Design, test and demonstration of an inverter for HLFC compressor applications utilizing a Model-Based Systems Engineering approach

Alexander Bismark, Patrick Juchmann, Oliver Bertram
DLR - Institute of Flight Systems

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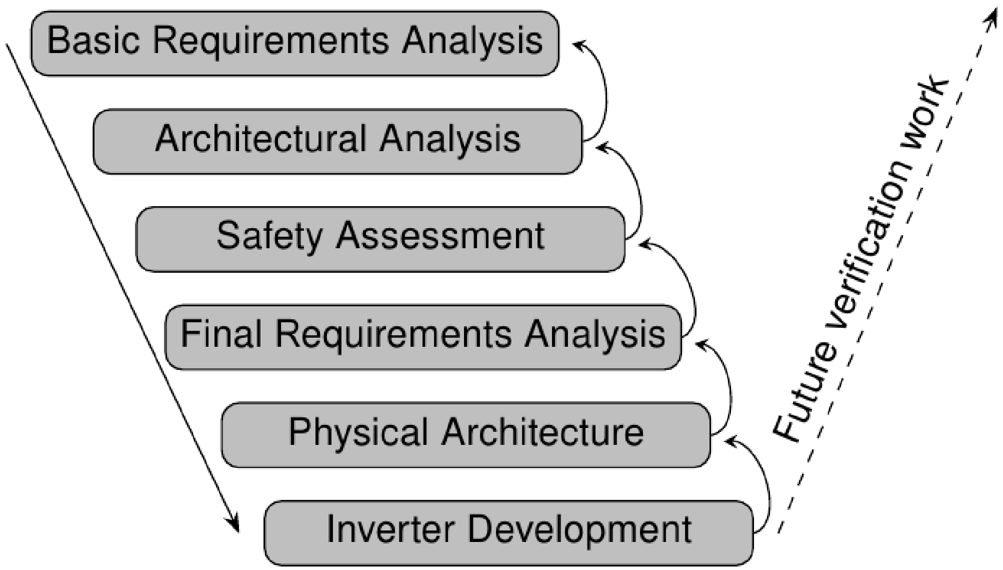
Agenda

- Motivation & Project Context
- Analysis Process
  - Requirements Definition
  - Functional & Physical Architecture
  - Safety Assessment
- Initial Component Design
  - Motor Characterization
  - Control Scheme and Electronics Design
  - Thermal Considerations
  - Experimental Testbed and Results
- Conclusion & Outlook



Motivation

- Pressure towards reduction of emissions rises
- Hybrid Laminar Flow Control (HLFC) one enabling technology
  - Reduction of emissions
  - Decrease in fuel costs
- Model-Based Systems Engineering (MBSE) gains importance in aerospace industry
- Goals for this work
  - Systematic analysis approach for a inverter design using MBSE
  - Show initial work on the inverter development for a compressor operated on ground

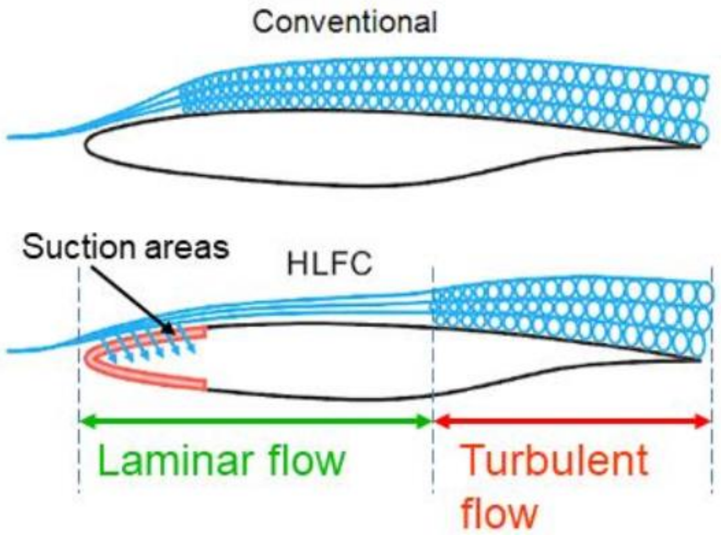
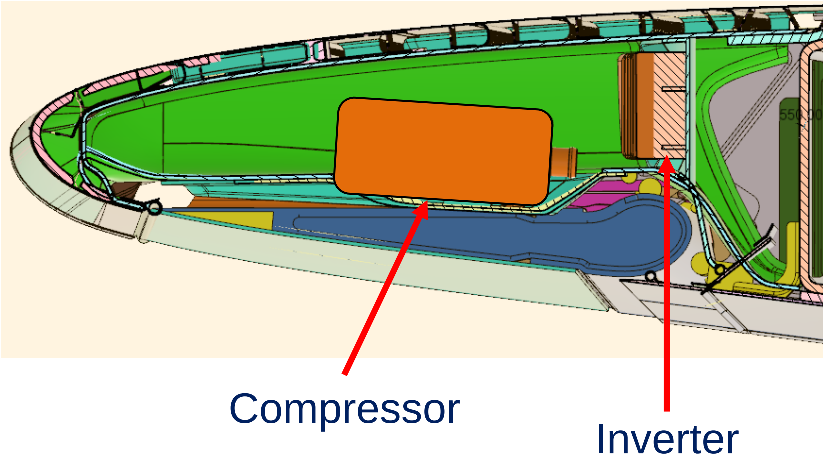
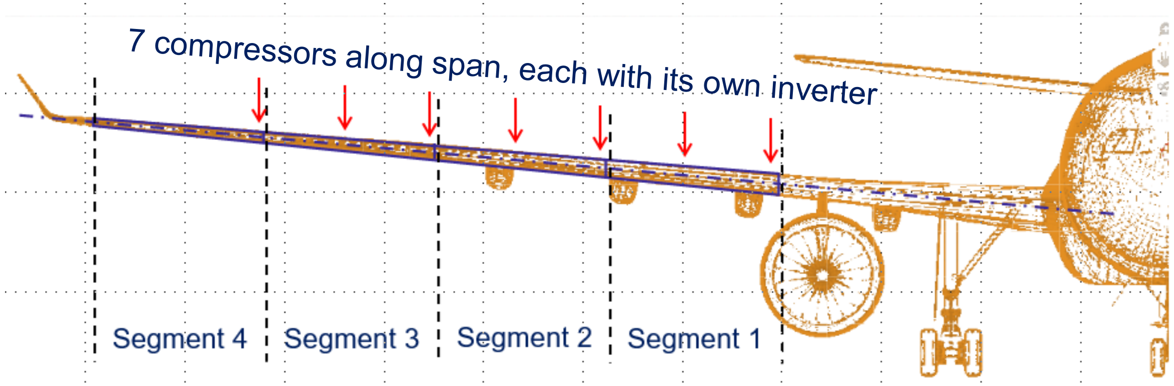


Image adapted from K.S.G. Krishnan

Project Context

- Functions to be performed by Inverter
  - Drive compressor motor
  - Forward monitoring data to control computer (via AFDX)
  - Receive the commanded compressor speed from control computer
- Challenges
  - High power density (> 5 kW on 100 mm x 100 mm x 250 mm)
  - Control of compressor motor (150,000 RPM)
  - Fluid cooling not feasible
  - Aviation certification rules must be met





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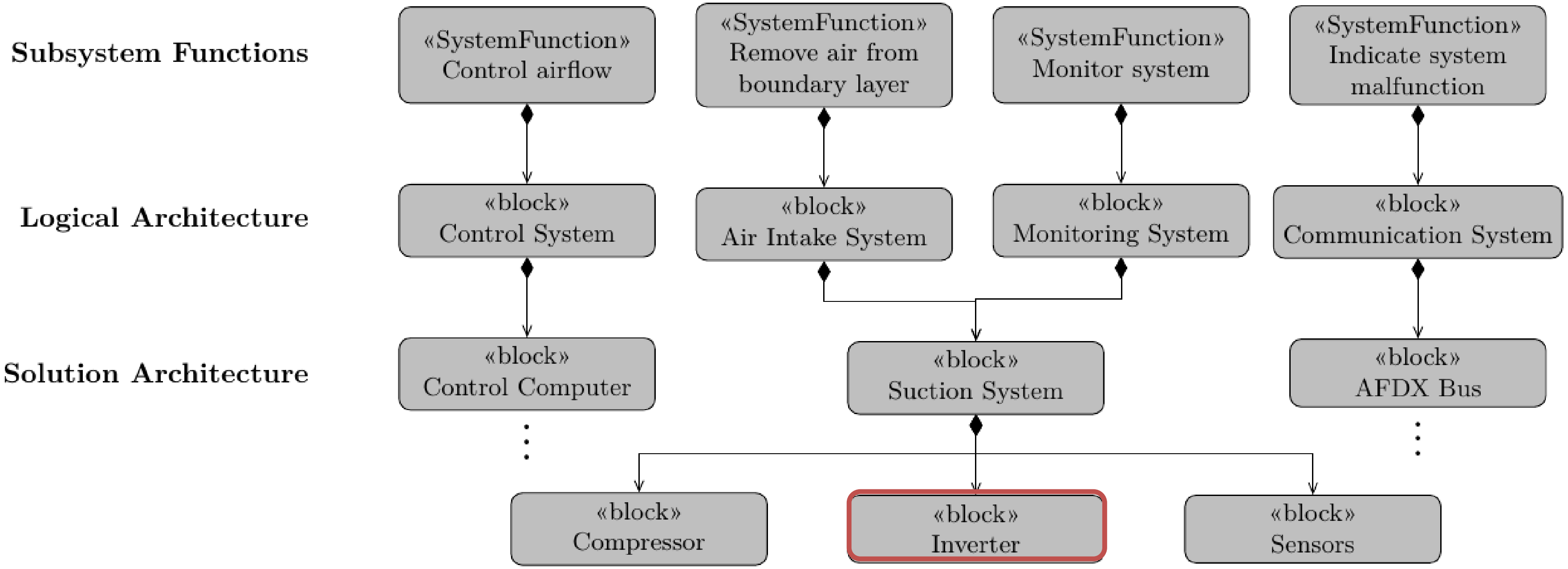
General Requirements

- CS-25/FAR-25 decisive regulation → AMC 25.1309 lists relevant standards to be considered
  - ARP4754A (Development Process) and ARP4761 (Safety Assessment Conduction)
  - DO-160G (Environmental Tests) → Categorization conducted for the inverter
  - DO-178C (Software Development) and DO-254 (Hardware Development)
- Basic requirements
  - Operation in cruise between FL330 and FL410 (max. ambient temperature -30°C)
  - System shall operate automatically and be unnoticeable to crew during normal operation
  - Fuel savings shall not be considered during fuel planning, Minimum Equipment List shall not be changed
  - Modern aviation concepts shall be followed (Integrated Modular Avionics, More Electric Aircraft)

Functional Decomposition

- Aim
  - System performs intended functions
  - generates generic baseline for solution candidates



Safety Assessment

- Usually not part of systems engineering, but required for certification in aviation
- Required analyses stated in ARP4754A, guidelines for conduction in ARP4761

Functional Hazard Assessment (FHA)

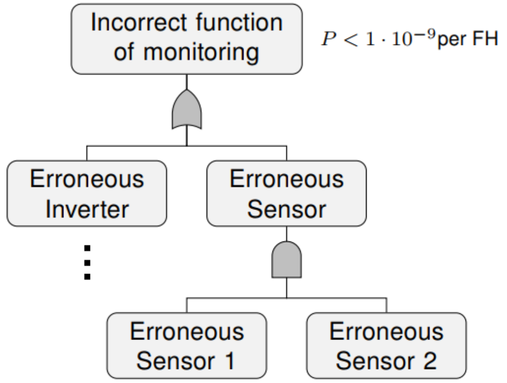
- Classifies severity in case of a loss or incorrect function for previously defined functions
- Inverter-related functions: Monitoring and Air Ingestion
- Loss of suction not critical (project directive)
- Category dictates effort for development process

Failure	Effect	Severity	Probability
Incorrect function of monitoring	Operation out of limits, possible rupture or fire	Catastrophic	$< 1 \cdot 10^{-9}$ per FH
Loss of monitoring	Operation out of limits, possible rupture or fire	Catastrophic	$< 1 \cdot 10^{-9}$ per FH

Critical failures →

Preliminary System Safety Analysis (PSSA)

- Benefit of Fault Tree Analysis (FTA)
- ✓ Requirements on architecture are set to meet defined failure rate and remove single causes
- ✓ Check whether current design fulfills safety requirements (literature and manufacturer data)
- Loss of monitoring not critical itself, but detection and deactivation of compressor must be ensured



Safety Assessment (2)

Common Cause Analysis (CCA)

Zonal Safety Analysis

- Failures arising from same installation area or interference between systems
- Example results: Redundant AFDX bus, separate harnesses for sensors

Particular Risk Analysis

- Failures resulting from external hazards
- Example results: Lightning strike protection, Electromagnetic Compatibilty (EMC) guidelines

Common Mode Analysis

- Verify independency of failure events in fault tree (PSSA)
- Example results: Dissimilar hardware and software implementation

- Increasing system complexity reveals limits of classical approach (ARP4754A/ARP4761)
  - STPA (Systems-Theoretic Process Analysis) by Nancy Leveson enables a more powerful hazard analysis
  - OMG-published beta version of Risk Analysis and Assessment Modeling Language (RAAML) containing UML libraries, among others for FTA and STPA → formalized integration of safety assessments in SysML
  - ➢ Future: Holistic approach using MBSE for development in aviation

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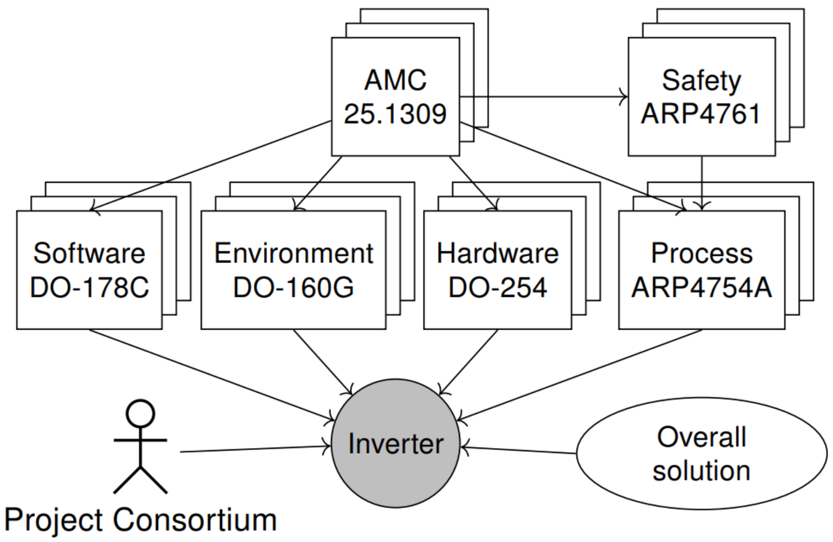
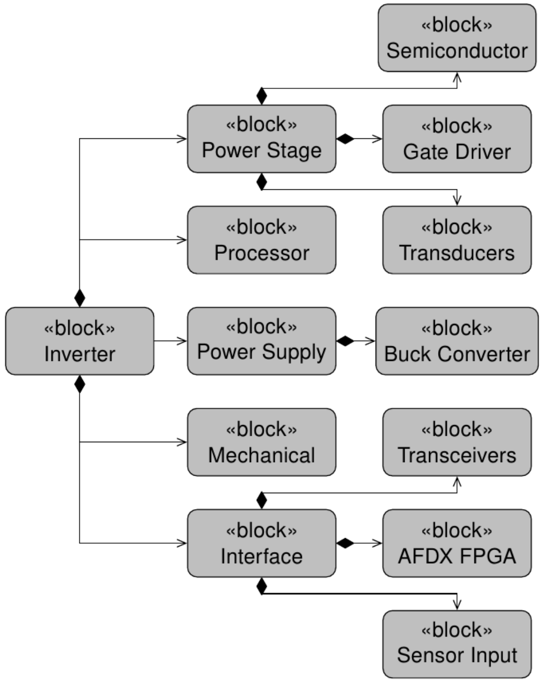
Final Requirements Analysis & Solution Architecture

- Prior to development phase, requirements to be checked in their entirety (complete and correct)
- All requirements implemented in model, usage of traceability matrices to specify sources
- HLFC in multidisciplinary surrounding → boundary conditions frequently change, thus adaptation of requirements necessary
- Advantage MBSE: Traceability allows fast identification of affected components and easy verification

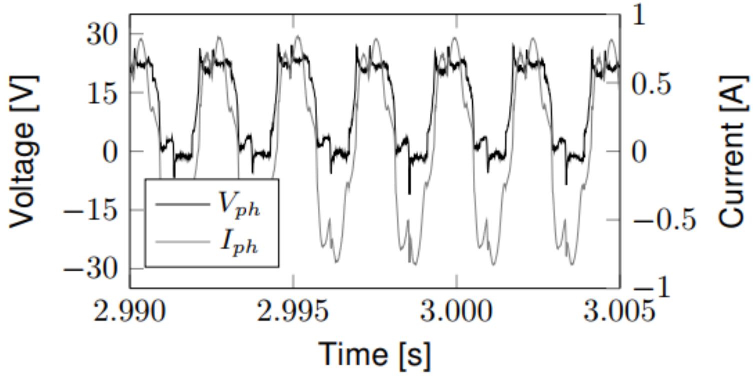




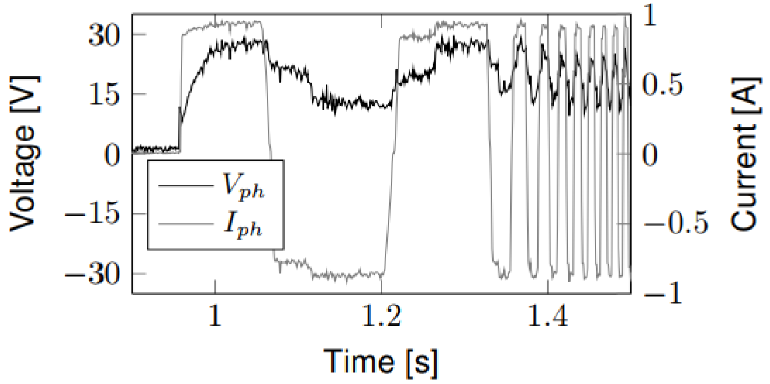
Motor Characterization

- Prior to preliminary electronics design, identify inverter design goals and parameterize motor models
- Measurements at varying operating points, stationary and transient
- Results of measurements
  - Base wave identical to mechanical frequency (416.6 Hz) → 1 Pole pair motor
  - Rotor-dependent phase inductance variation → Interior Permanent Magnet Synchronous Motor (IPMSM)
  - 'Align and go' methodology used by manufacturer

Motor Parameter	Value
Pole Pairs [-]	1
Phase Resistance [Ω]	0.205
Phase Inductance [mH]	0.300
Speed Constant [Vs/rad]	0.0013
Phase Voltage max. [V]	100
Phase Current max [A]	17
Speed max. [min^{-1}]	150,000



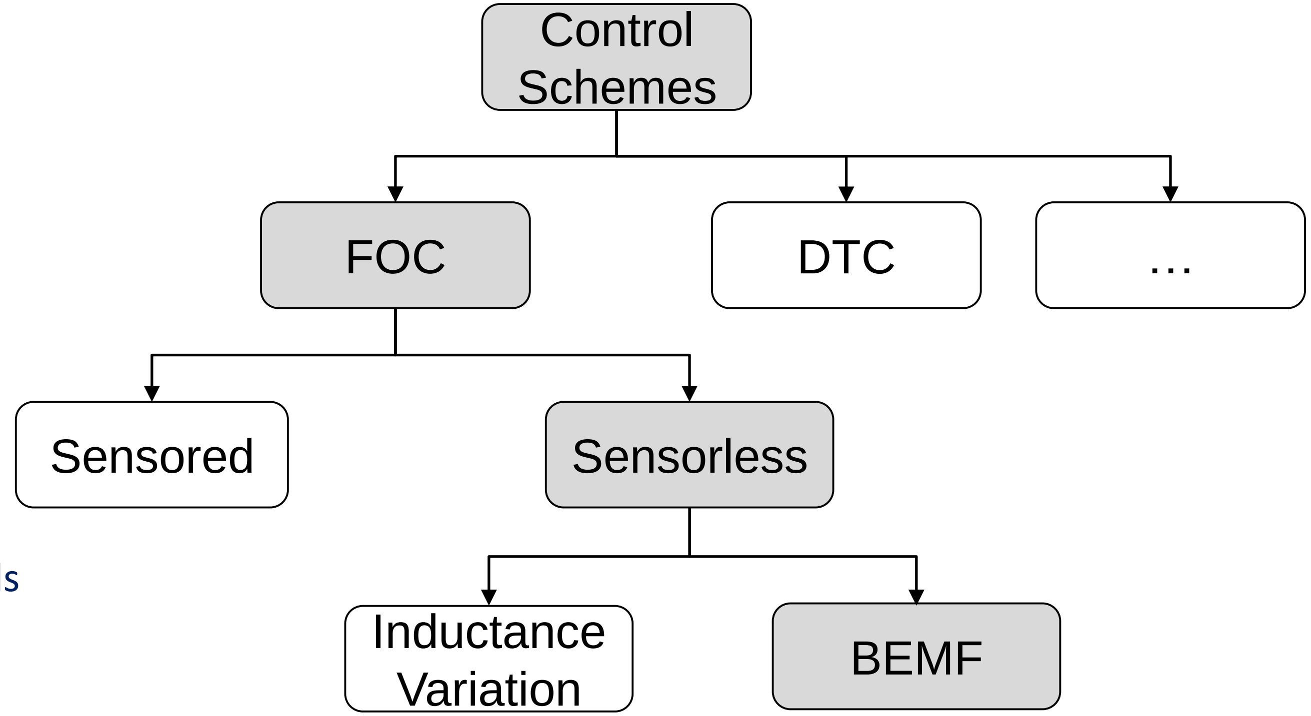
Base wave at 25.000 1/min



Base wave at startup

Control Scheme

- Field Oriented Control (FOC) favorable due to
  - Low torque ripple
  - Usage of reluctance torque
  - Constant switching frequency
- Sensorless rotor angle determination
  - No loss moment
  - Reduced system complexity
- Rotor angle estimation based upon Back ElectroMotive Force (BEMF)
  - Specific operating point of compressor at high speeds
  - Utilization of already prevailing measurements
  - Reduced complexity



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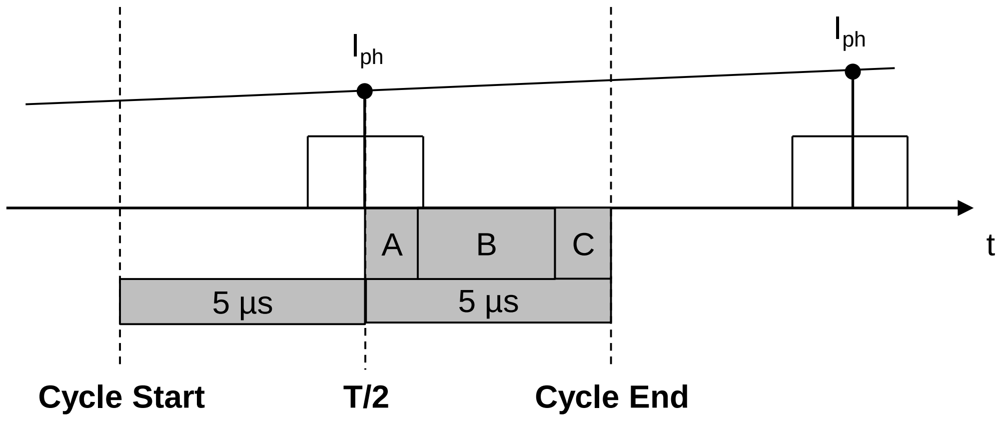
Control Scheme (2)

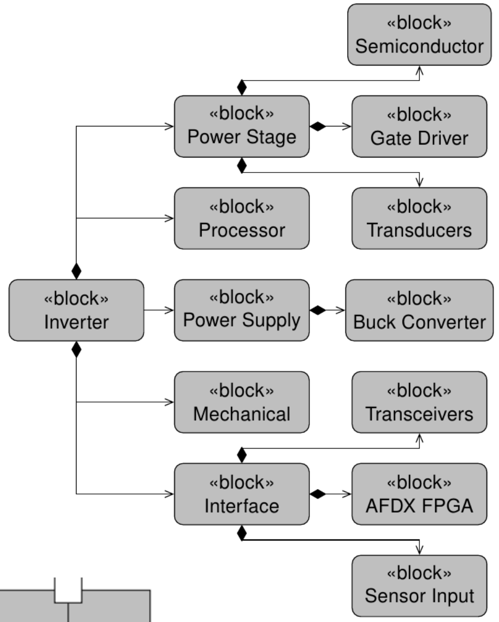
- 1 pole pair motor → maximum base wave frequency corresponding to mechanical speed
- Sufficiently high switching frequency to modulate base wave
- PWM frequency set to 100 kHz → 40 pulses per revolution
- Regular sampling shall be applied, meaning new updated duty cycle at every pulse
- Sampling of phase current and voltage values at 1/2-point of pulse
- Switching delays of power module and gate drive circuitry < 200 ns → 2 % reduction of duty cycle
- Current control loop period < 5 µs must be achieved

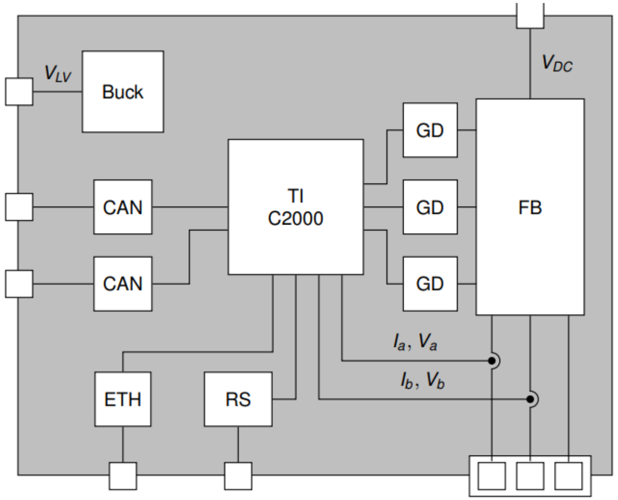


A – Acquire
B – Calculate Current Control Loop
C – Update Duty Cycle
(not to scale)

Preliminary Electronics Architecture

- 28 VDC low-voltage supply for low-voltage components; 270 VDC power stage supply
- Transceivers for Ethernet, CAN, RS232
- TI C2000 MCU
  - Dual-core architecture enabling partitioned processing of control loop and peripheral tasks
  - Optimized current control loop implementations demonstrated < 1 µs calculation time
- Integrated power stage Infineon CoolSiC
  - Spatial efficiency
  - Thermally enhanced
- Isolated gate drivers
- Inline phase current and voltage measurement circuitry





Thermal Considerations

Preliminary study on fin size for cooling

- Power loss of semiconductors from data sheet: 190 W
- Power module connected to cooling plate (100 mm x 250 mm) with fins, located at inlet airstream of compressor (ca. 10 m/s)
- Boundaries: Ambient air max. -30°C, power module de-rated 120°C
- Estimated temperature rise between junction and heatsink: 49°C
- Determination of heat dissipation by convection (steady-state)

$$P \ = 190\ [W] = h_c \cdot A \cdot \Delta T = h_c \cdot A \cdot [(120°C - 49°C) - (-30°C)]$$

- Simplification: Laminar flow over a flat plate

$$h_c \approx 20\ W/(m^2 \cdot K)$$

$$\underline{\underline{\Rightarrow A = 0.093\ m^2}}$$

- Selecting fin thickness of 3 mm and separation of 3 mm

  → 16 fins with a length of 250 mm and a height of ca. 8.5 mm

- Results validated in Simscape™ model using data sheet information
- Verification will be achieved by tests in a climate chamber

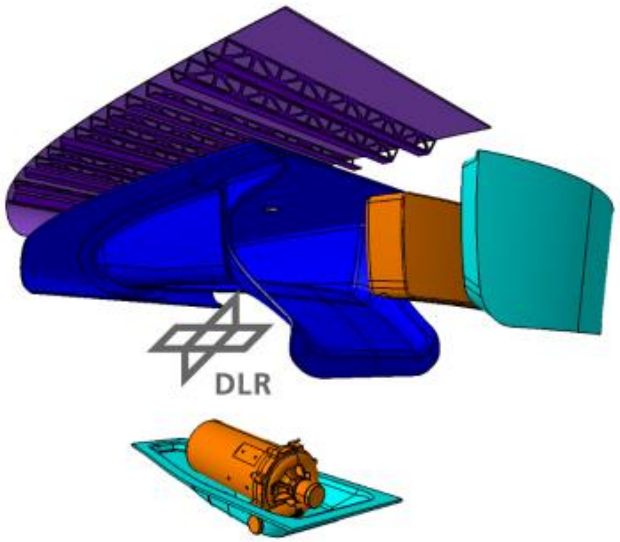
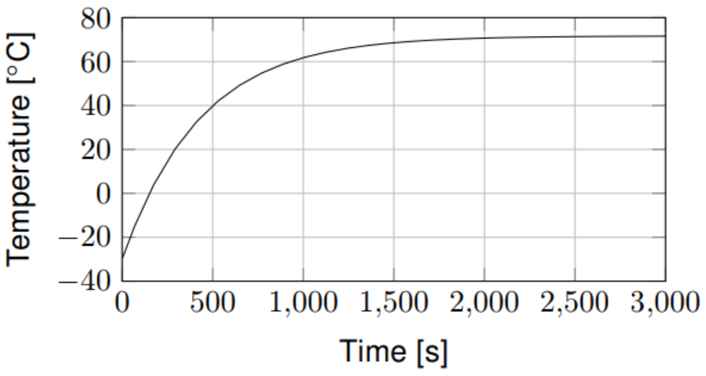
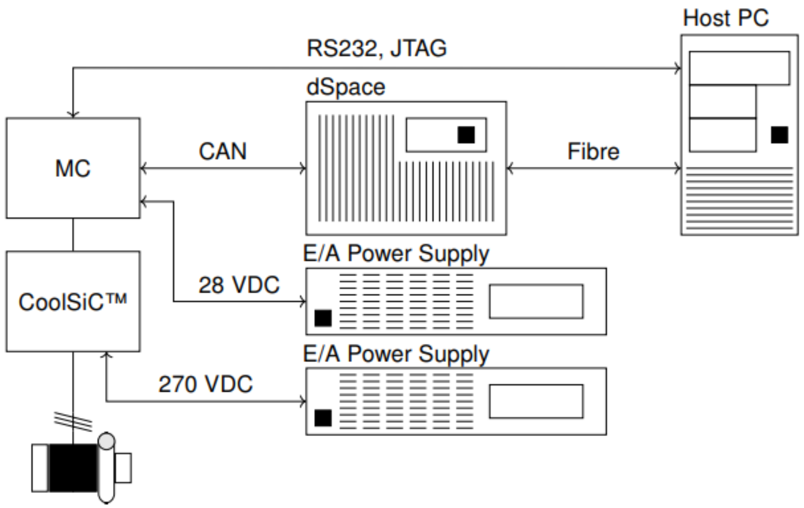


Image Courtesy: Thomas Haase



Experimental Testbed

- Setup for continuous testing of future electronics
- Proper function of power electronics demonstrated (incorporating Infineon CoolSiC power module)
- Input and output voltages measured → Propagation delay of 160 ns determined, complies with data sheet values
- Testing of control concepts in progress and electronics miniaturization



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Conclusion & Outlook

- Systematic approach applied to prepare component development using standards from systems engineering and aviation regulations
  - Detailed analyses for derivation of requirements
  - Functional breakdown and definition of solution architecture
  - Safety assessment according to regulations
- All steps implemented into a model
- Initial work on the inverter development
  - Characterization of the compressor motor
  - Selection of a suitable control concept and preliminary electronics design
  - Preliminary thoughts on cooling concept
  - Experimental testbed built up, first measurements conducted

Outlook

- Miniaturization of current electronics and subsequent testing in climate chamber
- Continuous implementation of all required features

Thank you for your attention!

Contact

Alexander Bismark

Deutsches Zentrum für Luft- und Raumfahrt (DLR). Institute of Flight Systems

Lilienthalplatz 7, 38108 Braunschweig

Alexander.Bismark@dlr.de ; +49 (0)531-2953425

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