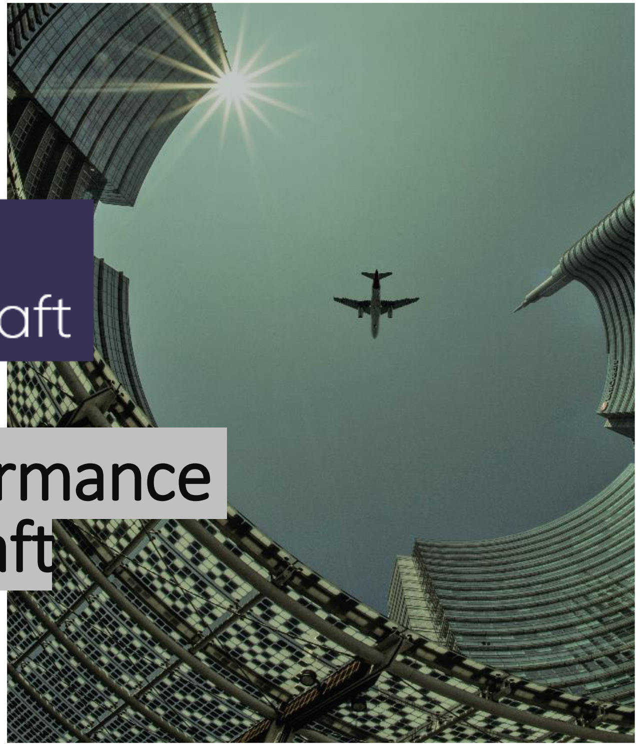
FUTure PRopulsion and INTegration
towards a hybrid-electric 50-seat regional aircraft



Electrified Propulsion System Modelling and Performance Considerations for FutPrint50 Regional Aircraft

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Cranfield Aerospace

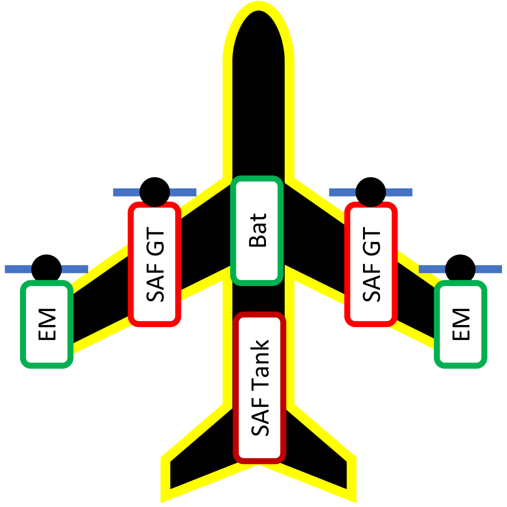
FUTPRINT50

12th EASN International Conference on Innovation in Aviation and Space for opening New Horizons
18 to 21 October 2022 Barcelona, Spain

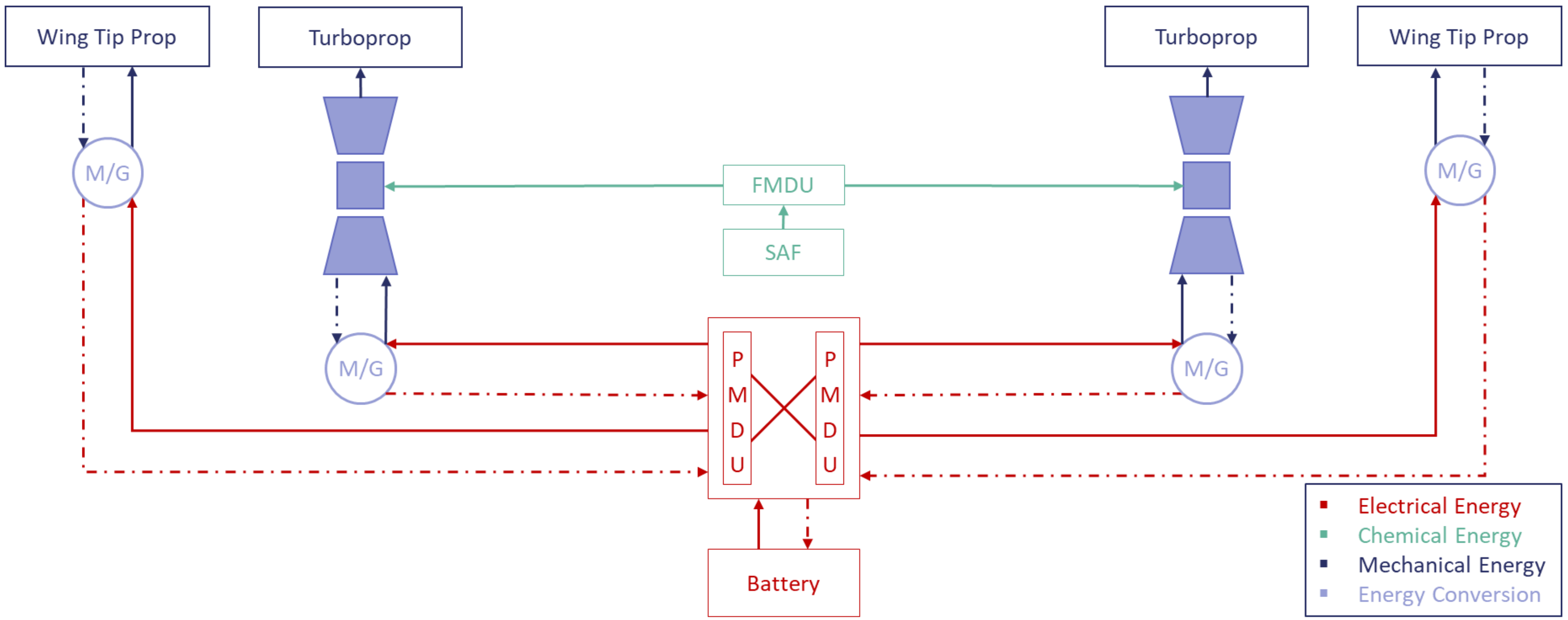
This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 875551

European Commission

FUTPRINT50 selected propulsion architectures: ex CO_2 neutral Architecture



- Parallel architecture
- Energy harvesting possible (WTP)
- Conventional turboprop
- Battery for energy storage
- „simple“ architecture



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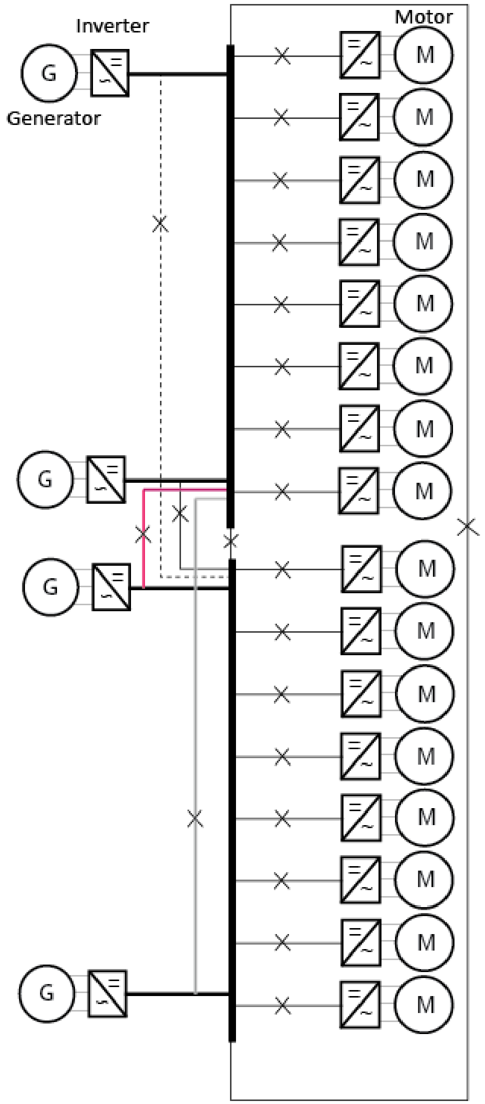
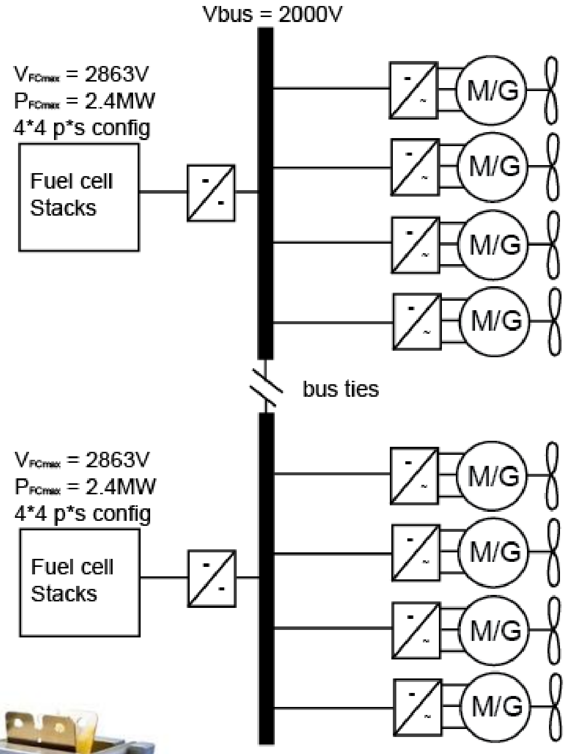
Electric Power System (EPS) architecture design considerations



Jones, C.E., Norman, P.J. and Burt, G.M. A modelling framework for efficient design of electrical power systems for electrical propulsion aircraft. *In AIAA/IEEE Electric Aircraft Technologies Symposium (EATS) (pp. 1-15). IEEE, 2021.*



Zhou T, Enalou HB, Pontika E, Zaghari B & Laskaridis P. Minimising the effect of degradation of fuel cell stacks on an integrated propulsion architecture for an electrified aircraft. In IEEE ITEC+ 2022.

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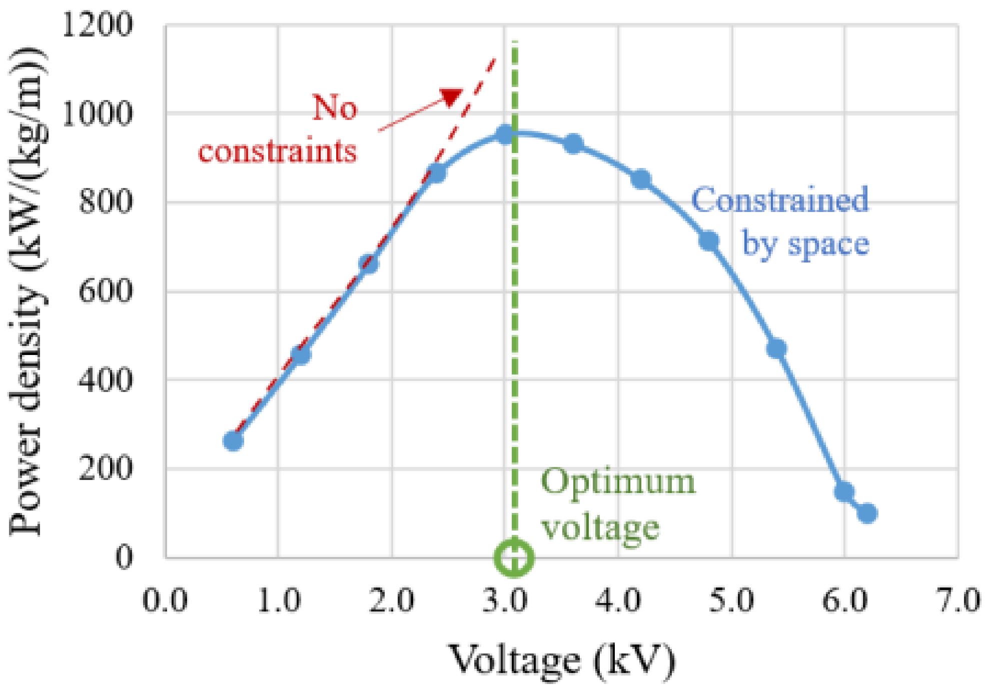
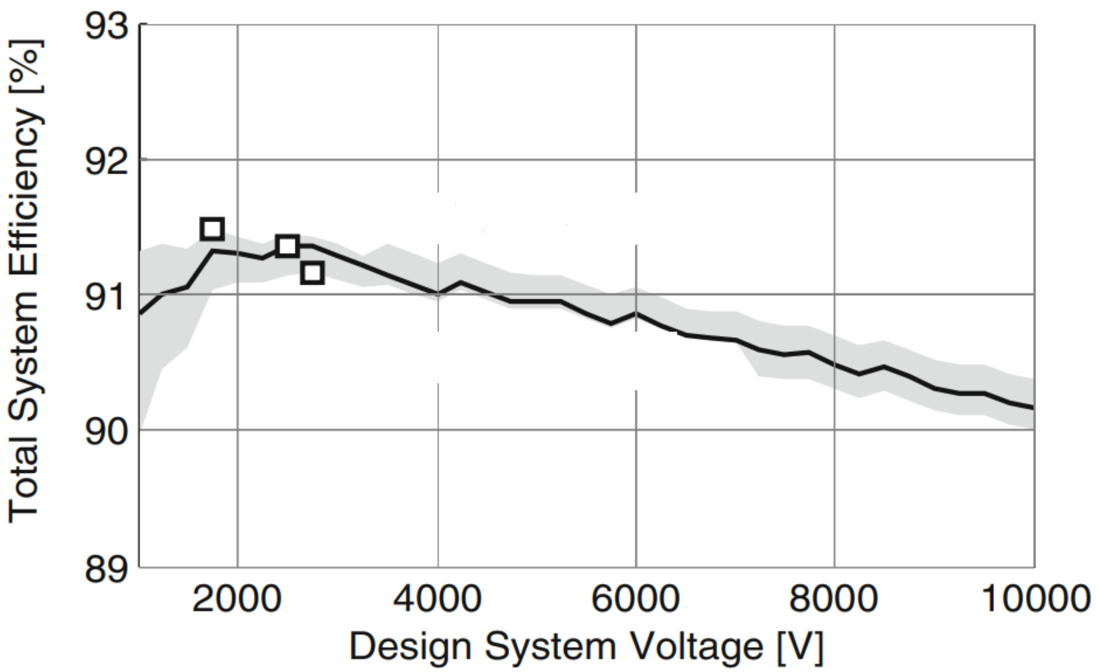
Distribution voltage as a design consideration





Recalde, Angel, et al. Optimal Voltage for More Electric Aircraft direct current cabling system. *IEEE Transportation Electrification Conference & Expo (ITEC)*. IEEE, 2021.

Vratny, P.C., Kuhn, H. and Hornung, M., 2017. Influences of voltage variations on electric power architectures for hybrid electric aircraft. CEAS Aeronautical Journal, 8(1), pp.31-43.

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Main questions to be answered

- How to analyse the **impact of Electric Power System (EPS) technologies** in the case of a generic 50 passenger regional aircraft?
- What design specifications to be considered when **designing electric power system architectures?**
- How to decide about the **number of components** (sources and sinks)?
- What are the impact of **distribution voltage** on the various electric components?
- How to inform **technology providers** about the requirements from system level integrations?

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Design methodology for EPS

Step II: Select a propulsion architecture
Ex1: CO2 neutral Architecture (fixed)

Step I: 1:Mission (fixed) and aircraft (fixed)

Step IV: Select EPS architectures

Step III: EMS fixed

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FutPrInt50

Design methodology for EPS

Step I: 1:Mission (fixed) and aircraft (fixed)

Step II: Select a propulsion architecture

Ex1: CO2 neutral Architecture (fixed)

Step III: EMS fixed

Step IV: Select EPS architectures

Step V: Define design decision handles

700<Vdc<2300, Freq(electrical), RPM(fixed, variable), torque, discharge rate, topologies, power ratios, cable parameters, Technological changes (roadmap studies),…

Step VI: Find the output parameters

Component tech assessment, weight, volume, efficiencies, losses, op temperatures, cooling requirements,…

Step VII: Decide on what needs to be changed

Configuration, size, power ratios, number of components,…
number of packs for batteries, FC configurations

Iteration

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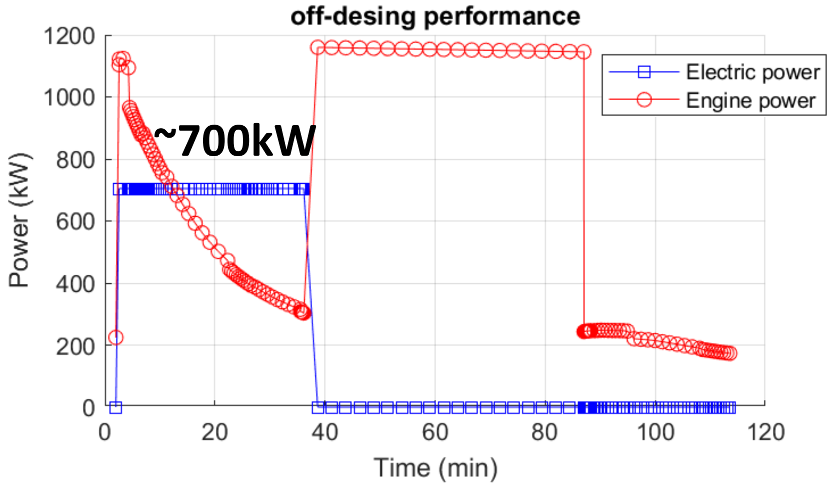
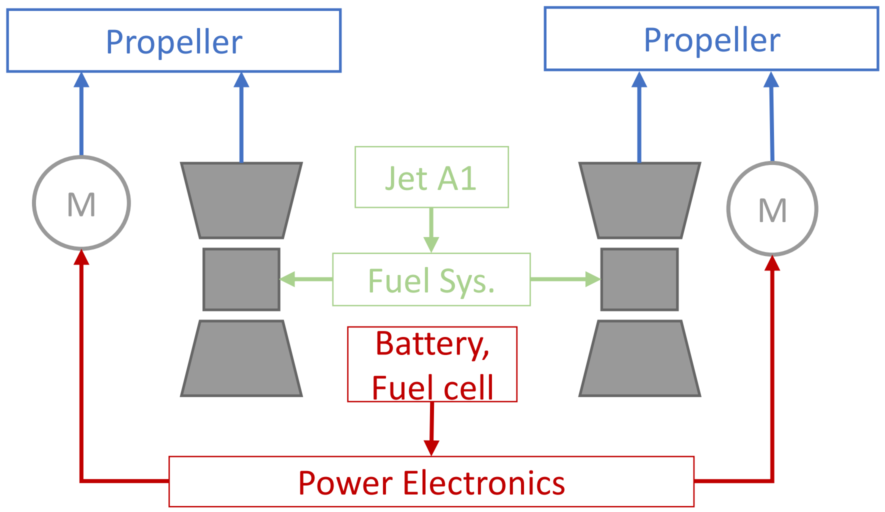
Aircraft, mission, Energy Management Strategy (EMS), propulsion architecture

- Retrofit: ATR72-600, Engine: PW127
- Fixed MTOW, mission and thrust requirement
- EMS: Hybrid TO-CL, Battery 400 Wh/kg [2035 prediction], depth of discharge 20%
- FC system: 1.2 kW/kg without TMS considerations

Range [nmi]	432
Cruise Alt [ft]	25000
Cruise Mach	0.498
MTOW [kg]	23000
OEW [kg] (baseline)	13450
PAX [kg]	5000
Block Fuel Burn [kg]	560
Total Reserve Fuel [kg]	614
Battery [kg]	3000
HEPS [kg]	375



Power profile for the main mission



Twin-turboprop parallel hybrid system

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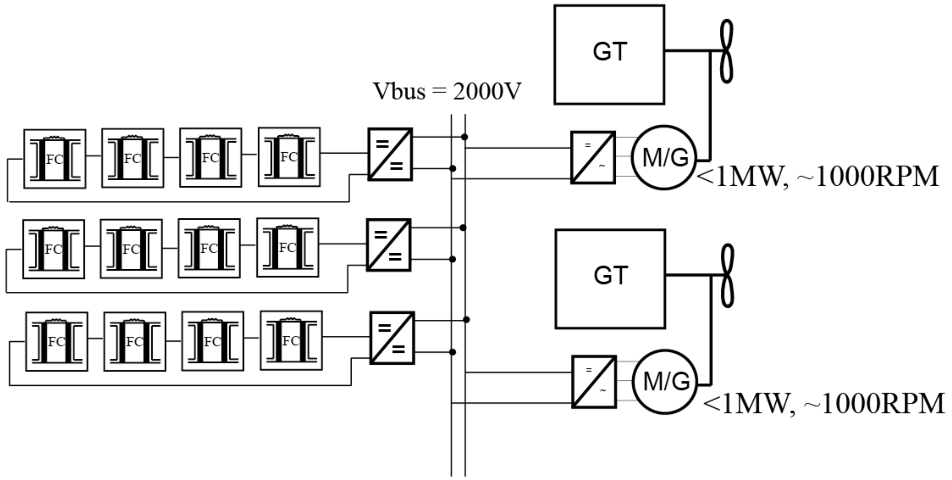
EPS architectures for a system with fuel cell stacks



Case 1

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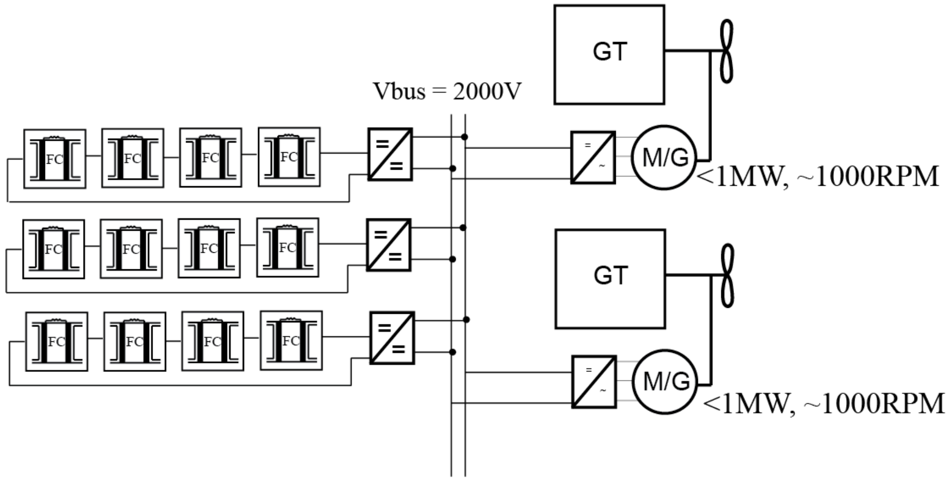
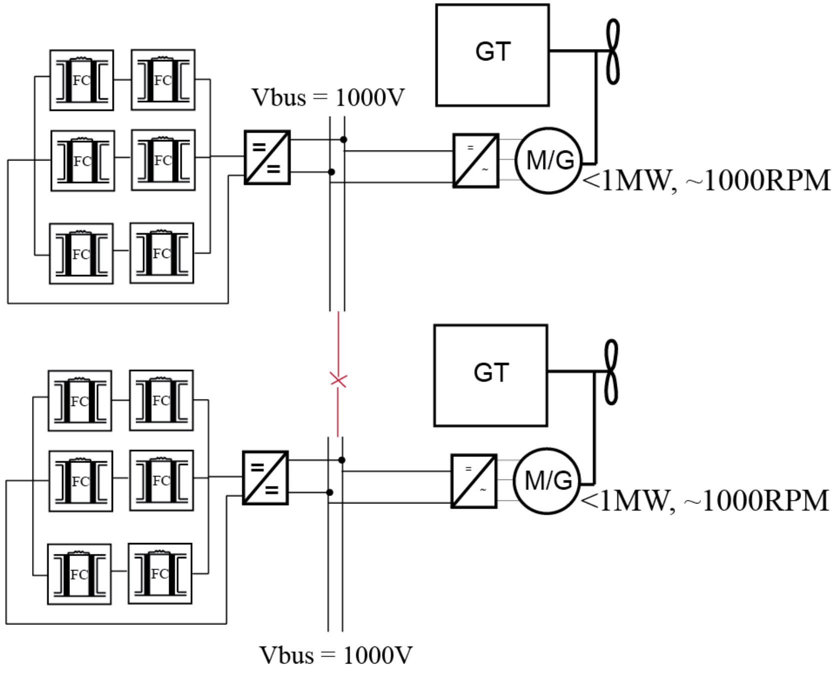
EPS architectures for a system with fuel cell stacks



Case 1



Case 2

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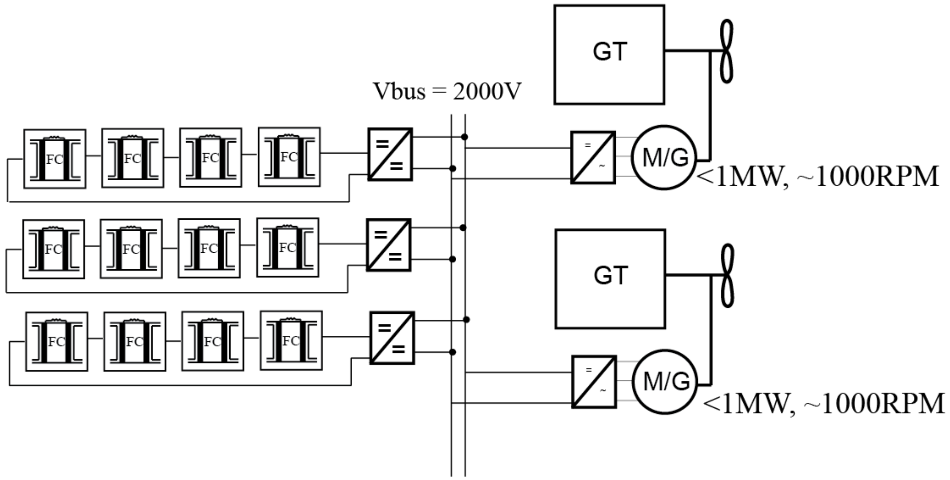
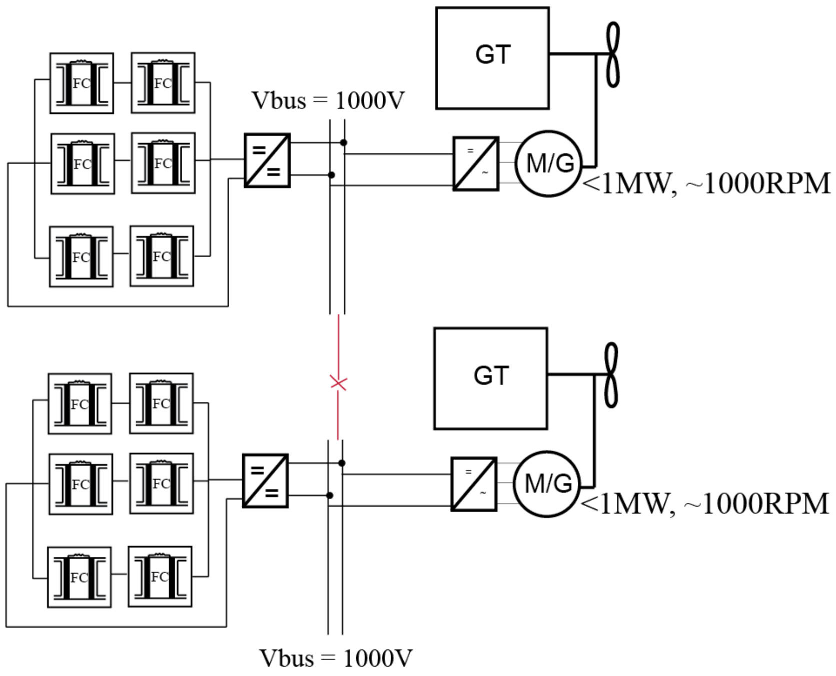
EPS architectures for a system with fuel cell stacks

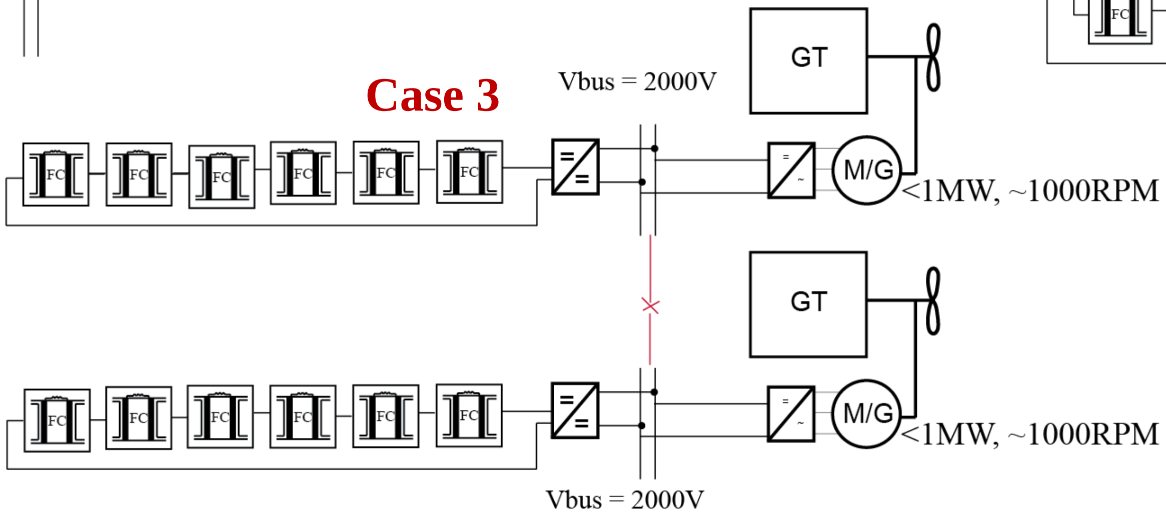


Case 1



Case 2

Case 3



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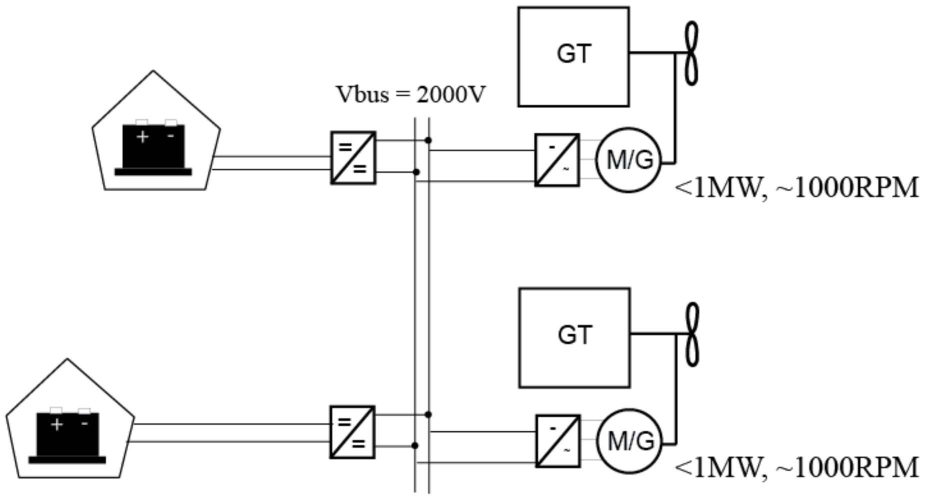
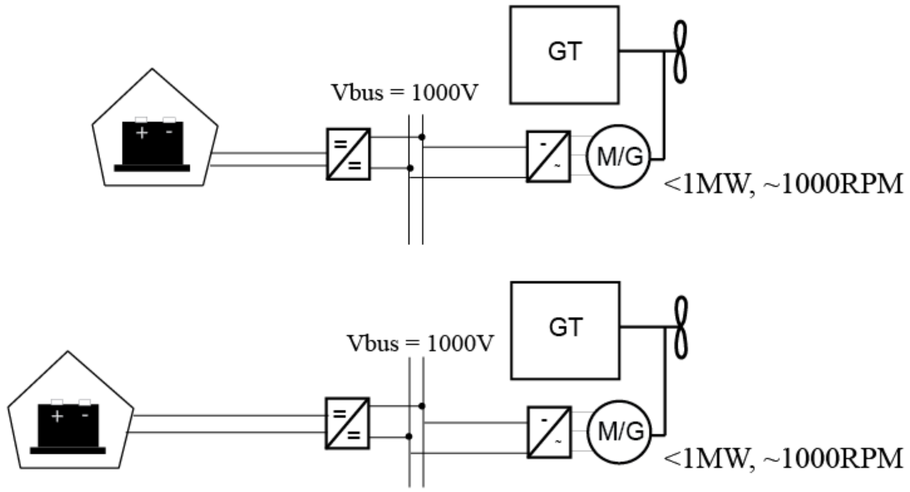
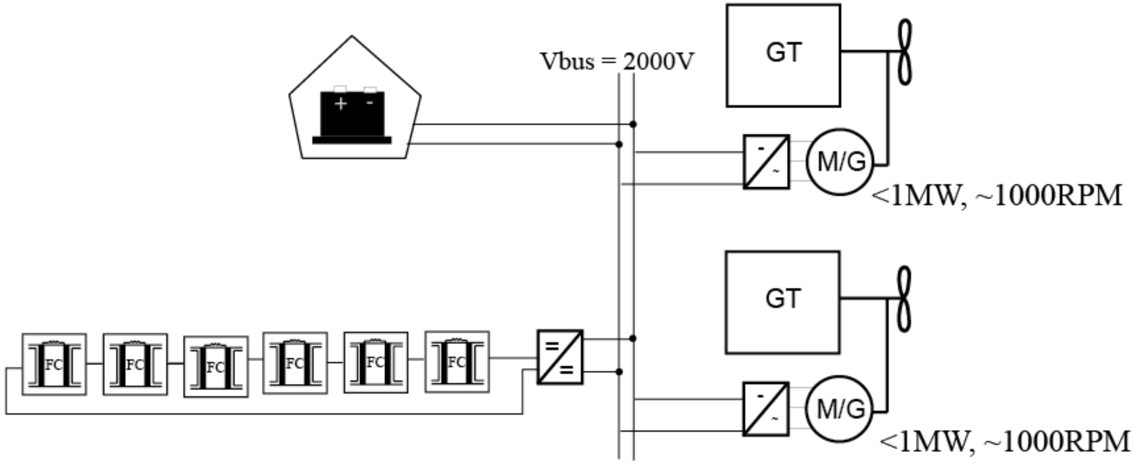
EPS architectures for a system with battery packs and fuel cell stacks







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Obtaining the efficiency maps for the electric motor

Aircraft model
FUTPRINT50 misson

Defining propulsion architecture, CONOPS, Failure cases, EMS, Electrical architectures

Design variables:

Shaft power
Torque
RPM
Motor Volume
DC voltage
Disdcharge current from battery
or FC output current

High fidelity motor model

Outputs from high fidelity FEM (results for design + off design)

Torque vs RPM - Efficiency
Torque vs RPM - Shaft Power
Torque vs RPM - id, iq, vd, vq
dc Voltage vs RPM - Efficiency
Phase current vs RPM - Efficiency
Pole pairs
all losses vs RPM
Machine topology
Machine weight
Machine volume
Thermal loss details
Varation of Torque, Voltage, Current per angle

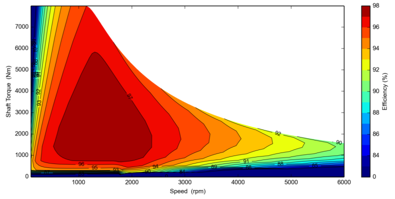
Export look up tables to MATLAB

Motor maps

for a fixed dc bus, motor topology, and geometry

id
iq
vd
vq

Torque
RPM
Pole pairs
VDC = Vbus



Sizing the battery packs
Model from CEA

Sizing the fuel cell stacks

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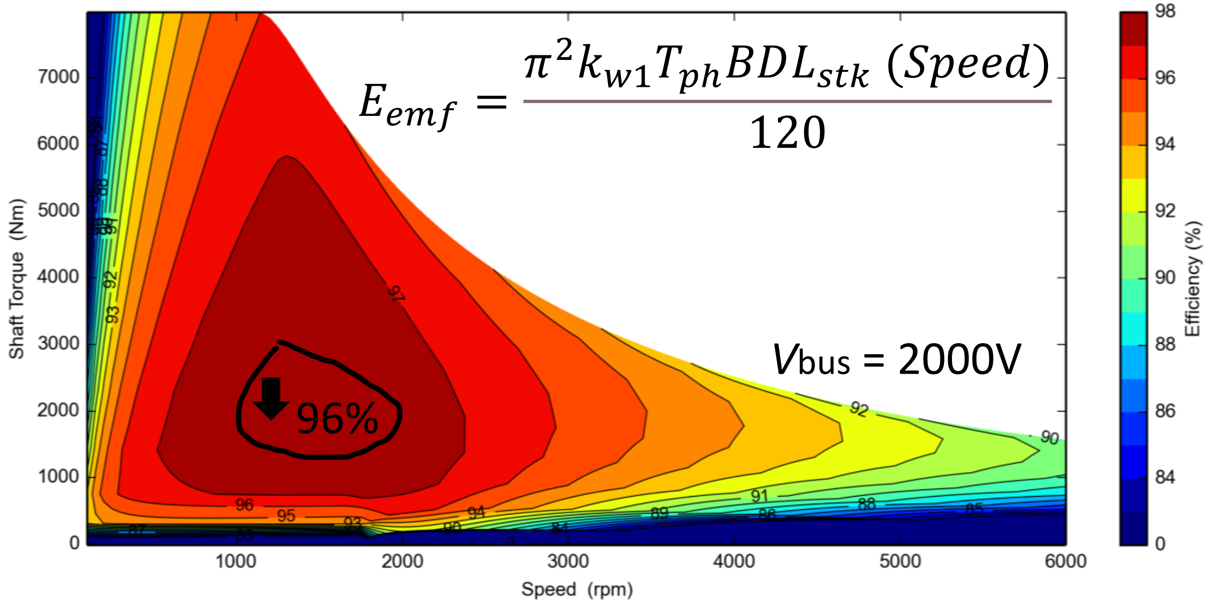

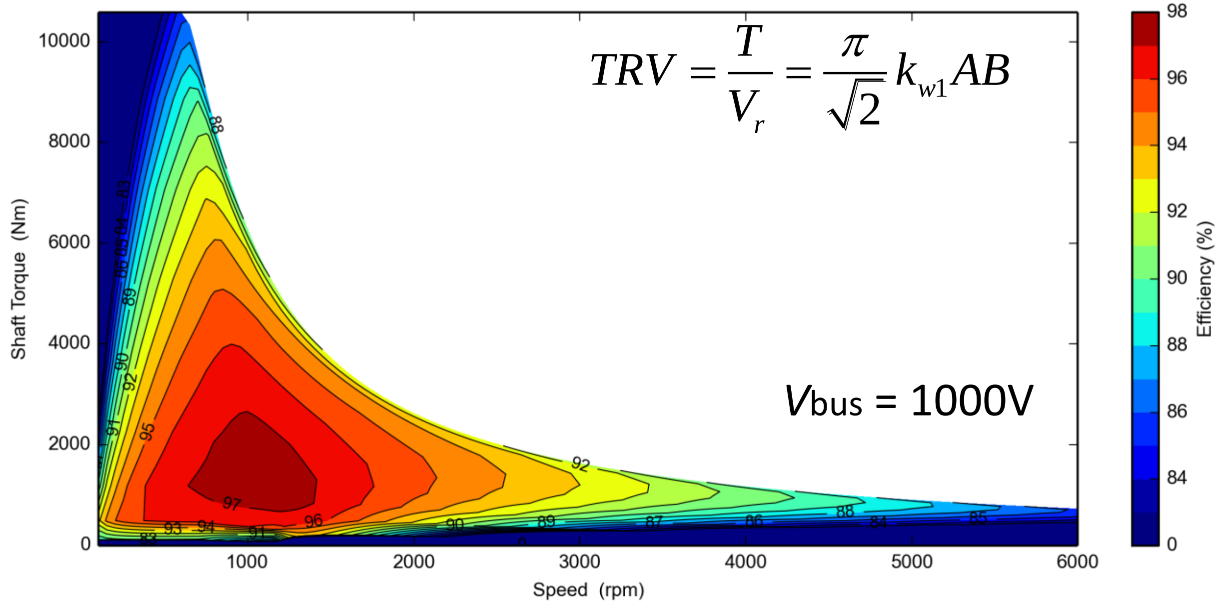

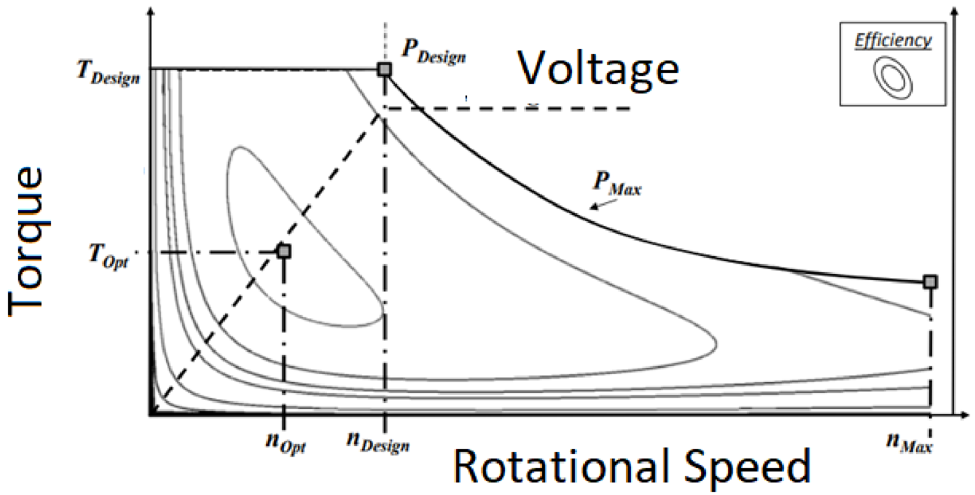

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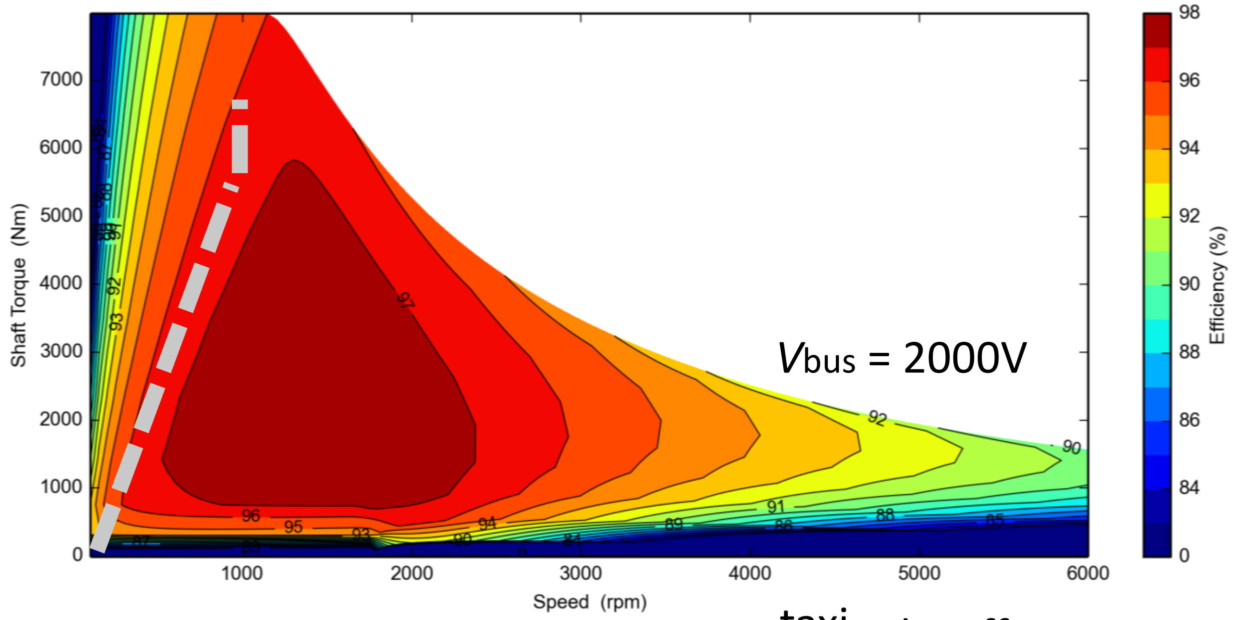

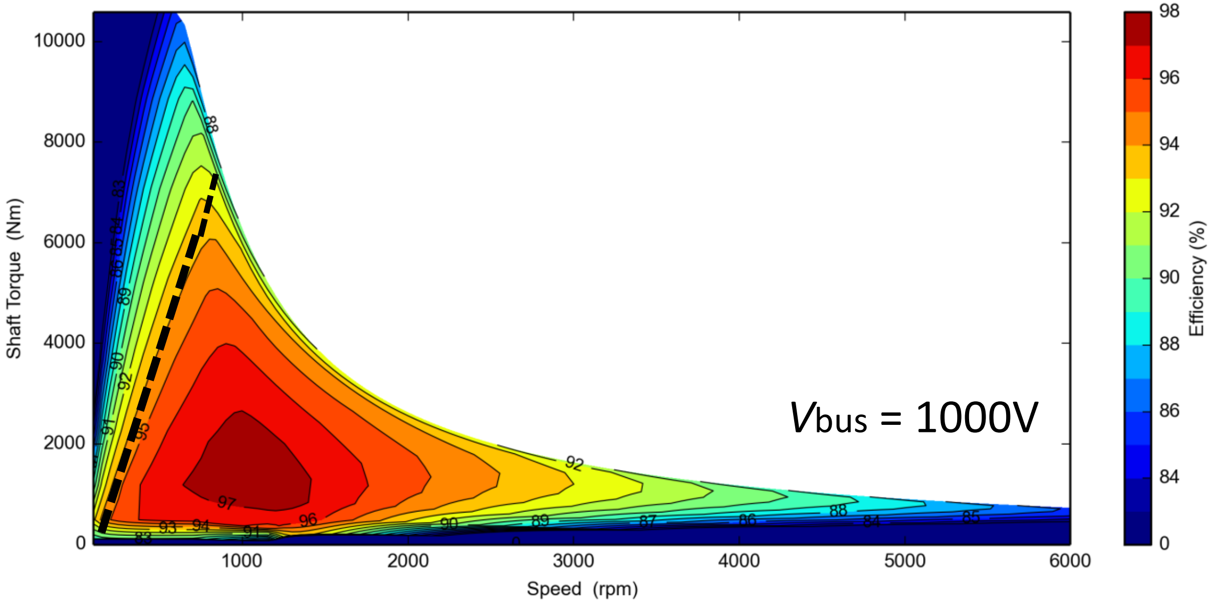

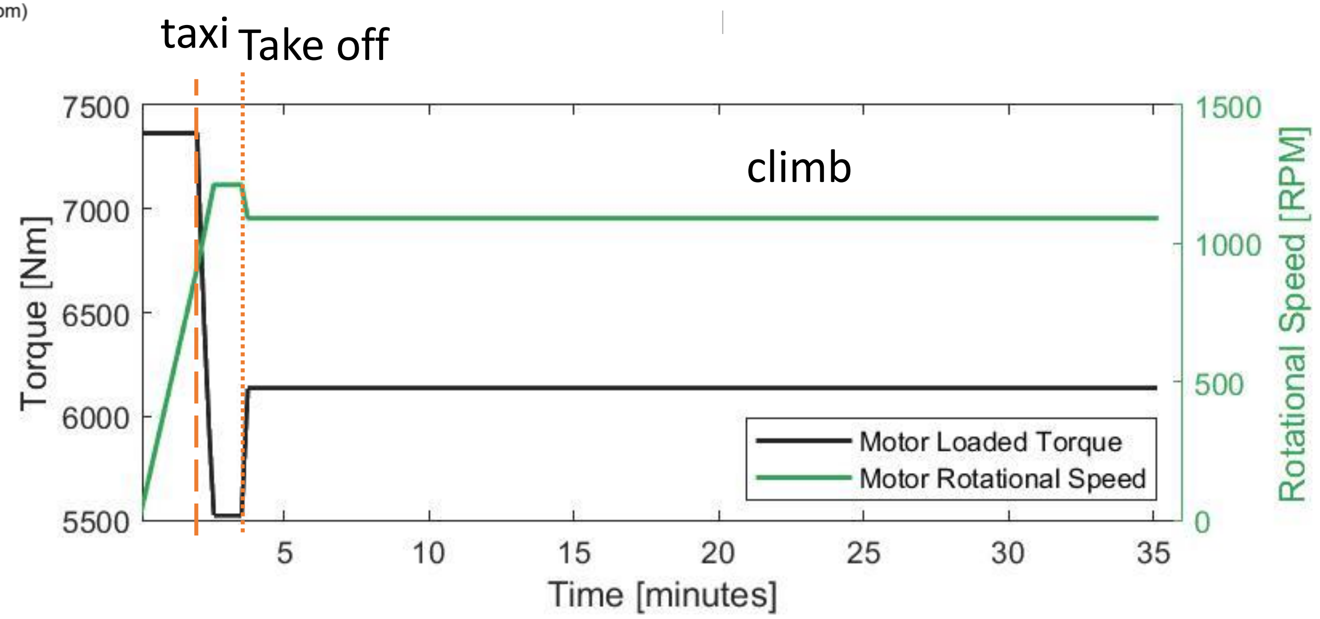

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Obtaining the efficiency maps for the inverter, and converter

id
iq
vd
vq

dq/abc

va
vb
vc

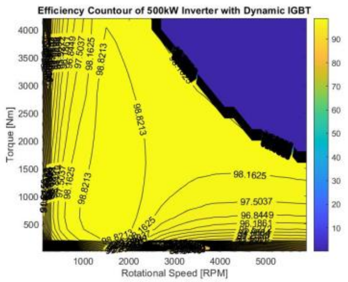
Inverter H-bridge Circuit
with six IGBTs

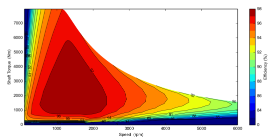
IGBT model
of an off the shelf component

Inverter efficiency map

Torque vs RPM - Efficiency

for a fixed Vdc = Vbus





Torque
RPM
Pole pairs
VDC = Vbus

Torque
RPM
Pole pairs
VDC = Vbus

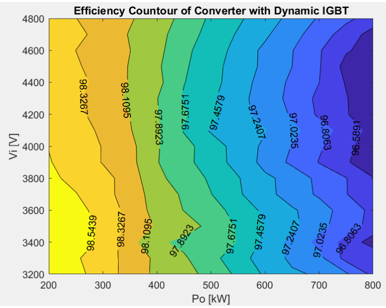
Pout = Vbus * I_discharge
Vinput = Vfule cell = Vbattery

Converter Circuit
with IGBTs

IGBT model and capacitor, inductor, diods
from an off the shelf component

Converter efficiency map

Vbus vs Pout - Efficiency



**I_discharge depends on motor efficiency and inverter efficiency for a given torque and RPM

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DC/DC Converter design

Converter Input Parameters

Operation Point Setting:

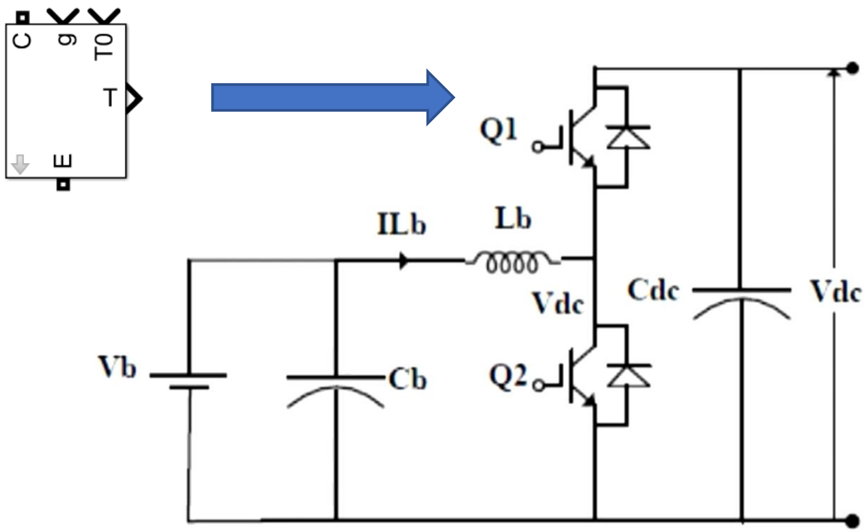
-- Output Voltage 2000V

Module Inputs:

- Input current FC output current
- Input voltage FC output voltage

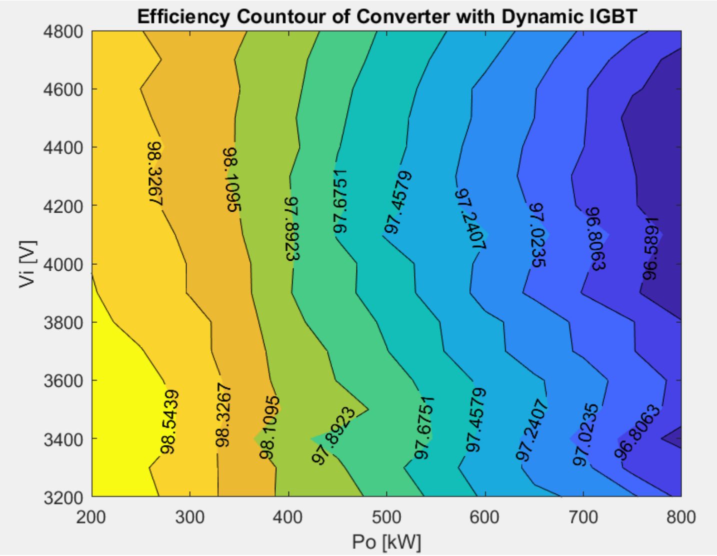
Inputs

IGBT & Non isolated bidirectional DC/DC Converter Model



Output Results

DC/DC Converter
- PWM Waveforms
- Efficiency
- Power Losses
- Output Voltage



Review of converters:
Ardi, H., Reza Ahrabi, R. and Najafi Ravadanegh, S., 2014. Non-isolated bidirectional DC–DC converter analysis and implementation. IET Power Electronics, 7(12), pp.3033-3044.

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Operation Point Setting:

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Module Inputs:

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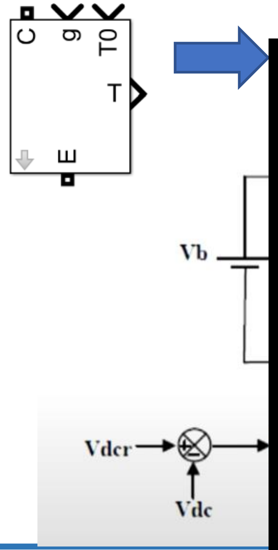
- Input voltage FC output voltage

Inputs

IGBT & Non isolated bidirectional DC/DC Converter Model



Output Results

DC/DC Converter

- PWM Waveforms
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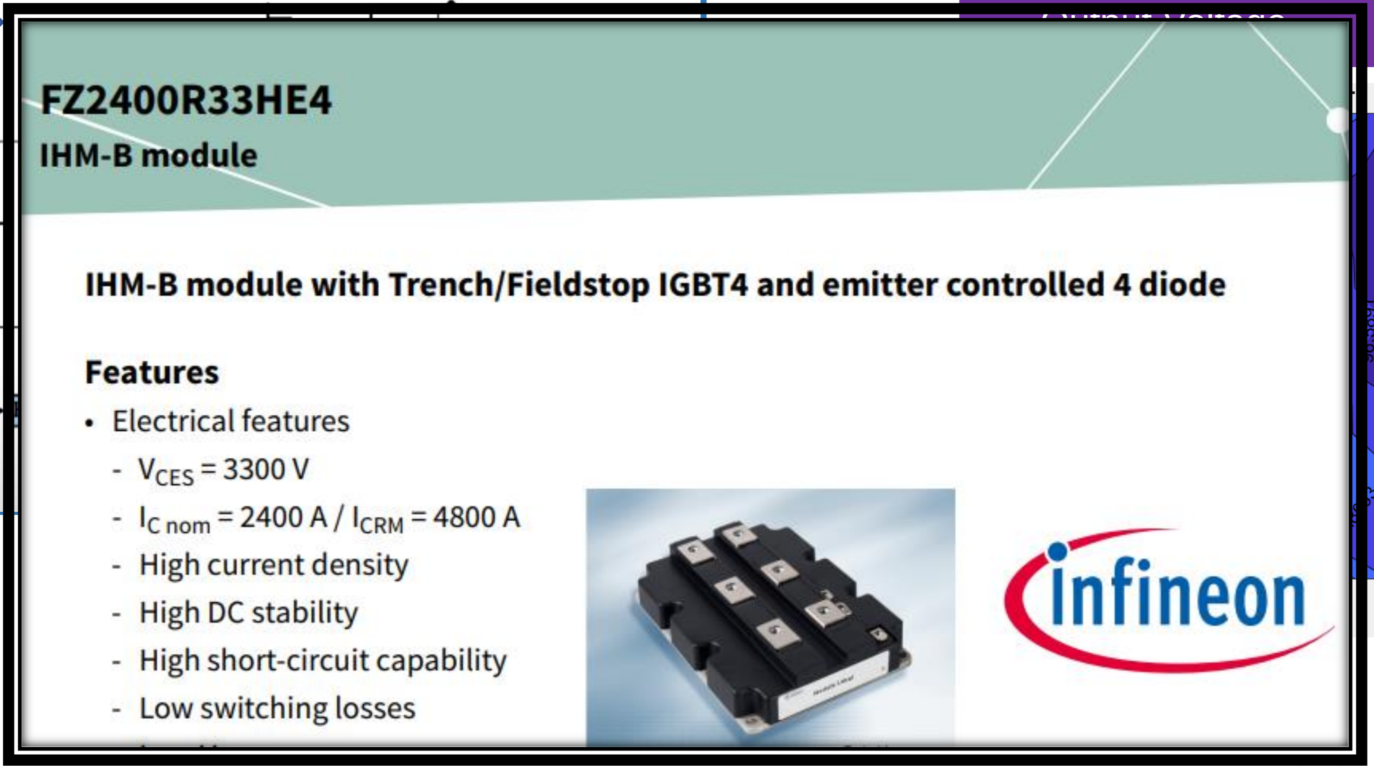

FZ2400R33HE4

IHM-B module

IHM-B module with Trench/Fieldstop IGBT4 and emitter controlled 4 diode

Features

- Electrical features
  - $V_{CES} = 3300$ V
  - $I_{C\ nom} = 2400$ A / $I_{CRM} = 4800$ A
  - High current density
  - High DC stability
  - High short-circuit capability
  - Low switching losses

Review of converters:

Ardi, H., Reza Ahrabi, R. and Najafi Ravadanegh, S., 2014. Non-isolated bidirectional DC–DC converter analysis and implementation. IET Power Electronics, 7(12), pp.3033-3044.

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DC/DC Converter design

Converter Input Parameters

<u>Operation Point Setting:</u>

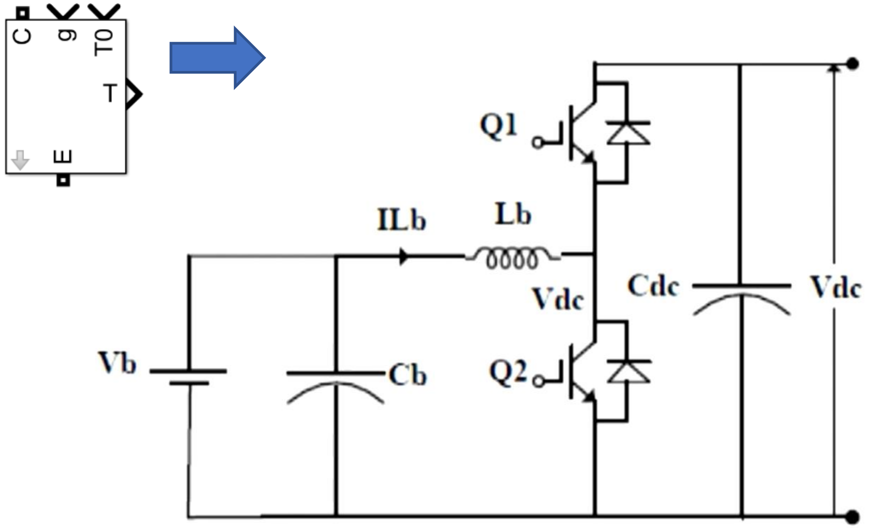
-- Output Voltage 2000V

<u>Module Inputs:</u>

- Input current	FC output current
- Input voltage	FC output voltage

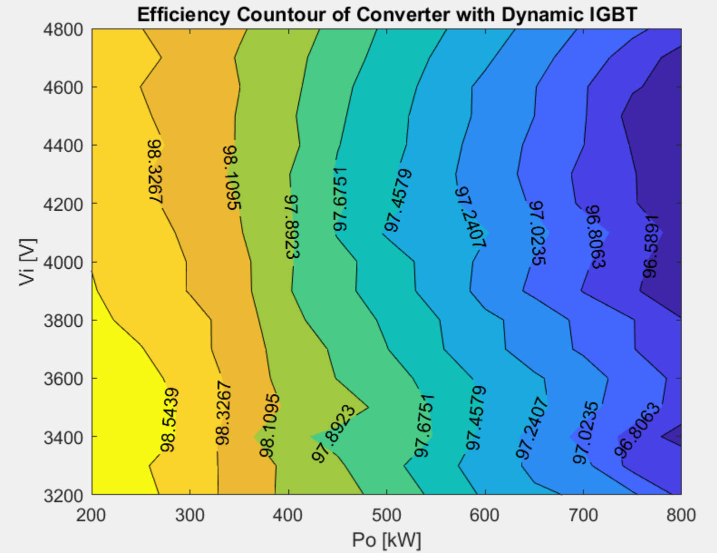
Inputs

IGBT & Non isolated bidirectional DC/DC Converter Model



Output Results

<u>DC/DC Converter</u>
- PWM Waveforms
- Efficiency
- Power Losses
- Output Voltage



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DC/DC Converter design

Converter Input Parameters

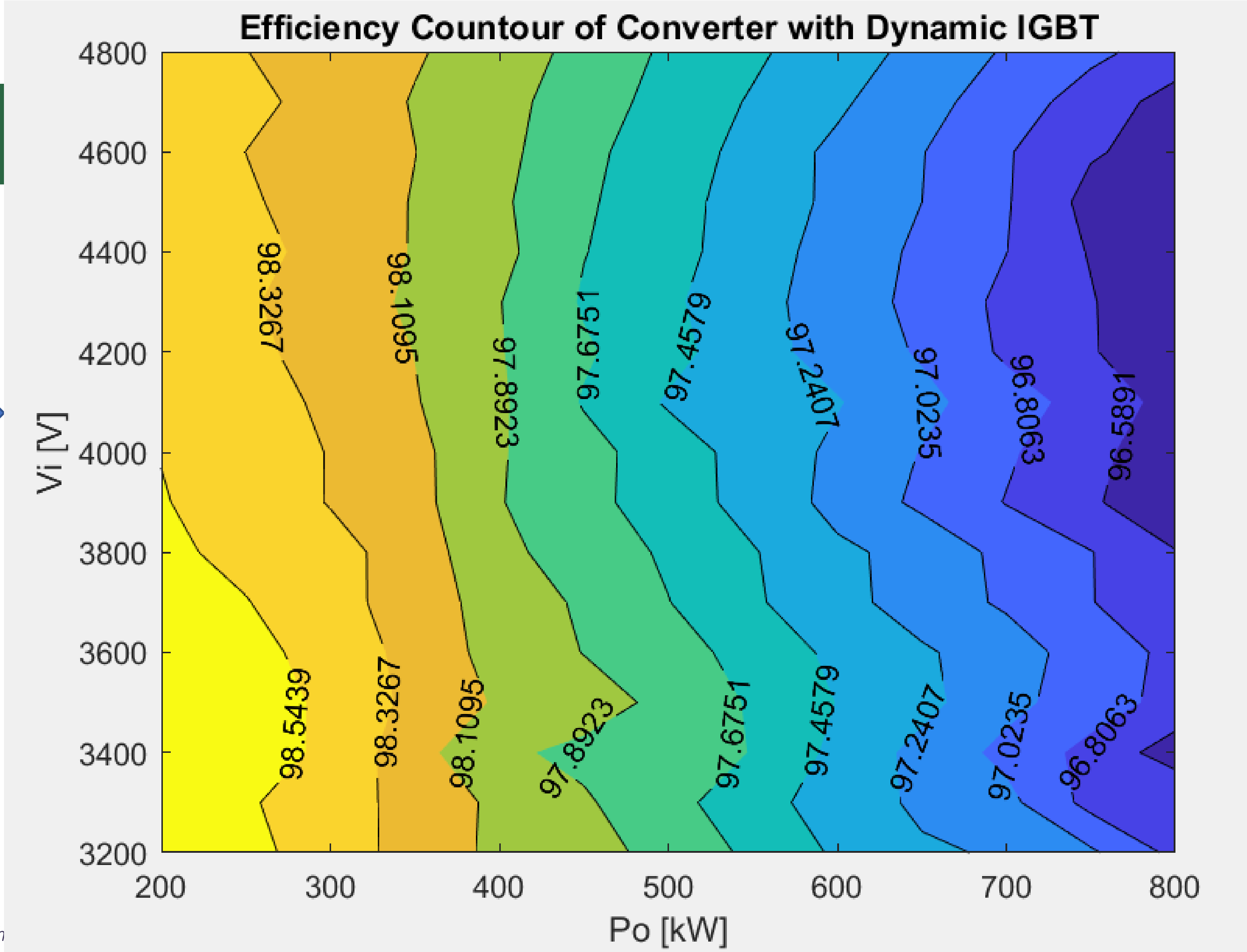
Operation Point Setting:

- Output Voltage 2000V

Module Inputs:

- Input current FC/Batt output current
- Input voltage FC/batt output voltage

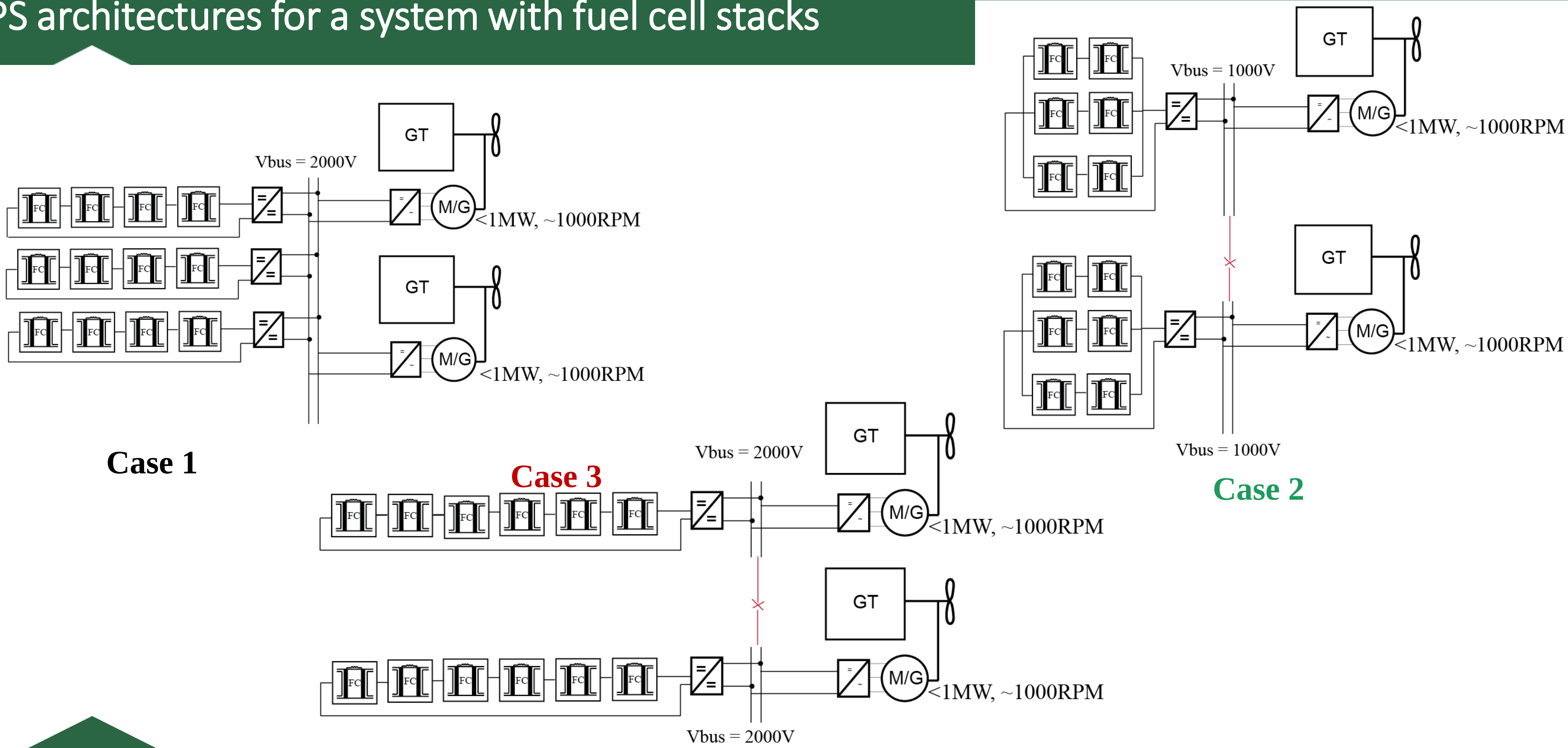
Inputs



DC/DC Converter for Case 3

This project h
under Grant Agreement No 875551

EPS architectures for a system with fuel cell stacks



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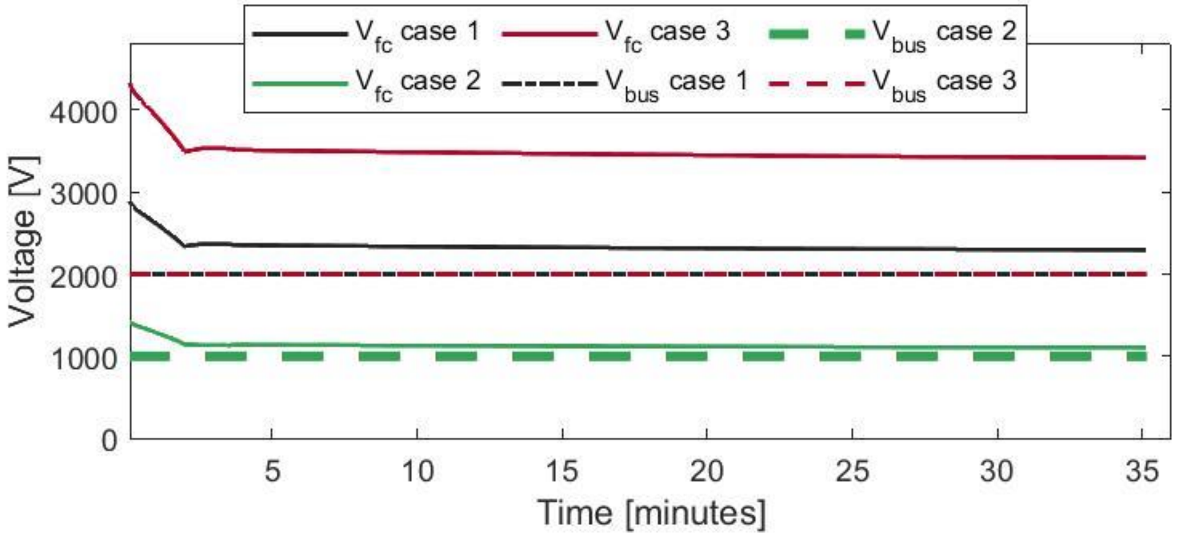
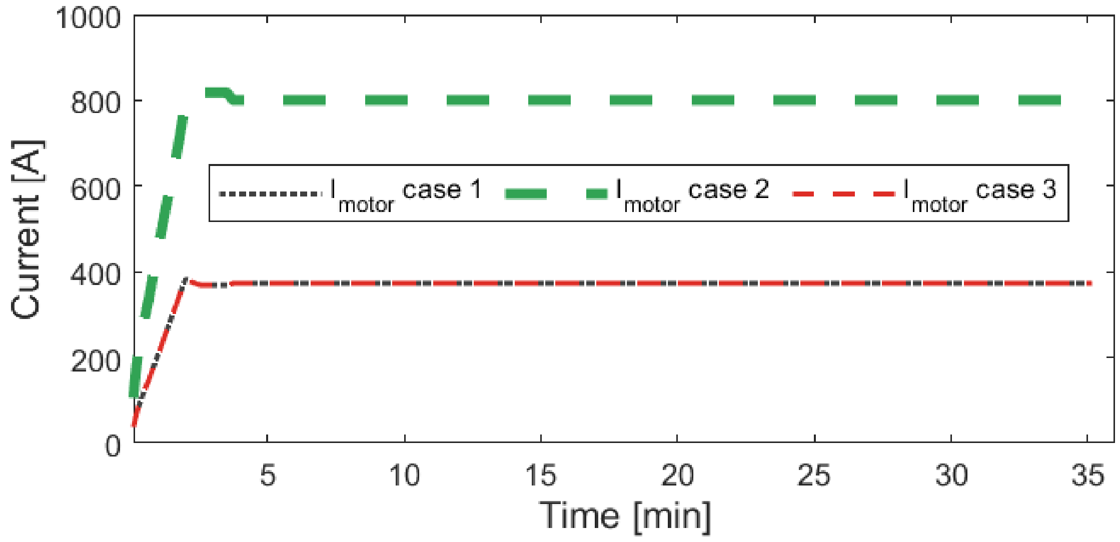
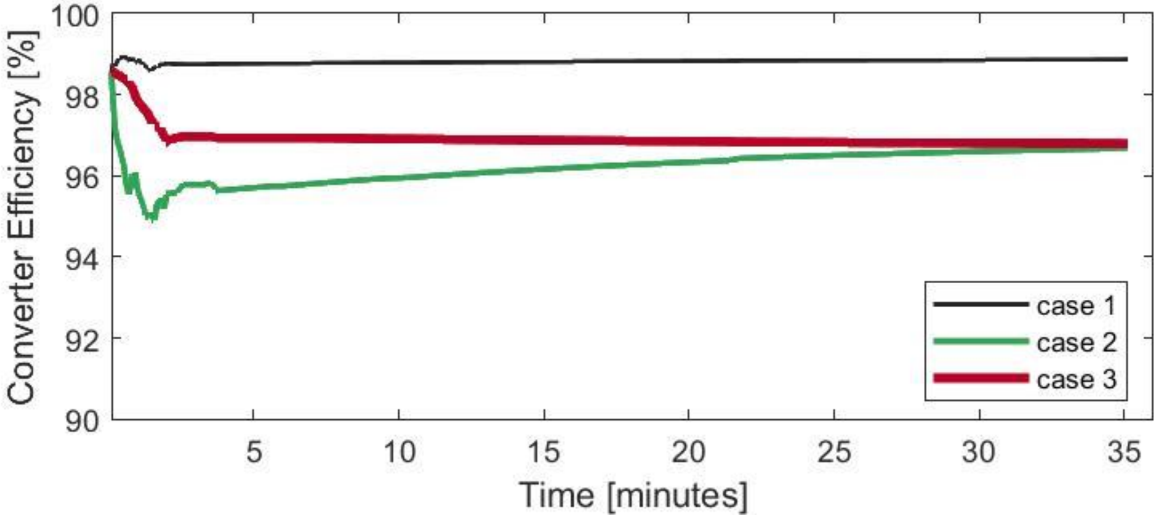
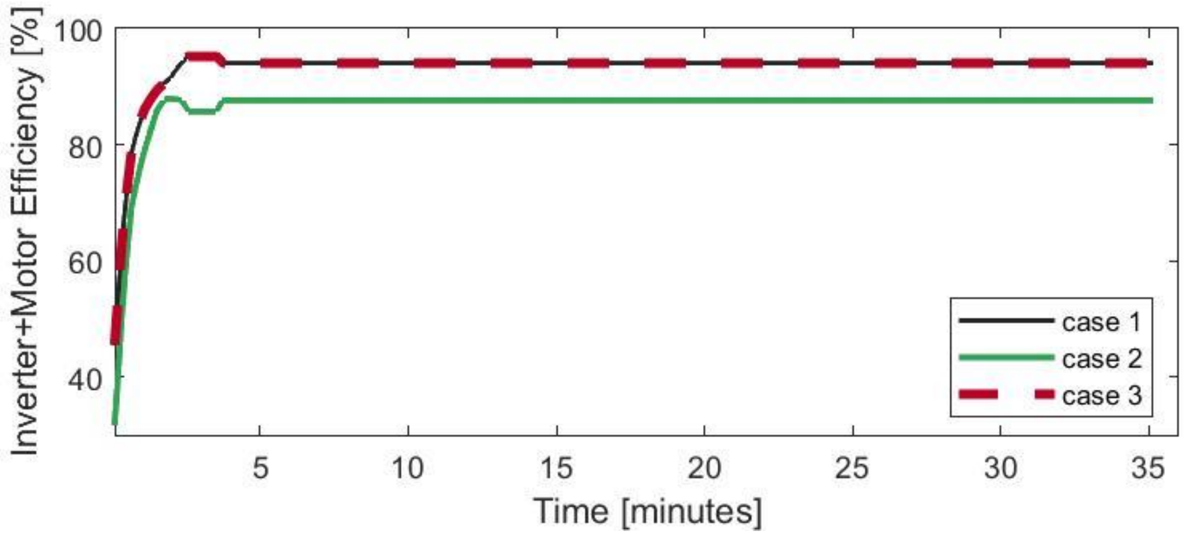
Results (EMS TO-CL)

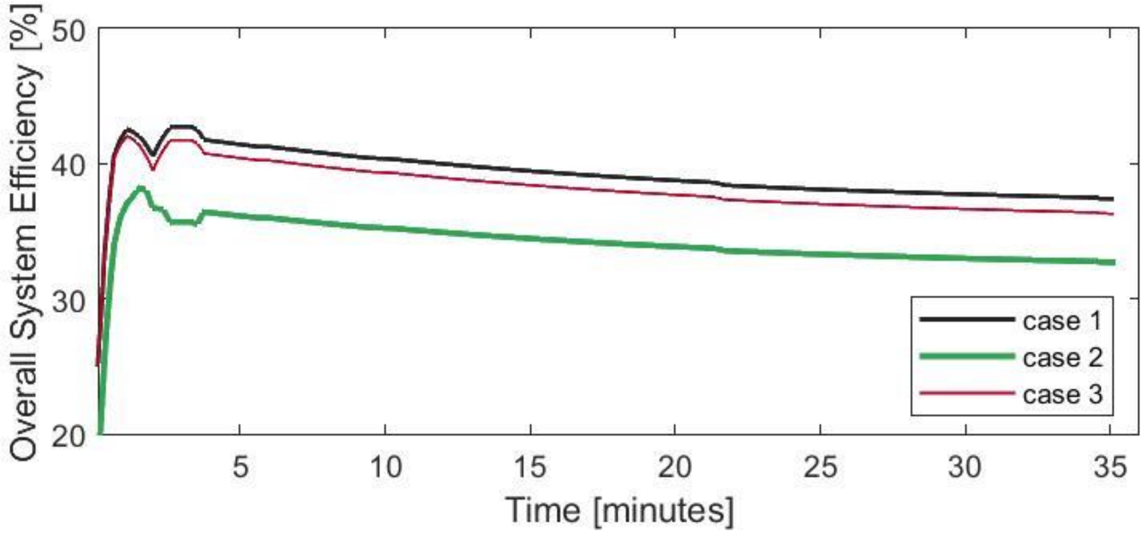


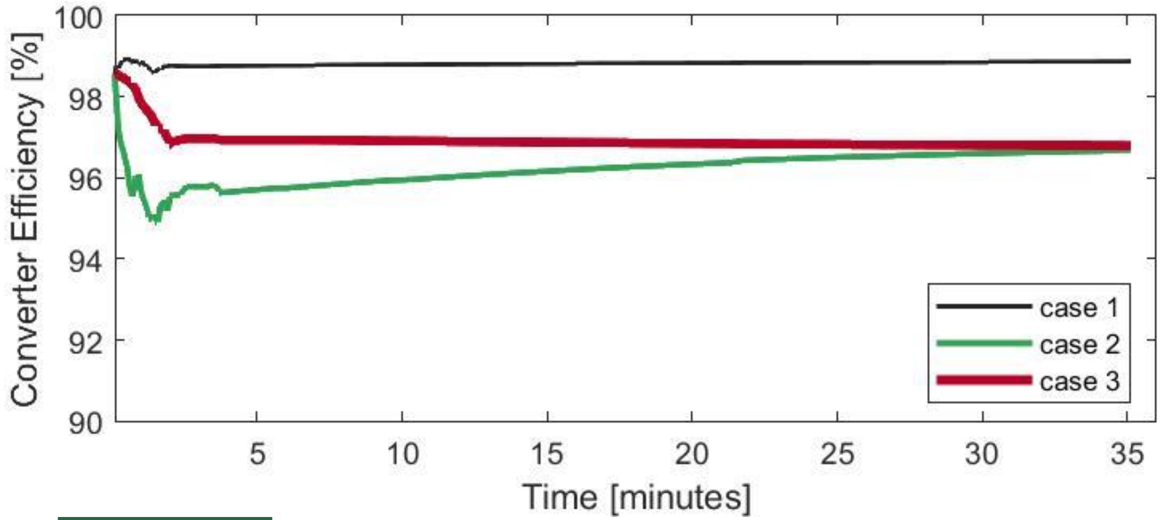


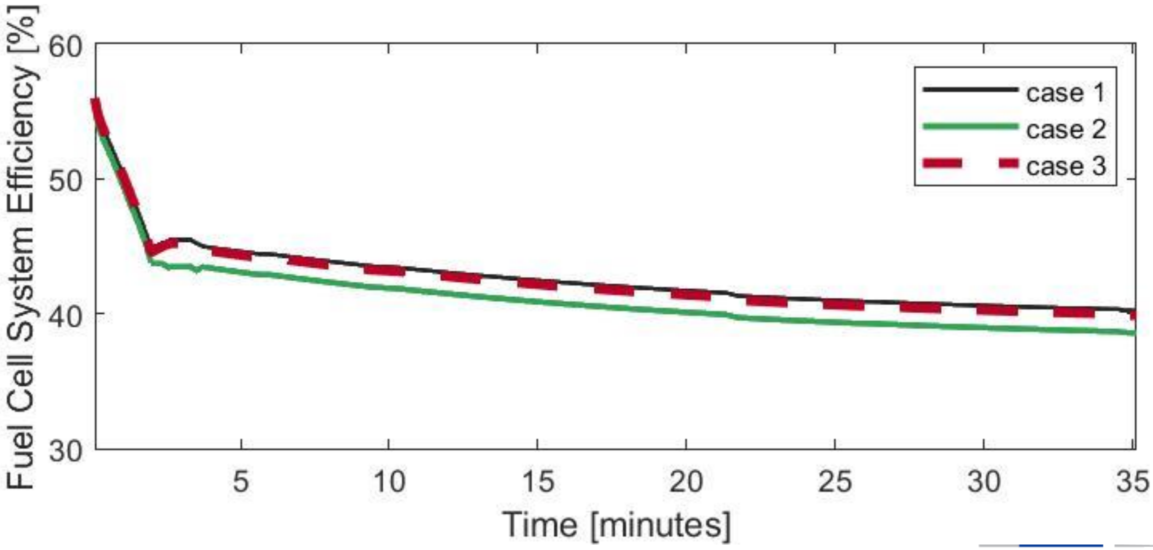


Results (EMS TO-CL)









Conclusions - Contributions and lessons learnt

- Achieving a **trade off studies** based on component interactions and their efficiencies, power densities, and sub-system integration considerations
- **Providing roadmap** for tomorrow’s developments, from detailed models that allow capturing limits in which components cannot operate today
- Modelling platform that can include variations in the component behaviour to analyse the system and sub-systems faced **different faults and degradations**
- Capturing the effect of **distribution voltage**
- **Reducing the miscommunication** between stakeholders and **incompatibilities** between the levels in which component are modelled that can lead to incorrect decisions
- **Evaluating Aircraft performance** based on analysing and comparing variations of operating points and efficiencies through the mission for different architectures

This project has received funding from the European Union’s Horizon 2020 Research and Innovation programme under Grant Agreement No 875551

Questions

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This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 875551

SCITECH FORUM 23–27 January 2023

The Impact of Multi-Stack Fuel Cell Configurations on Electrical Architecture for a Zero Emission Regional Aircraft

Bahareh Zaghari[*], Tianzhi Zhou[†], Hossein Balaghi Enalou[‡], Evangelia Pontika[§], Timoleon Kipouros[¶] and Panagiotis Laskaridis[‖]

Cranfield University, School of Aerospace Transport and Manufacturing, Cranfield, MK43 0AL, UK

All-electric aircraft can eliminate greenhouse gas emissions during aircraft mission, but the low predicted energy storage density of batteries (=0.5 kWh/kg), and their life cycle, limits aircraft payload and range for regional aircraft. Proton Exchange Membrane Fuel Cells (PEMFCs) using hydrogen are explored as an alternative energy source. As the effort on designing high power density fuel cell systems continues, a trade off study on the effect of fuel cell configurations and the electrical conversion strategy on system efficiency, total weight, failure cases, and reduction of power due to failures, will inform future designs. Introducing viable fuel cell stacks and electrical configurations motivates such a trade off study, as well as concentrated design effort into these components. In this study, multi-stack fuel cell configurations and the selected DC/DC converters are assessed. Their impact on the required power and thrust for a selected mission will be presented in the final paper.

Acknowledgement

The research leading to these results has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 875551.

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European Commission