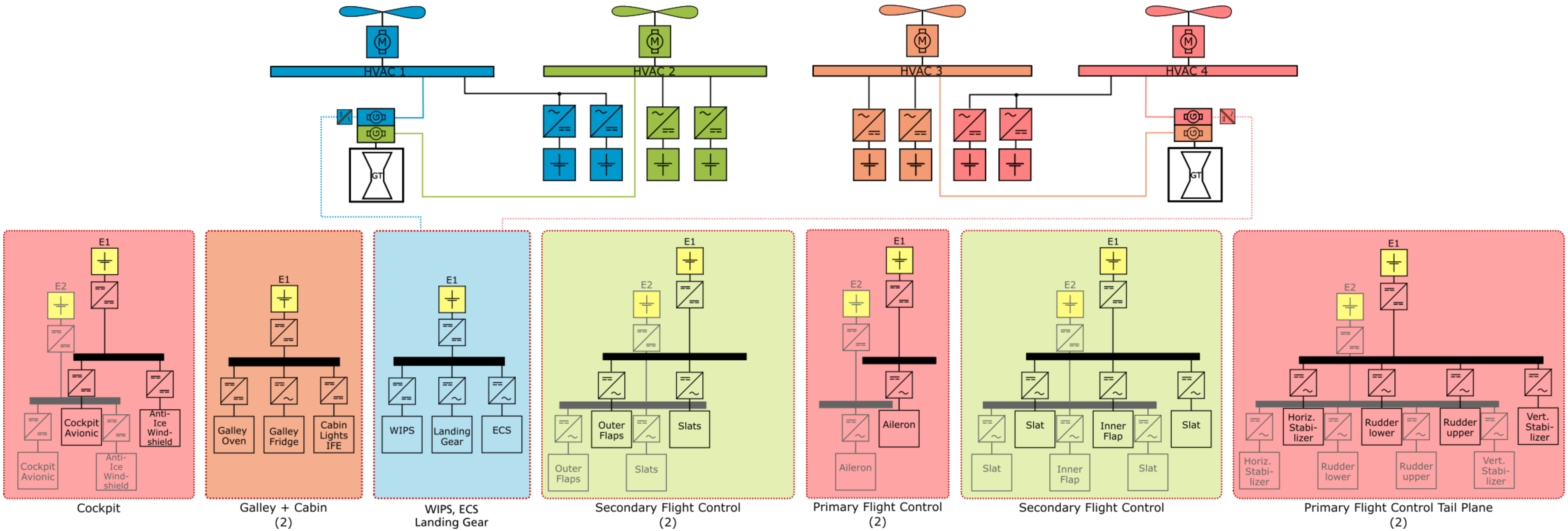
All Electric Aircraft – Islanded Microgrids



Islanded Microgrids: Battery Weight & Charging

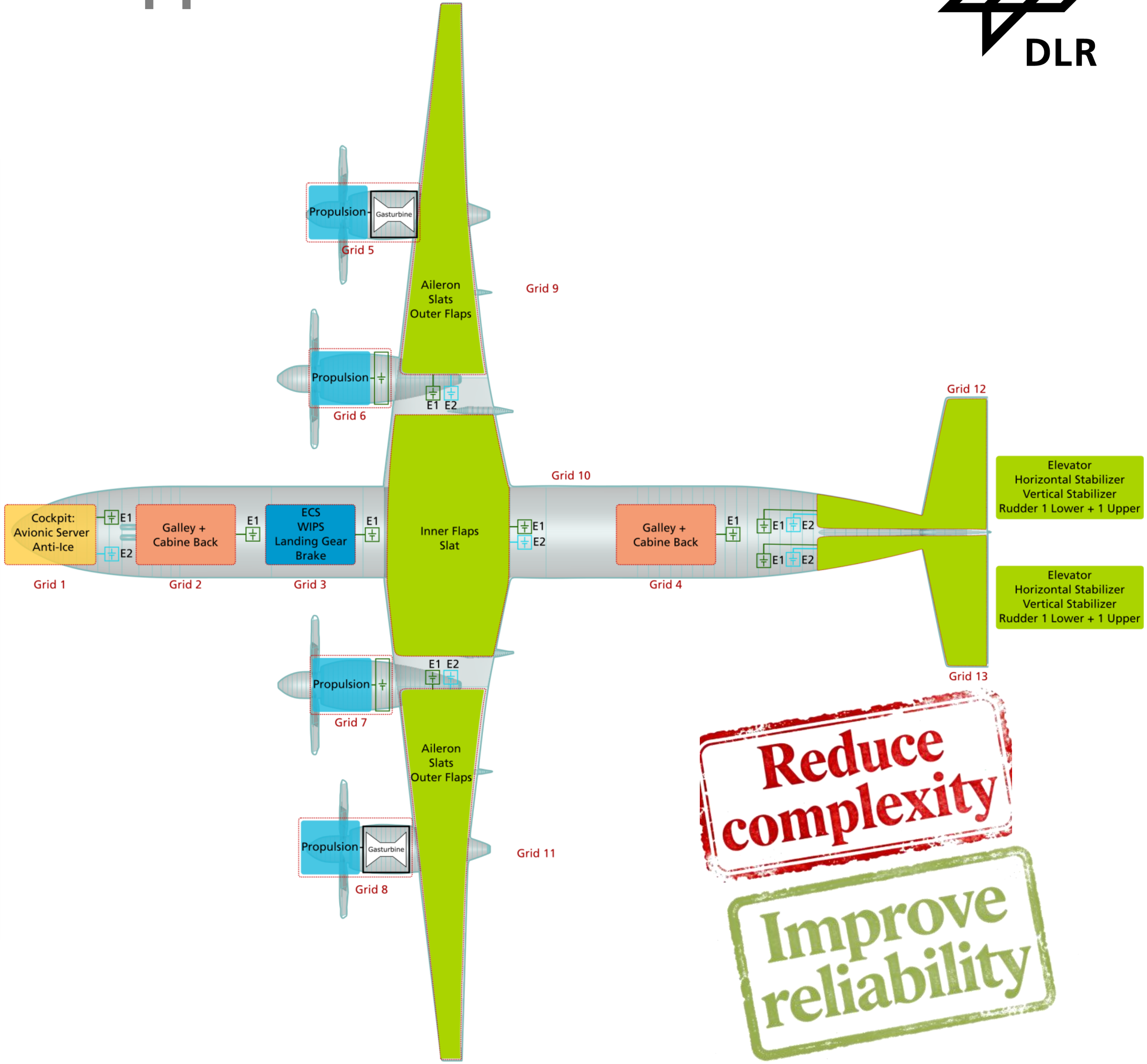


All Electric Aircraft – Islanded Microgrids



All Electric Aircraft - Disruptive Approach: Islanded Grid

- \+ Batteries isolated from each other → improved fail-safety
- \+ Fault current amplitude is lower → fewer components connected in parallel
- \+ Less galvanic isolation required
- \+ Shorter cable lengths, improved EMC → less complex filters
- \+ Separation of safety-relevant and non-safety-relevant grids
- \+ Decreased total weight: increased battery weight, but decreased cable weight
- \+ Severity and impact of faults, e.g. single line faults is reduced → increases availability
- – Batteries are distributed throughout the aircraft
- – Failure of one engine → battery capacity can **not** be used → charging lines?



Method of Procedure

Analyze the **state of the art** and **map** it to the selected aircraft configuration

↓

Conventional Approach: Connected Grid

Focus on **new** aircraft configuration and the **technical innovations** and associated advantages for the system level

↓

Disruptive Approach: Islanded Microgrids

Method of Procedure

Analyze the **state of the art** and **map** it to the selected aircraft configuration

Conventional Approach: Connected Grid

Focus on **new** aircraft configuration and the **technical innovations** and associated advantages for the system level

Disruptive Approach: Islanded Microgrids

Compare the **advantages** of the **conventional approach** with the **disadvantages** of the **disruptive approach** and derive a **hybrid** of both approaches.

Intermediate Approach

Features Hybrid Approach

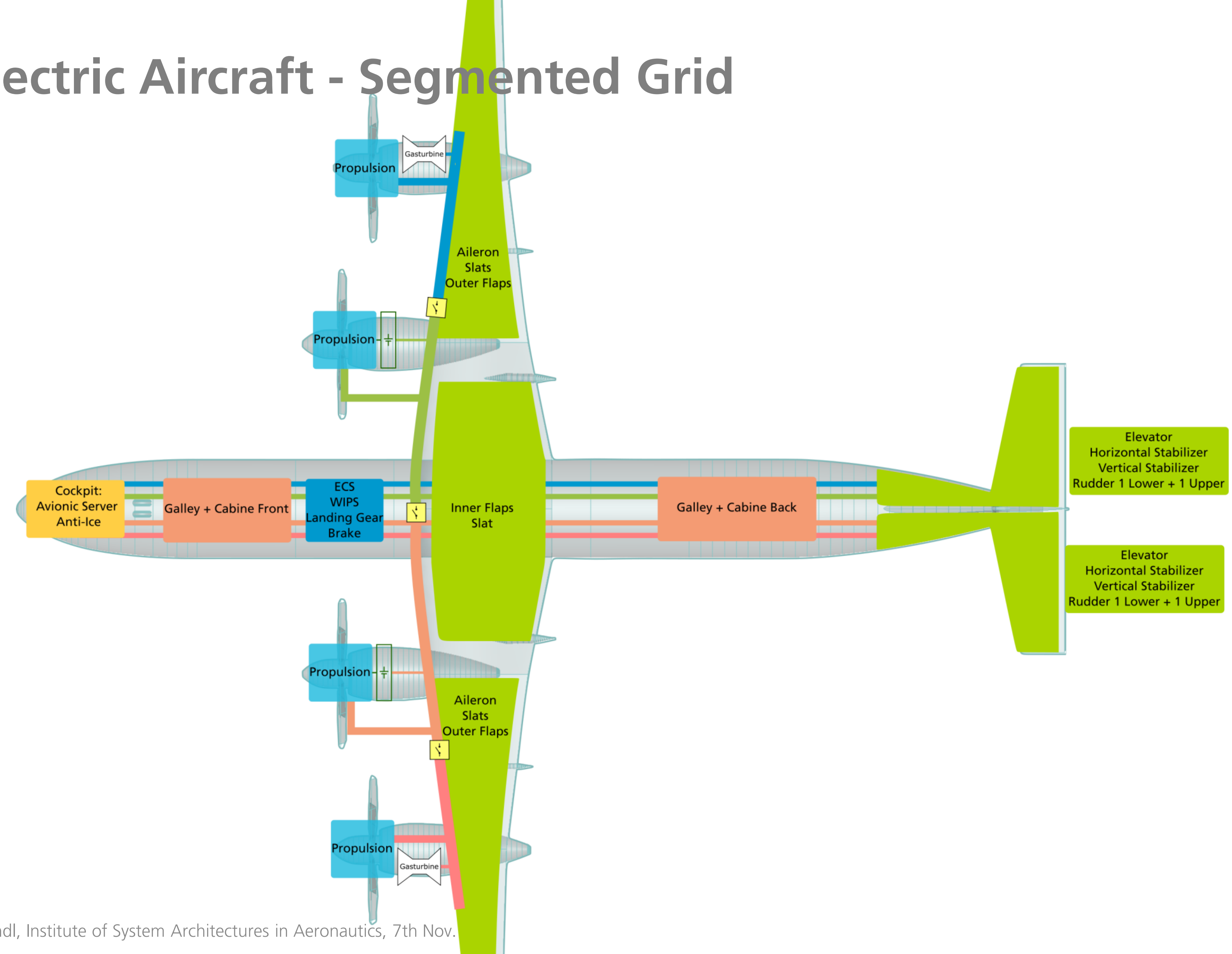
The objective is a grid architecture that offers these advantages additionally

- \+ Failure of one engine: available battery capacity is used to operate and overpower functional e-machines → availability
- \+ Failure of a single battery pack has little effect on the system
- \+ Batteries are placed in the narcelles: the fire load is separated from the remaining aircraft in case of a thermal runaway

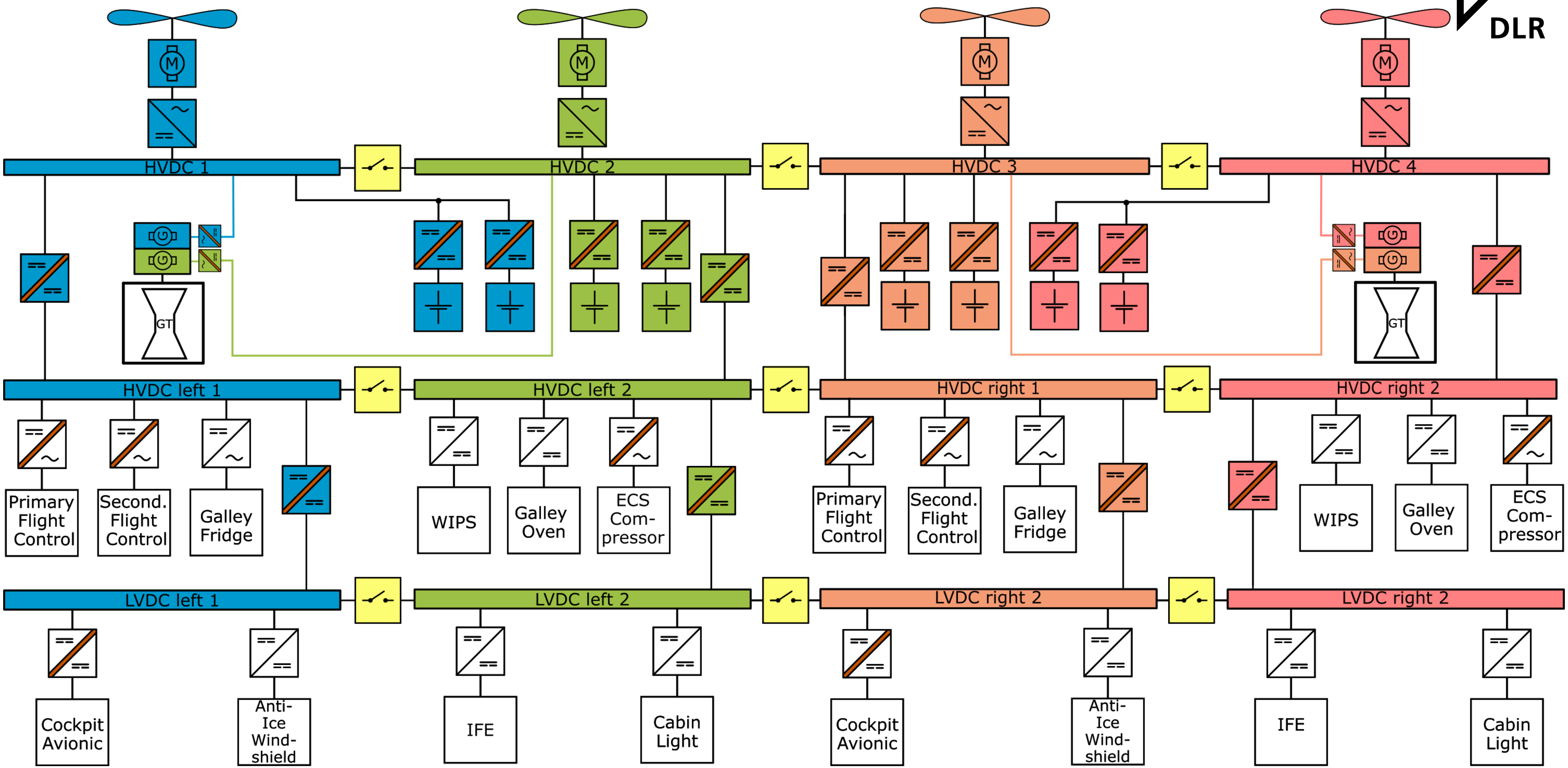
while overcoming the following disadvantages

- – Batteries are distributed throughout the aircraft
- – Failure of one engine → battery capacity can **not** be used

All Electric Aircraft - Segmented Grid



All Electric Aircraft - Segmented Grid



All Electric Aircraft - Hybrid Approach: Segmented Grid

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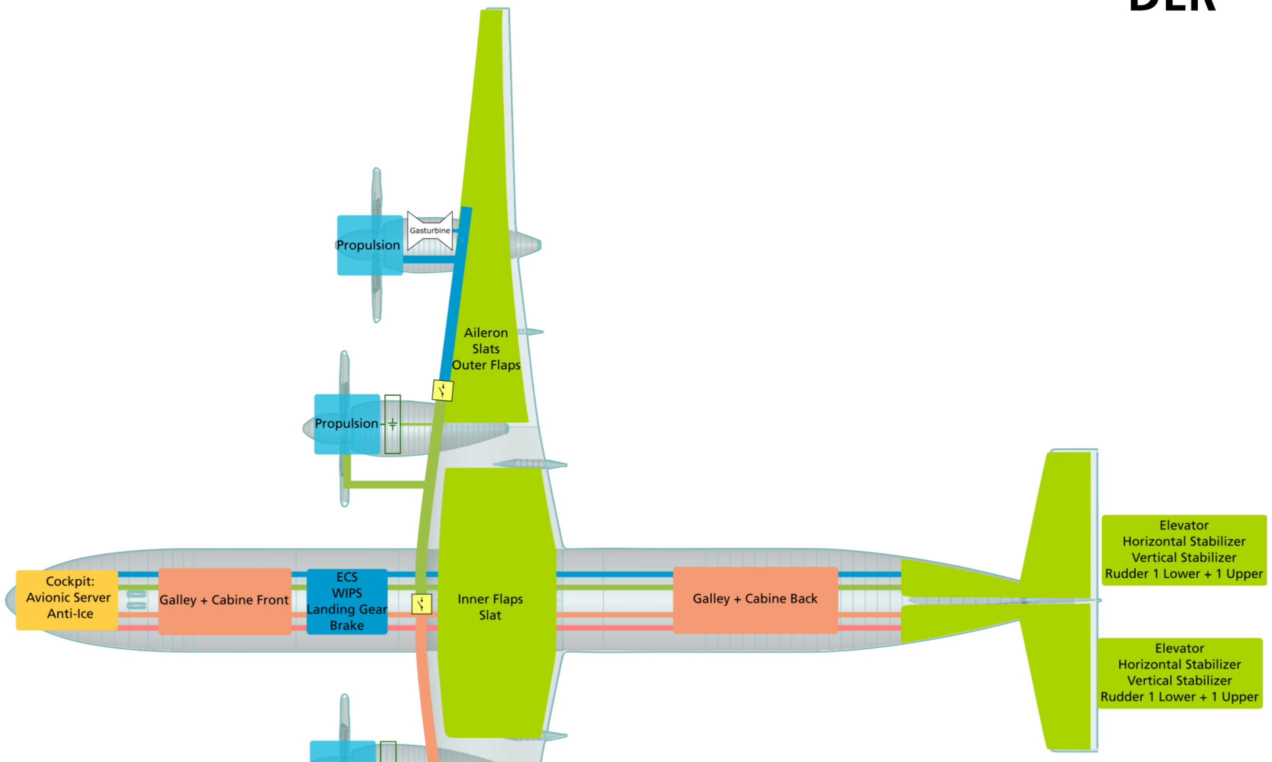
- \+ Failure of a single battery pack has little effect on the system
- \+ Batteries are placed in the narcelles: the fire load is separated from the remaining aircraft in case of a thermal runaway
- \+ Batteries isolated from each other → improved fail-safety
- \+ Severity and impact of faults, e.g. single line faults is reduced → increases availability
- \+ High voltage DC connection → minor risk
- \+ Less components connected in parallel: lower fault discharge currents
- \+ Two different energy sources
- – Fault currents and line faults only affect the sub-system
- – Galvanic isolation is required at several points → heavy transformers, less efficiency
- – No separation of critical and non-critical grids



Conclusion

Analyze the **state of the art** and **map** it to the selected aircraft configuration

Conventional Approach: Connected Grid

Focus on **new** aircraft configuration and the **technical innovations** and associated advantages for the system level

Disruptive Approach: Islanded Microgrids

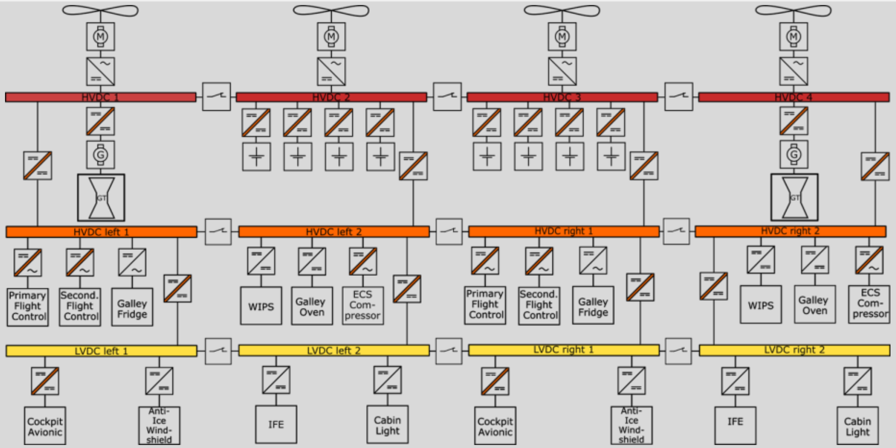
Compare the **advantages** of the **conventional approach** with the **disadvantages** of the **disruptive approach** and derive a **hybrid** of both approaches.

Intermediate Approach: Segmented Grid

Preliminary design: basic models for weight study following electric simulation

ALL ELECTRIC AIRCRAFT
ELECTRICAL SYSTEM ARCHITECTURES

Conservative Approach: Connected Grid
The grid is subdivided into a left and a right sub-grid corresponding to the feeding generators. In some configurations, there is also a mandatory grid that is connected to both, the left and the right generators. The sub-grids are connected to each other during normal operation and can be separated in the event of a fault using corresponding circuit breakers.



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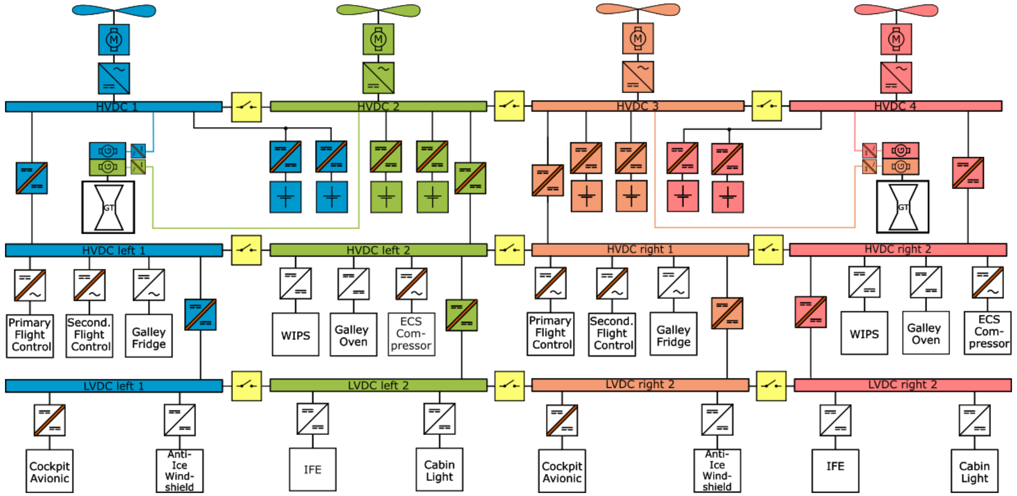
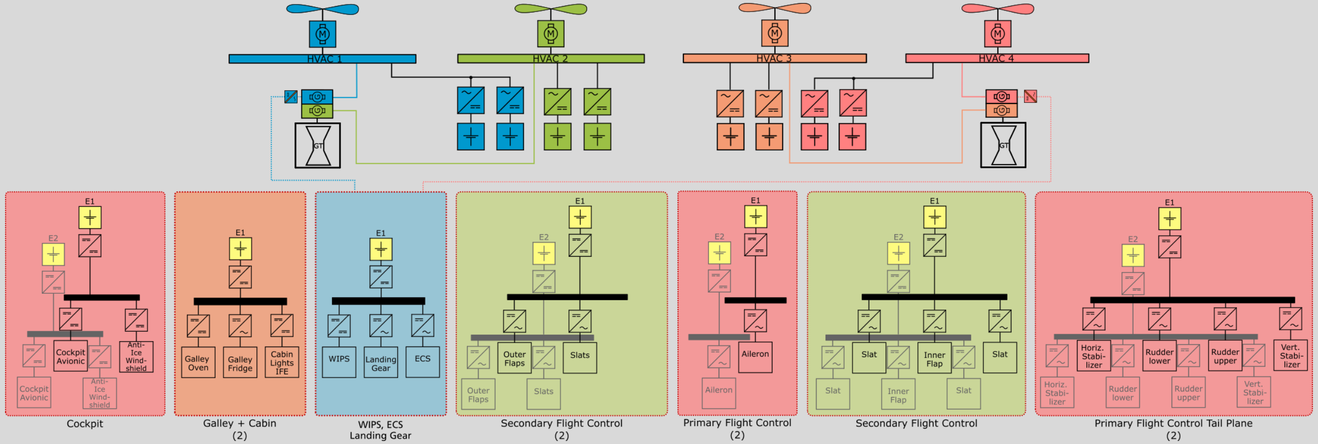
Hybrid Approach: Segemented Grids
The segmented grid is a mixture of the conventional grid approach and the islanded microgrids. In normal operation, the electrical subgrids are divided depending on their supplying battery pack. If a fault occurs, the grids can be reconfigured and individual or all loads of a grid can be connected to another grid.



Disruptive approach: Islanded Grids
The electrical system is divided into several subgrids that are electrically isolated from each other. These subgrids are never connected to each other, neither in normal operation nor during charging. Subgrids that contain safety-critical components are designed redundantly. Both the batteries and the electrical lines are implemented multiple times. In the event of a fault, individual subgrids can be connected to each other via the charging lines.



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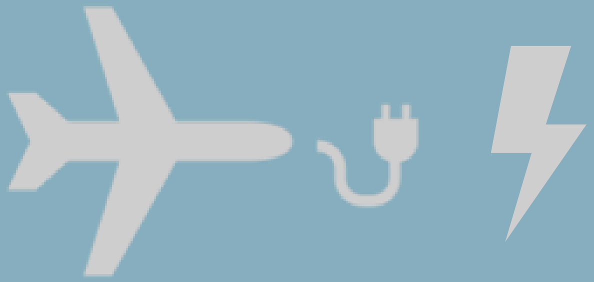

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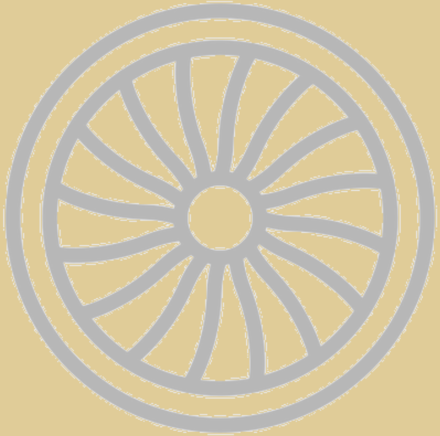
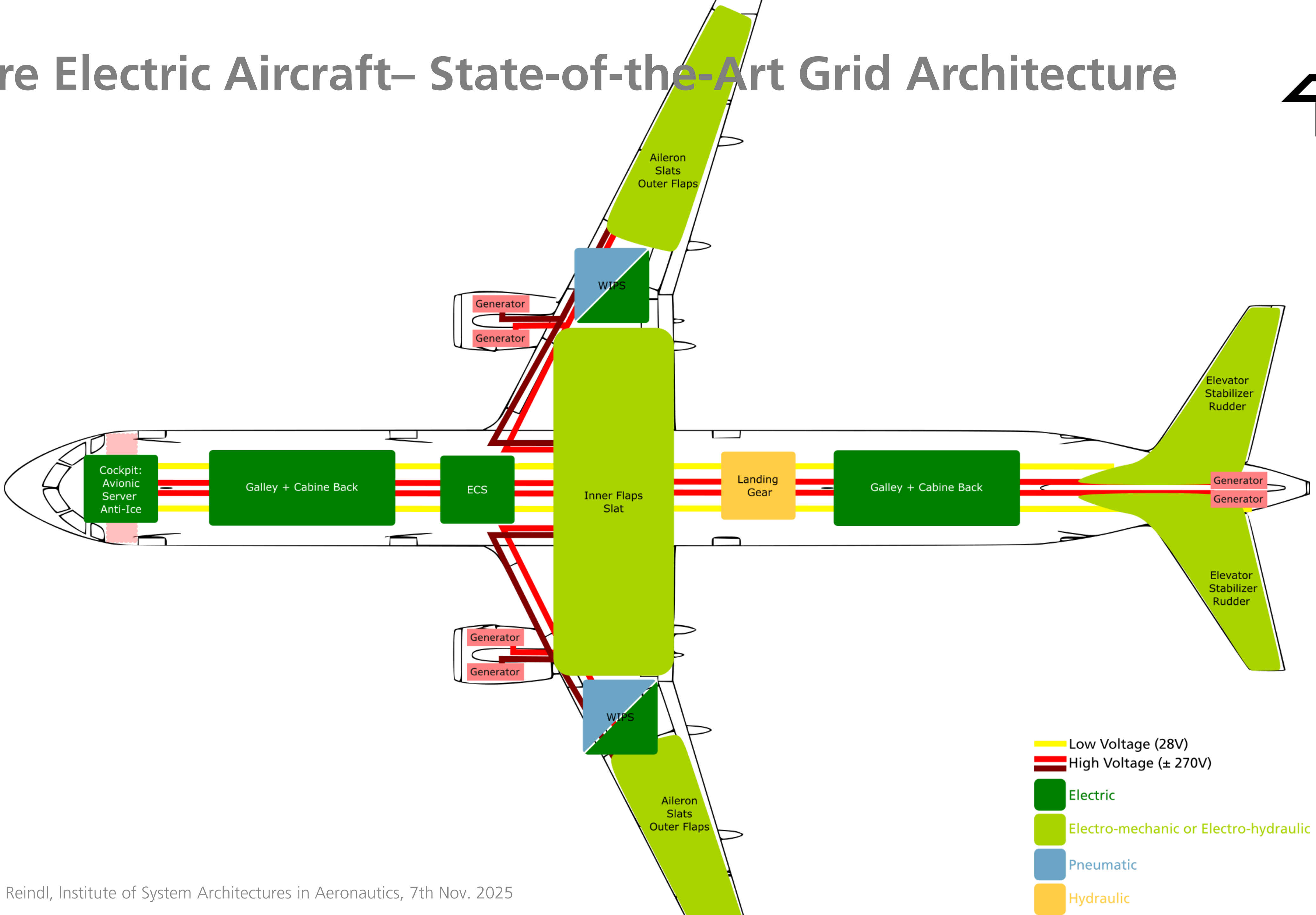


More Electric Aircraft– State-of-the-Art Grid Architecture



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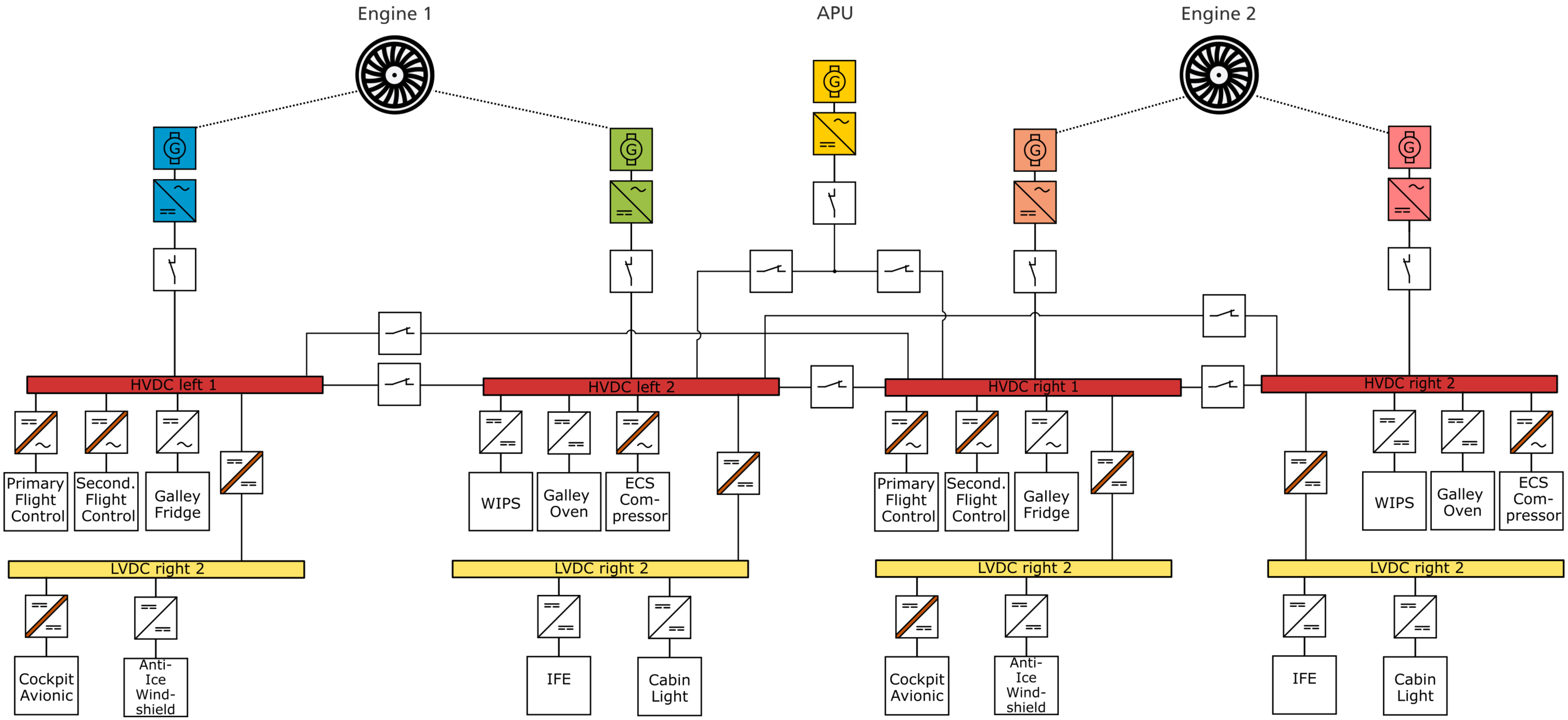

Method of Procedure

Slight changes to SOA, ensuring that most of the components utilized are **already in use** in the aircraft.

↓

Conventional Approach

Focus on **technical innovations** and associated advantages for the system level

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Disruptive Approach

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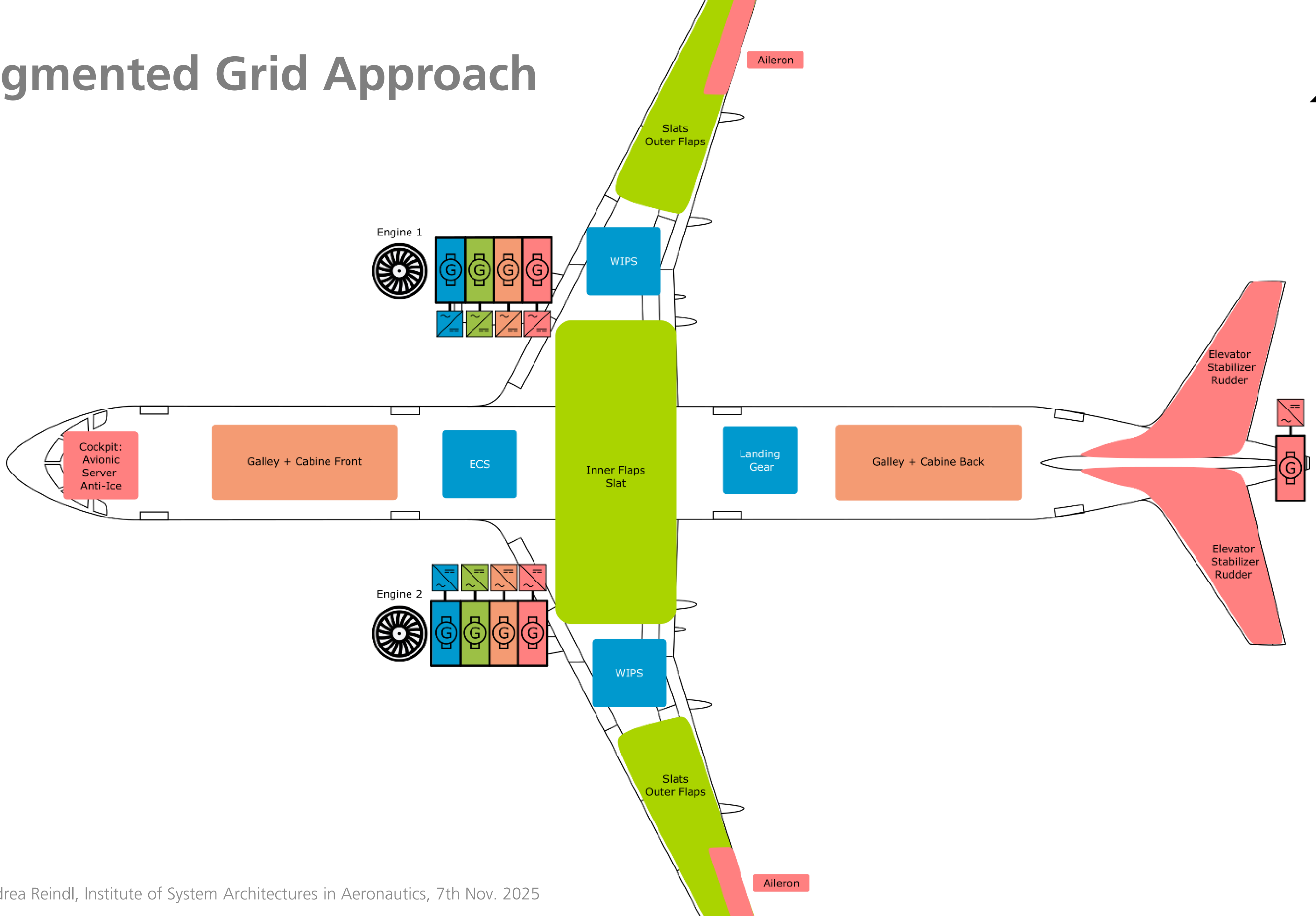
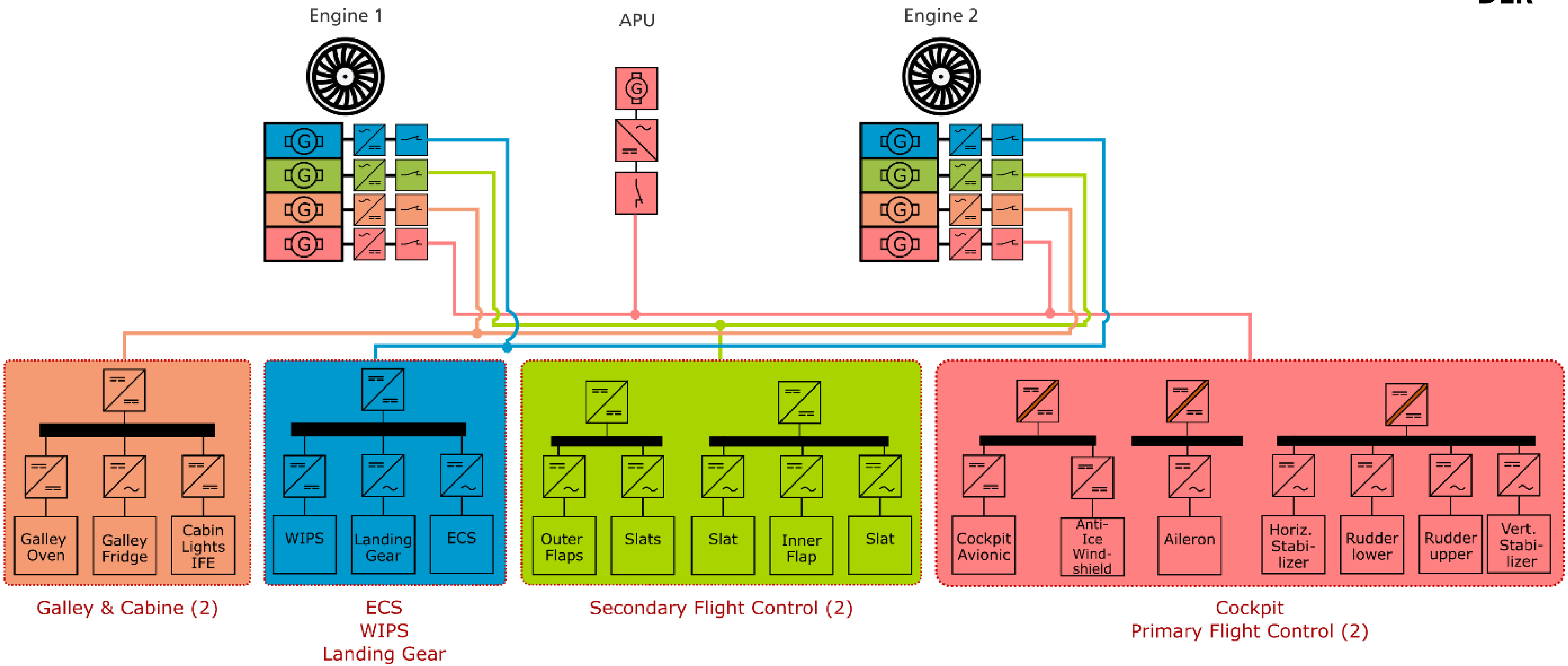
Segmented Grid Approach

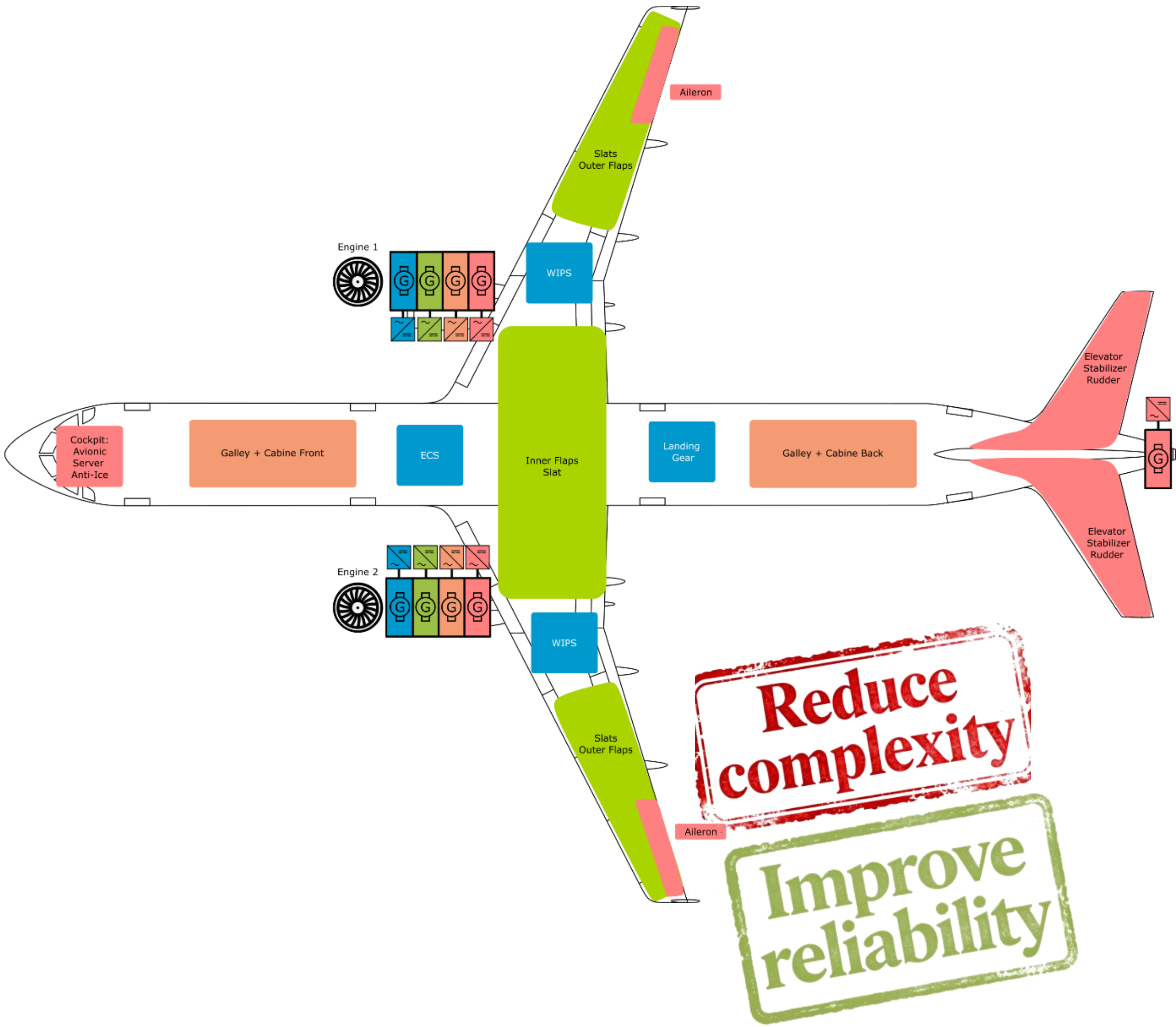


Segmented Grid Approach



Segmented Grid

- \+ Reduced fault propagation due to electrical separation
- \+ Improved fault management: Easier fault detection, localization, and isolation within smaller sub-grids.
- \+ Enhanced safety and reliability: Safety-critical loads are isolated in a dedicated safety grid with multiple redundant supply options.
- \+ Simplified certification: Different grids can meet different EMI and power-quality requirements.
- \+ Lower component count: Fewer separation and isolation devices needed.
- \+ Shorter cable lengths: Reduced EWIS weight and improved EM compatibility.
- \+ Architectural flexibility: Each sub-grid can be optimized for its specific voltage level, load dynamics, and reliability needs.
- \+ Higher overall availability: More generator units (e.g., 9 vs. 5) increase redundancy.
- – Reduced power-sharing capability: No common busbars
- – Limited energy management flexibility: Load peaks cannot be smoothed across grids.
- – Additional mechanical complexity: Requires modified gearbox



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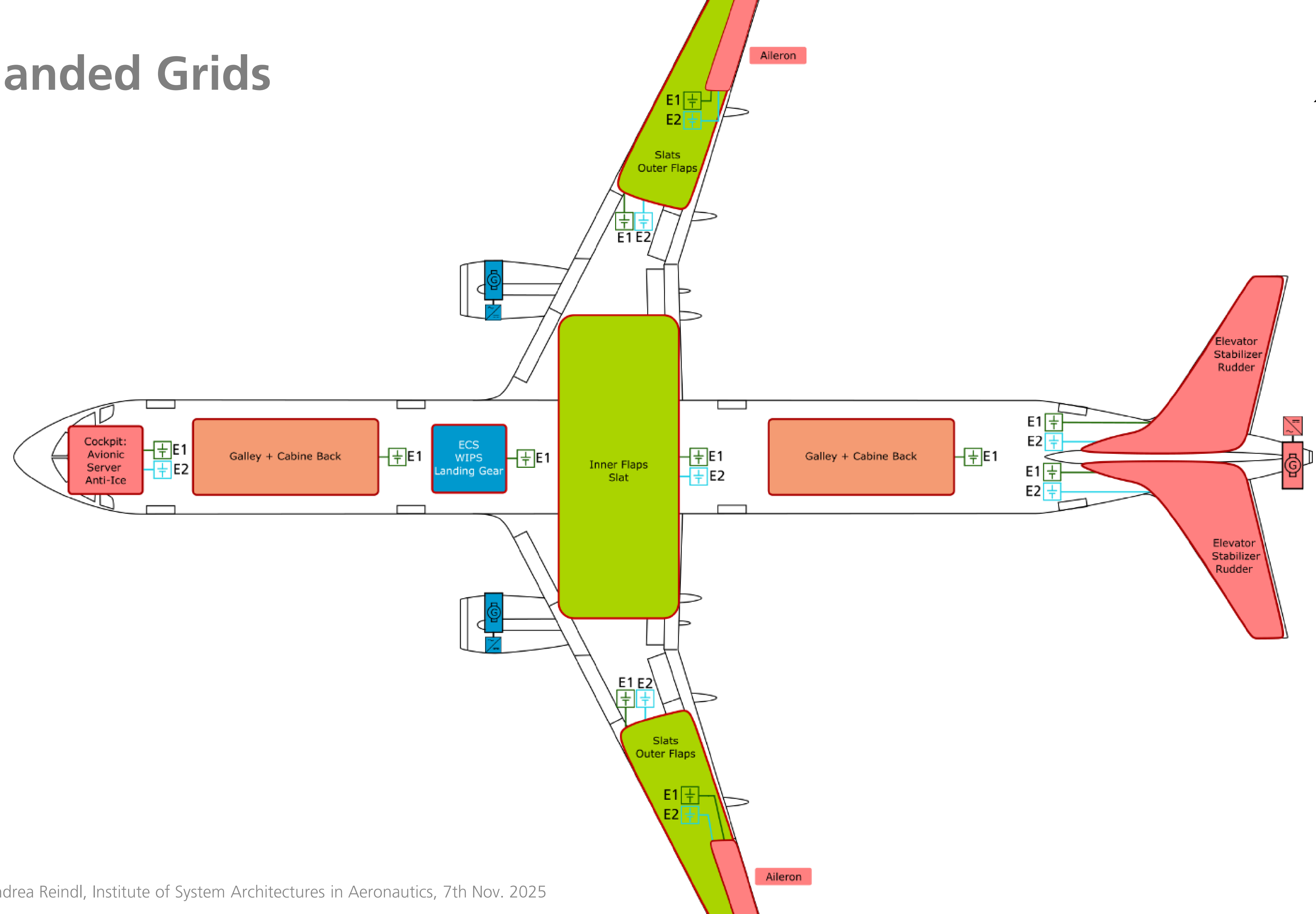
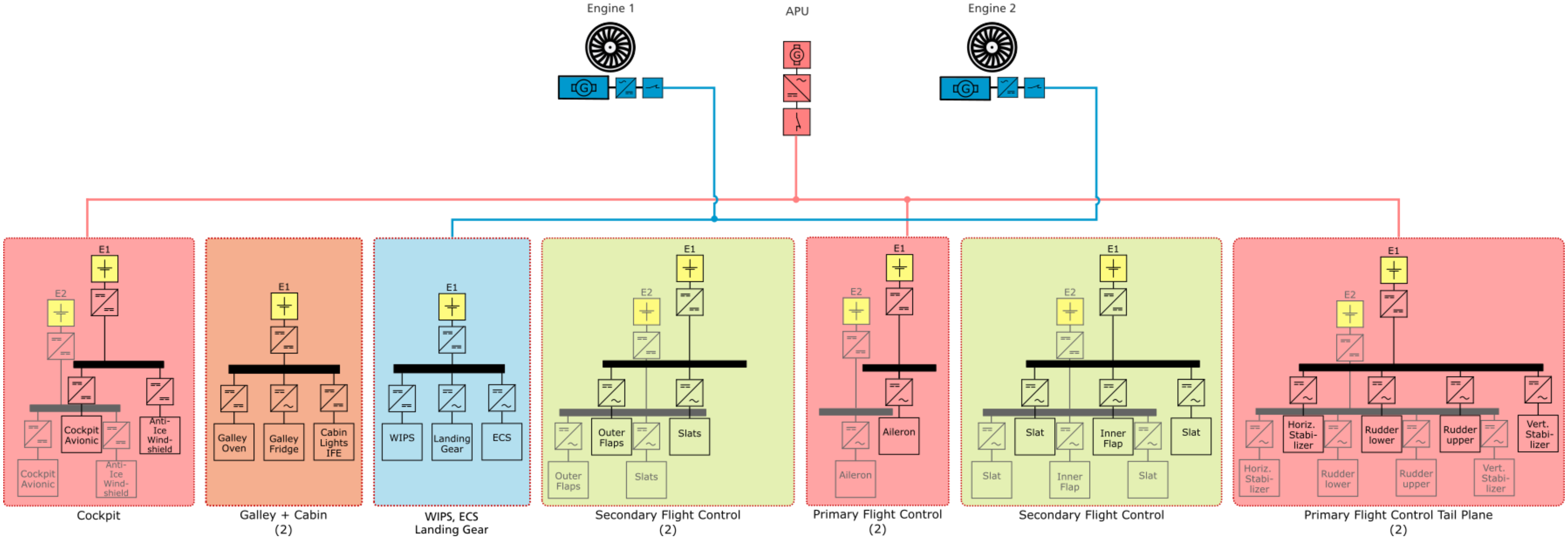
Disruptive Approach

Islanded Grids

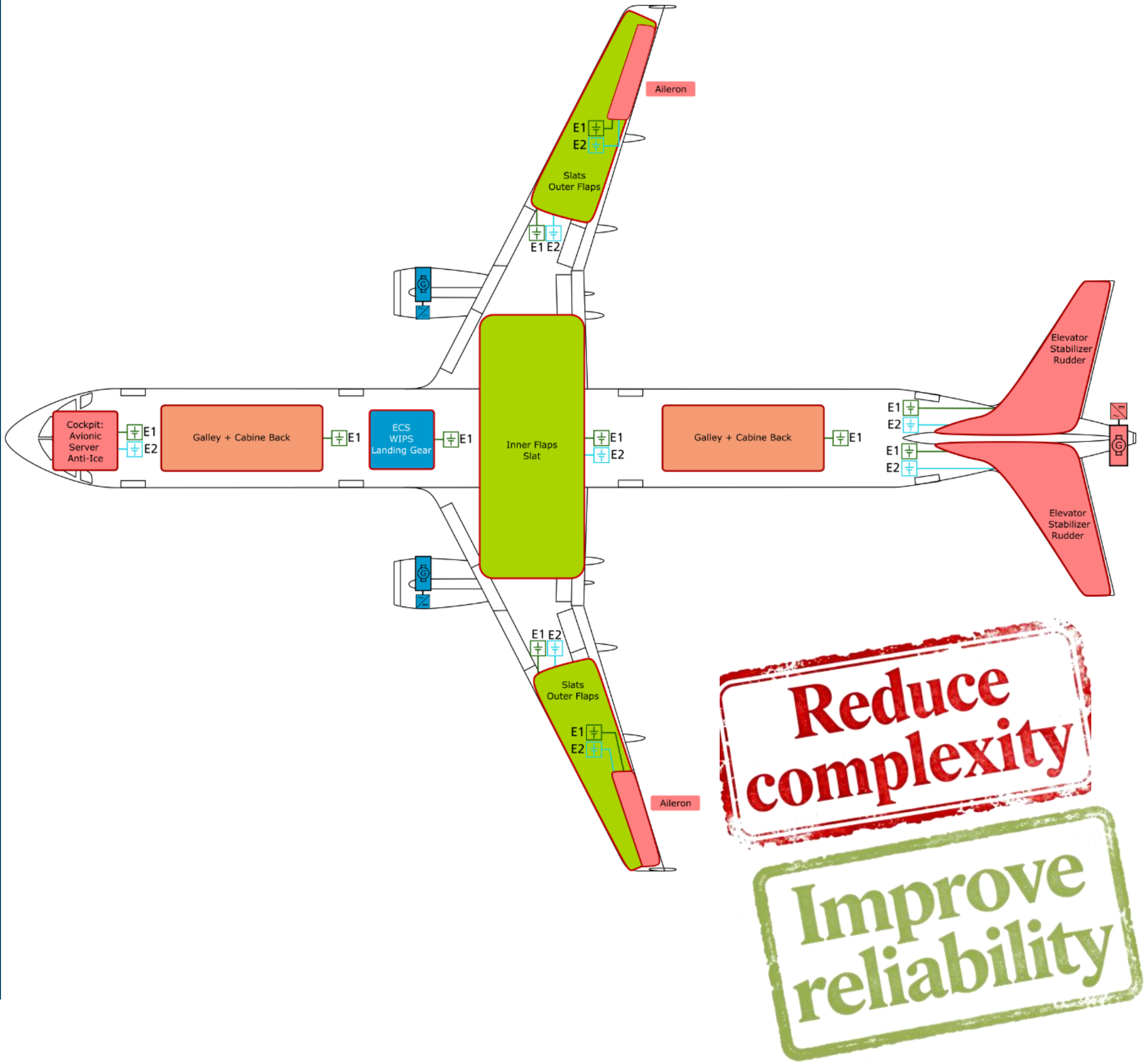


Islanded Grids



Islanded Grids

- \+ Complete electrical decoupling of propulsion and on-board systems ⟶ reduced common-cause failures.
- \+ Improved power quality: No coupling of propulsion load transients or harmonics into avionics or cabin systems.
- \+ Improved EMC performance: Subgrid-specific optimization of filters, grounding, and dV/dt / dI/dt control.
- \+ Shorter cable lengths: Local batteries near loads reduce EWIS weight, inductance, and loop area.
- \+ Reduced filter and converter effort: Less need for galvanic isolation ⟶ lower mass, smaller footprint, and lower losses.
- \+ High redundancy and reliability: Reconfigurable batteries and multiple independent supply paths for safety-critical grids.
- \+ Architectural flexibility: Each microgrid can be optimized individually (voltage, control, protection).
- – Increased battery mass
- – Distributed batteries require advanced containment and monitoring for thermal runaway.
- – Higher maintenance effort: Many decentralized battery units increase service and inspection complexity.
- – Charging infrastructure required
- – Limited operational flexibility: Dependence on stored energy reduces mission range and endurance without in-flight charging.



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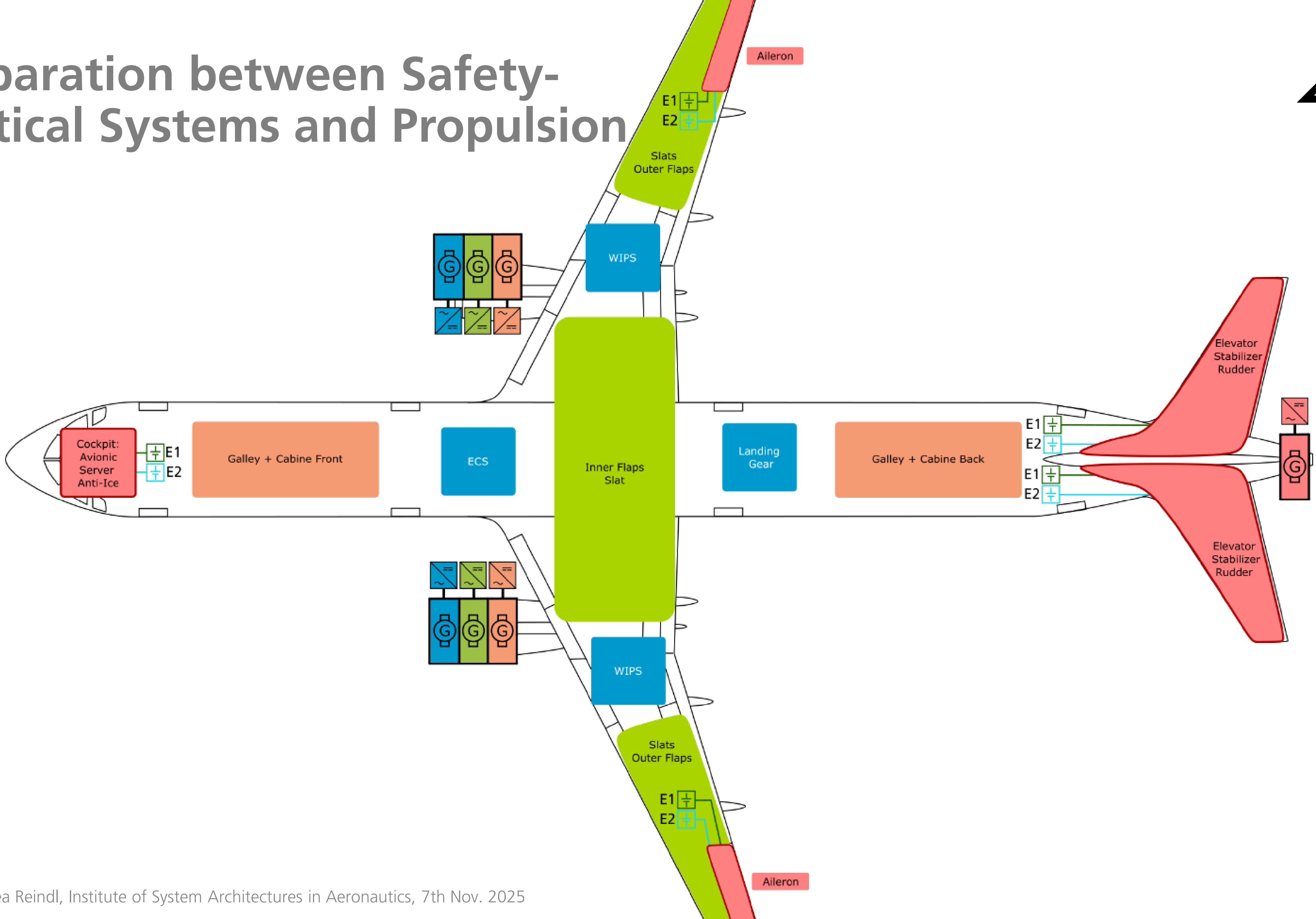
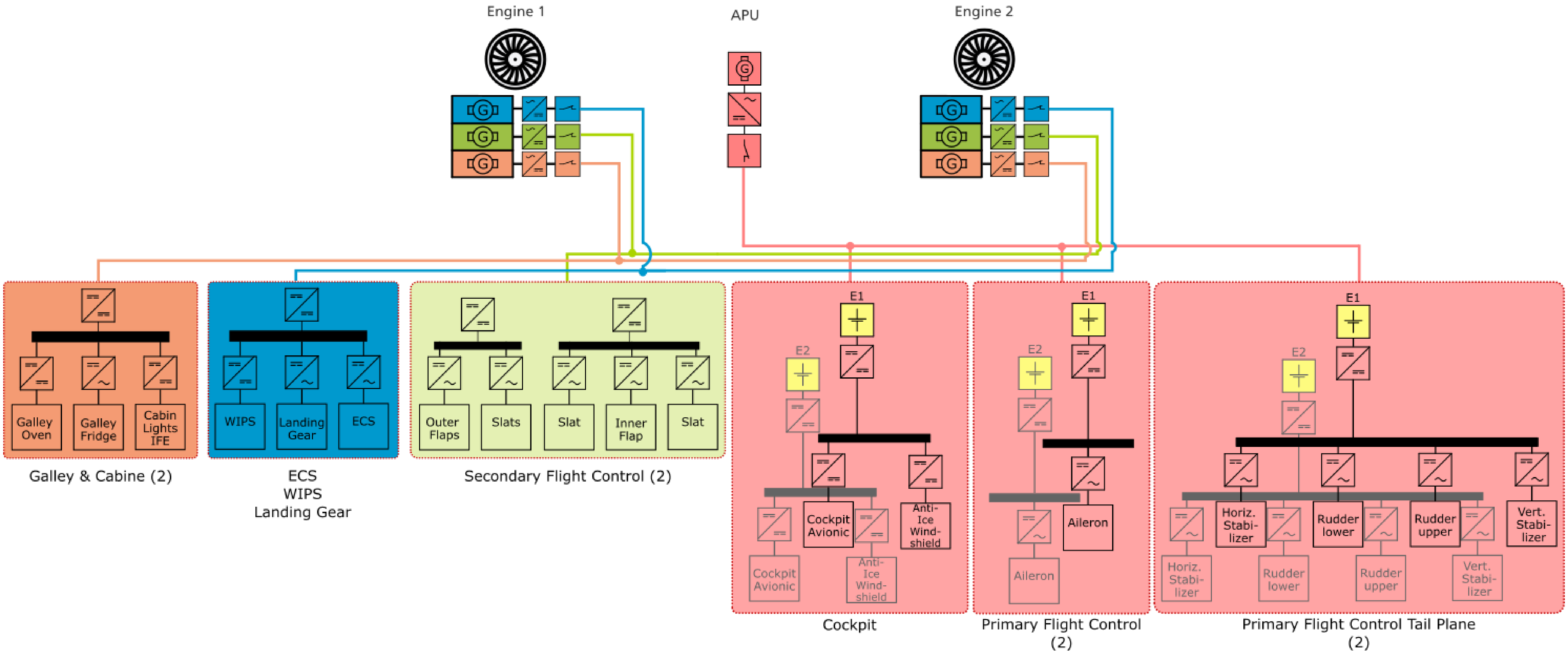
Intermediate Approach

Separation between Safety-Critical Systems and Propulsion

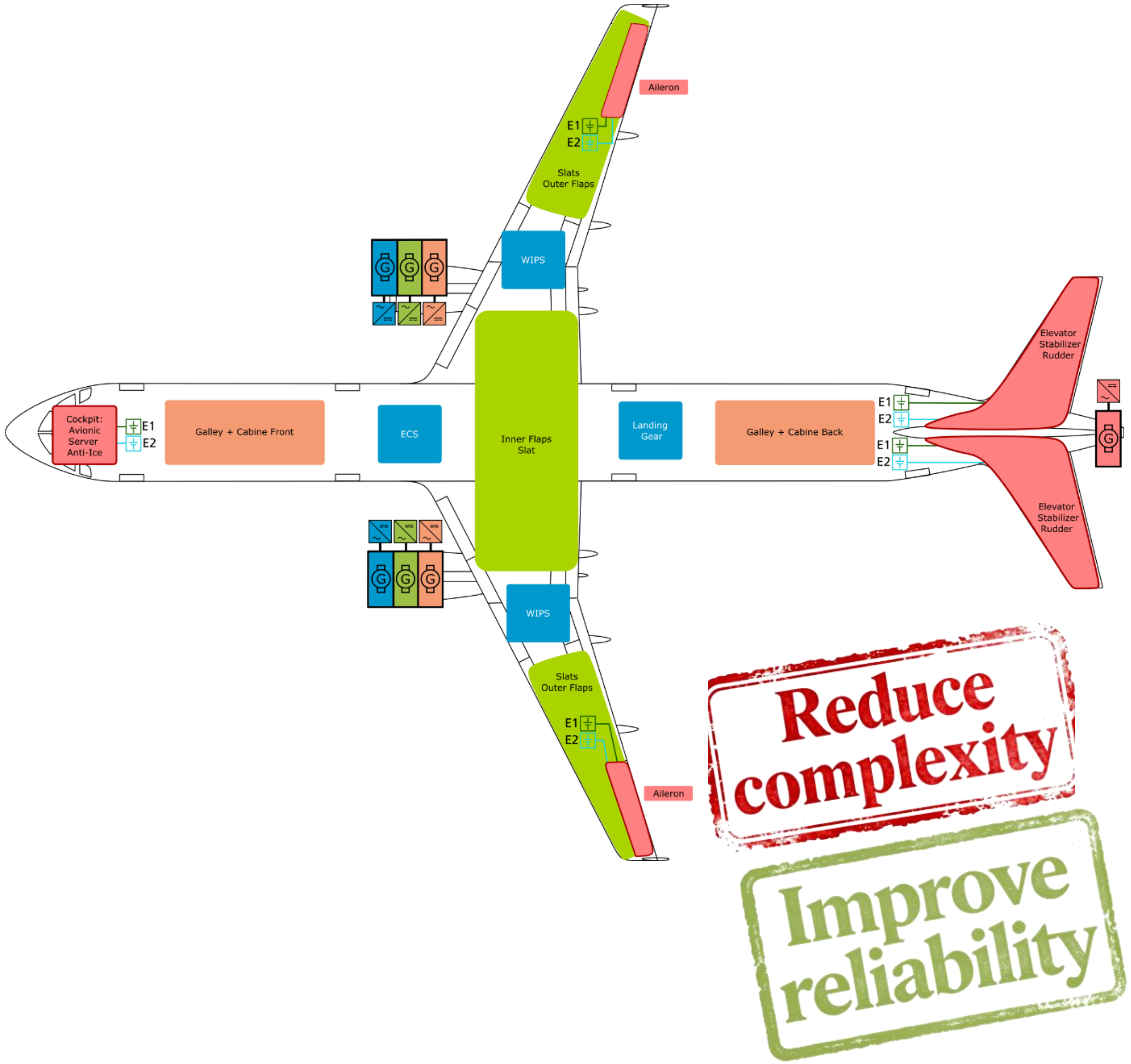


Separation between Safety-Critical Systems and Propulsion



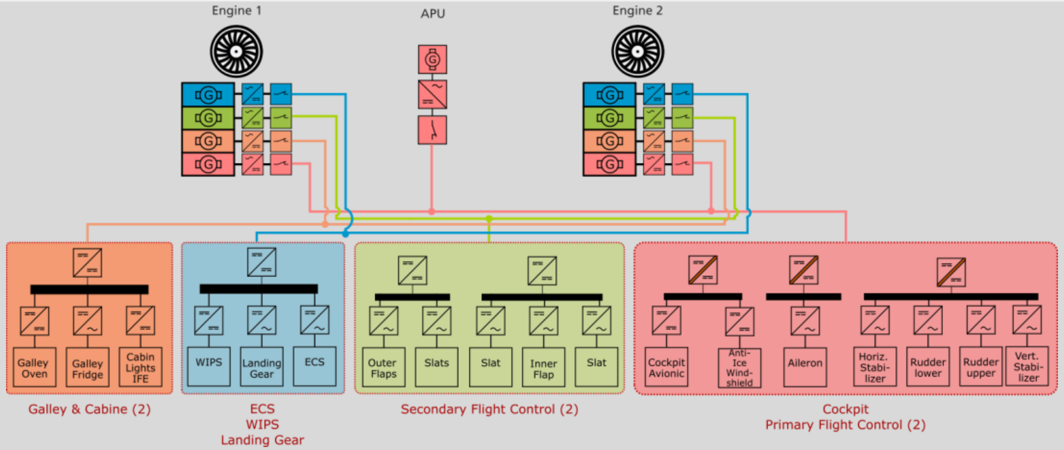
Islanded Grids

- \+ Isolation of safety-critical grid: Primary flight control and avionics are fully decoupled from the propulsion system → improved safety and fault containment.
- \+ Reduced battery count
- \+ Simplified charging concept: Batteries are recharged via the APU on the ground — no airport charging infrastructure required.
- \+ Compact installation: Battery packs concentrated in nacelles → easier integration and thermal management.
- \+ Improved reliability: Dedicated, independent power supply for safety-critical loads
- – Partial loss of decoupling: Non-safety-critical systems remain coupled to propulsion → residual common-cause risk.
- – Longer cable runs: Compared to the islanded concept → higher EWIS weight and increased EMI susceptibility.
- – More separation and isolation hardware required: Additional protection devices and converters increase system complexity and mass.
- – Reduced EMC flexibility: Common buses reintroduce potential interference between subsystems.
- – Limited scalability: Architecture less flexible for future all-electric or hybrid-electric extensions.



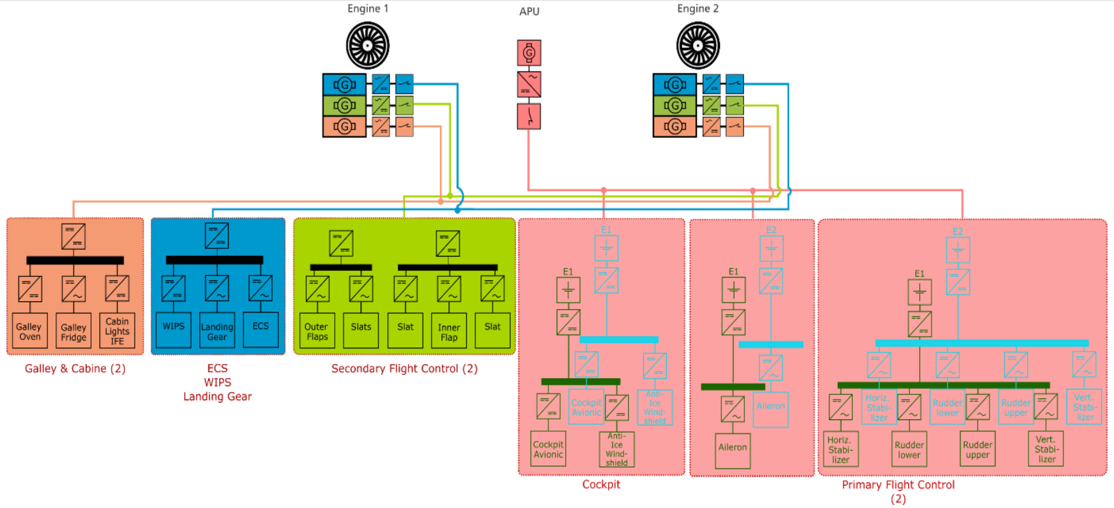
Conservative Approach: Four Separated Grids

Four stacked generators with the same power rating are used instead of the previous two generators. The generator for the galley and cabin can be used to supply the more safety-relevant grid if one of the other generators fails. Additionally, the safety-relevant grid (cockpit and primary flight control) can also be supplied by the APU.



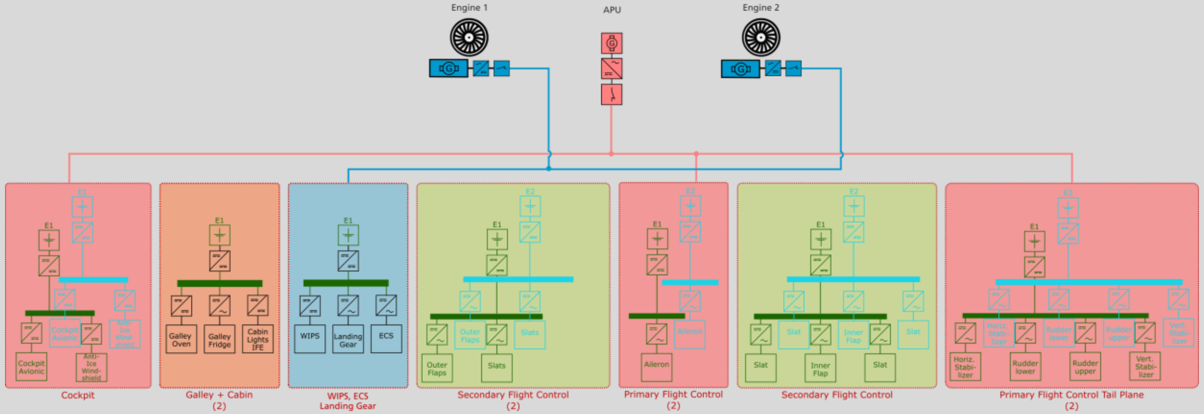
Hybrid approach: Separation between Safety-critical Systems and Propulsion

This approach completely separates the safety-critical grid (primary flight control and cockpit avionics) from the propulsion system, whereby batteries are used to ensure the supply of these grids. In order to improve the reliability, the APU is connected to these systems and two separate battery-supplied DC busses are available.



Disruptive approach: Islanded Grids

The on-board system is divided into disconnected islanded grids, which in turn have at least one DC bus with a supplying battery pack. In safety-relevant grids, the DC grids with battery packs are designed redundantly. Only the grid with the environmental control system is fed by a comparatively small (lower power rating) generator. The APU can also supply the safety-relevant grids in the event of a fault.



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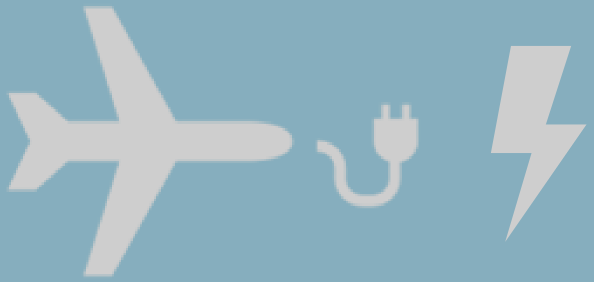
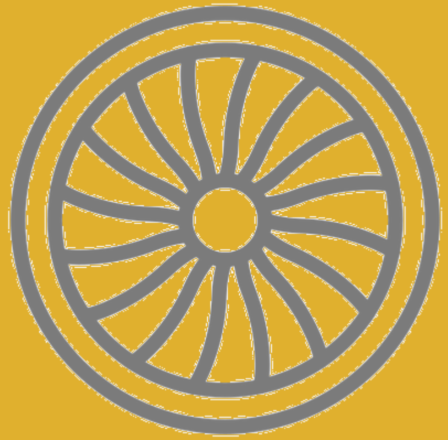
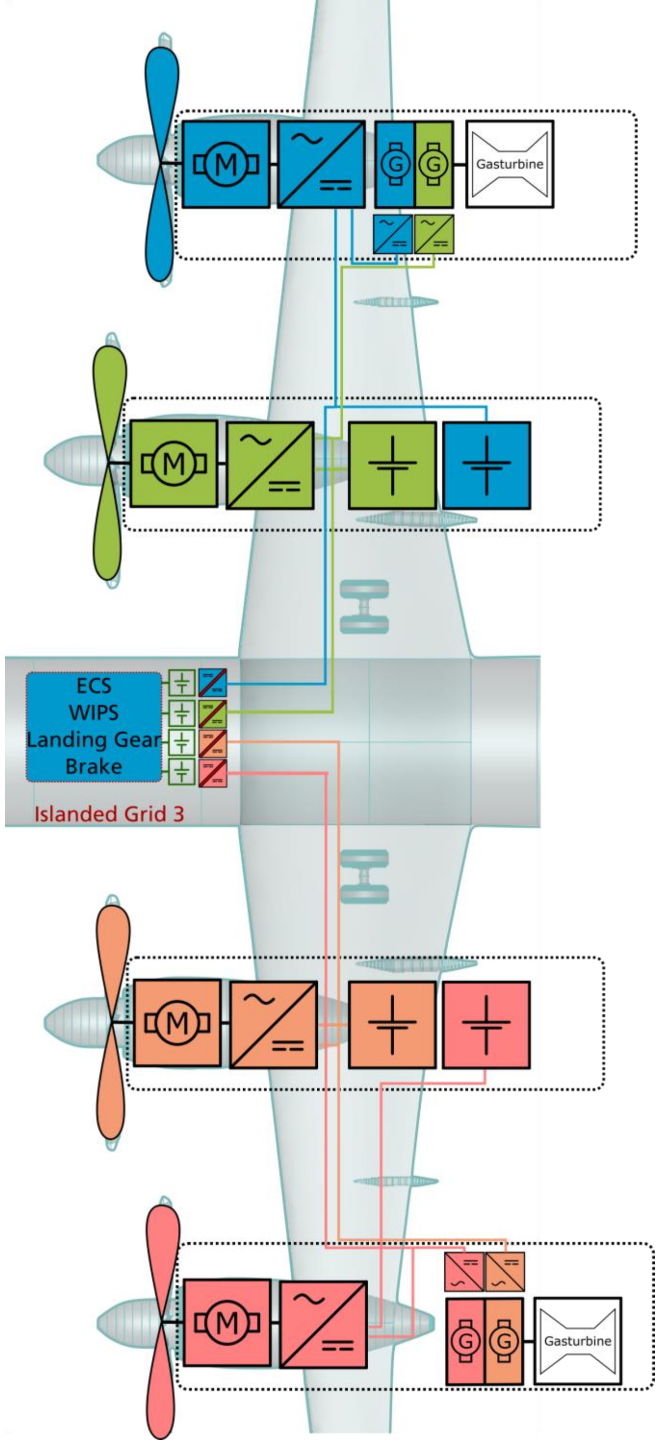


2. MORE ELECTRIC AIRCARFT ELECTRICAL SYSTEM

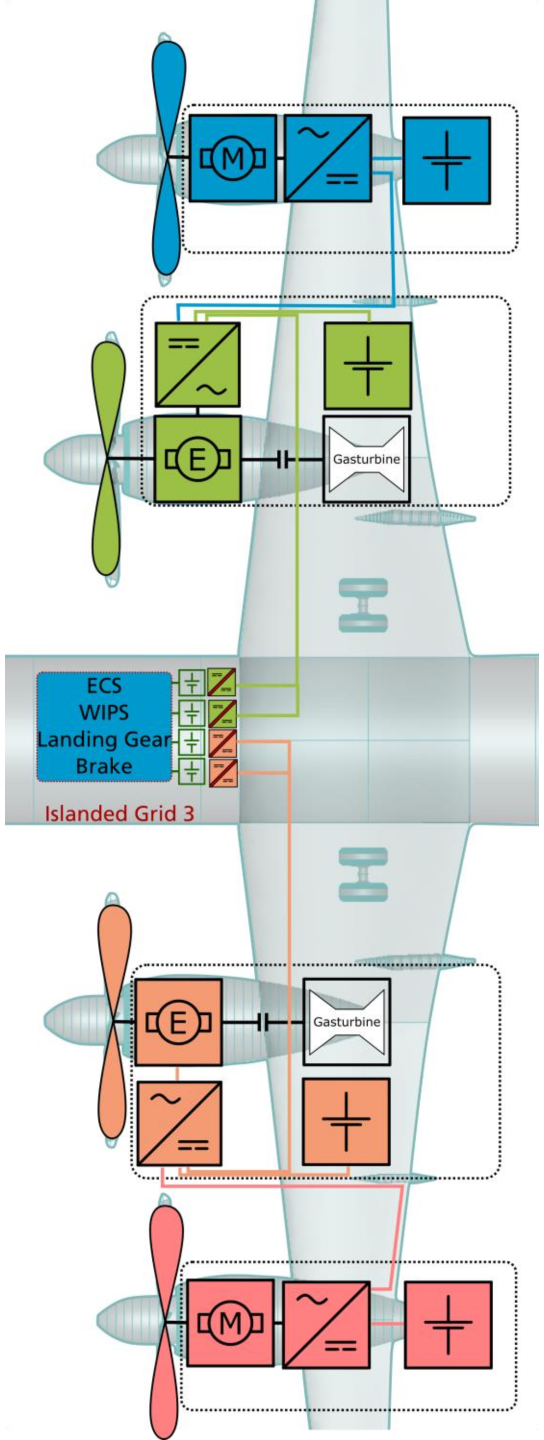
3. PROPULSION SYSTEM ARCHITECTURE



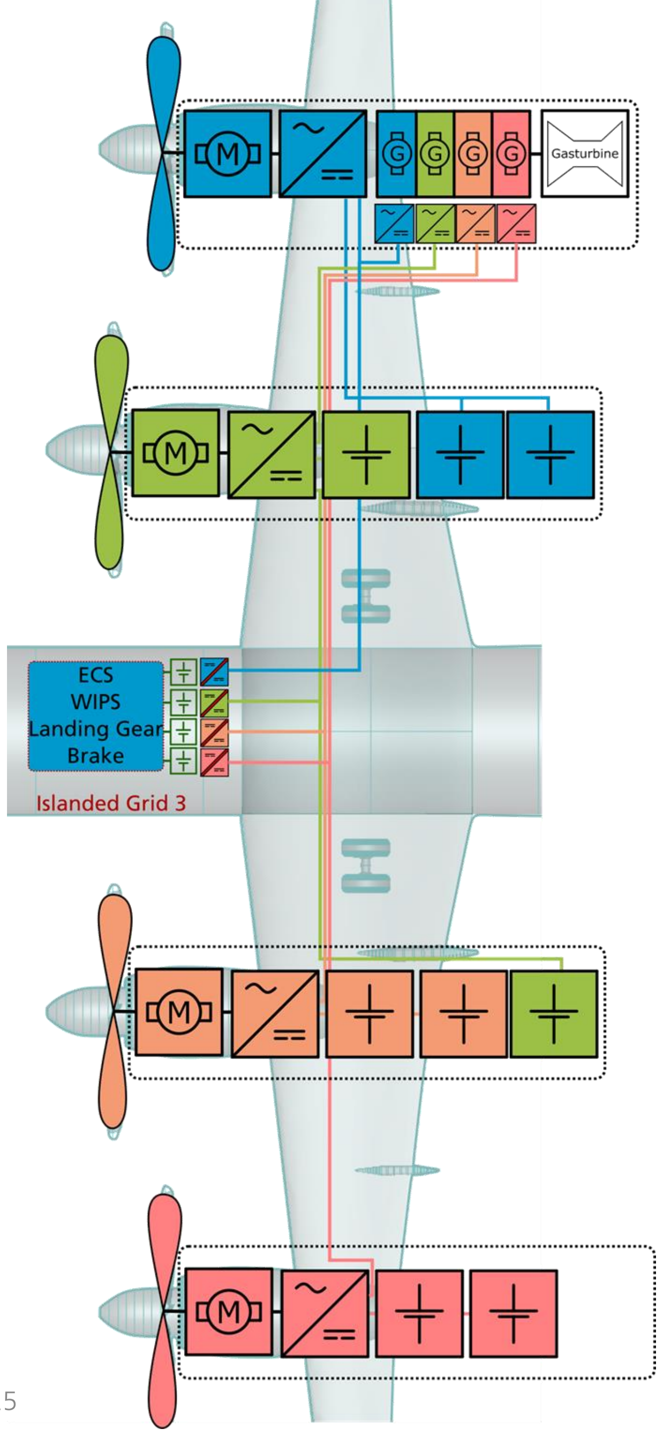
Plug-In-Hybrid
Serial
Two Gas-Turbines



Plug-In-Hybrid
Parallel
Two Gas-Turbines



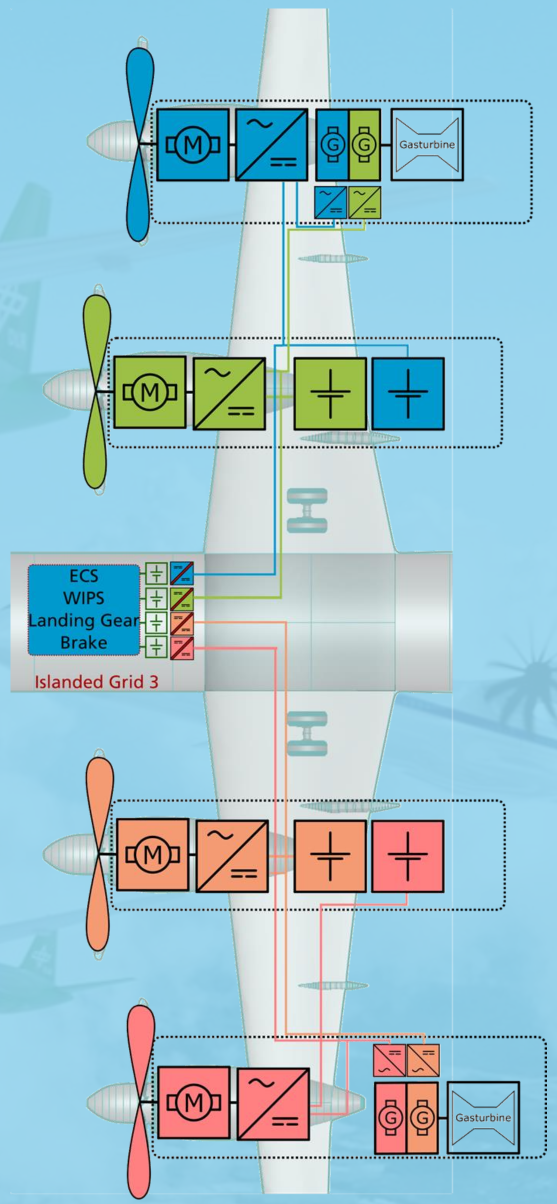
Plug-In-Hybrid
Serial
One Gas-Turbine



Key Take-Away-Messages

- Reconsider old architectures, as they are often no longer valid!
- Weight is not everything—efficiency and reliability are at least as important.

  Higher weight with better efficiency reduces thermal problems and thus the size of the thermal system.
- Therefore, good system architectures are required!



- ☐ TLAR considered
- ☐ Airport qualification
- ☐ Frame pitch cabin
- ☐ Frame pitch nose
- ☐ Frame pitch rear end
- ☐ Family/ sectioning concept
  - ☐ Center section
  - ☐ Wing size
- ☐ Outer cross section
- ☐ Inner cross section
- ☐ Window size
- ☐ Passenger door size and position
  - ☐ Distance
  - ☐ Door type and uniform distribution rule considered
  - ☐ Clearance - engines
  - ☐ Clearance - slide rafts
  - ☐ Clearance - ground vehicles
- ☐ Cargo door size and position
- ☐ System integration (APU/ Air Condition – Family concept
- ☐ FWD freight hole optimized
- ☐ AFT freight hole optimized
- ☐ Structure/ volume limited payload check
- ☐ Bulk door optimized
- ☐ Pressure bulk head integration
- ☐ Wing size (family concept/ man holes)
- ☐ Center section integration (fuselage/ wing)
- ☐ Fuel capacity
- ☐ Main (Nose) Landing Gear integration (family concept/ kinematic)
- ☐ (clearance flaps/ keel beam) / MAC/ CG/ Nose Landing Gear loads)
- ☐ CG management (ground/ flight)
- ☐ Tail clearance (family concept)
- ☐ Bank angle
- ☐ Engine integration/ clearance (HLS/ maintenance access)
- ☐ HTP size (trim area/ trim spindle integration/ volume coefficient/ family concept)
- ☐ VTP size (volume coefficient/ family concept)
- ☐ High Lift System check (family concept/ TLAR, flap tracks/ kinematic)
- ☐ Ground maneuvering (stability/ pass behavior)
- ☐ Disc burst - clearance check (system, fuel)
- ☐ Pavement check
- ☐ Part size (manufacturing, integration, transportation)
- ☐ Second life considered
- ☐ Sustainability
- ☐ Disposal