Energy Management in More Electrical Aircraft

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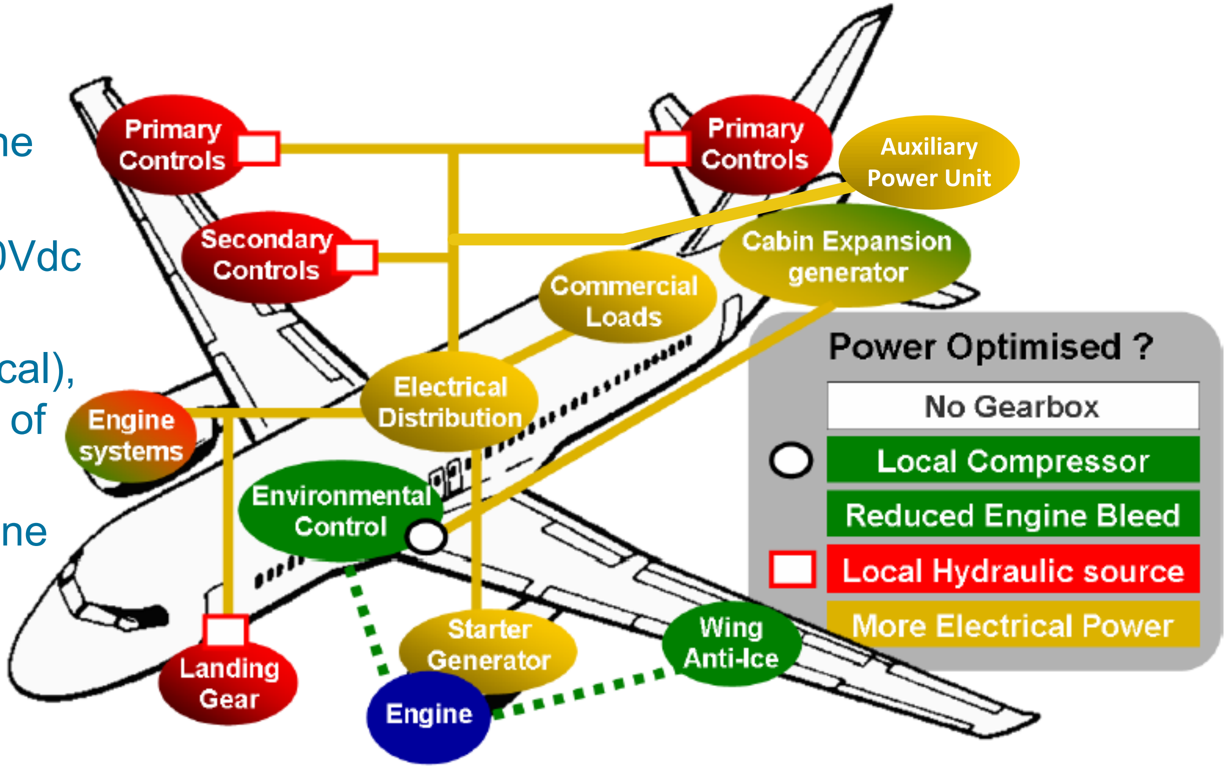
More Electrical Aircraft (MEA)

- Aircraft non-propulsive aircraft systems employ four types of power:

Power Type	Sourcing
Hydraulic	Gear box driven pumps, auxiliary power unit (APU)
Pneumatic	Bleeding from the high pressure stage of the turbine engine
Mechanical	Gear boxes driven by the main turbine engines
Electrical	Gear box driven generators, APU

Prominent to MEA are:

- use of Li-ion batteries
- electrical starting of the engine using S/G
- HVDC distribution at 270/540Vdc instead of 115/230Vac
- single power network (electrical), enhancing the manageability of AES
- replacement of the APU turbine with a fuel cell.



Context

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COPPER bird®

Characterisation & Optimisation of Power Plant & Equipment Rig

SAFRAN
Labinal Power Systems

Electrical Test Bench (ETB) reproducing the entire electrical network of an aircraft such as regional jets, private jets and rotorcraft (2002–2006 European project Power Optimised Aircraft).

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SEPDC www.sepdc-fp7.eu

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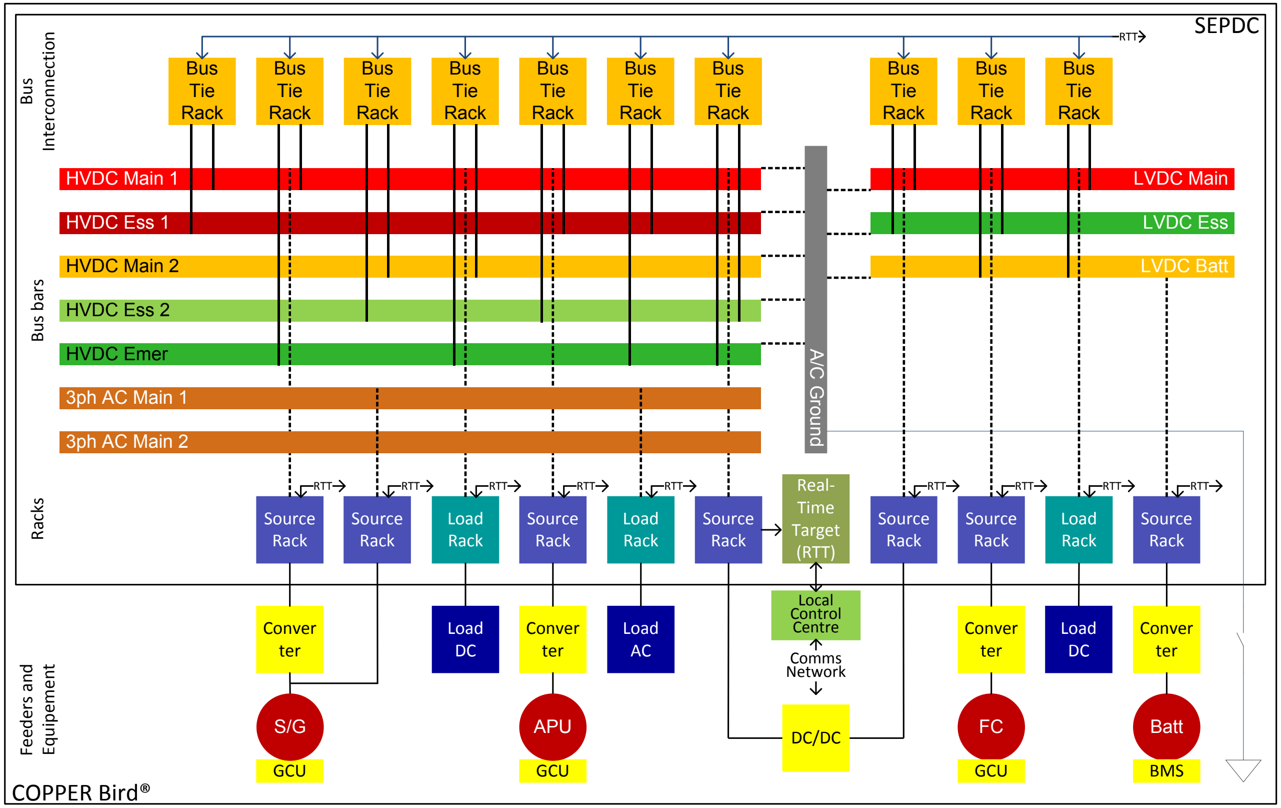
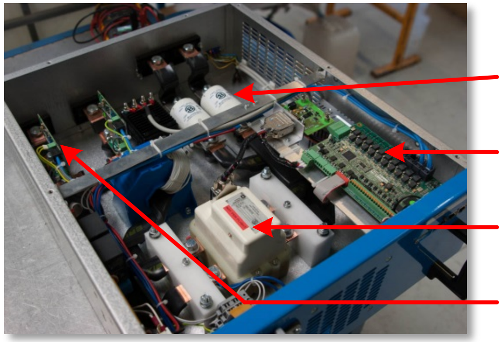


SEPDC Specifications	
Total Power	500 kW
Busbar V & I	1000 V, 1000 A_{rms}
Voltage Ranges	0/+28V_{dc}, 0/+270V_{dc}, 0/+540V_{dc}, ±135V_{dc}, ±270V_{dc}, 115/230V_{ac}
# of Racks	50 DC, 10 AC
Rack V & I	1000 V, 450 A_{peak}, 4500 A_{peak} for 50 ms
Resolution	16 bits at 51.2 kHz
Data Rate (30 Racks)	1.57 GB/min



Fuse

Controller

Contactor/SSPC

V&I Measurement

Two Rack types:

- DC: Sources, Loads, Busbar Tie
- AC: Sources, Loads

Real-time system handles Rack control, data storage and comms

Research Objectives

The research objectives are:

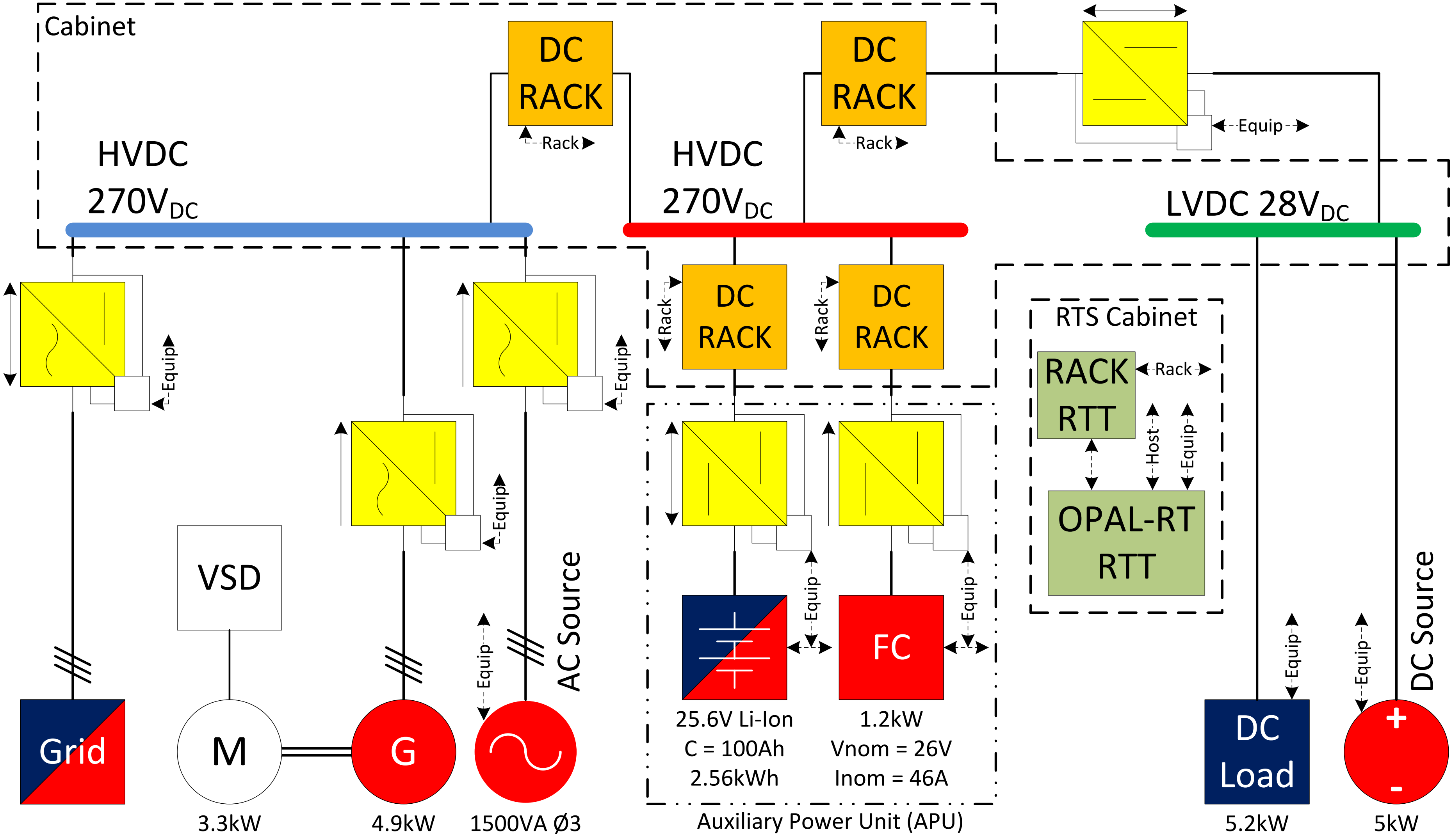
- Develop a 5 kW laboratory scaled version of the updated COPPERbird ETB, called the Small Scale Test Bench (SSTB)
- Create a Virtual ETB through modelling of the SSTB equipment:
  - behavioural and functional level models
  - execution in a real-time simulation environment
- Hybridize a 1.2 kW proton exchange membrane (PEM) fuel cell with a 100 Ah $LiFePO_4$ Li-ion battery as APU replacement
- Develop an EMS for the hybrid APU:
  - ensure optimal power split between sources subject to operation constraints
- Validate the EMS through simulations and experimental testing using the VETB and SSTB

Contents

- Introduction
- **SMALL SCALE TEST BENCH**
  - Layout
  - Sources and Loads
  - Converters
  - Real-time System
- Modelling
- Energy Management System
- Simulation and Experimental Results
- Conclusions

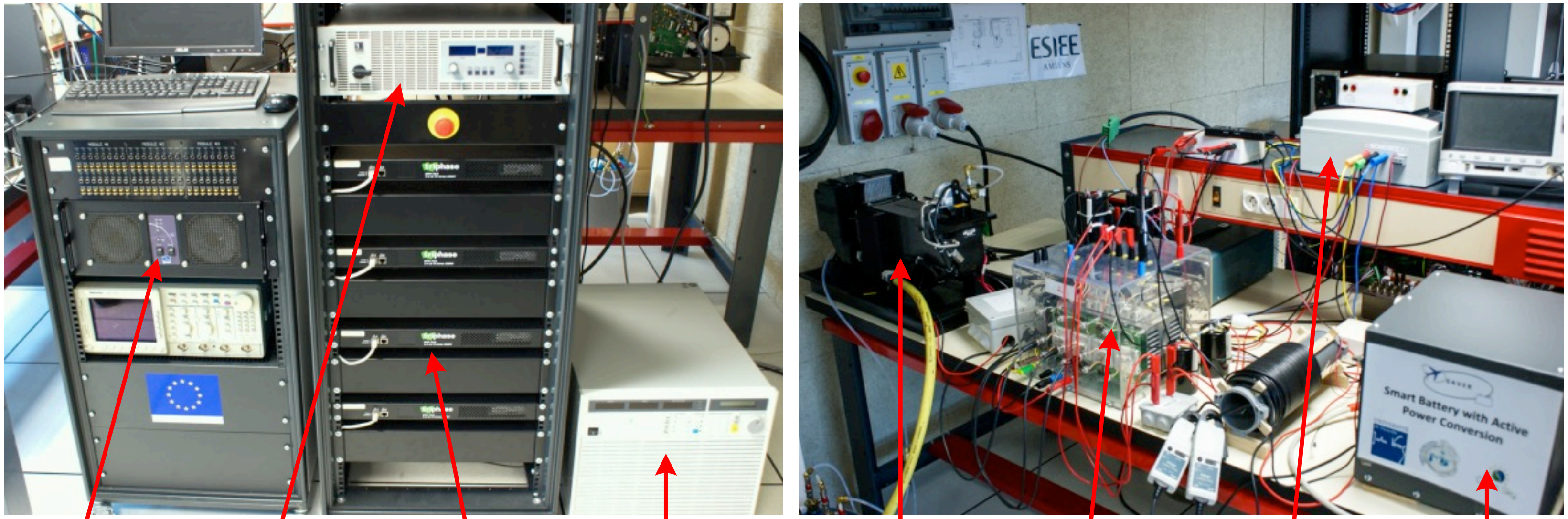
The SSTB Layout

REAL TEST BENCH



FC: Fuel Cell, **HV**: High Voltage, **LV**: Low Voltage, **RTS**: Real-time System, **RTT**: Real-time Target, **VSD**: Variable Speed Drive

Small Scale Test Bench



Opal-RT
RTT

5 kW
DC Source

Racks

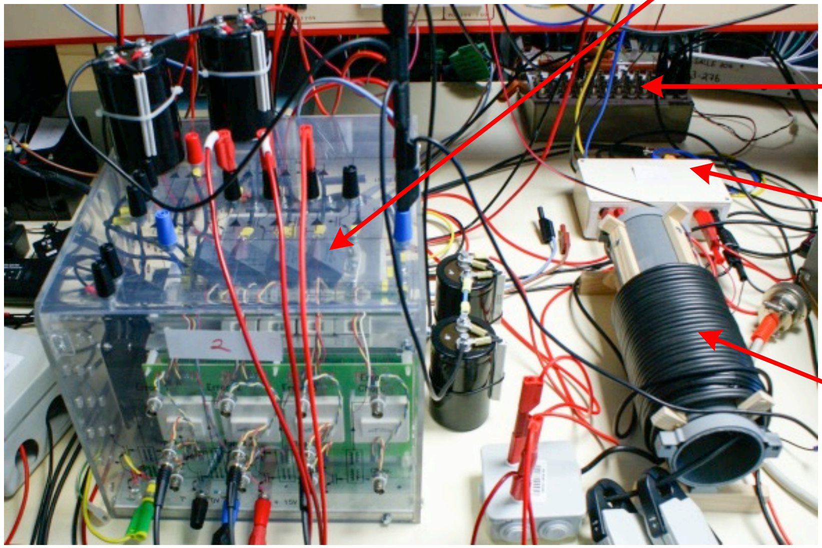
5.2 kW
DC Load

1.2 kW
Fuel Cell

Semiteach
IGBT Stack

±15 V
Aux Supply

100 A h
Li-ion Battery



RTT
I/O Box

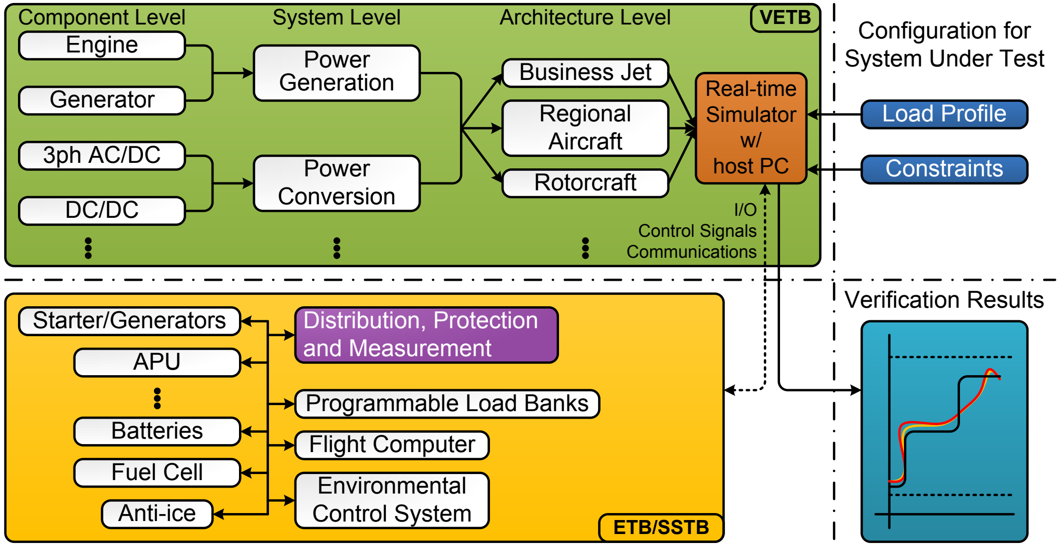
VI
Measurement
Box

Air Core
Inductor

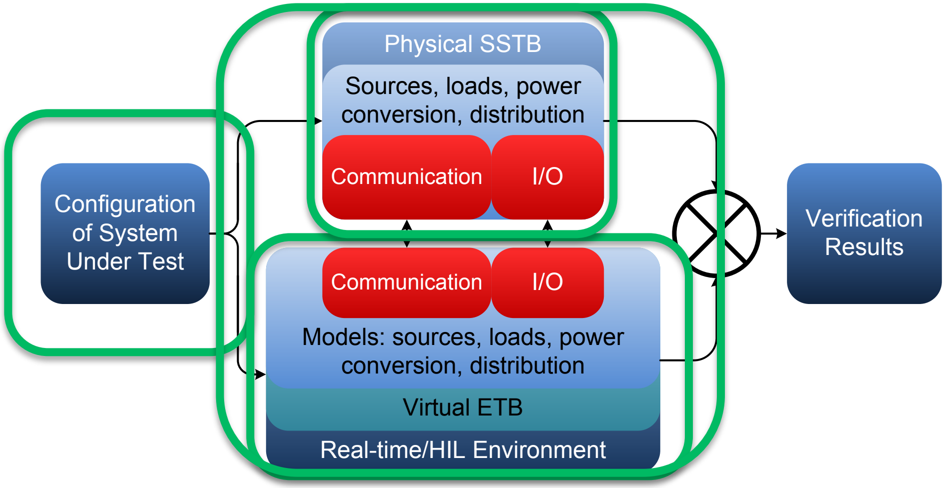
Virtual Electrical Test Bench

- Real-time simulation environment provides RCP, HIL and SIL functionalities, but also constraints: simulation step times of <20 us, no algebraic loops

- **VETB Organisation:**



- **VETB Workflow:**



Contents

- Introduction
- Small Scale Test Bench
- **MODELLING**
- Energy Management System
- Simulation and Experimental Results
- Conclusions

- Battery
  - SOC Estimation

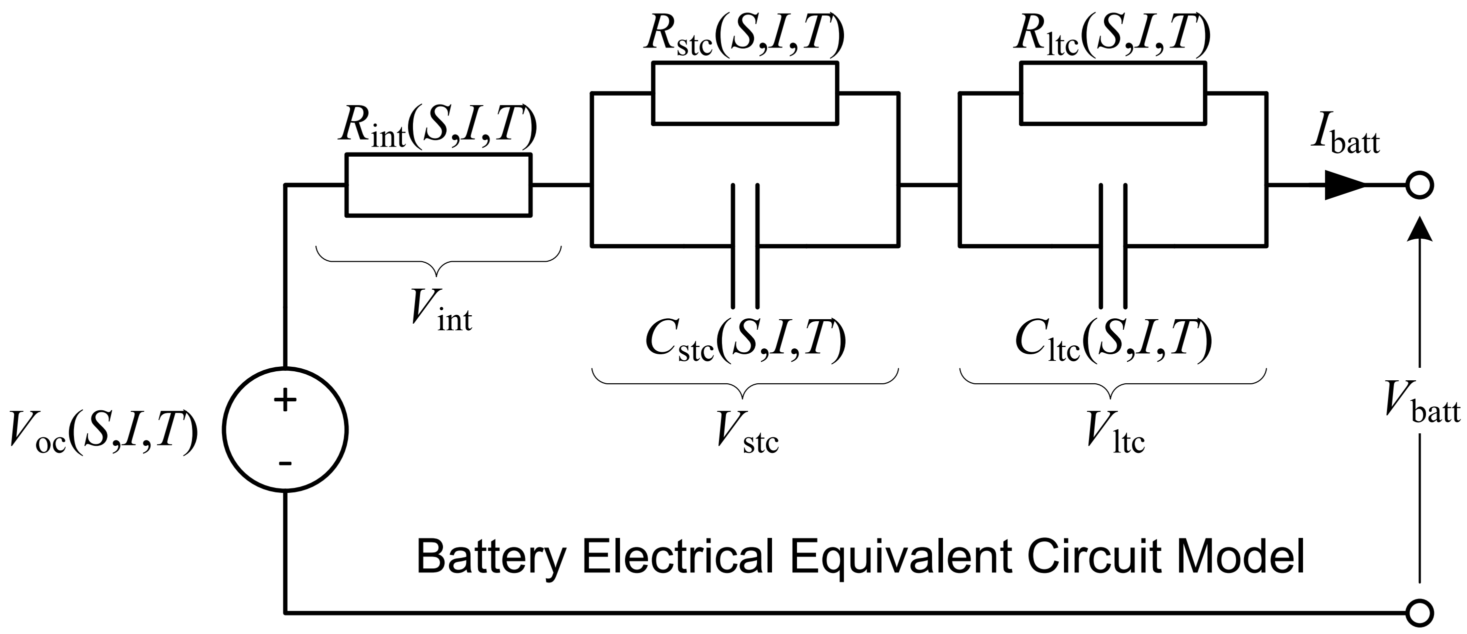
Li-ion for MEA

- More Electrical Aircraft (MEA) will rely much more heavily on the battery, with **lithium-ion** stepping in as the most appropriate battery technology
- Lithium-ion as a replacement for the industry standard sealed lead-acid (SLA) battery stems from their **inherently high specific power and energy ratings** which result in lower weight and the capability to deliver the high currents required for engine starting via the Starter/Generator
- Advanced aircraft energy management (EM) schemes can also **use the battery to satisfy peak power demand**, especially when paired with a fuel cell as an auxiliary power unit (APU) replacement.
- Current developments looking at safer chemistries: $LiFePO_4$ and Li-S

It is thus highly desirable to be able to predict the electrical behaviour of the lithium-ion battery during both normal and high stress engine starting operations, all whilst having accurate knowledge of its state of charge (SOC) for proper energy management decisions.

Battery Modelling

- Thevenin circuit with two RC parallel networks in series
- Two circuits provide the best compromise between accuracy and computational intensity (Zhang and Chow, 2010)
- Facilitates simulation with other electrical circuitry
- Characterised using current pulse techniques



Battery Electrical Equivalent Circuit Model

where S = State of Charge (0-1), I = battery current (A), T = temperature (K)

EEC State Space

- Battery terminal voltage equals OCV minus the losses

$$V_{term} = V_{oc}\left(S,I,T\right) - I_{batt}R_{\text{int}}\left(S,I,T\right) - V_{C_{stc}}\left(S,I,T\right) - V_{C_{ltc}}\left(S,I,T\right)$$

- State space representation

$$\begin{bmatrix} \dot{V}_{C_{stc}} \\ \dot{V}_{C_{ltc}} \\ \dot{S} \end{bmatrix} = \begin{bmatrix} \dfrac{-1}{R_{stc}\left(\alpha\right)C_{stc}\left(\alpha\right)} & 0 & 0 \\ 0 & \dfrac{-1}{R_{ltc}\left(\alpha\right)C_{ltc}\left(\alpha\right)} & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} V_{C_{stc}} \\ V_{C_{ltc}} \\ S \end{bmatrix} + \begin{bmatrix} \dfrac{1}{C_{stc}\left(\alpha\right)} \\ \dfrac{1}{C_{ltc}\left(\alpha\right)} \\ \dfrac{-1}{3600 \cdot C_{use}\left(I,T\right)} \end{bmatrix} I_{batt}$$

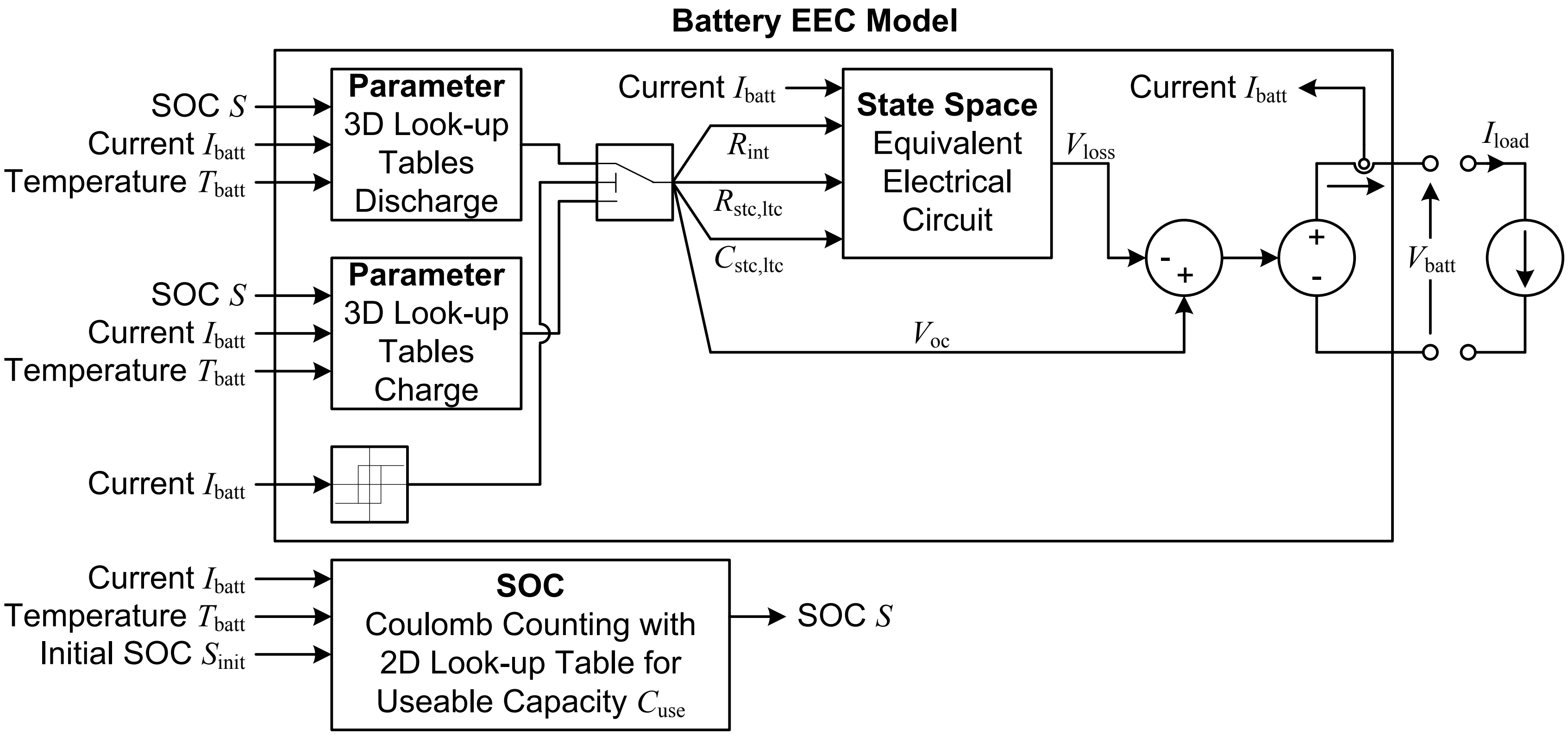
$$\text{where } \alpha = S,I,T$$

- Coulomb counting method (positive current equals discharging)

$$S = S_{init} + \frac{-1}{Q_{\max}\left(I,T\right)}\int_0^t I_{batt}\,dt = S_{init} + \frac{-1}{C_{use}\left(I,T\right)\cdot 3600}\int_0^t I_{batt}\,dt$$

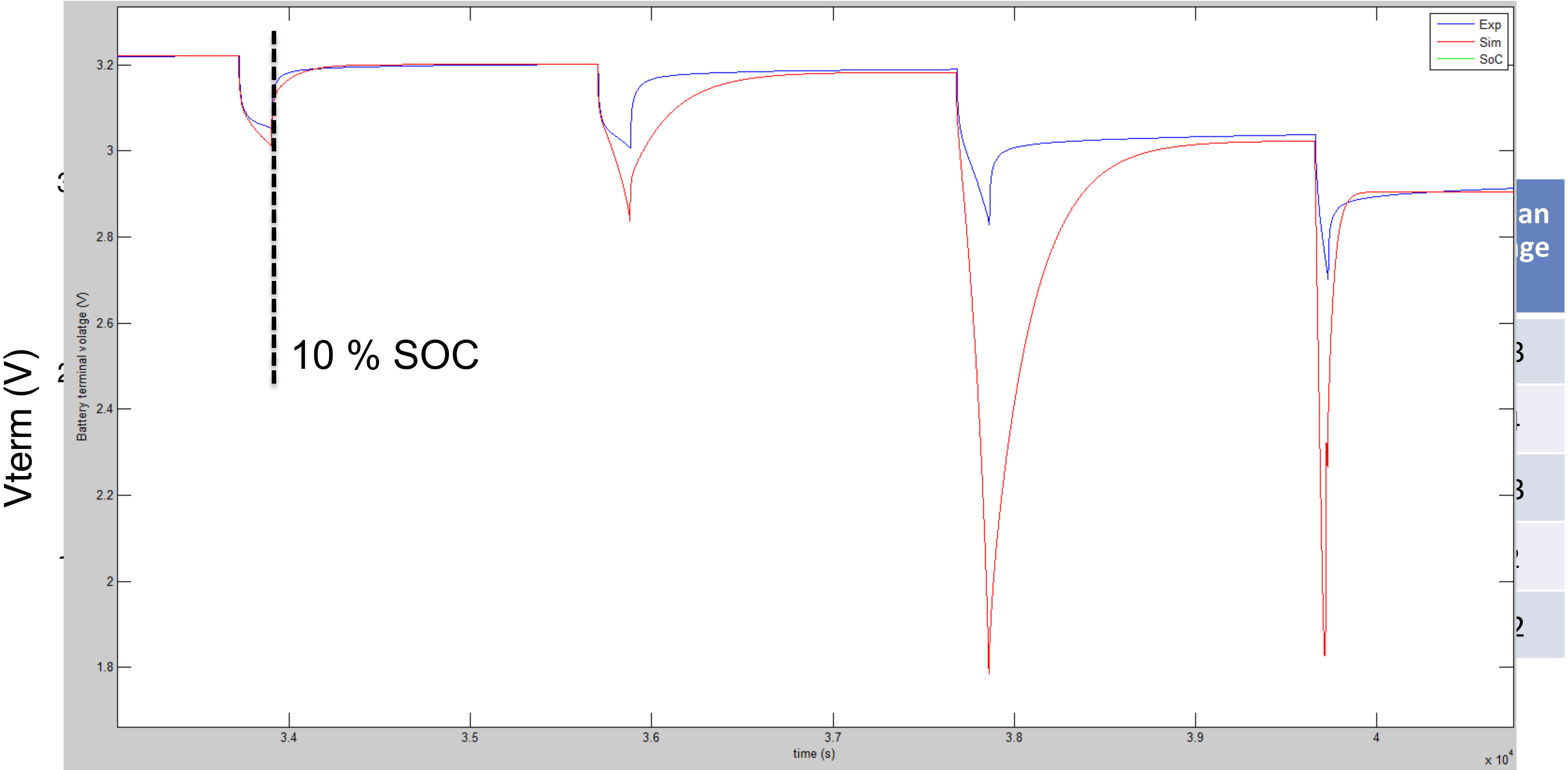
EEC Model Block Diagram Simulink

- The parameters values are extracted using HPPC
- The parameter values are sensitive to the current direction to compensate for hysteresis in the OCV



Battery Model Validation

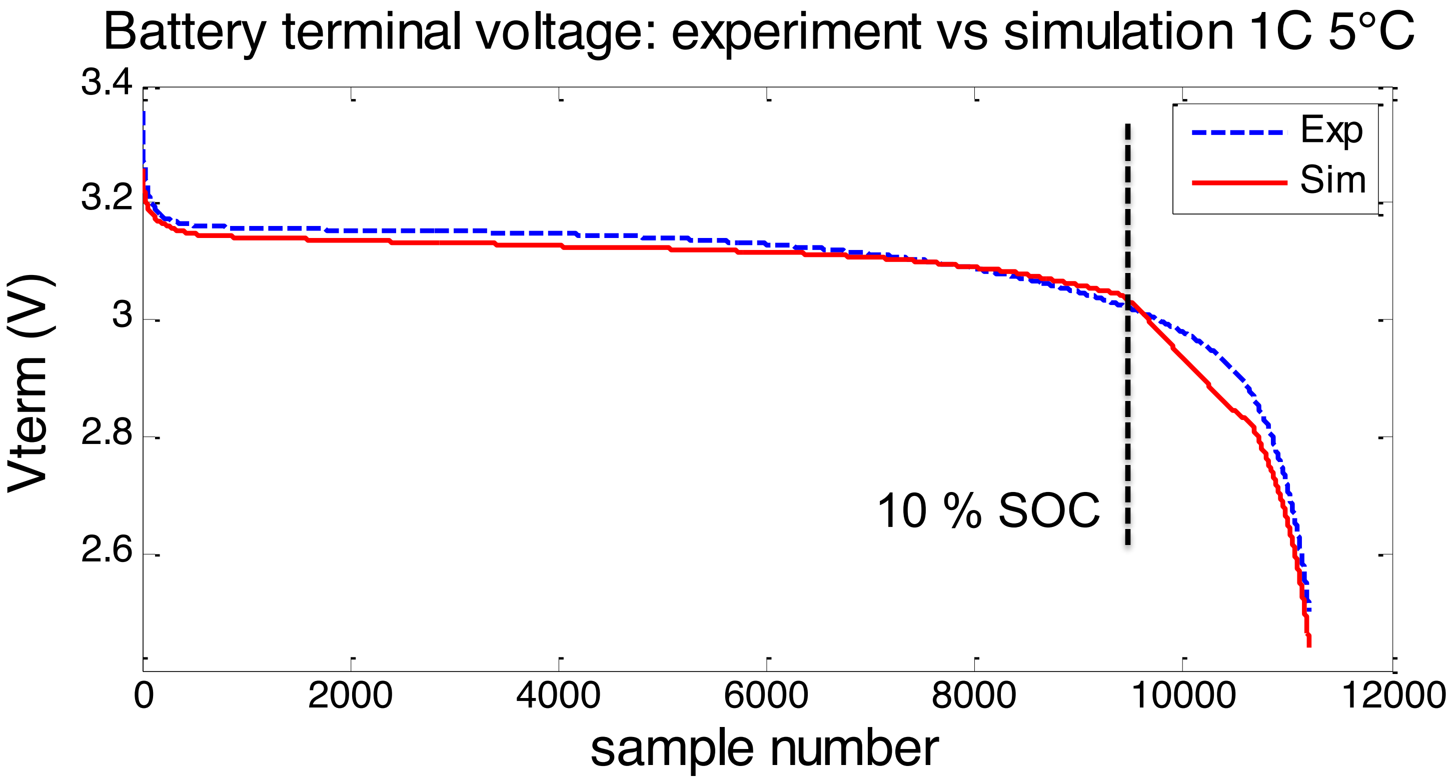
- Test 1: Reapply the current profiles used for the characterisation



Battery Model Validation

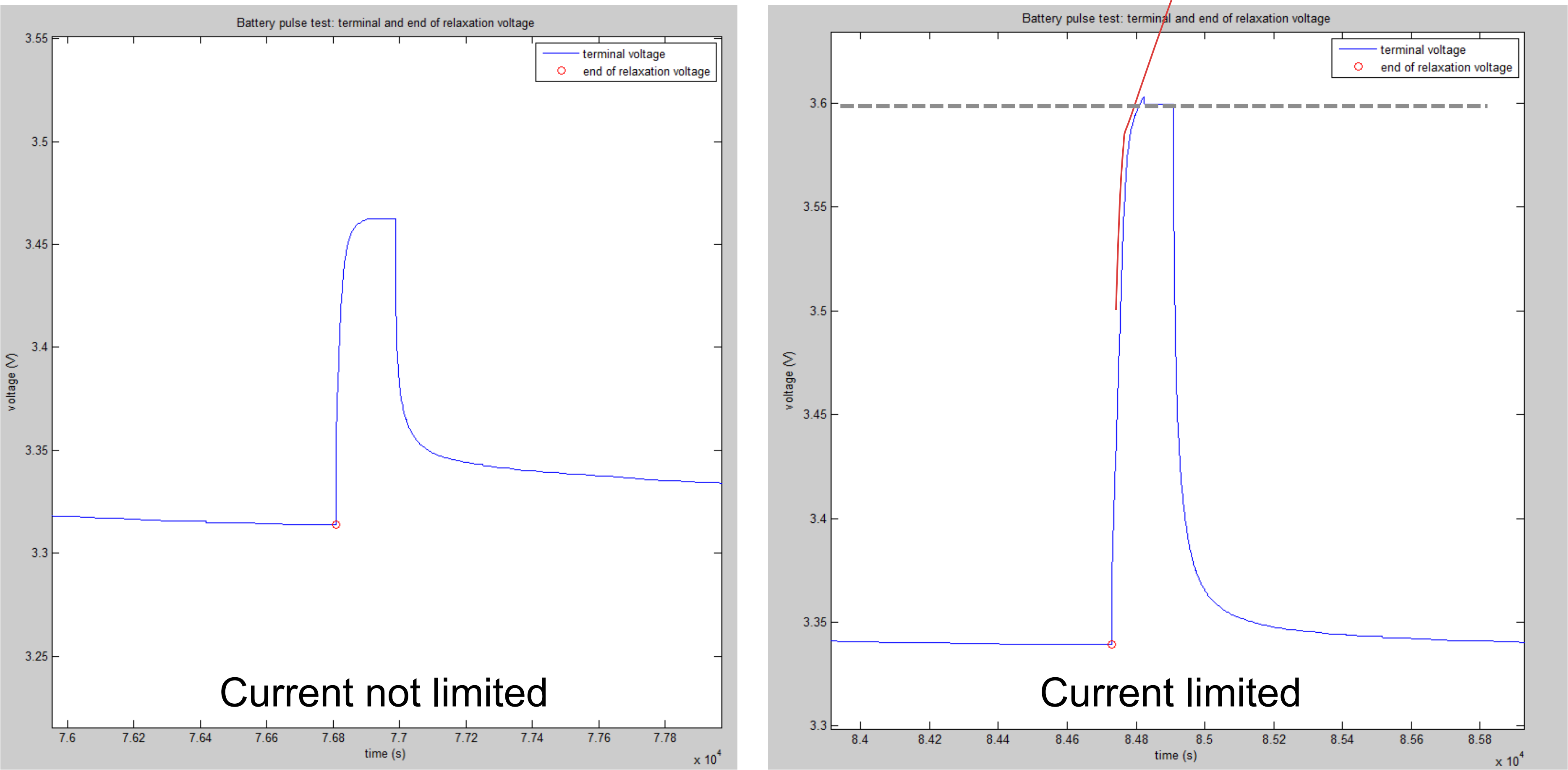
Test 2: Apply a constant current discharge at 1C and 5°C

C-rate	T (°C)	Error mean (V)	Error mean percentage (%)	Type
1C	5	-0.0166	-0.5490	CC



Parameter Extraction Explanation

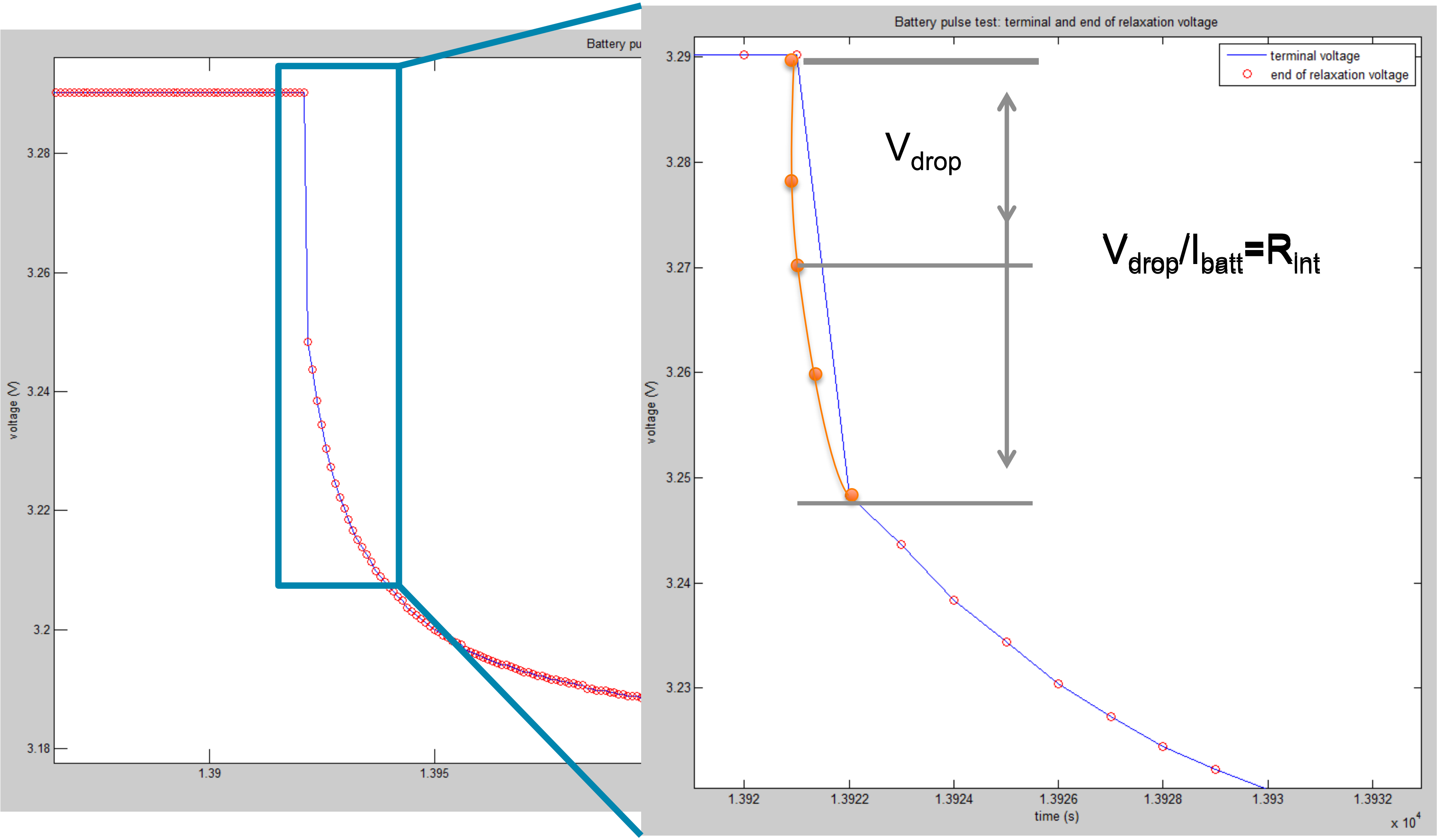
- Li-ion batteries are sensitive to over- and undervoltage situations
- At high and low SOC levels, the pulse current must be limited
- Leading to a deformed voltage curve



Applying a charge pulse at high SOC level

Parameter Extraction Problems

- Undersampling can lead to misidentifying the internal resistance



V_{drop}

$V_{drop}/I_{batt}=R_{int}$

Battery SoC Estimation

- **Coulomb counting:** integrates battery current but suffers from accumulated errors stemming from sensor noise and bias

Solution: couple the state space model with an estimator which generates an estimated value of the SOC by observing the battery current and battery terminal voltage whilst minimising the error between battery and model output.

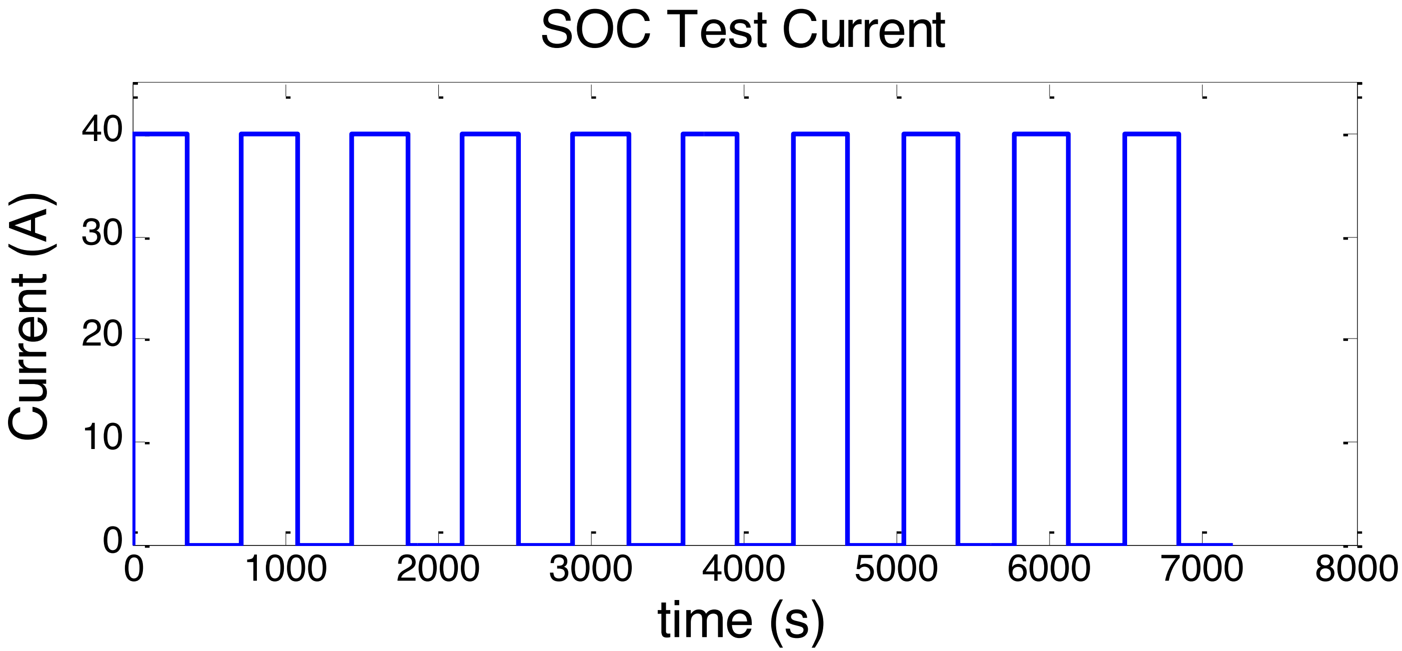
- **Kalman filter (KF)**: for linear systems

- **Extended KF**: non-linear with the current mean and covariance linearised

SOC Estimation Validation

- The non-linear battery model is subjected to a pulsed load current at 40 A
- The input current has added noise with a covariance of Q=1x10^{-3}, and the output added measurement noise with a covariance of R=1.

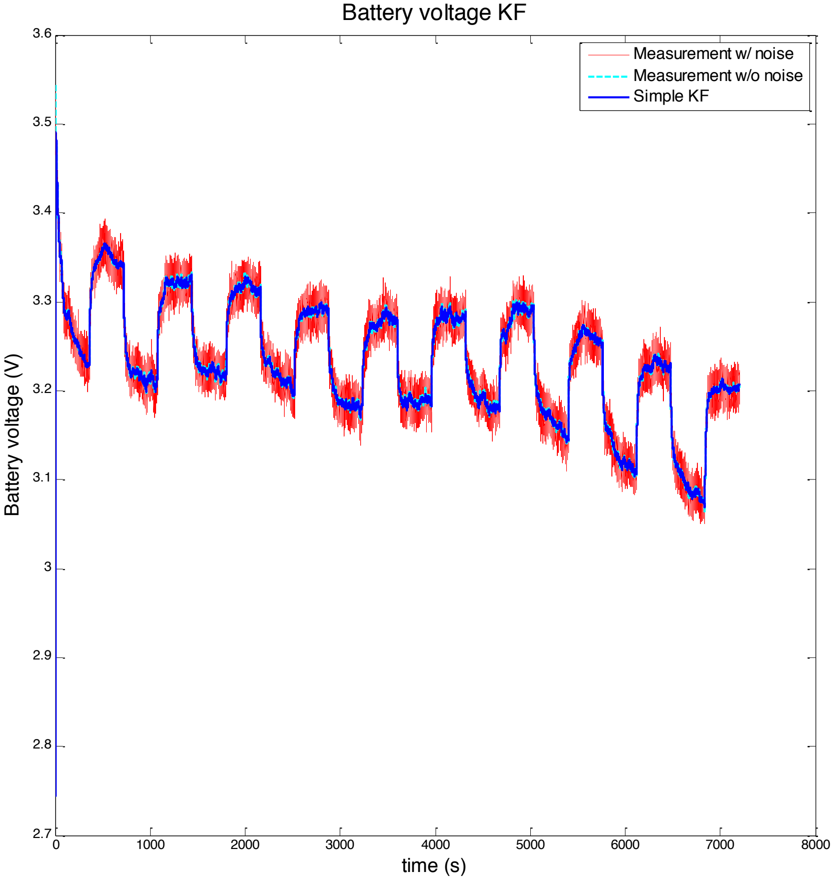
Parameter	Battery Model	Kalman Filter
X1_init	0.5	0
X2_init	0.2	0
SOC_init	1	0.8

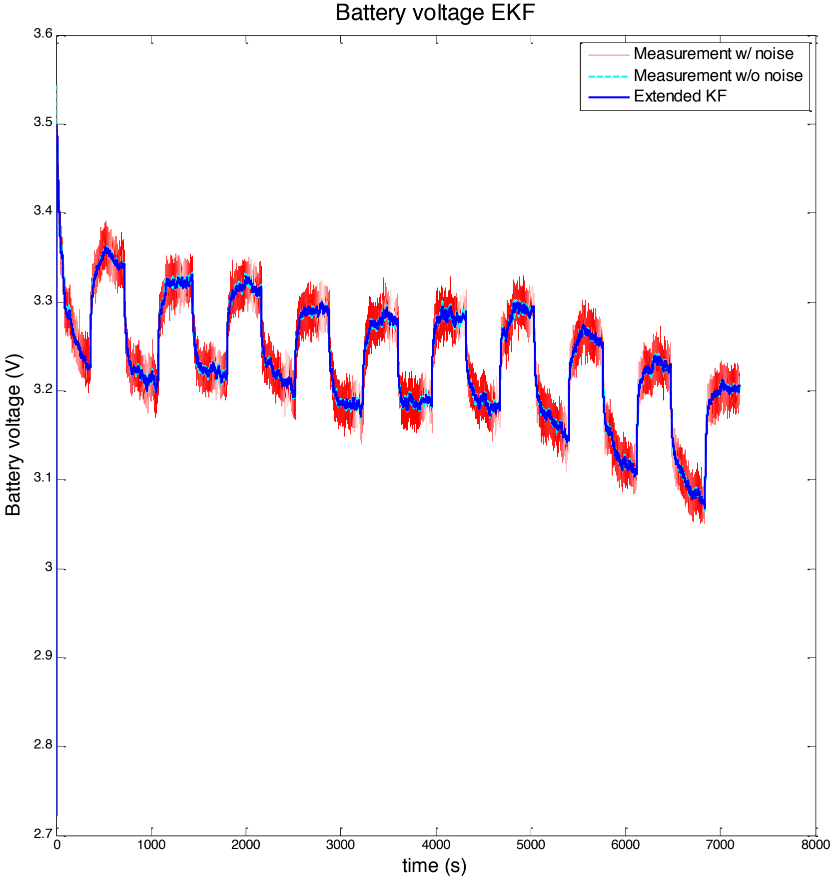


Results: Battery Terminal Voltage

- **Both filters track the battery terminal voltage very well**, showing that the KF would suffice should the estimation of the terminal voltage be the aim.

Battery Terminal Voltage Estimation		
Kalman Type	V_{term} error max (mV)	V_{term} error mean (mV)
Simple	16.68	1.90
Extended	10.80	1.80

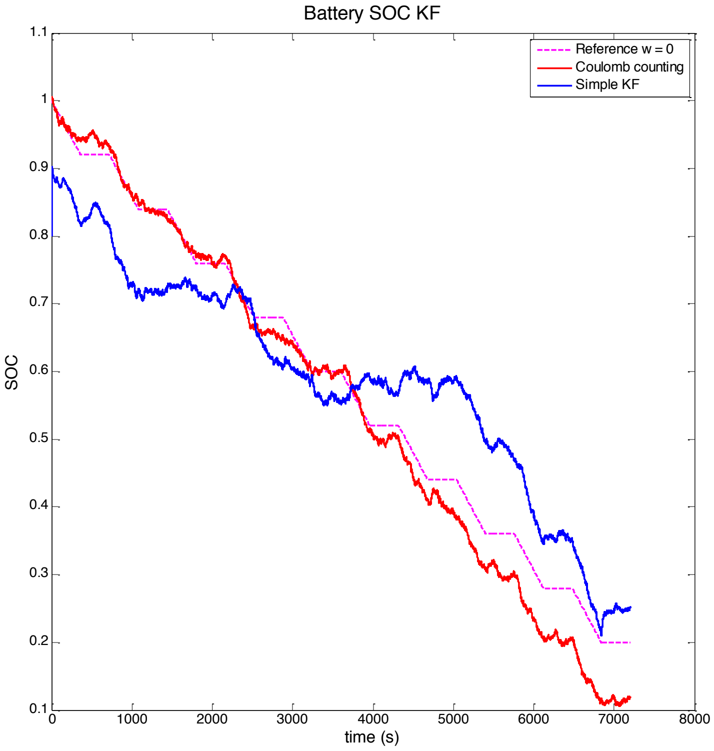

Battery voltage KF

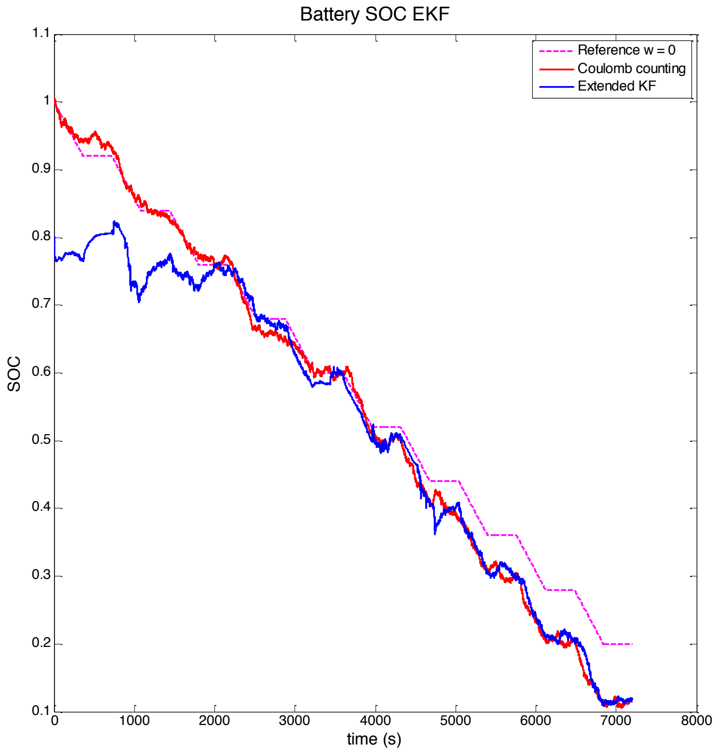

Battery voltage EKF

Results: SOC Estimation

- Simple Kalman filter fails to converge due it attempting to estimate a non-linear process using a linear model

SOC Estimation			
Kalman type	SOC error max	SOC error mean	Convergence time (s)
Simple	-	-	-
Extended	0.0628	0.011	1991


Battery SOC KF


Battery SOC EKF

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- **THE HYBRID APU**
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  - APU Test Bed
  - Test Bed Limitations
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Fuel Cell for APU

Replacement of the gas turbine with a FC holds potential benefits:

- reducing noise and exhaust gas pollution
- producing water usable for on-board purposes
- **DC output simplifies electrical interfacing to the HVDC bus**
- **estimated fuel efficiency of 61% for sea level and 74% for altitude conditions versus the average 20% of the turbine APU.**

Hybridizing the FC with an energy storage element holds benefits:

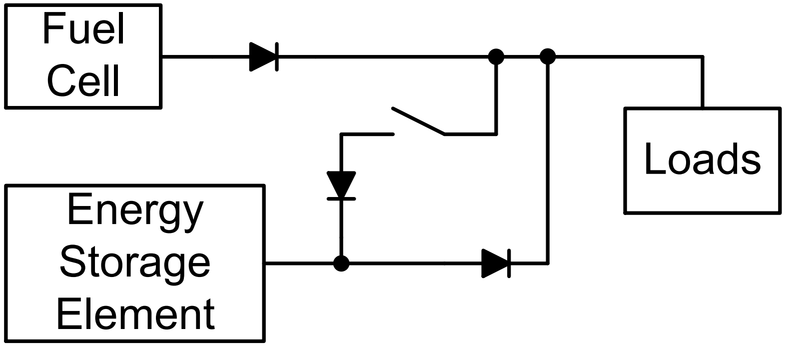
- near constant current operation
  - reduce operational stresses, extending operational life
  - operation in highest efficiency region

Given multiple sources energy management becomes essential to reach and impose system operational goals and constraints

Hybridization Techniques

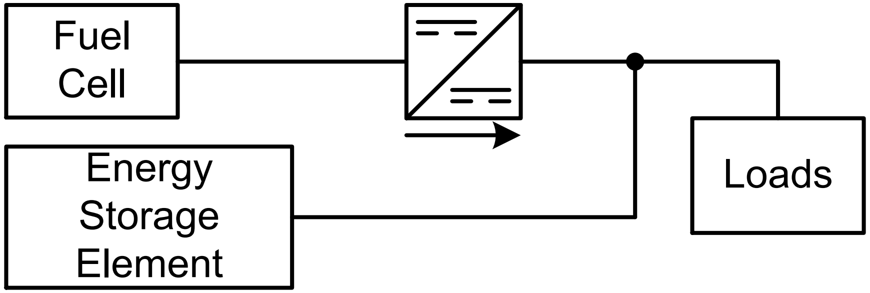
Passive power sharing

Passive hybridization through direct coupling

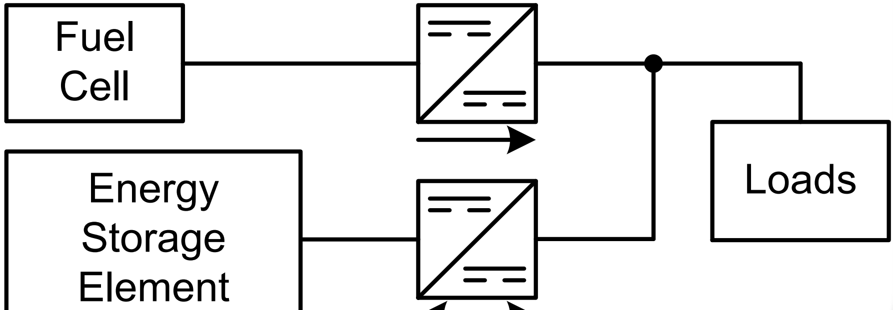


Active power sharing

Active hybridization through semi–direct coupling



Active hybridization through indirect coupling



☑ Control each source individually
Maintain constant bus voltage

☒ Two converters increases control complexity and increases weight

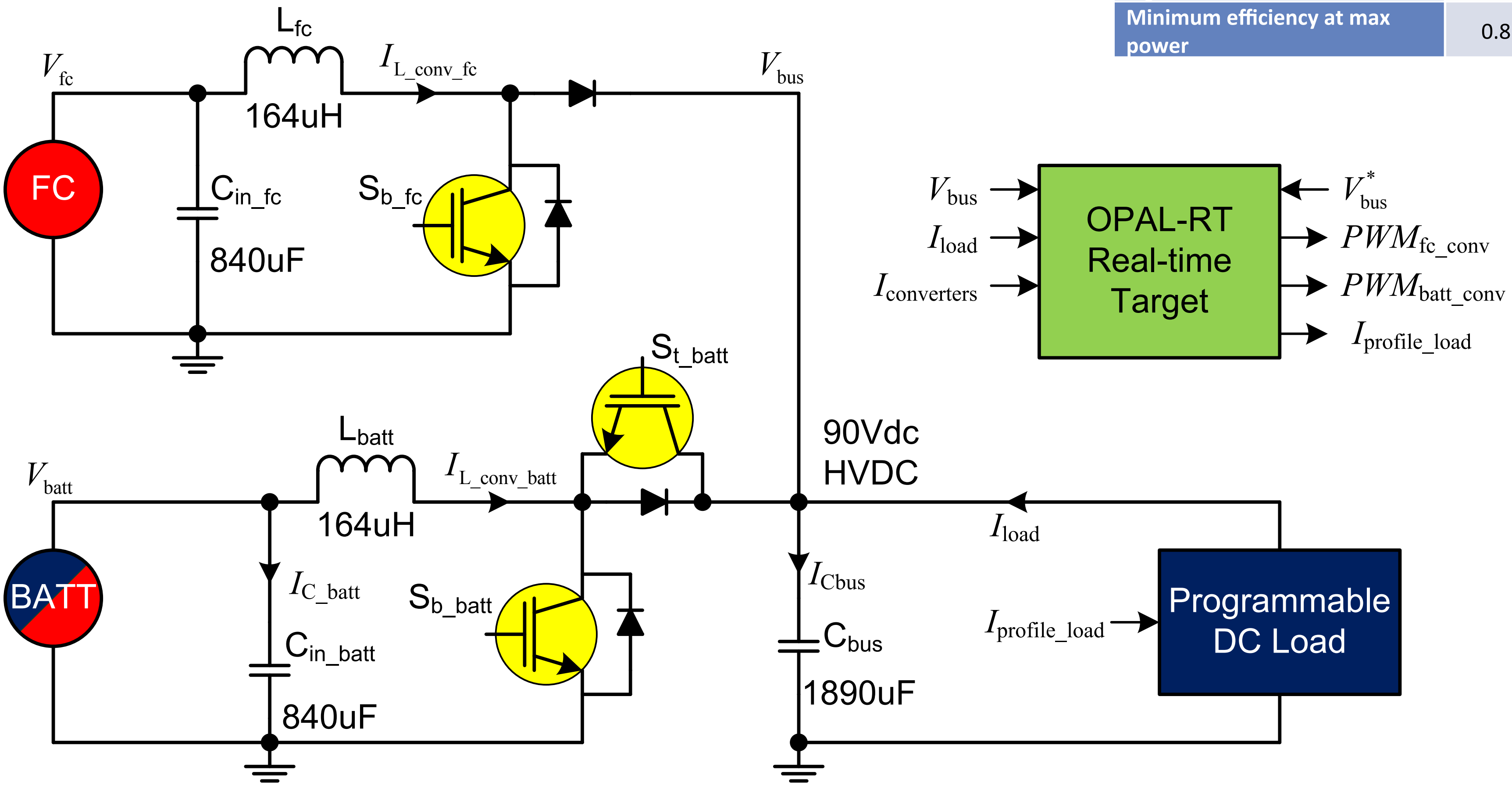
Hybridized APU Test Bed

MIPEC: multiple-input power electronic converter (Ferreira et al., 2008)

Fuel cell	
Type	PEM
Maximum net power	1.2 kW
Operating net voltage range	23 V to 41 V
Voltage at rated net power	26 V
Current at rated net power	46 A
Number of cells	47

Battery	
Type	Li-ion (LiFePO$_4$)
Operating voltage range	24 V to 28.8 V
Nominal voltage	25.6 V
Nominal capacity (C/2)	100 Ah
Nominal energy	2.56 kWh
Cell configuration	8s2p

MIPEC Converter	
Fuel cell and battery inductor	164 µH (50mΩ)
Bus capacitor	1890 µF (69mΩ)
Bus reference voltage	90 V
Buck output capacitor	840 µF (69mΩ)
Switching frequency	20 kHz
Maximum output power per leg	510 W
Minimum efficiency at max power	0.855 (boost)



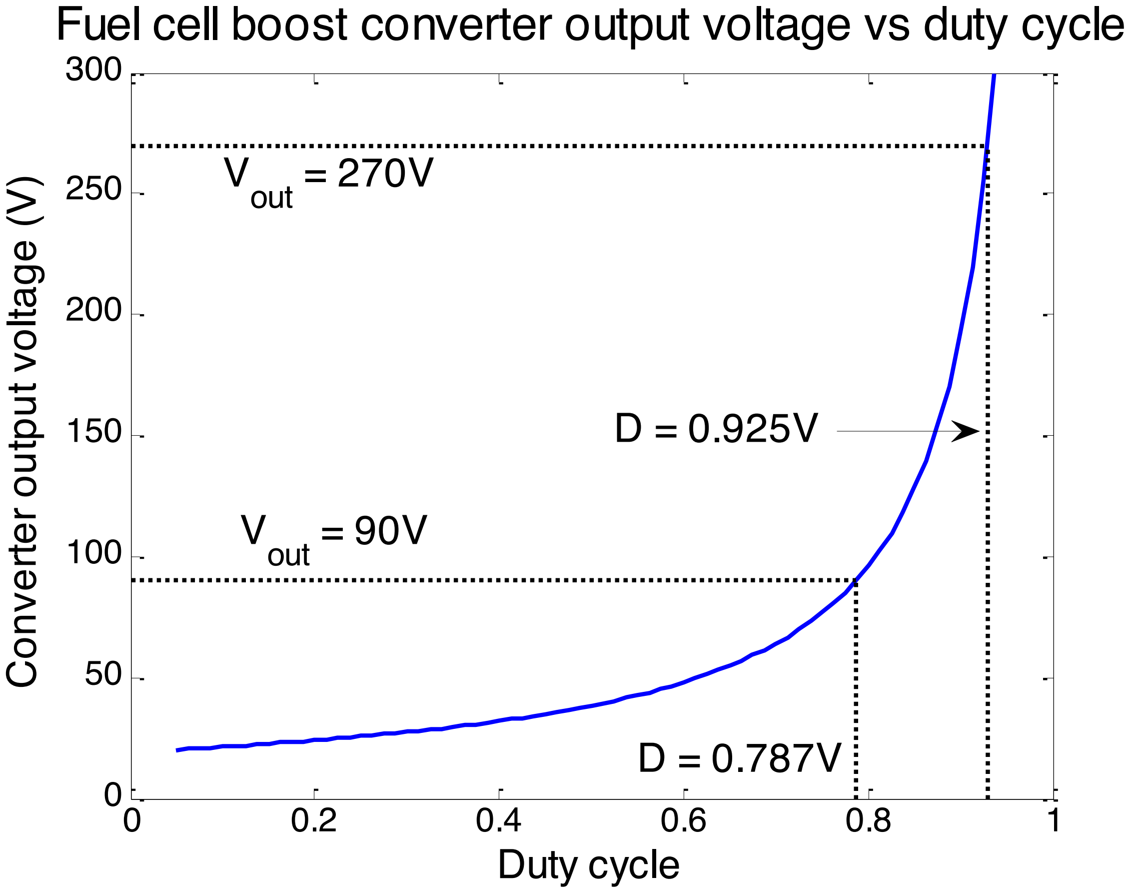
Test Bed Limitations

For basic boost converters it is advised to

•maintain the duty cycle of a boost converter below the ”knee”, i.e. D ≤ 0.8,

•not exceed an output-input voltage ratio of more than 6

otherwise control loop stability becomes an issue.



$$D = 1 - \frac{\eta \cdot V_{in}}{V_{out}} = \frac{0.8 \cdot 24}{270} = 0.929$$

$$\frac{V_{out}}{V_{in}} = \frac{270}{24} = 11.25$$

$$D = 1 - \frac{\eta \cdot V_{in}}{V_{out}} = \frac{0.8 \cdot 24}{90} = 0.787$$

$$\frac{V_{out}}{V_{in}} = \frac{90}{24} = 3.75$$

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- Small Scale Test Bench
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- The Hybrid APU
- **ENERGY MANAGEMENT SYSTEM**
  - Goals
  - Hierarchy
  - Level 1 Fuzzy Power Split
  - Level 2 Mode Determination
  - Level 3 Converter Control
- Simulation and Experimental Results
- Conclusions

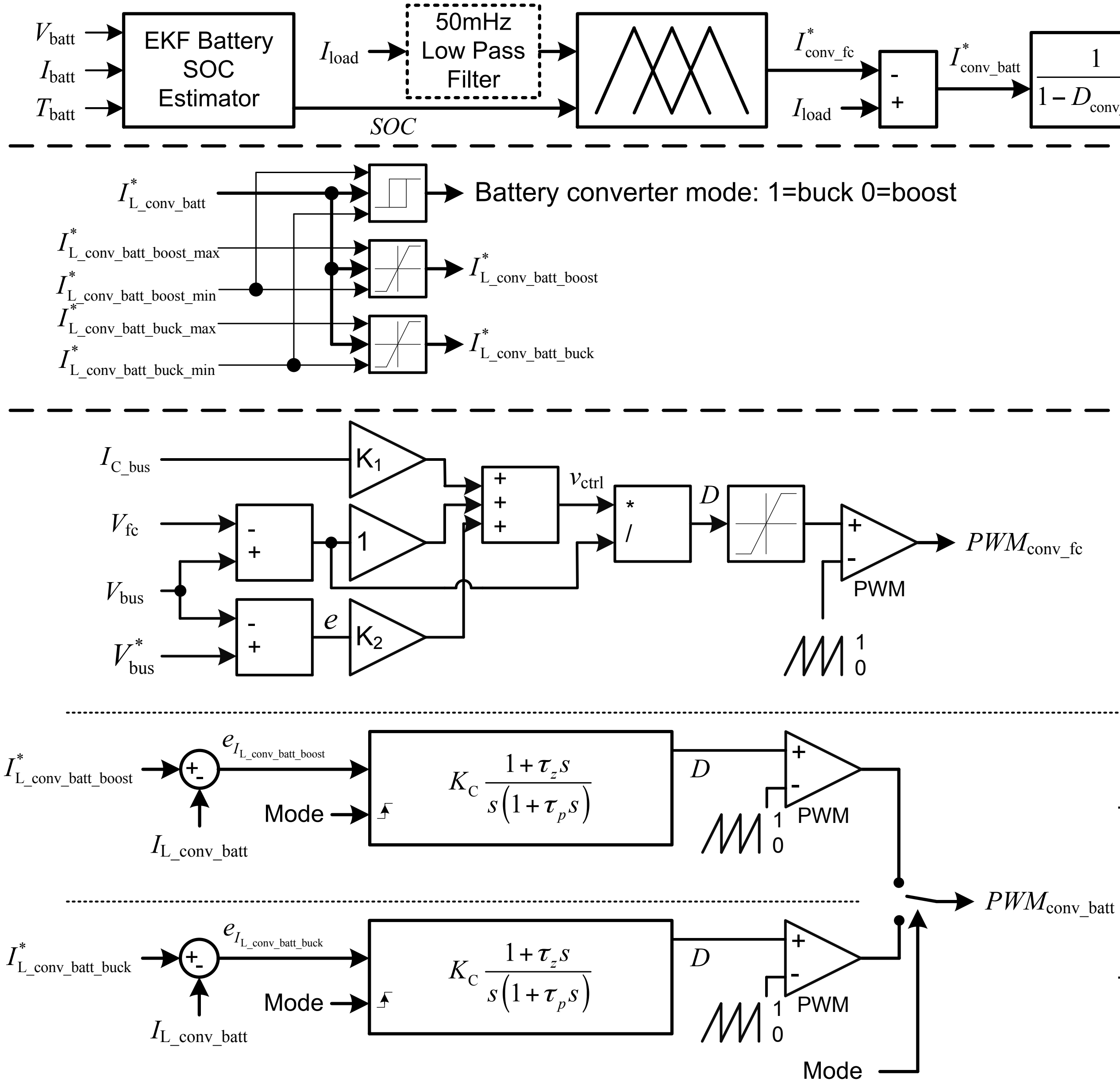
Energy Management Strategy (EMS)

The EMS goals, i.e. operational constraints, are:

- avoid operation of the fuel cell at its maximum power, instead opting for its nominal power for higher efficiency and extended lifetime
- maintain the battery SOC at an optimal range of 0.5<SOC<0.9 for it to always be able to supply and absorb power
- avoid operation of the battery at low SOC<0.5 values in order to extend its operational lifetime.

In this study the FC maintains the bus voltage whilst the battery is current controlled to supply load transients

EMS Hierarchy



Supervisor Level 1

Power Splitting

Supervisor Level 2

Converter Mode Determination

Fuel Cell Boost Converter

Sliding Mode Controller

Maintain bus voltage

Control Level 3

Battery Boost Converter

Type II Compensator

Current reference tracking

Converter Control Loops

Battery Buck Converter

Type II Compensator

Current reference tracking

Fuzzy-logic Supervisor

Advantages:

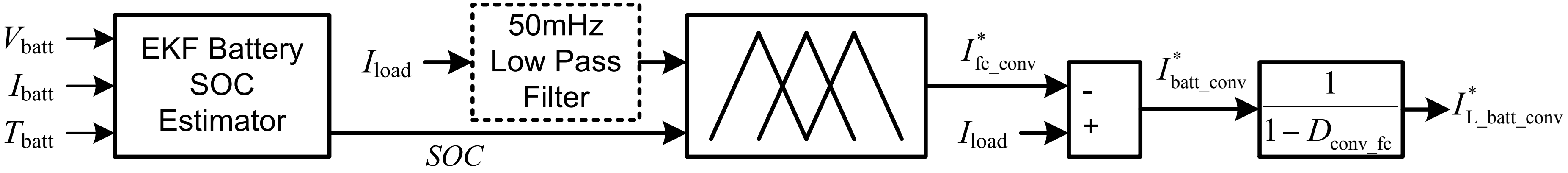
- well adapted to multi-objective energy management
- accommodates the intrinsic non-linear characteristics of the sources
- achieves adequate efficiency without compromising source performance and reliability
- aids in building comprehensive and intuitive control strategies.

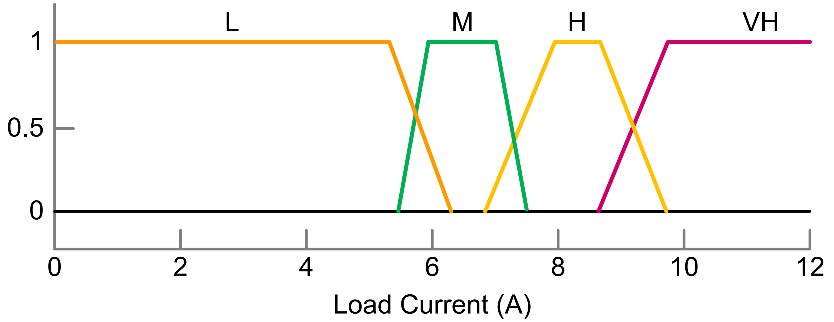
Disadvantages:

- relies heavily upon the designer's knowledge of the power system sources in order to correctly define the fuzzy rules and membership functions.

Membership Functions

Supervisor Level 1: Power Splitting





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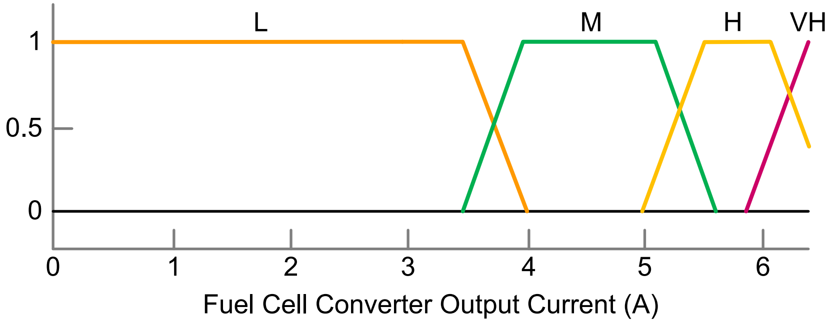

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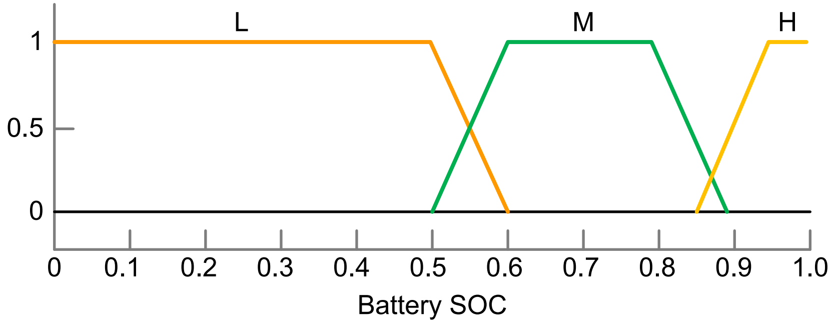


c)

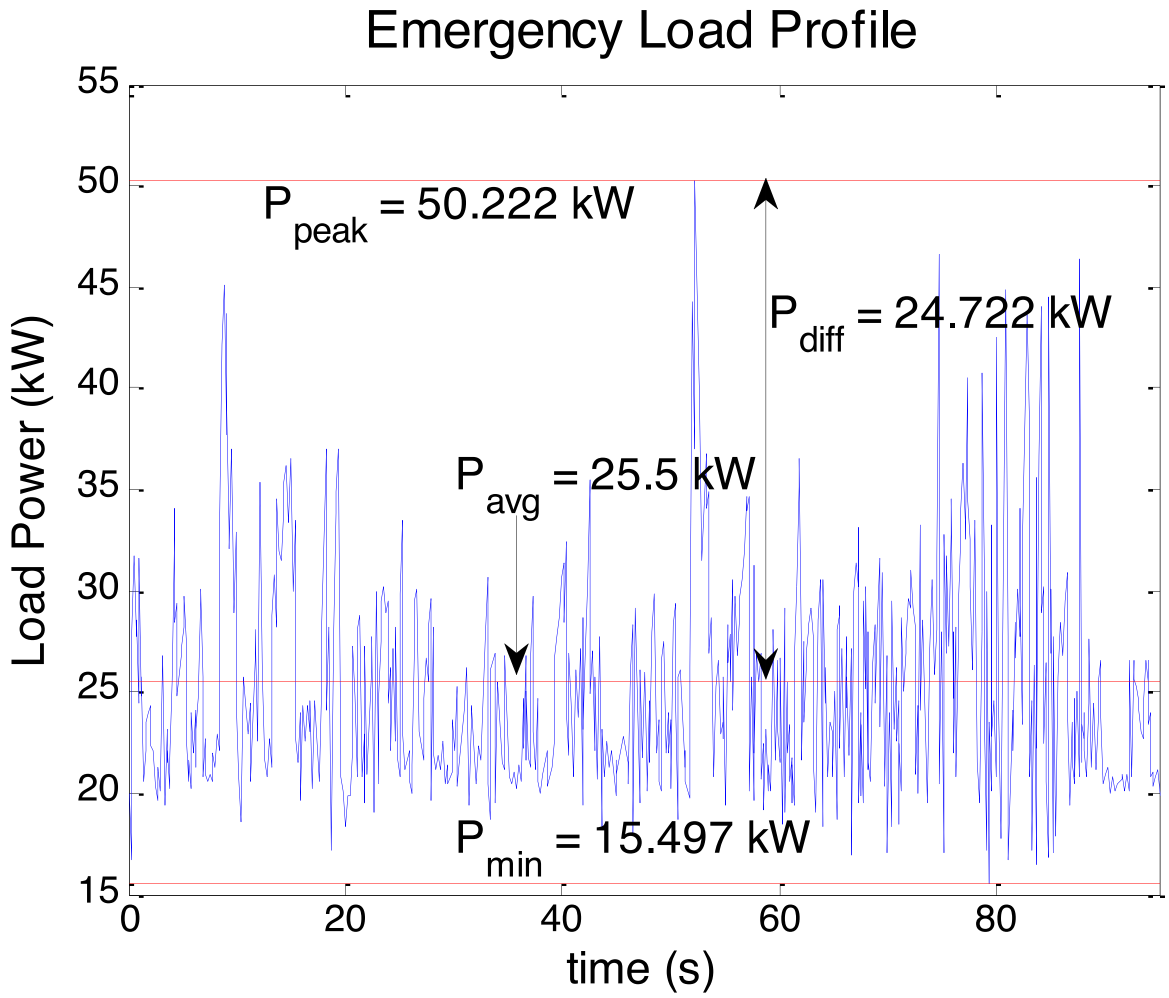
I_{load}	SOC	$I_{\text{fc\_conv}}$
IF	*AND IF*	*THEN*
L	L	VH
M	L	VH
H	L	VH
VH	L	VH
L	M	H
M	M	VH
H	M	VH
VH	M	VH
L	H	L
M	H	M
H	H	H
VH	H	VH

d)

Contents

Emergency Load Profile

- Study based on a hypothetical MEA the same size as an Airbus A330 with electrohydraulic actuators (EHA) (Langlois, 2006)
- Scaled by 1/50 for SSTB



EHA total

- 5.5 kW average power
- 30 kW peak power
- 4.5 kW regen power

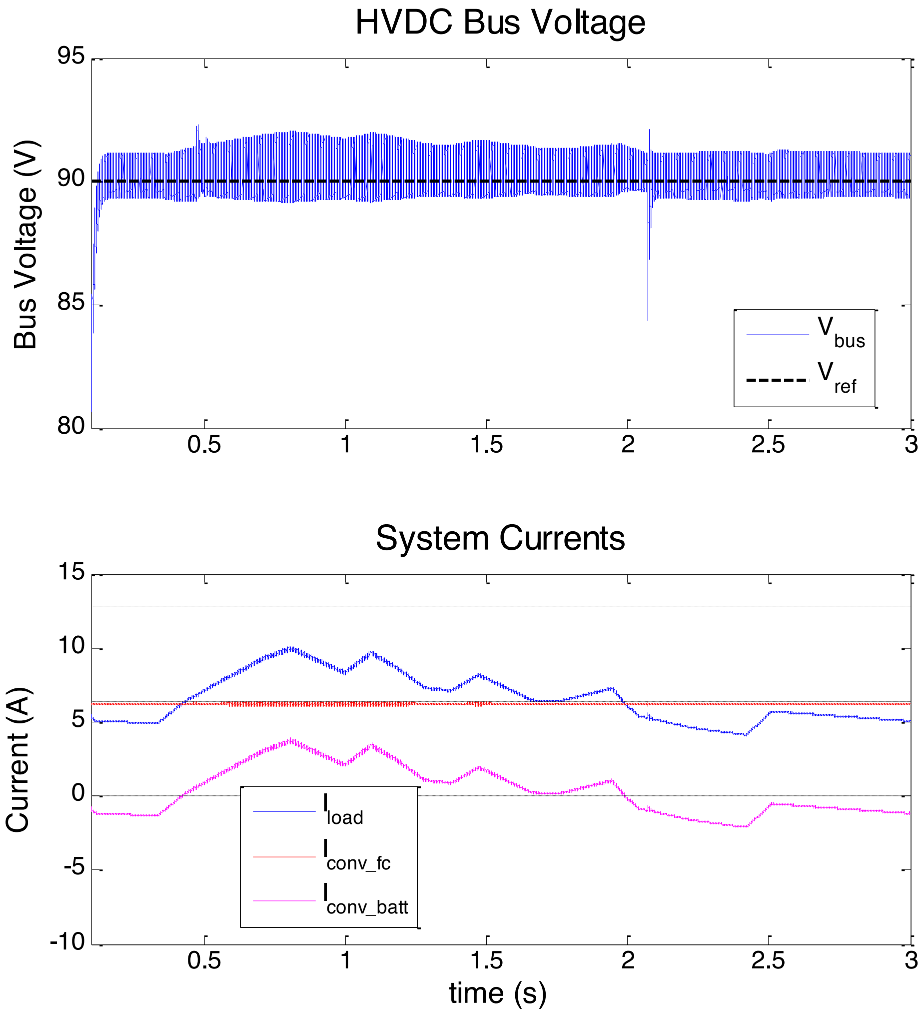
With 20 kW static load

- 50 kW peak load
- 25.5 kW average load
- 24.5 kW fluctuating power

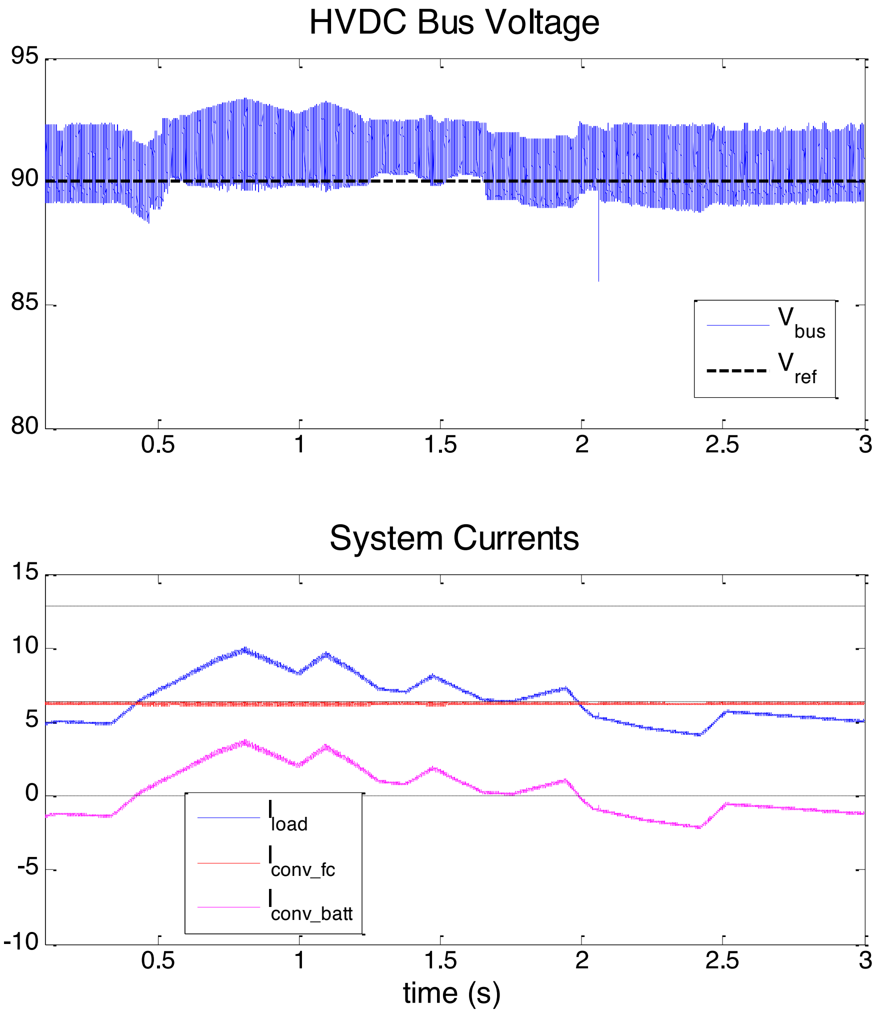
Hybrid APU Load Profile Test (VETB)

- Bus voltage and system currents

Cascade PI Control

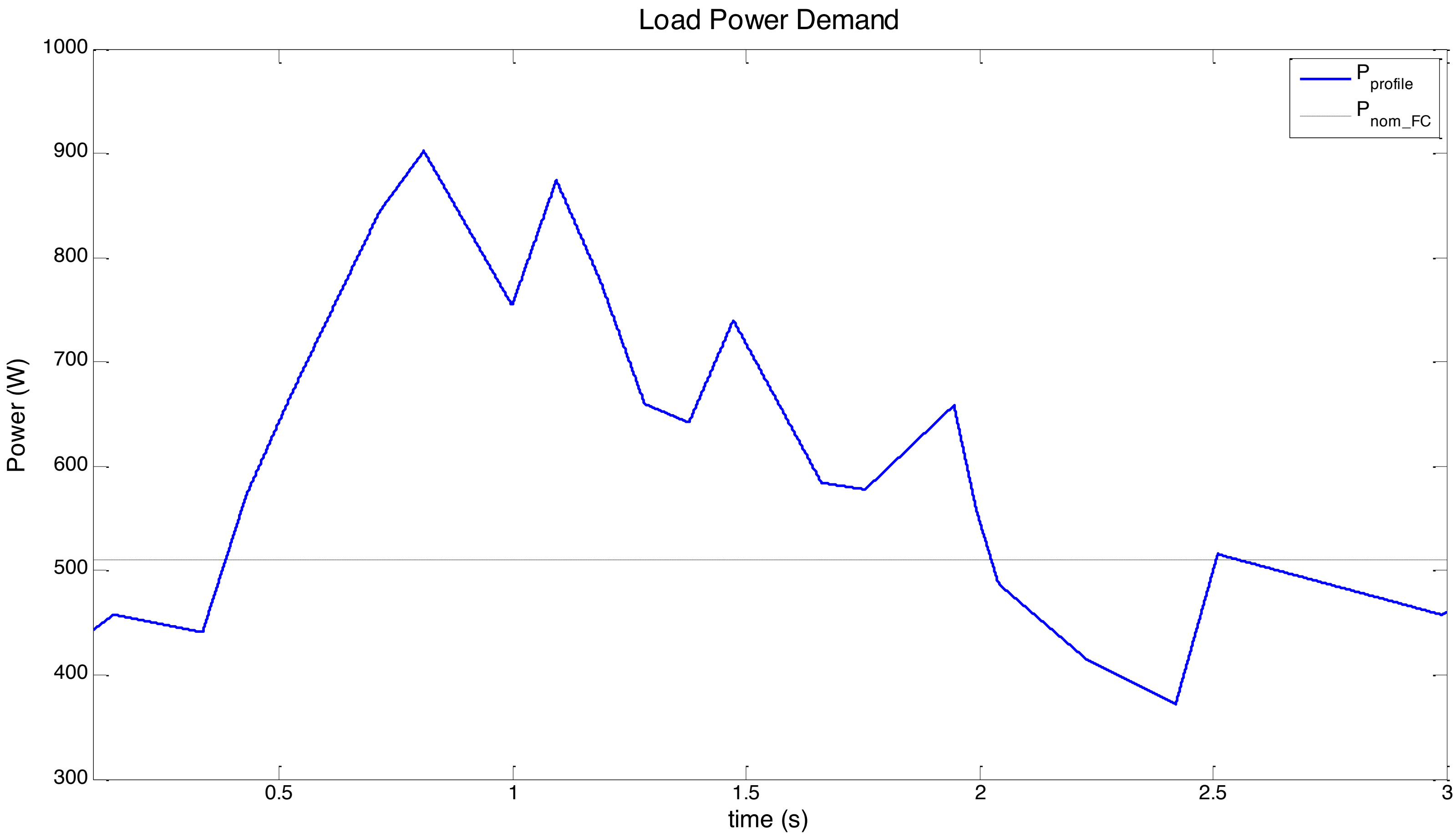


Sliding Mode Control



Hybrid APU Load Profile Test

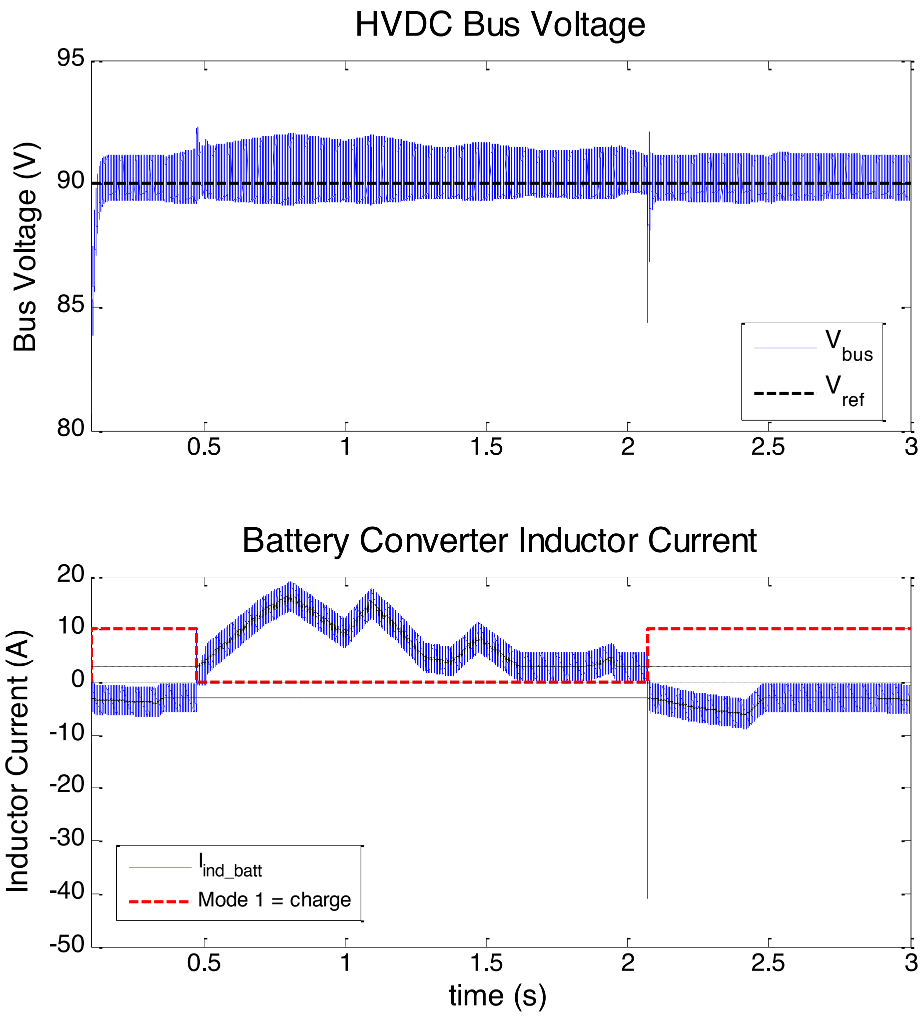
- Subject the hybrid APU to a dynamic section of the load profile



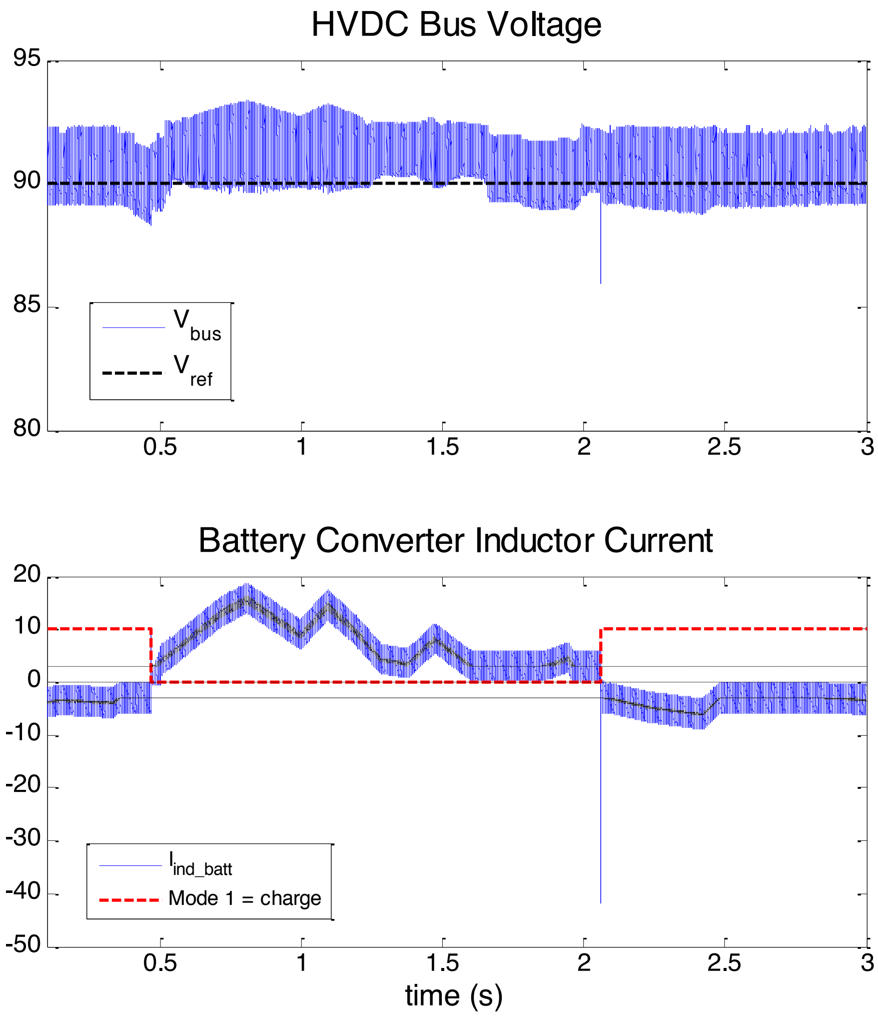
Hybrid APU Load Profile Test (VETB)

- Bus voltage and system currents

Cascade PI Control

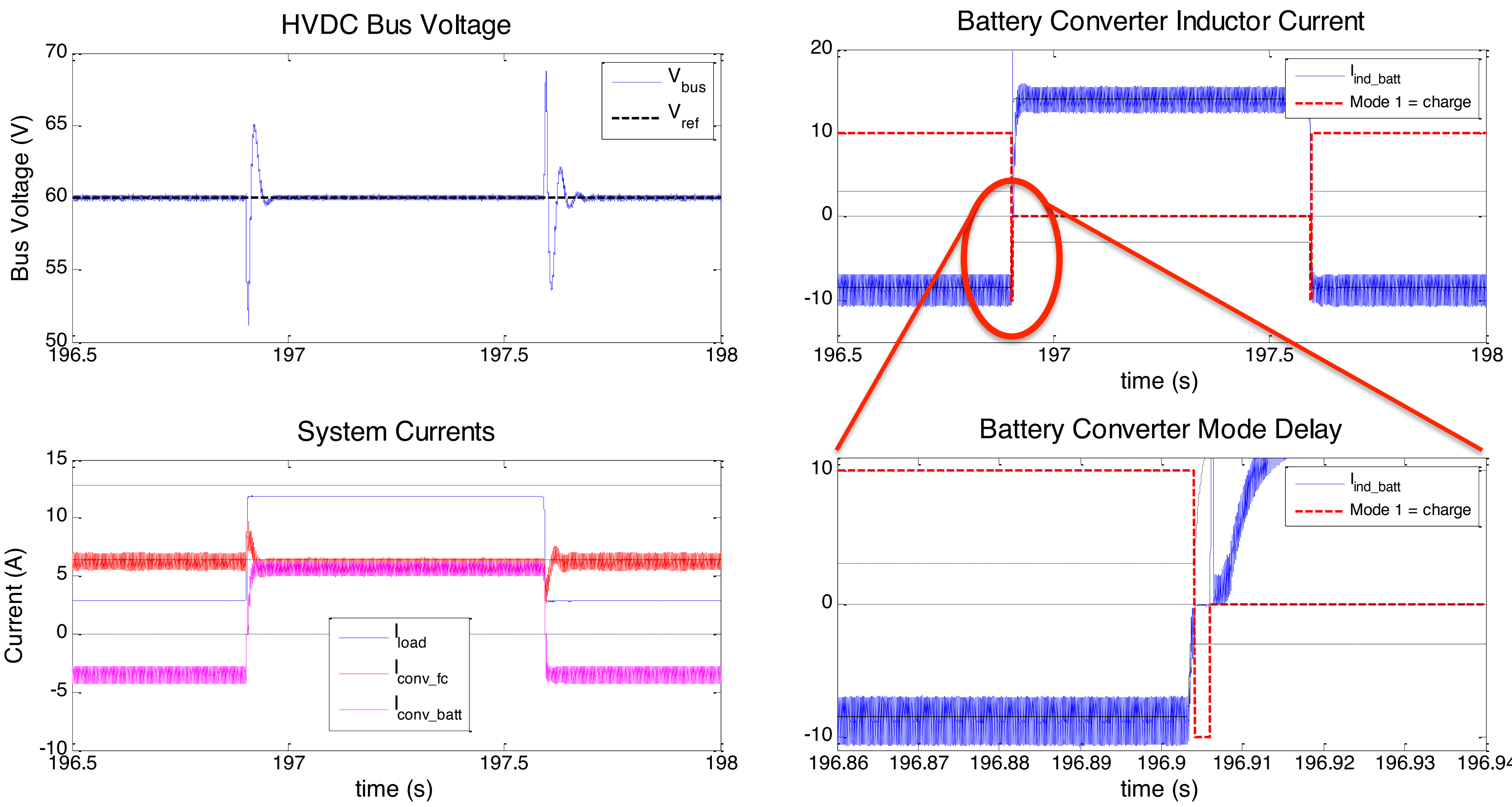


Sliding Mode Control



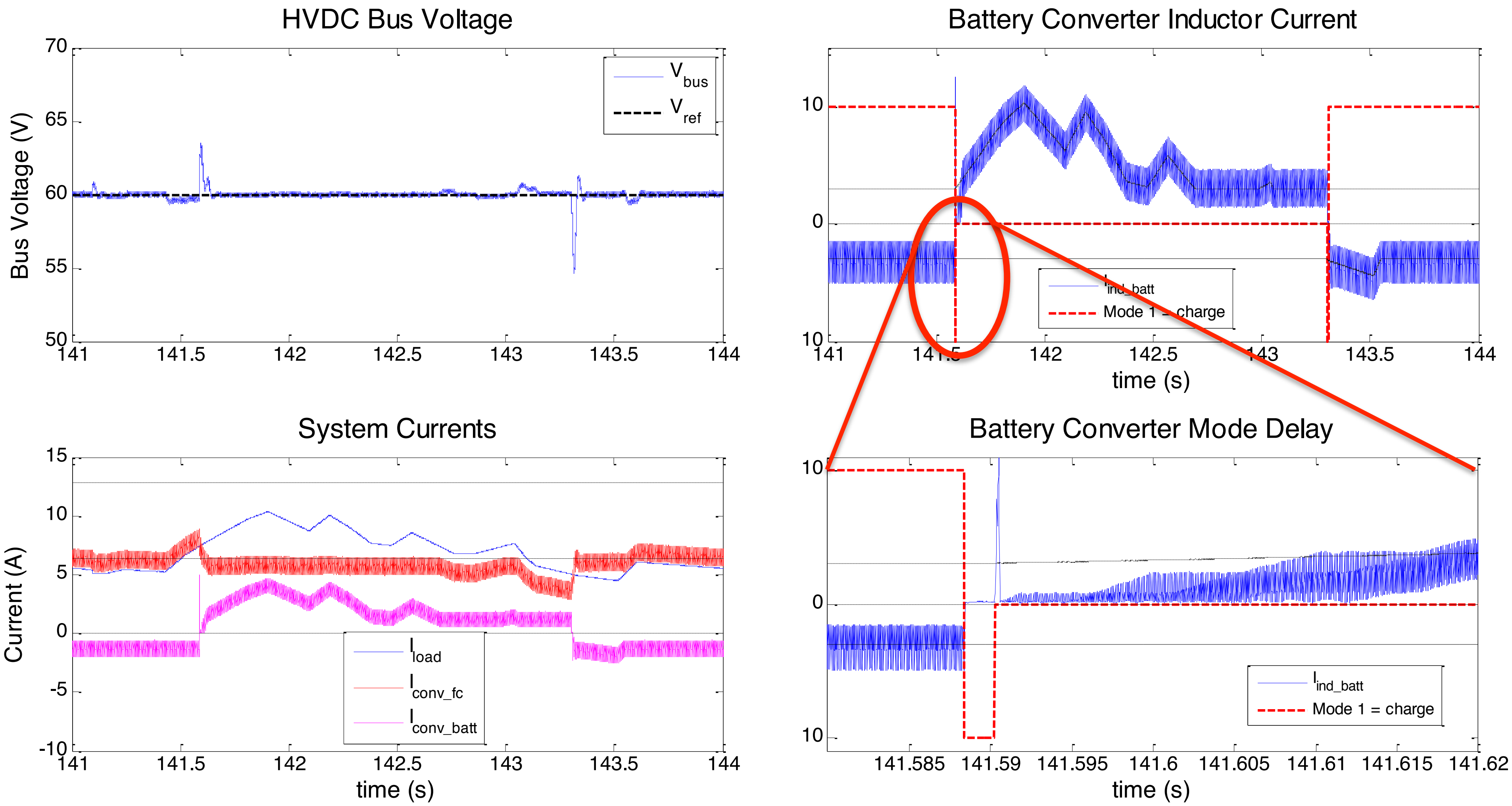
Hybrid APU Load Step Test (SSTB)

- Cascade PI control, step 200 W to 800 W
- **Transients within MIL-STD-704F range of V_{max} = 73 V, V_{min} = 44 V**



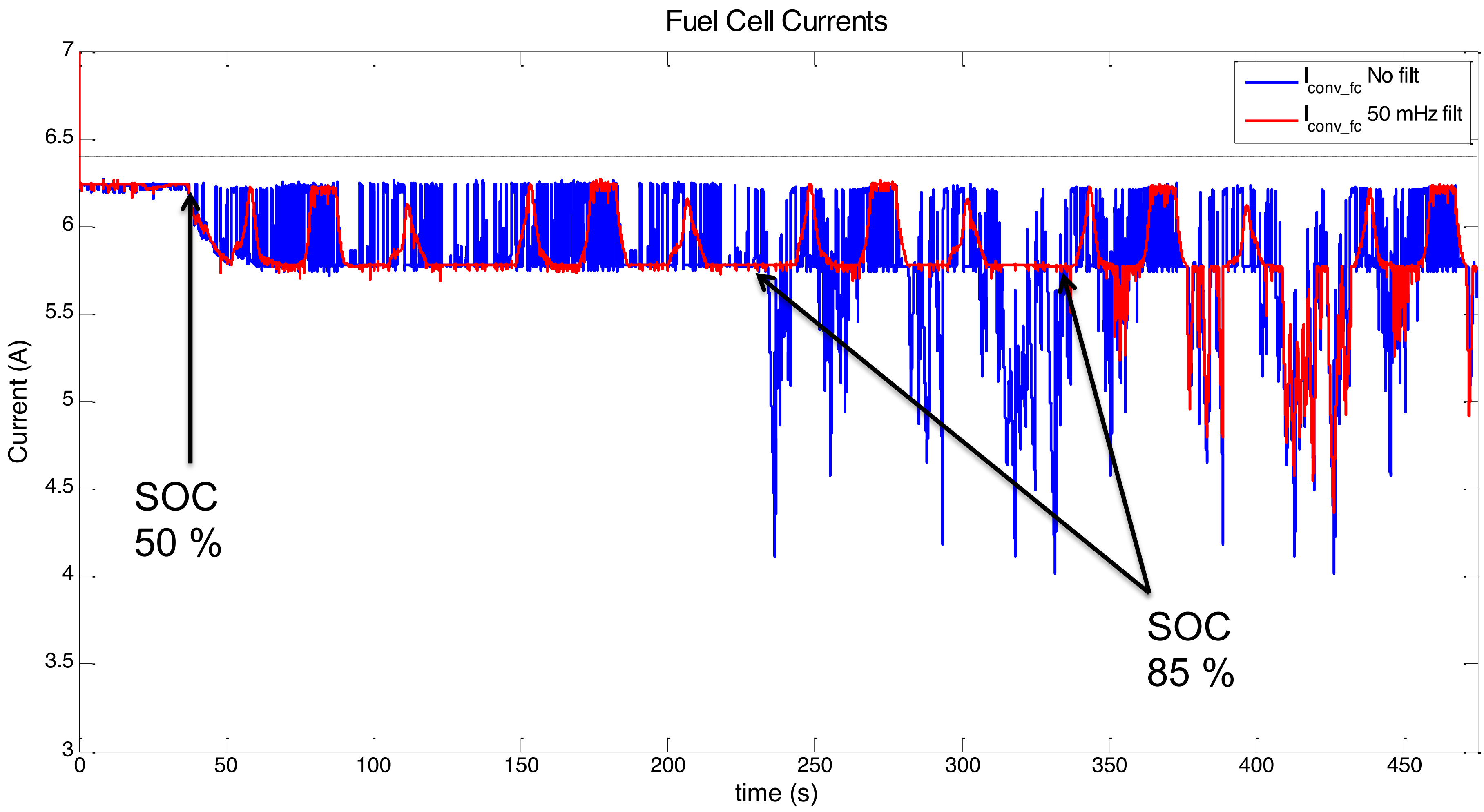
Hybrid APU Load Profile Test (SSTB)

- Cascade PI control
- **Transients within MIL-STD-704F range of V_{max} = 73 V, V_{min} = 44 V**

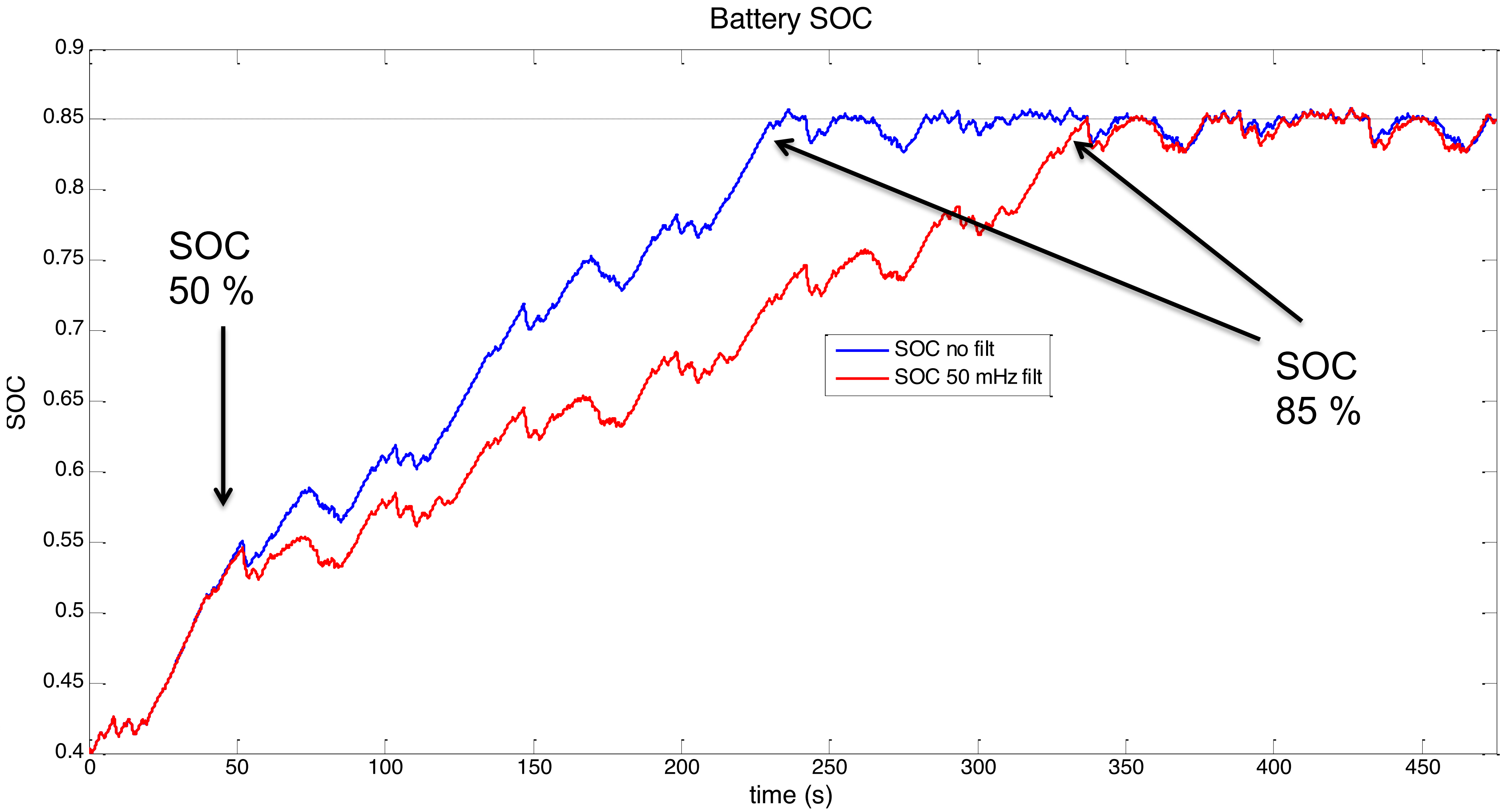


Fuzzy Supervisor Validation

The fuzzy-logic supervisor is validated assuming the worst case scenario of a battery SOC at 40 %, with and without frequency decoupling of 50 mHz.



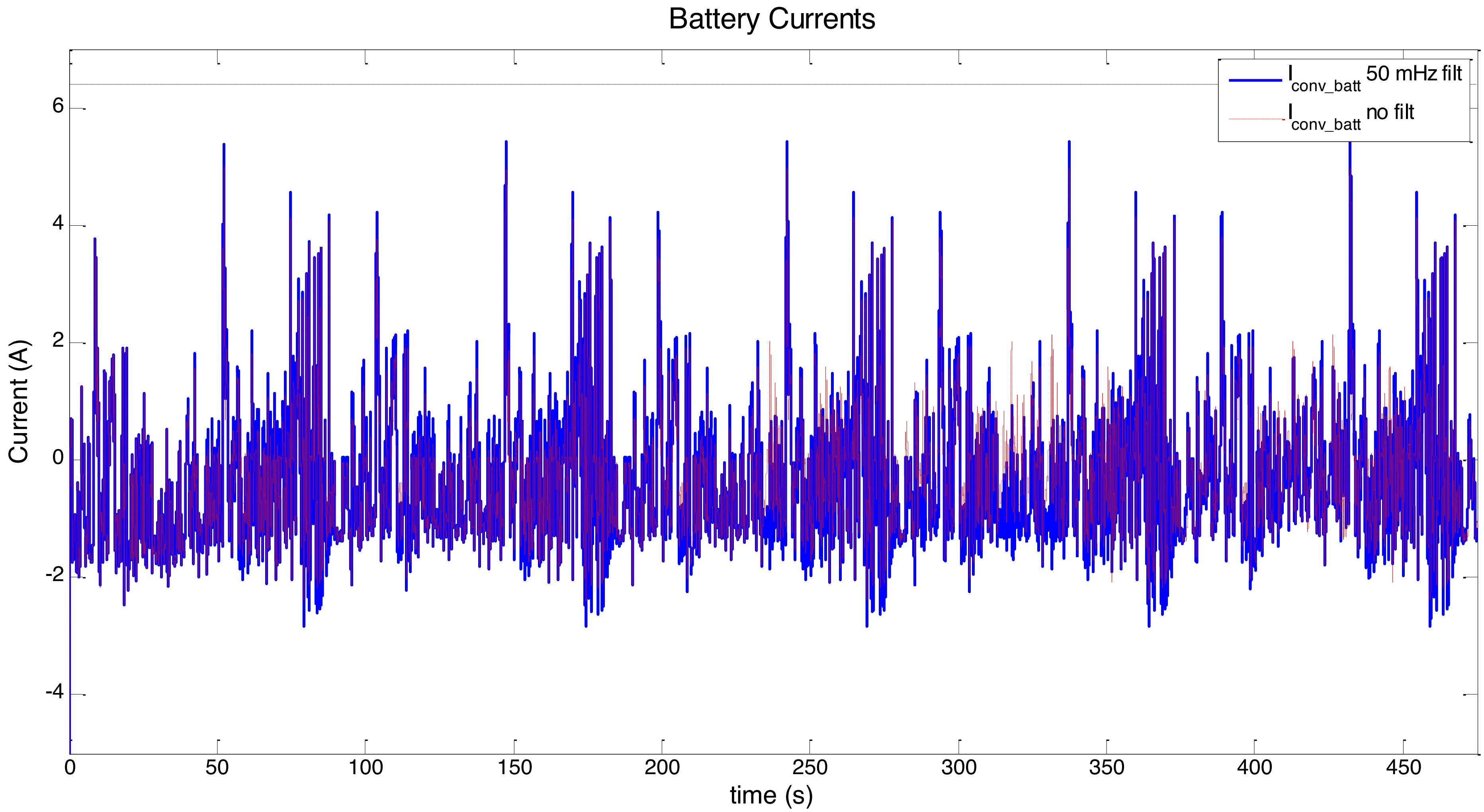
Fuzzy Supervisor Validation



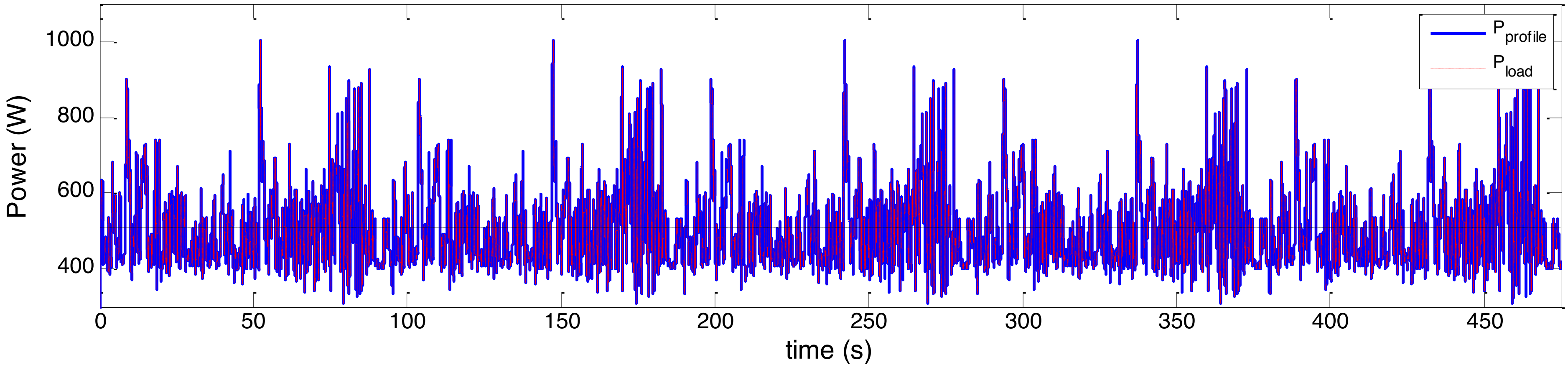
SOC
50 %

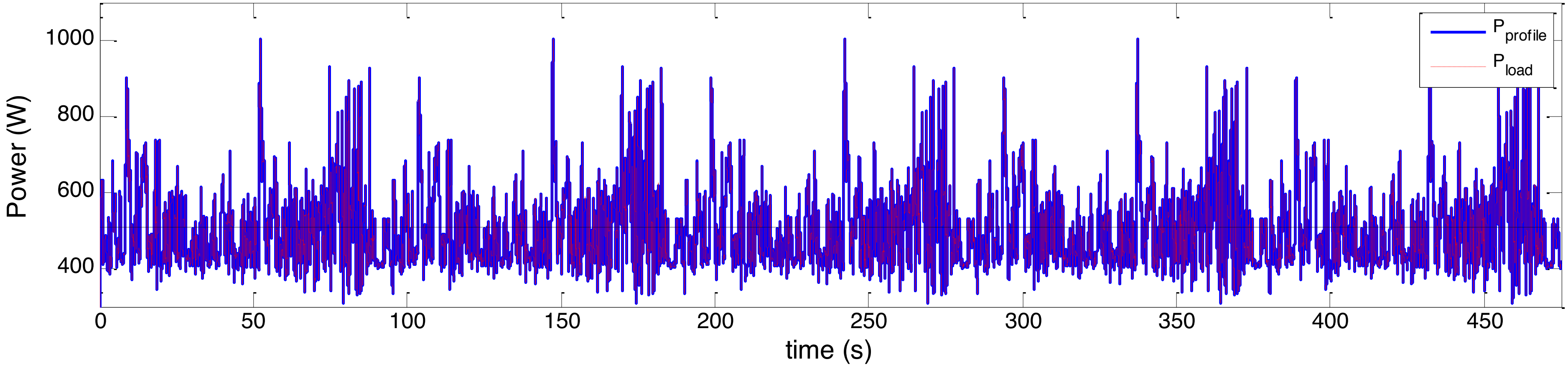
SOC
85 %

Fuzzy Supervisor Validation



Fuzzy Supervisor Validation


Load Power Demand no filter


Load Power Demand with 50 mHz filter

Contents

Conclusions

- 5 kW Small Scale Test Bench is derived from the COPPERbird ETB
- VETB models Li-ion battery with EKF for SOC estimation
- A PEMFC is hybridized with a Li-ion battery to replace the traditional gas turbine based APU
  - Active hybridization using indirect coupling allows active power sharing whilst maintaining a fixed bus voltage
  - The FC converter regulates the bus voltage whilst the battery converter handles load transients in current control
- The EMS assumes three levels
  - 1. Fuzzy-logic supervisor for power splitting
  - 2. Mode determination with hysteresis
  - 3. Converter level control employing SMC and type II compensators
- Fuzzy-logic supervisor attains EMS goals of maintaining the battery SOC around 85 % whilst avoiding operation of the FC at full power
- Being able to fulfil the load demand of the most stringent of flight phases, a FC and battery combination could well be used as an APU replacement.

Future Works

- Incorporate specially developed converters to attain 270Vdc operation, then reintegrate SMC
- Incorporate more energy storage elements such as supercapacitors
- The converter roles are to be swapped with the battery controlling the bus voltage with the fuel cell in current control
- Expand the VETB with models of the starter/generator (S/G), EMA, electrical taxiing, environmental control system (ECS), etc.
- Implement Electrical Load Management (ELM) algorithms for load shedding during emergency operations
- Incorporate more EMS goals such fuel cell current rate limiting, hydrogen consumption, etc., and expand EMS to the whole bench

Merci - Thank You