UNIVERSITY OF SALERNO

Department of Mechanical Engineering

Development of a Model-Based Diagnostics Tool for Solid Oxide Fuel Cells

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Presentation Outline

- Motivation, goals, approach
- Design/Control/Diagnosis oriented model for APU
- Application of the model
  - Design and Control
  - Simulation of a typical automotive auxiliary load profile
  - Diagnostics
- Conclusions

Motivations and goals

Motivations

- Developing SOFC technology to face environmental- and energy-related issues.
- High SOFC potential for both residential and mobile applications (high efficiency, cogeneration, modularity, fuel flexibility, low emissions and noise).
- Specific short-term target: enhance the development of highly-efficient SOFC-APUs destined to a wide application area (ground transportation, marine and airplane APUs).

Goals

- Development of model-based tools for Fast Design, Control and Diagnosis of SOFC systems.
- Adopt lumped modeling approach to meet the trade-off between computational burden, experimental efforts and model accuracy.

On-Field Diagnosis of SOFC Systems

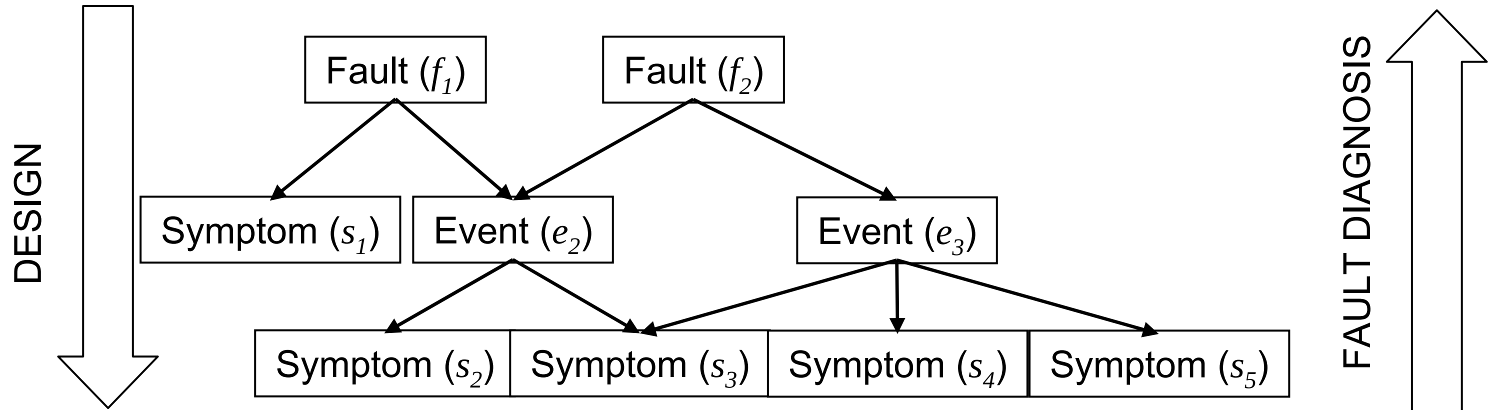
Objectives

- Prevent SOFCs from highly damaging system failures
- Monitoring SOFC operations throughout its lifetime
- Detect and manage faults

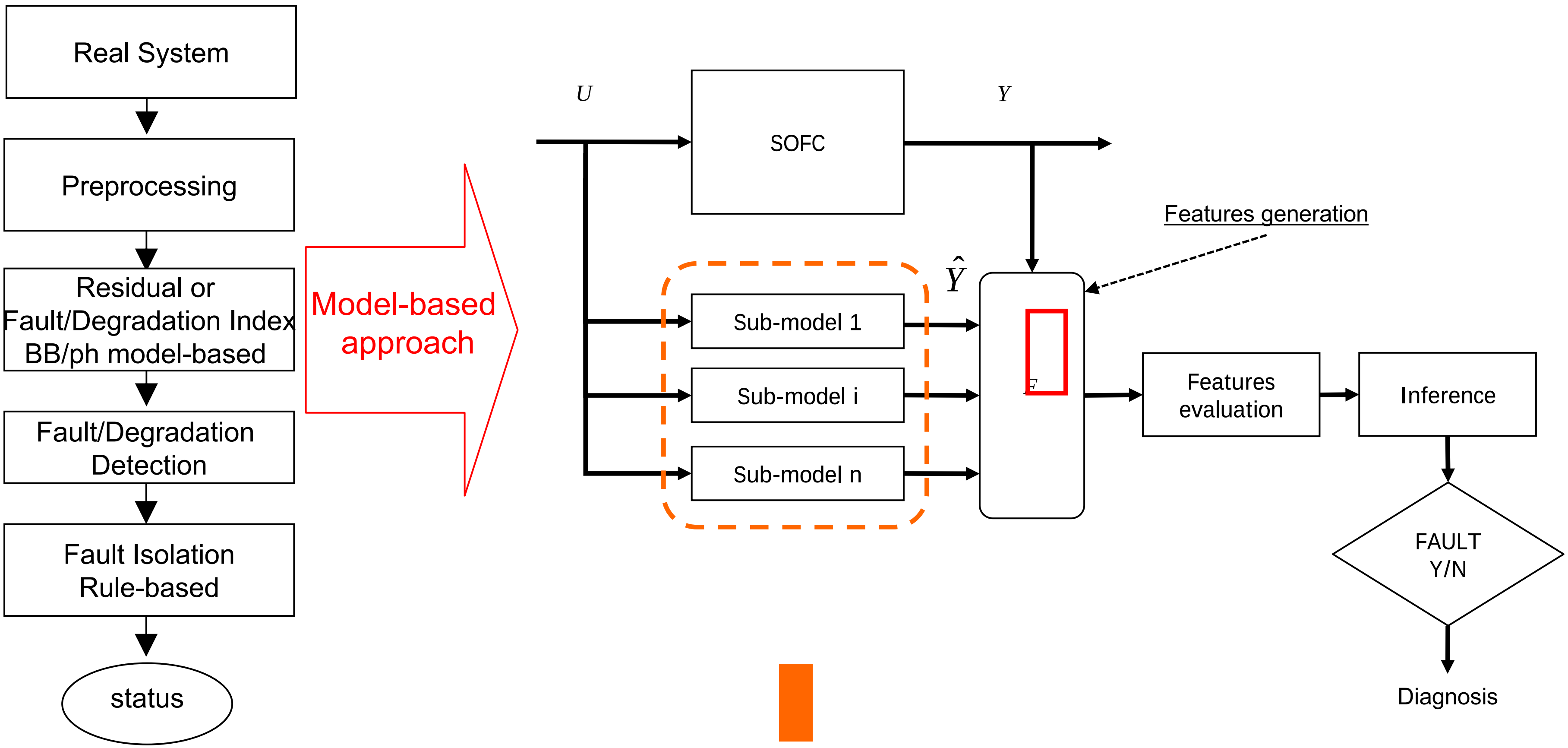
Type of faults

- BoP level
  - Sensors (pressure, temperature) & Actuators (electric motors, valves)
  - Auxiliaries (blower/compressor, heat exchangers, reformer)
  - Components (pipes, manifolds)
- Stack level
  - Material degradation
  - Electrodes poisoning
  - Etc.

Design and real time operation of diagnostics tools



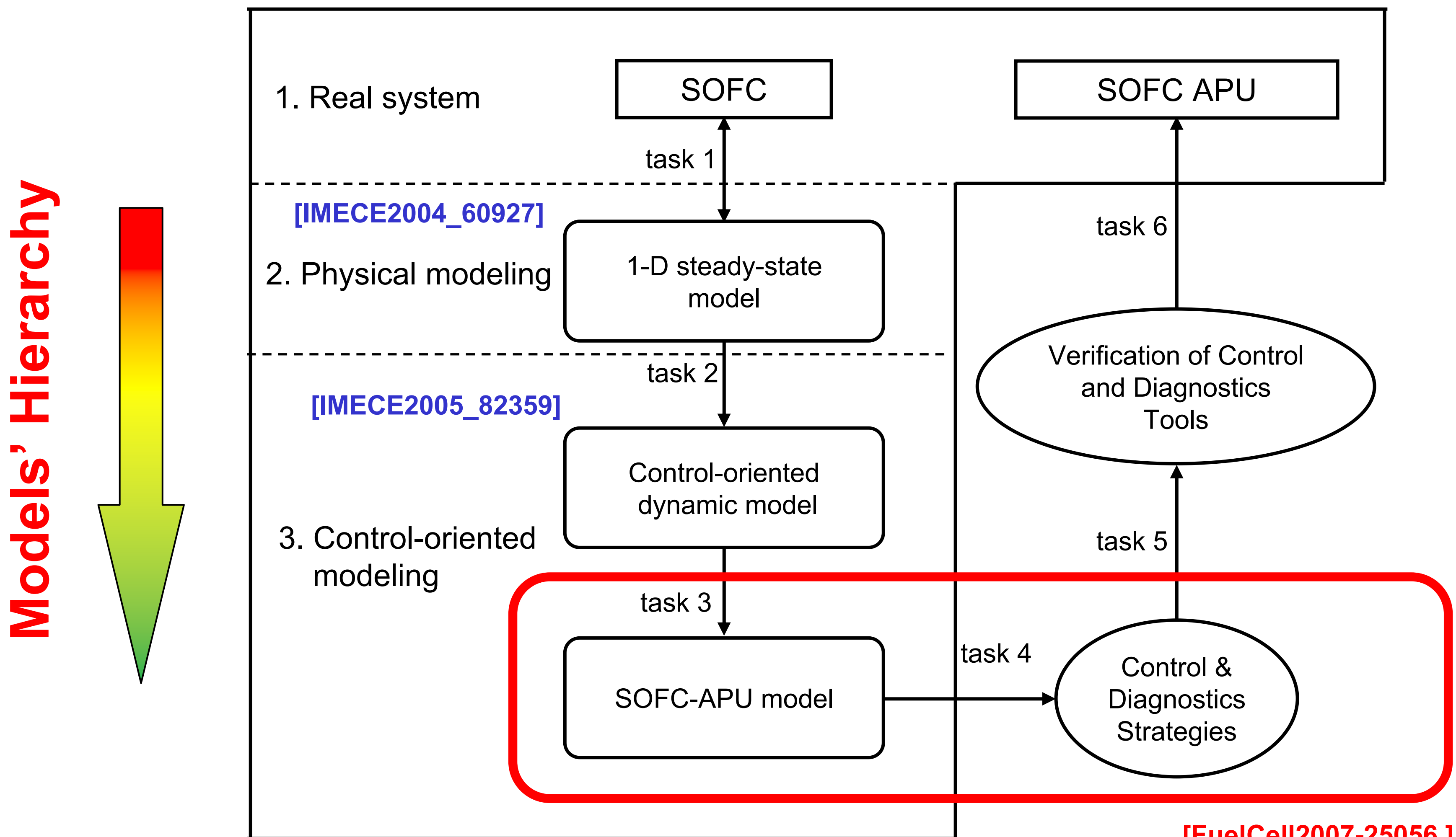
Diagnostic process



It requires suited SOFC+BoP models

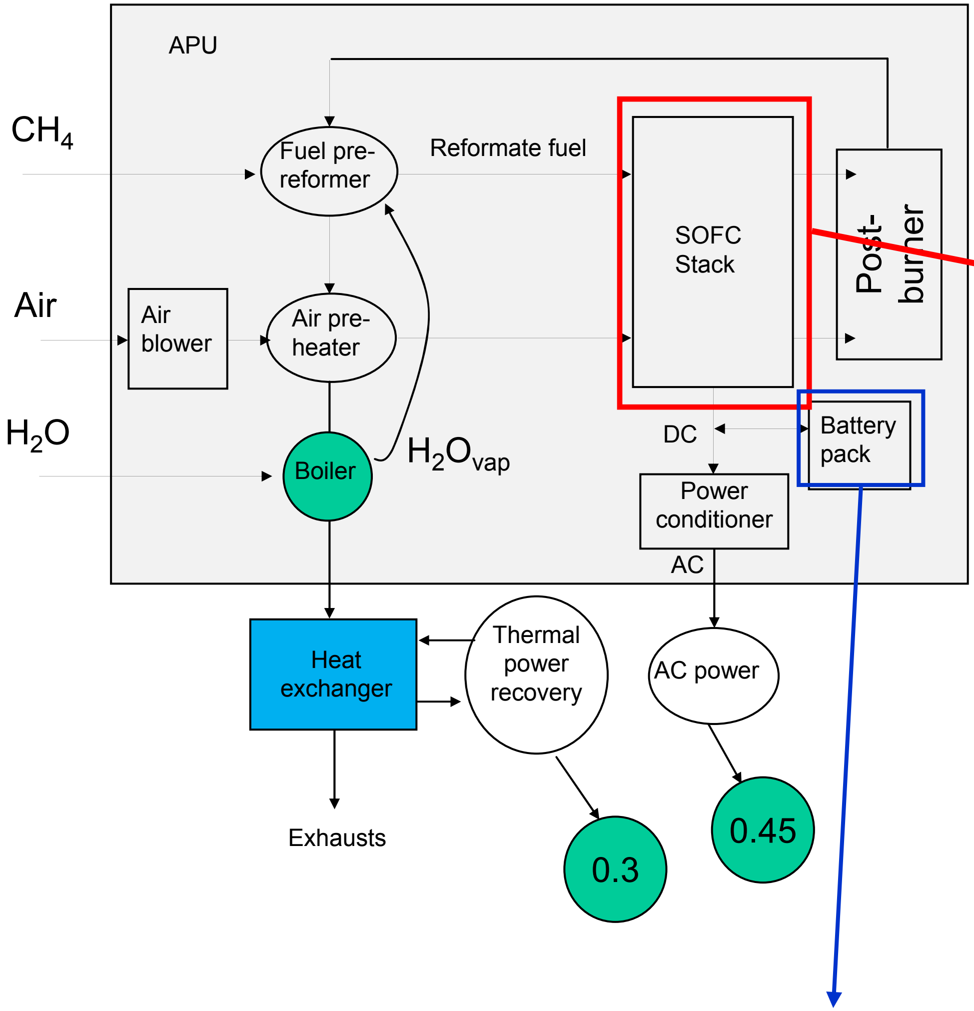
Modeling Approach

A hierarchical structure combining several models was developed to achieve accurate and fast SOFC APU dynamic model



[FuelCell2007-25056]

SOFC APU Block Diagram



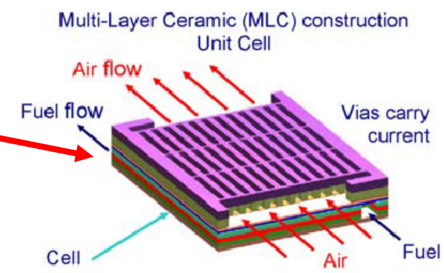


Figure 3. A 5-cell cross-flow stack assembled from co-fired cells and interconnects. The air and fuel channels are seen on the two faces of the stack shown.

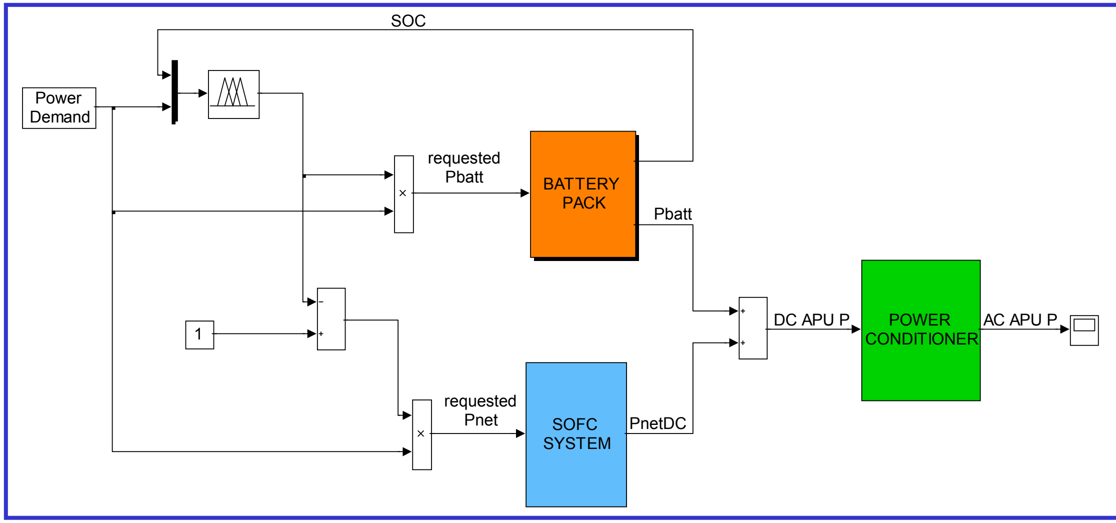
(planar configuration)

Source: SOFCo - EFS

Planar co-flow SOFC

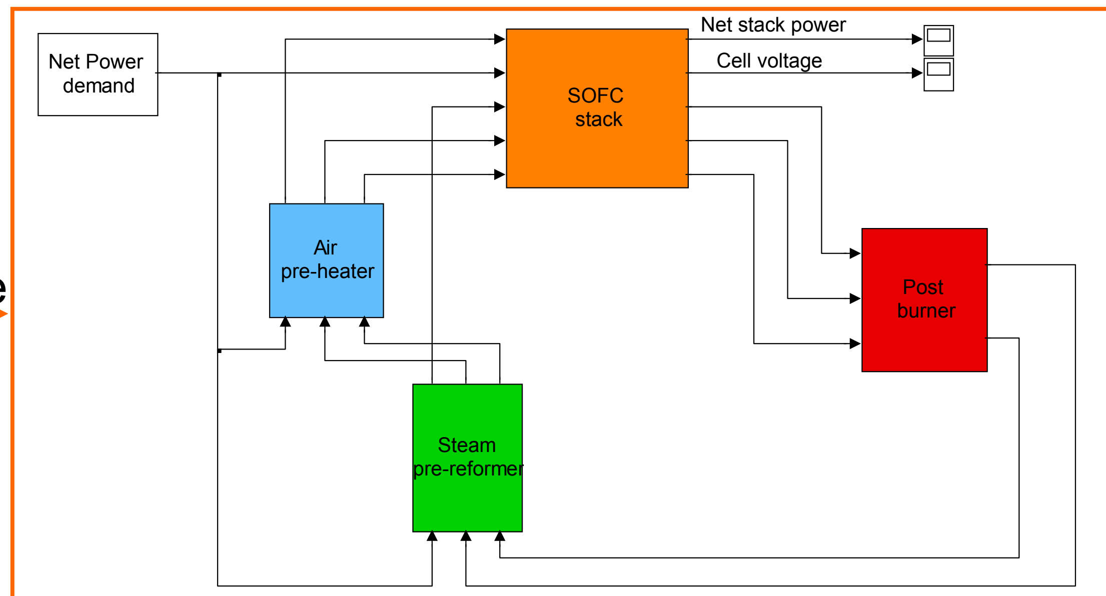
Hybridized with battery for
start-up; peak power; transients; energy storage

Modeling scheme



Outer APU scheme

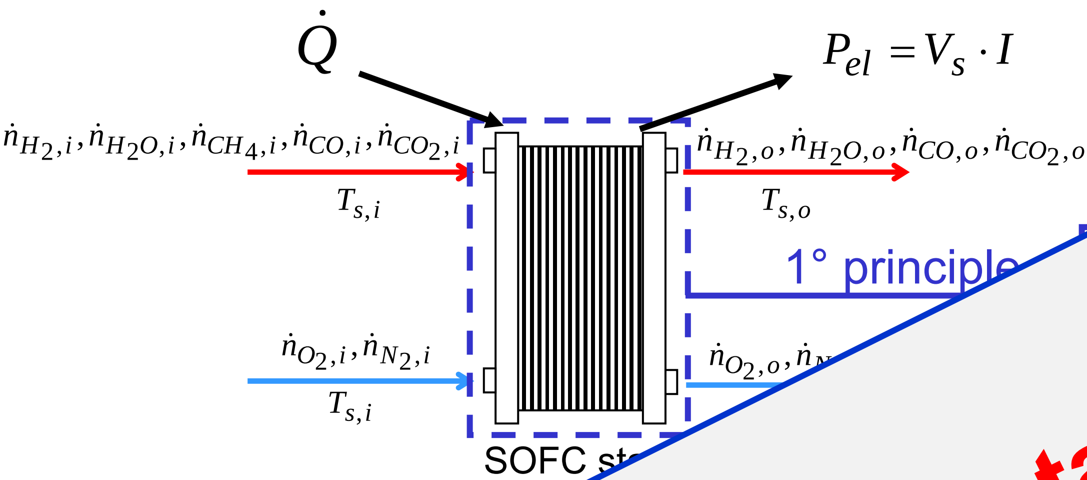
Inner SOFC system scheme



Modeling assumptions

- Spatial variations are not considered, i.e. lumped modeling approach.
- Thermal dynamics is predominant; mass transfer and electrochemistry were assumed instantaneous.
- Lumped heat transfer coefficients were assumed to model heat exchangers.
- Adiabatic components.
- Water gas shift reaction is considered at equilibrium.

SOFC dynamic model

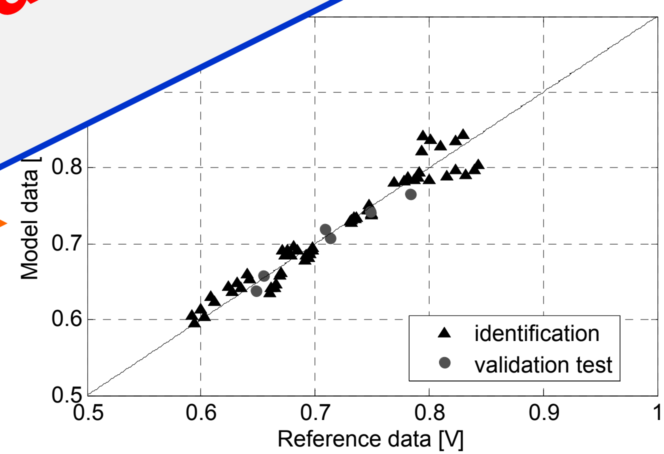


The outl… ture
is … le

$I \cdot V_s$

$V_s = f(x,u) \Rightarrow V_s = 0$ … $0.7153 \cdot \frac{T_{s,in}}{1000}$

a…
m…
[IM…



The entire model (stack+BoP) is ≈ 100 time faster than real-time !!!

Model-based design

SOFC stack

Configuration	Planar
Material	Ceramic
Electroactive area	100 cm^2
Anode thickness	600 μm
Electrolyte thickness	50 μm
Cathode thickness	50 μm
Interconnect thickness	500 μm
Heat capacity	**8234 J/K**
Pressure	1 bar
Temperature in	700 °C
Temperature out	825 °C
Number of cells	150
Max DC Gross Power @ 0.8 A/cm^2	7.5 kW
Max AC Net Power @ 0.8 A/cm^2	**5 kW**
Fuel utilization	0.7
x_{fuel} - reformate	x_{H2} = 0.273 x_{H2O} = 0.483 x_{CH4} = 0.171 x_{CO} = 0.019 x_{CO2} = 0.054

Air pre-heater

Type	Printed plate
Material	Ceramic
Heat transfer coefficient	200 W/m^2/K
Heat Transfer Area	0.56 m^2
Heat capacity	**588 J/K**

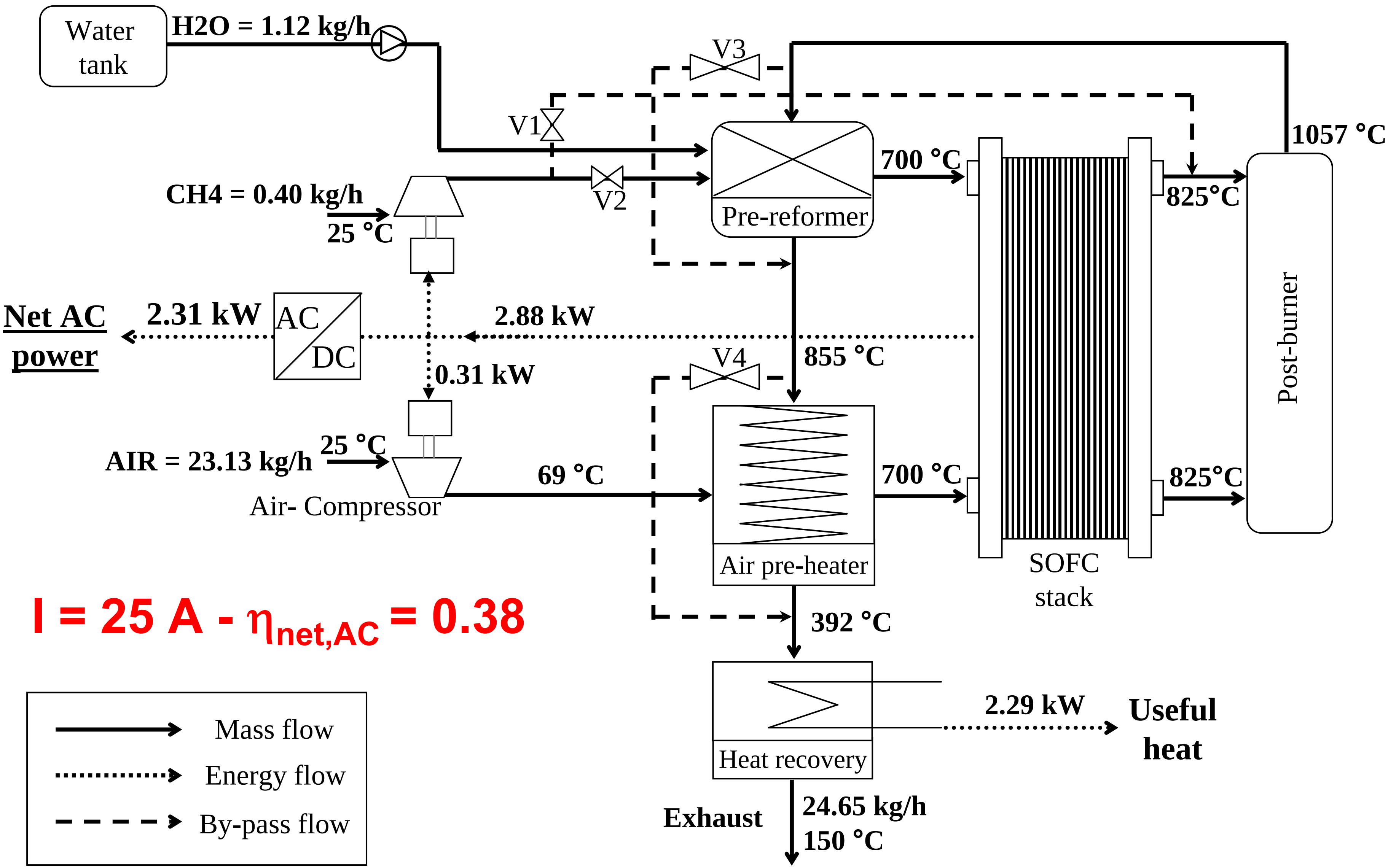
Pre-reformer

Type	Steam
Material	Ceramic
CH4 conversion efficiency	0.3
S/C	2.5
Heat transfer coefficient	200 W/m^2/K
Heat Transfer Area	0.04 m^2
Heat capacity	**44 J/K**

Battery-pack

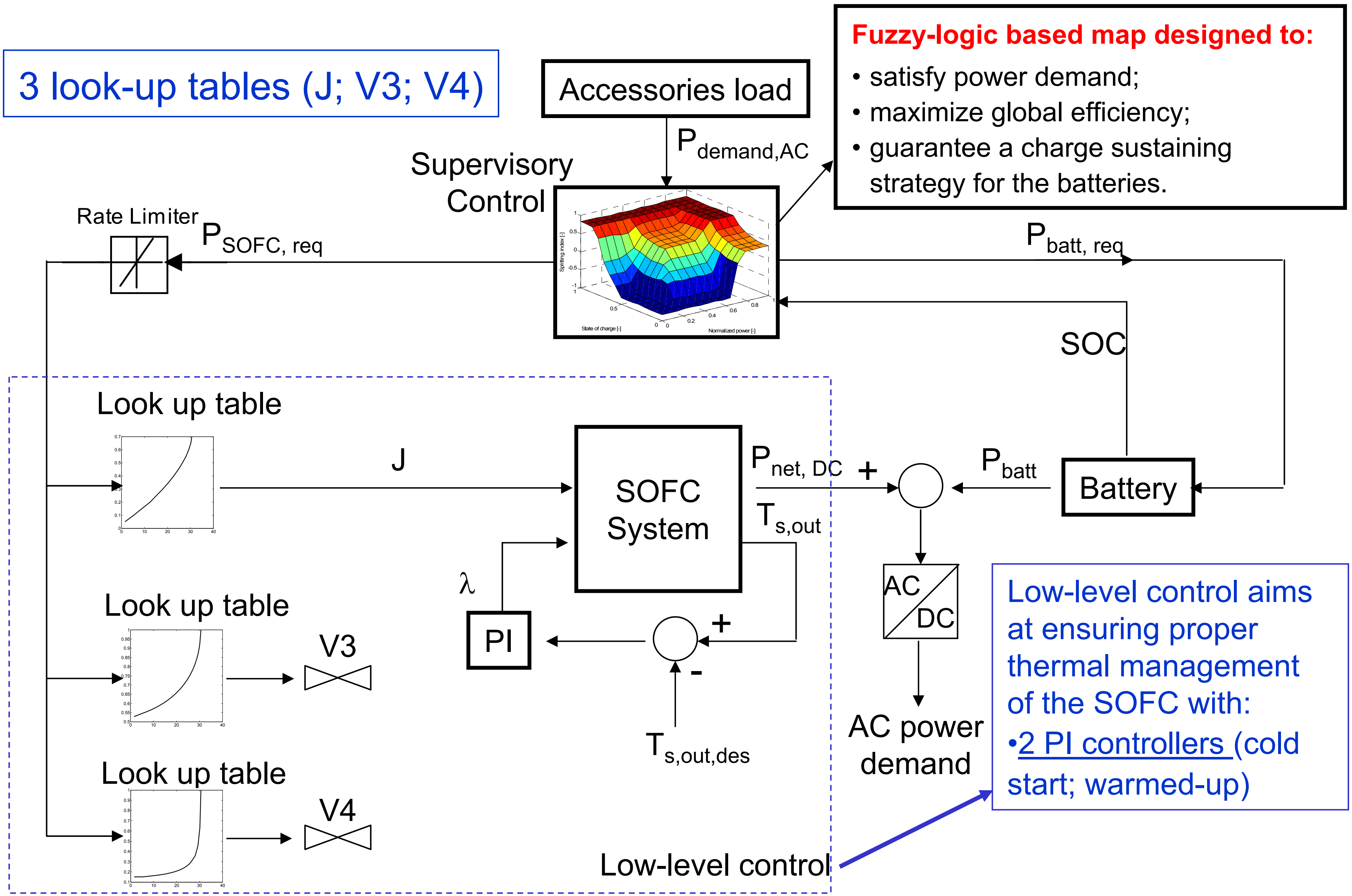
Type	Lead-acid
Number of modules	**15**
Open circuit voltage	12 V
Capacity	25 Ah

SOFC system – Block diagram



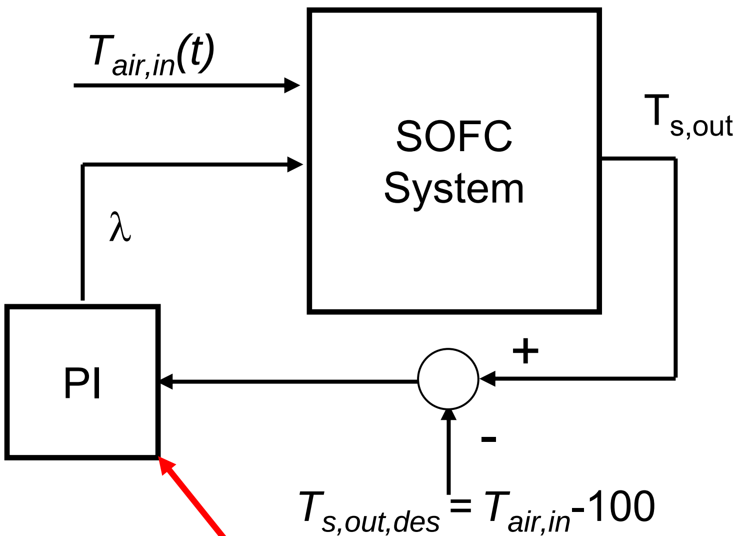
I = 25 A - $\eta_{net,AC}$ = 0.38

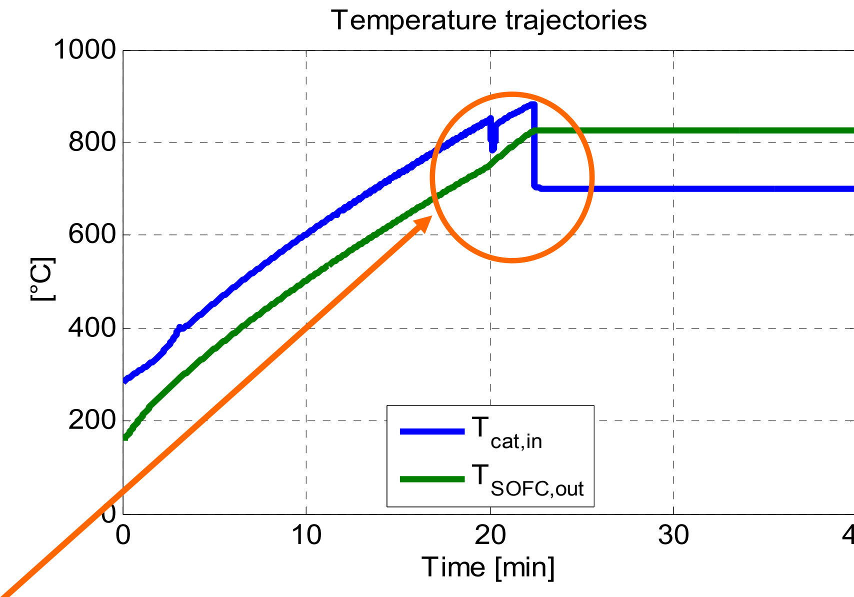
APU control scheme

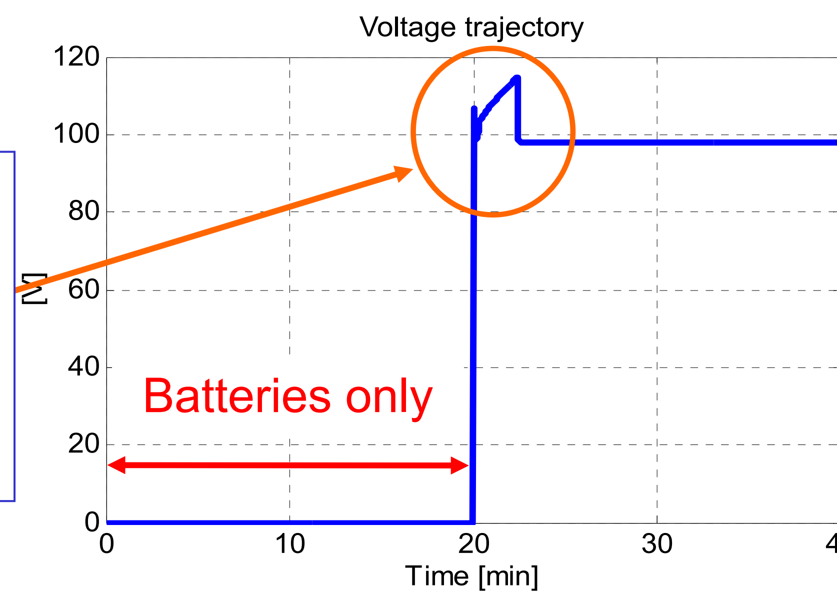


SOFC - Cold-start control

SOFC are air-cooled then λ is control variable

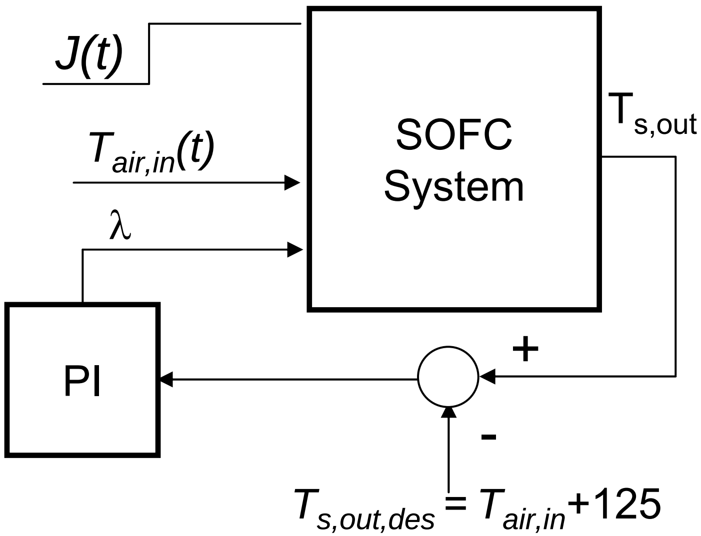


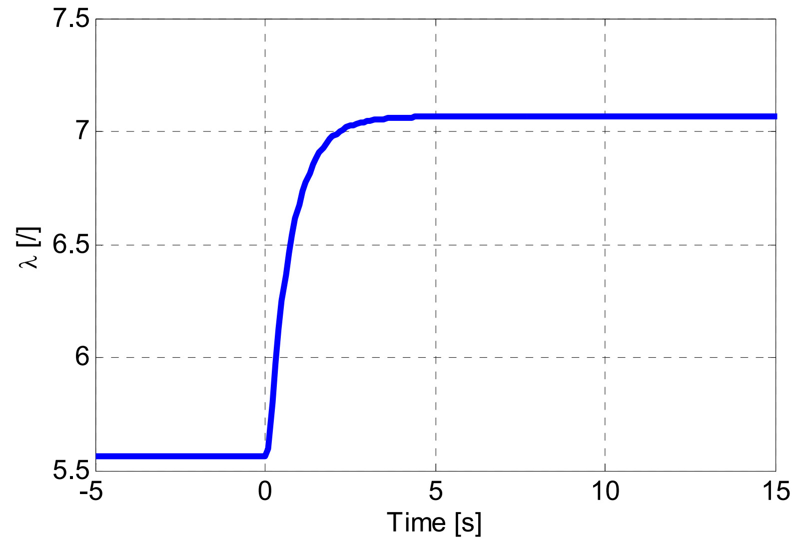


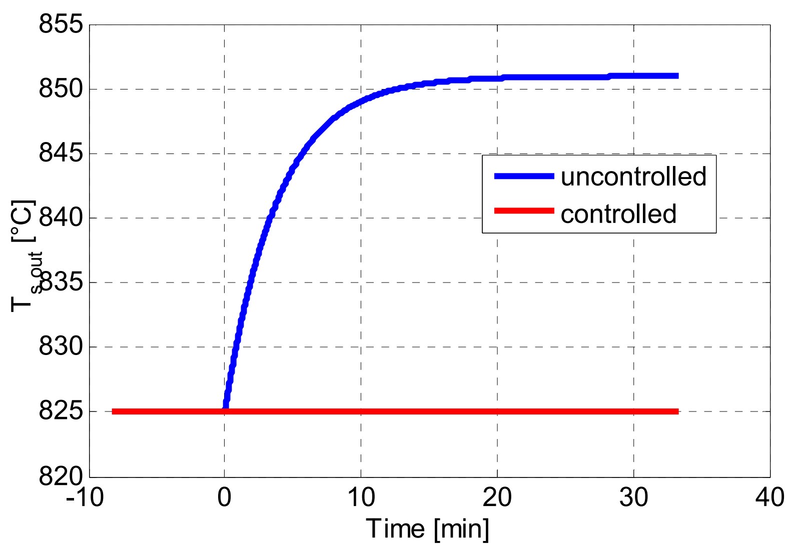


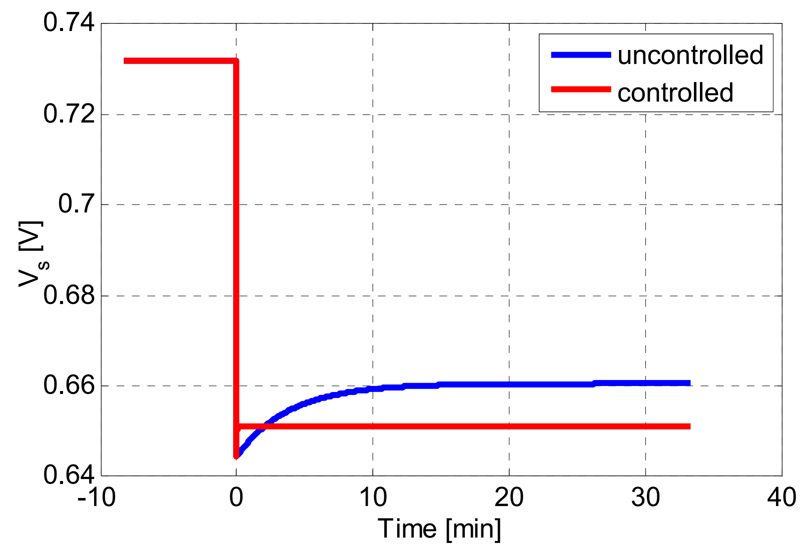
- The **PI acts** on the excess of air to limit the difference between $T_{air,in}$ and $T_{s,out}$ below 100 °C.
- **20 minutes Start-up** time was obtained.

SOFC - Warmed-up control







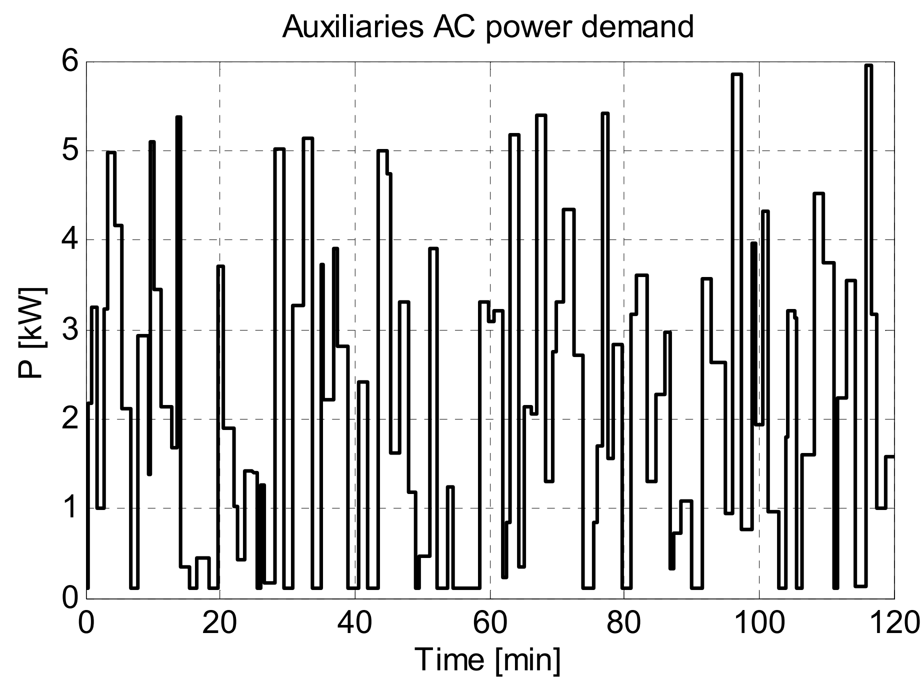


Simulated power profile

- Simulation-based testing of the SOFC-APU model.
- The reference profile, generated randomly, is a typical auxiliary load profile for commercial trucks in parked idling phase.
- Two scenarios were analyzed:

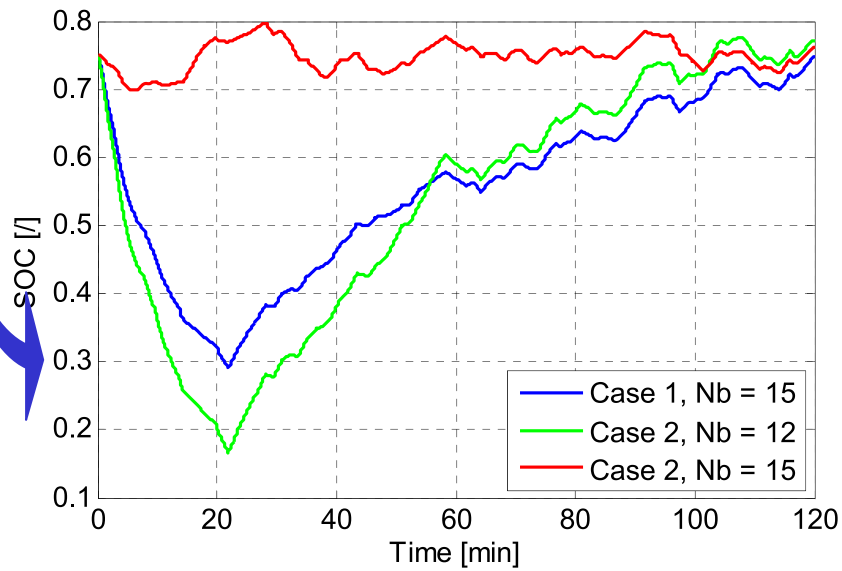
P_{av} = 2 kW
P_{max} = 6 kW

Case 1	with SOFC cold-start
Case 2	warmed-up SOFC

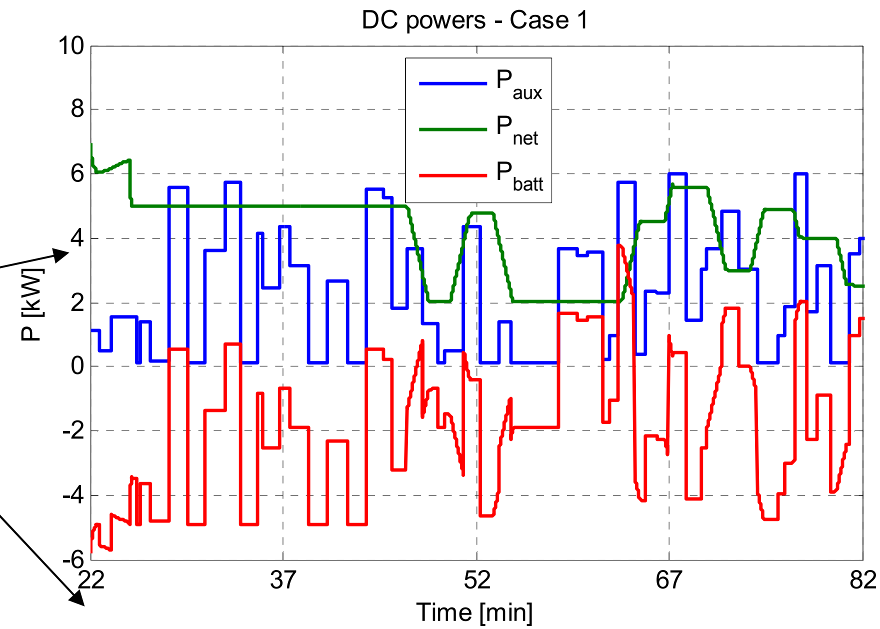


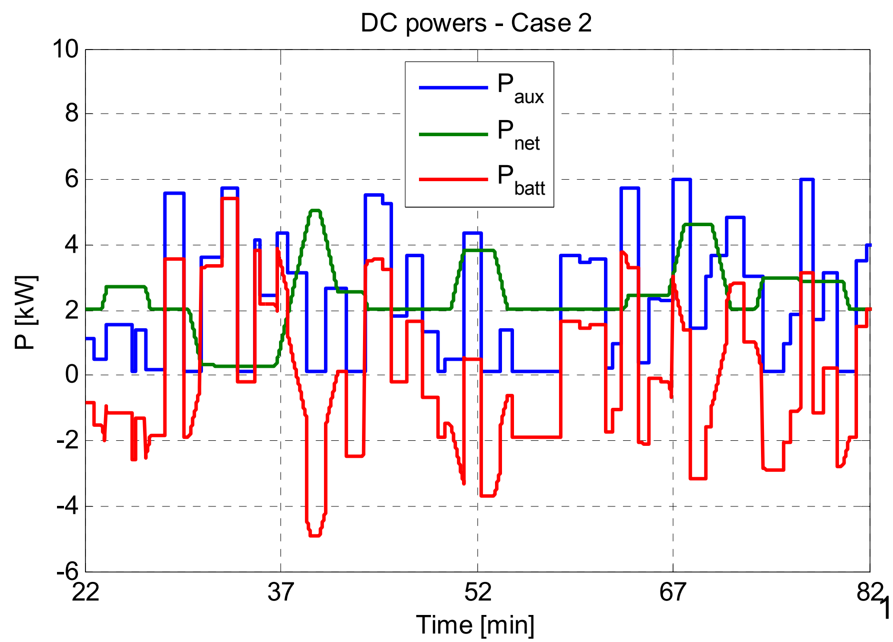
Simulation results

- The selected number of modules allows a more conservative operation of the battery pack.
- Cold-start influences SOFC power requests (case 1).



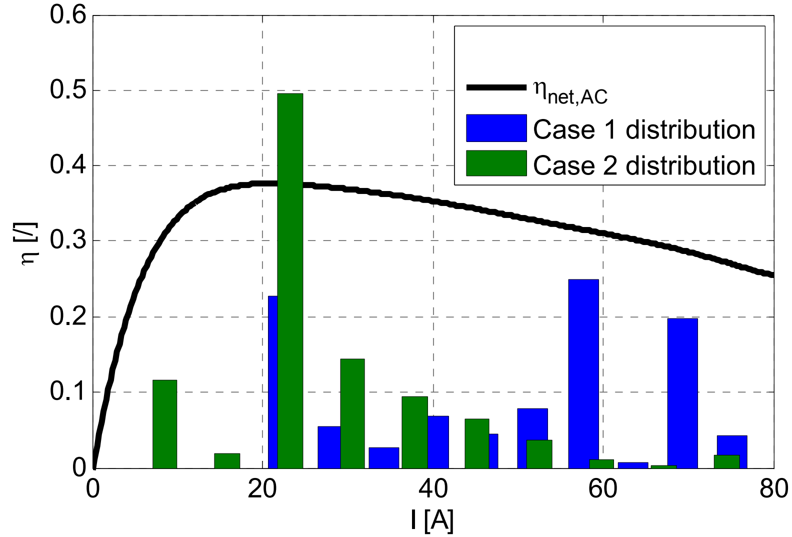
Case 1 warm-up period



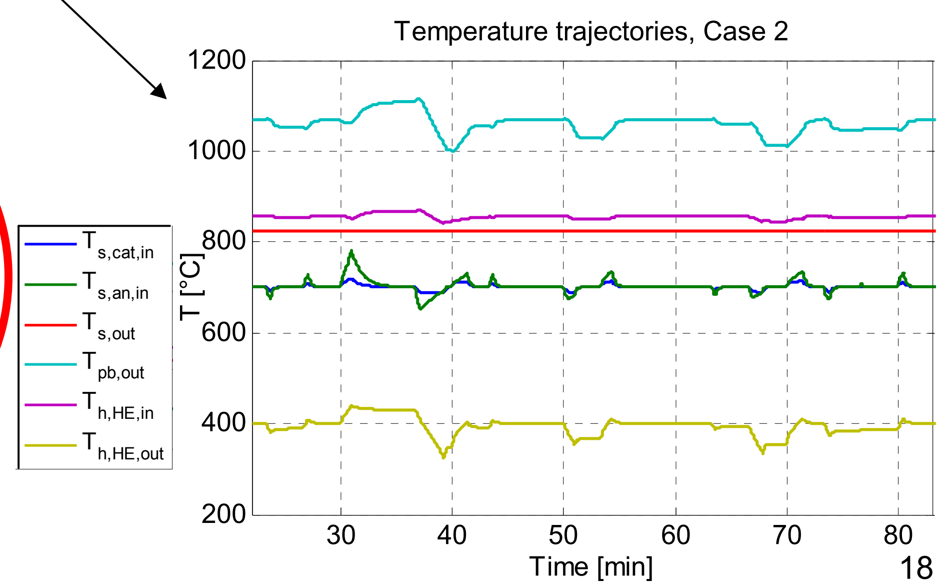


Simulation results

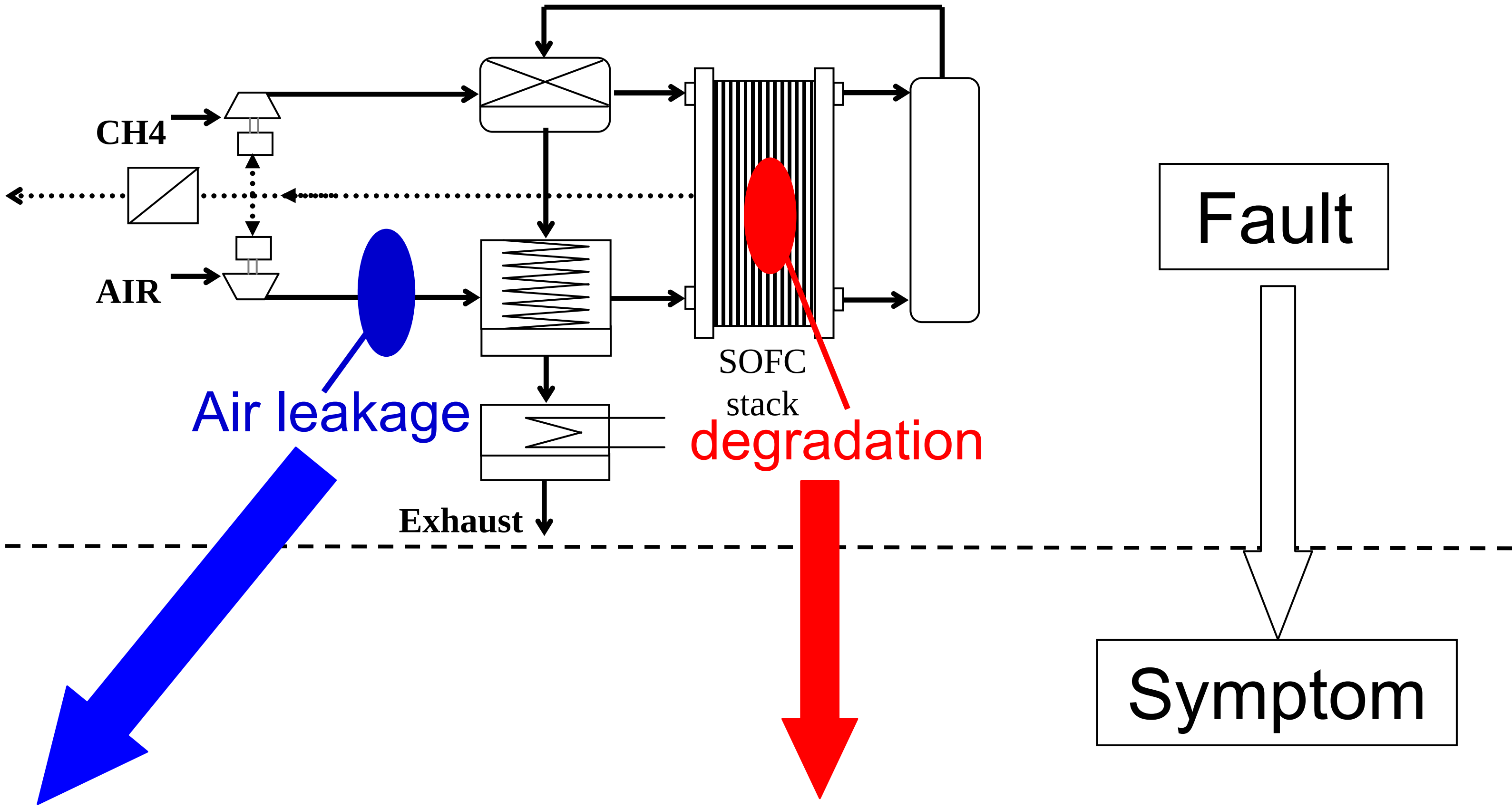
- Cold-start operation impacts on fuel consumption.
- Low-level control guarantees a proper thermal management.



	m_{CH4} [kg]	$m_{Diesel,eq}$ [kg]	$m_{Diesel,c}$ [kg]	Fuel savings [% of $m_{Diesel,c}$]
Case 1	1.54	1.80	3.19	44
Case 2	0.84	0.98	3.19	70



Diagnostics Application



$\lambda \uparrow \rightarrow P_{cp} \uparrow$

$P_{gross} =$

$\Big\} \; P_{net} \downarrow$

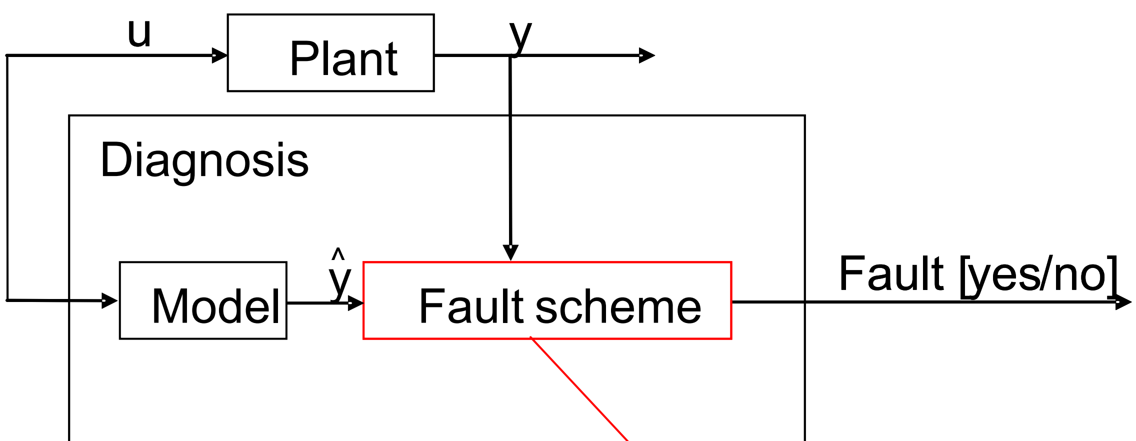
$P_{gross} \downarrow$

$\lambda \uparrow \rightarrow P_{cp} \uparrow$

$\Big\} \; P_{net} \downarrow$

Diagnostics scheme

Detection of air leakage (i) and stack degradation (ii) with Parity-equation based diagnostics method:



$$R1 = \left| P_{net,p} - P_{net,m} \right|$$

$$R2 = \left| P_{gross,p} - P_{gross,m} \right|$$

$$R3 = \left| P_{cp,p} - P_{cp,m} \right|$$

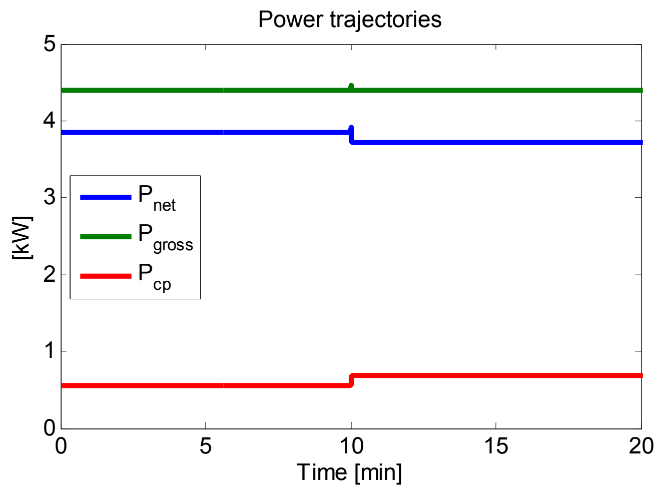
Inference from symptoms

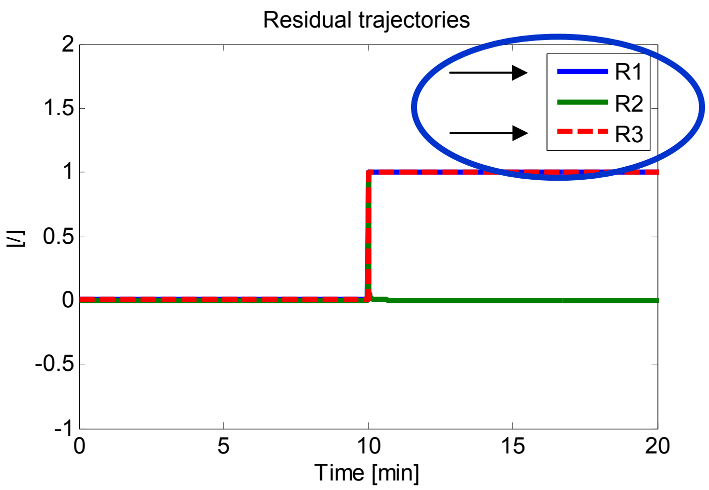
Fault	R1	R2	R3
i) Air leakage	1	0	1
ii) Increased Ohmic losses	1	1	1

redundancy

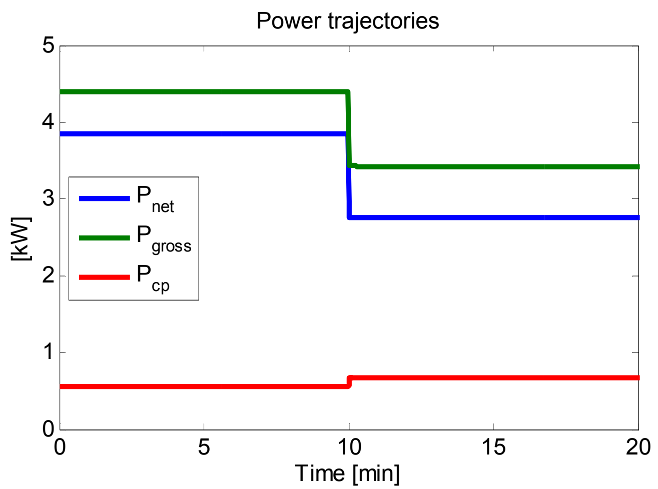
Fault detection

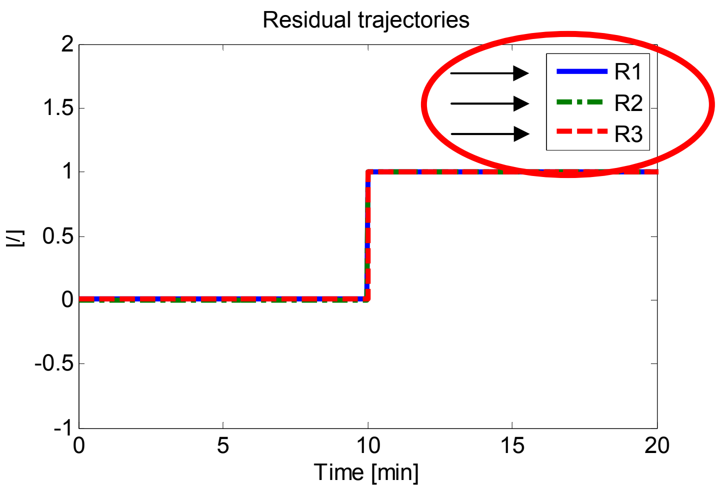
i) Stepwise Air leakage





ii) Stepwise Stack degradation





Conclusions

- Modeling methodologies were proposed to develop control-/diagnostic-oriented models of SOFC cells/stacks.
- Model-based design of suited control strategies to ensure optimal energy and thermal management.
- The developed model and related control strategies were tested via simulation of a typical auxiliary power demand profile for commercial heavy-duty trucks.
- Model suitability for developing appropriate diagnostics strategies/architecture.
- Future work will focus on diagnosing the whole SOFC system and perform experimental testing of control and diagnostic strategies.