Effect of Hybridization on the Performance of Fuel Cell Energy/Power Systems (FCEPS) for Unmanned Aerial Vehicle (UAV)

(Paper No: IMECE2010-38884)

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ASME Congress & Exposition, November 12-18, 2010

OUTLINE

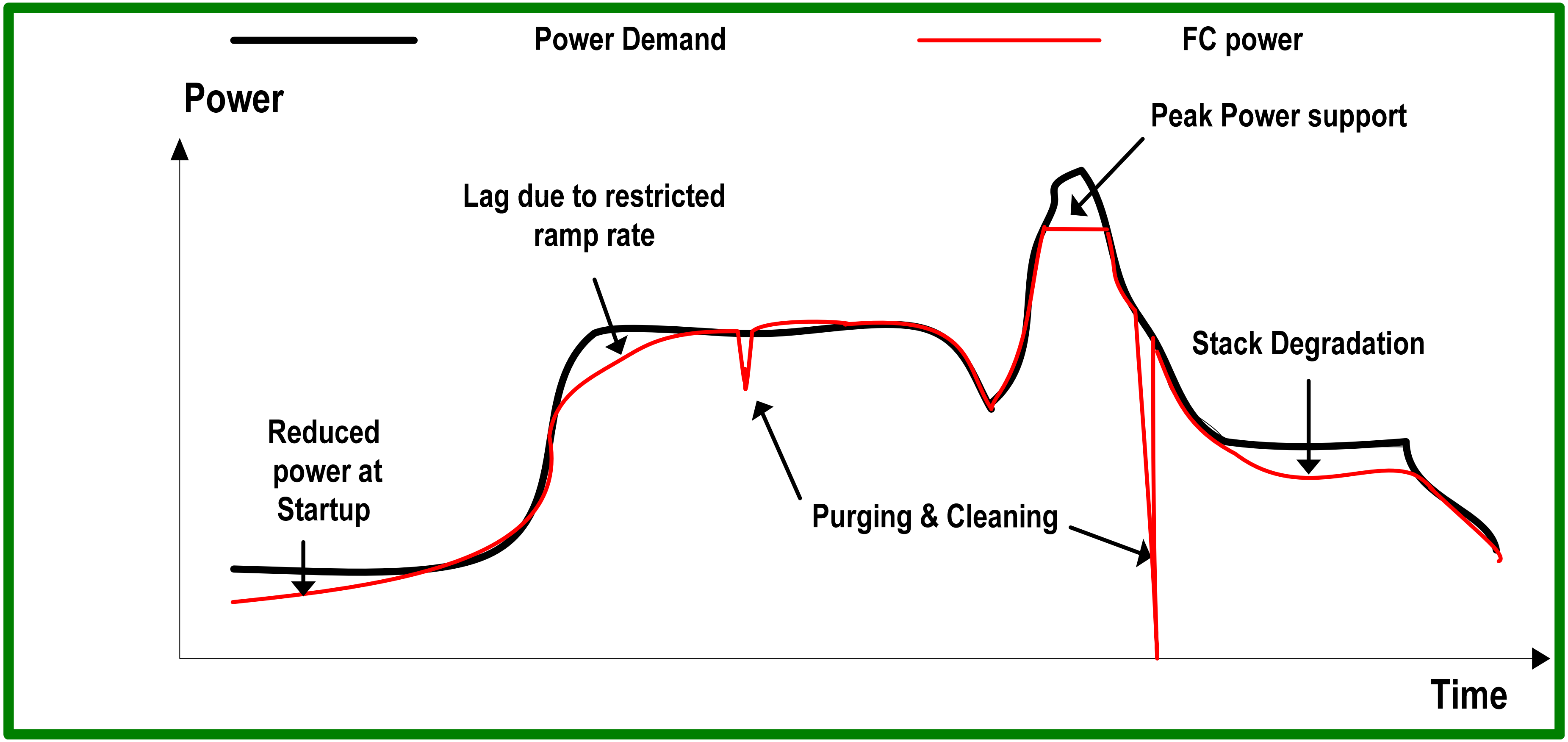
- **Objective**
- **Hybridization of the Unmanned Aerial Vehicles (UAVs) Proton Exchange Membrane Fuel Cell (PEMFC) System – Why?**
- **UAV PEMFC Systems Configurations**
- **UAV PEMFC System Design Consideration**
- **System Simulation & Results**
- **Hardware-in-the-Loop (HiL) Methodology & Setup**
- **Real-Time HiL Test Results & Energy Balance**
- **Conclusions**

OBJECTIVE

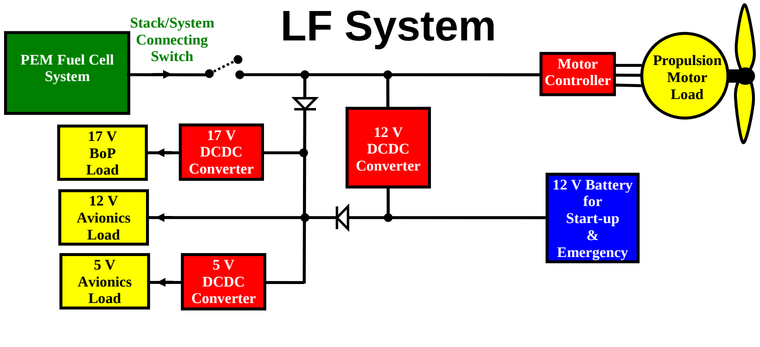
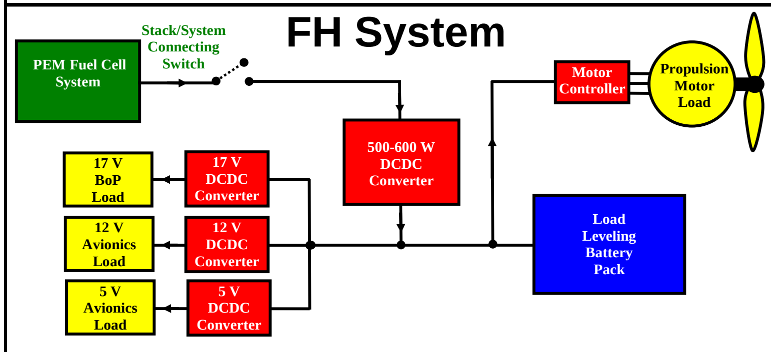
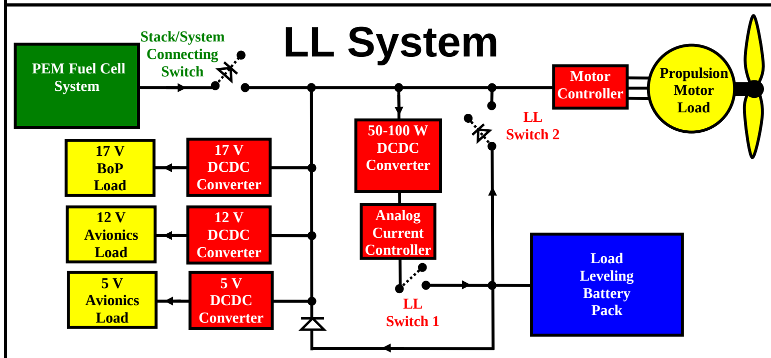
- **Three UAV PEMFC Systems with Different Degree of Hybridization**
  - **Two Traditional UAV PEMFC Systems**
    - Load Following (LF, non-hybrid) ⇒ Used as baseline system
    - Full Hybrid (FH) ⇒ Commonly used hybrid system
  - **Novel Hybrid System Design**
    - Load Leveling (LL)
- **Methodology of Characterization and Performance Comparison**
  - **PEM-FCEP System Simulation for 24+ hours Endurance Study to:**
    - Determine the UAV flight duration with a full tank of fuel & a fully charged battery pack using a repeated 20 minutes load profile
  - **Hardware-in-the-Loop Test System for Real Time Study to:**
    - Measure the performance of the system under a 20 minutes load profile with an actual PEMFC stack and some balance of plant (BoP) components
    - Estimate the energy balance over the 20 mins period

Hybridization of the UAVs PEMFC System – Why?

Benefits of Hybridization:



UAV PEMFC System Configurations

UAV System Types	Pros	Cons
LF System 	• Smaller battery pack • Smaller DC-DC converter for battery charging • No weight penalty	• Only stack provides all power to the system • Stack always operates in dynamic mode • Lower durability and lifetime of stack
FH System 	• Battery takes all dynamics • Stack operates at constant or controlled dynamics • Down sizing of stack • Improve durability and lifetime of the stack	• Large dc-dc converter • High power losses • Weight penalty • Battery discharges quickly at continues peak power • Stack can't provide power to the system directly
LL System 	• Flexible mode of operations • Stack & battery supply power • Smaller dc-dc converter • Stack operates at high efficiency • Improves durability and lifetime of the stack	• Weight penalty • Complex system • Extra hardware for control

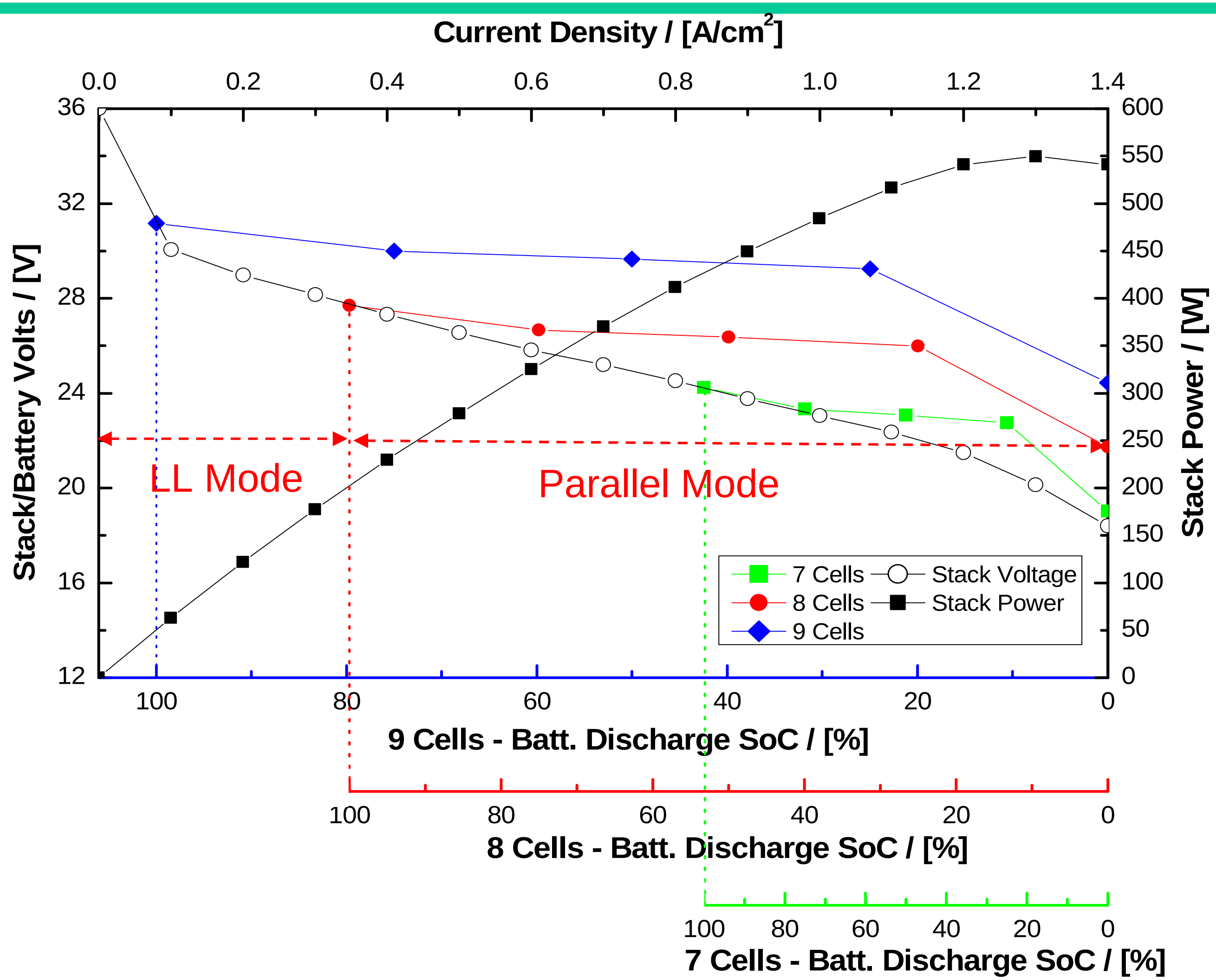
Load Level UAV System Design Consideration

- **Modes of Operation**
  - Parallel
    - Battery and fuel cell supply power to the system
    - Battery voltage regulates the stack power
    - No battery charging
  - Load Leveling
    - Fuel cell supplies the power to the system
    - Maximum fuel cell power is limited (LL), above LL power limited ⇒ Parallel Mode
    - Charging power = Fuel Cell Power – System Power
  - Load Following when Battery SoC < 20%
    - Fuel cell supplies all the power to the system
    - Fuel cell power allowed to go to Maximum
    - Battery charging power controlled

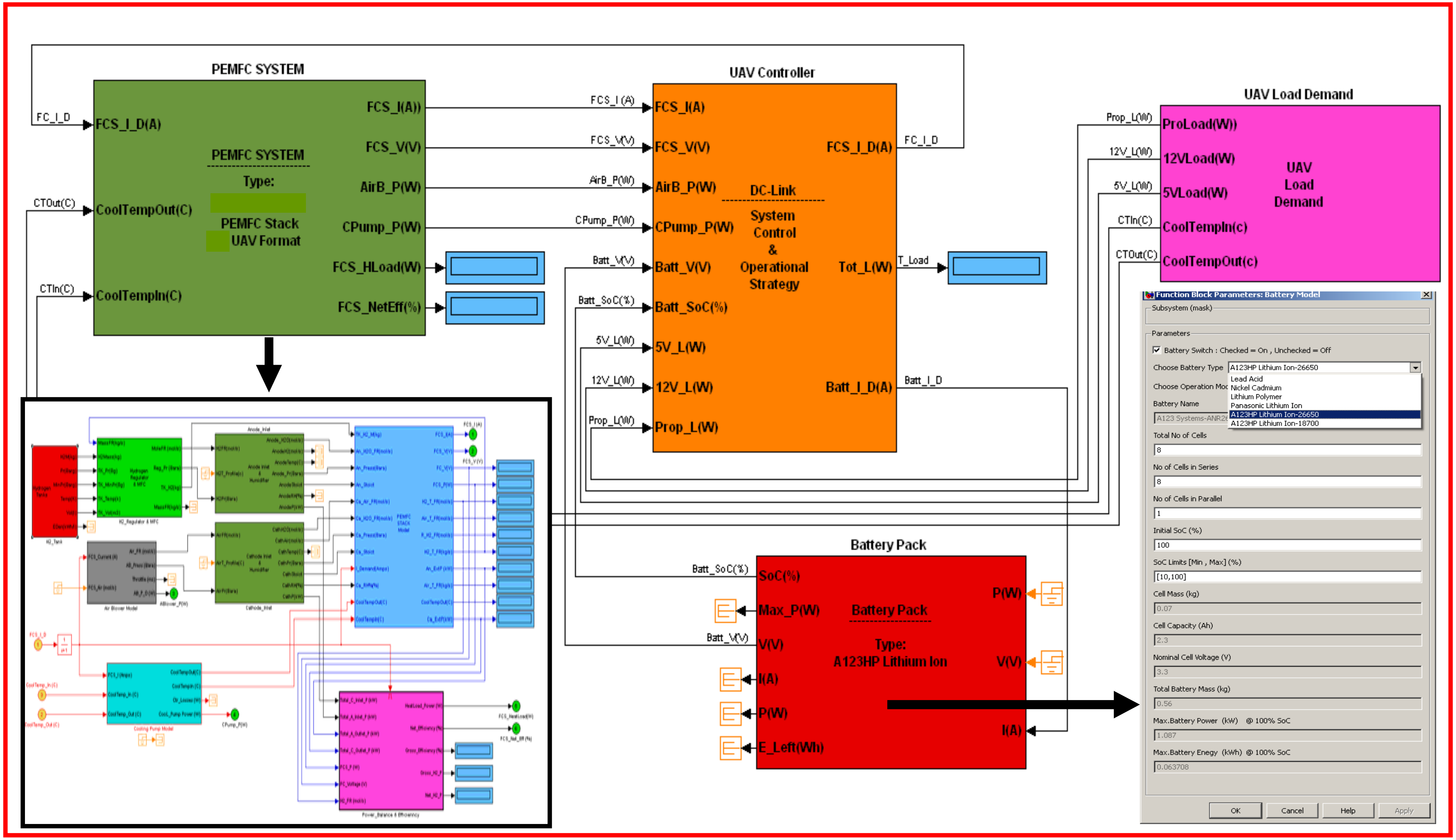
- **DC-DC Converter Size**
  - Large enough to maintain battery state of charge (SoC) between 60-50%
  - Small enough to minimizes power losses and weight penalty

- **Battery Pack Size**
  - Voltage optimized for parallel/LL ratio
  - Voltage range in operating range of motor controller
  - Pack size should be small to minimized weight penalty

Sizing-up of Hybrid Battery Pack



FCEPS Simulation Tool: UAV Simulation



FCEPS Simulation Tool: UAV Simulation

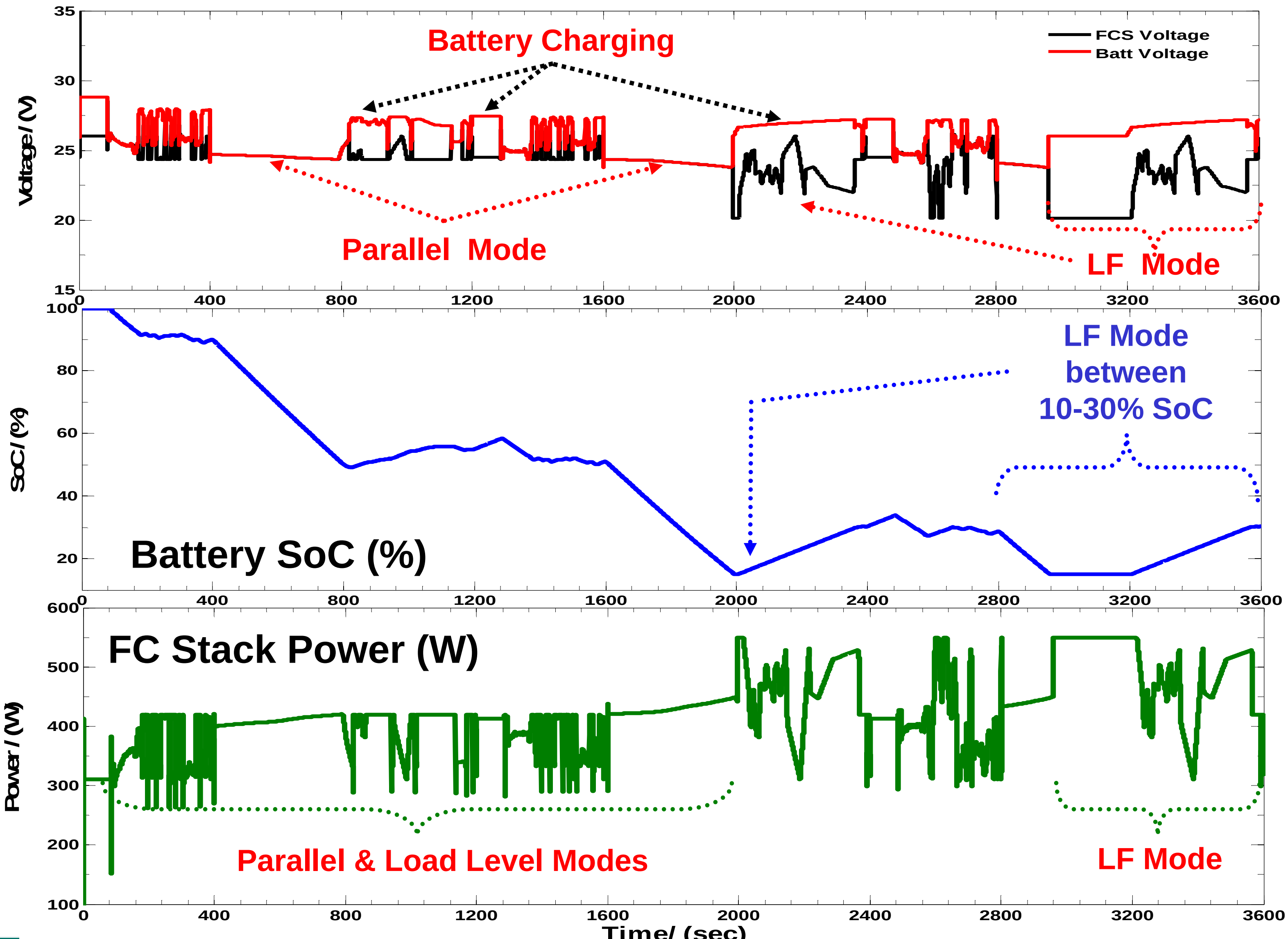
- **Capable of modeling any fuel cell system for different applications such as UAV, UUV, Auto-FCV, Stationary-CHP**

- **Flexibility in analyzing different system configurations and system components.**
  - ➢ **Load Following (LF) Vs. Load Leveling (LL) Vs. Full Hybrid (FH)**
  - ➢ **Fuel Cell Vs. Batteries Vs. Super capacitor**
  - ➢ **Liquid Vs. Gaseous Fuel tanks**

- **Characterization of overall system and systems components performance under different:**
  - ➢ **Mission profiles, drive cycles, dynamic load profiles**
  - ➢ **Operating conditions (temp, pressure, RH, stoich)**
  - ➢ **Operating strategies (LF, LL, FH, dead-end, purge cycle, oxide clean-up)**
  - ➢ **Control strategies (constant, average, dynamic components operational)**

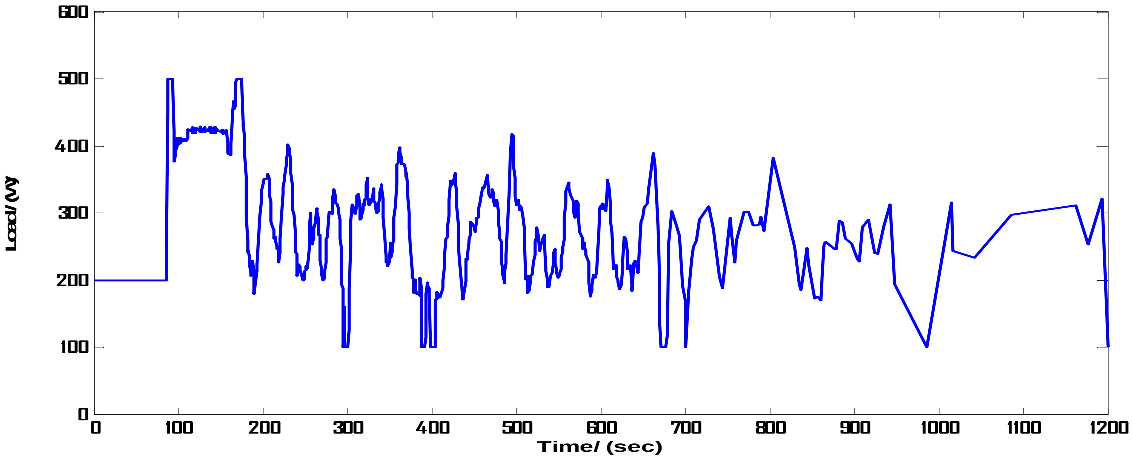
- **Easily convertible to real time simulation and used in Hardware-in-the-Loop (HiL) testing with actual system components under realistic dynamic conditions.**

LL UAV System Response Under a Load Profile



Simulation Setup for 24+ Hrs Endurance Test

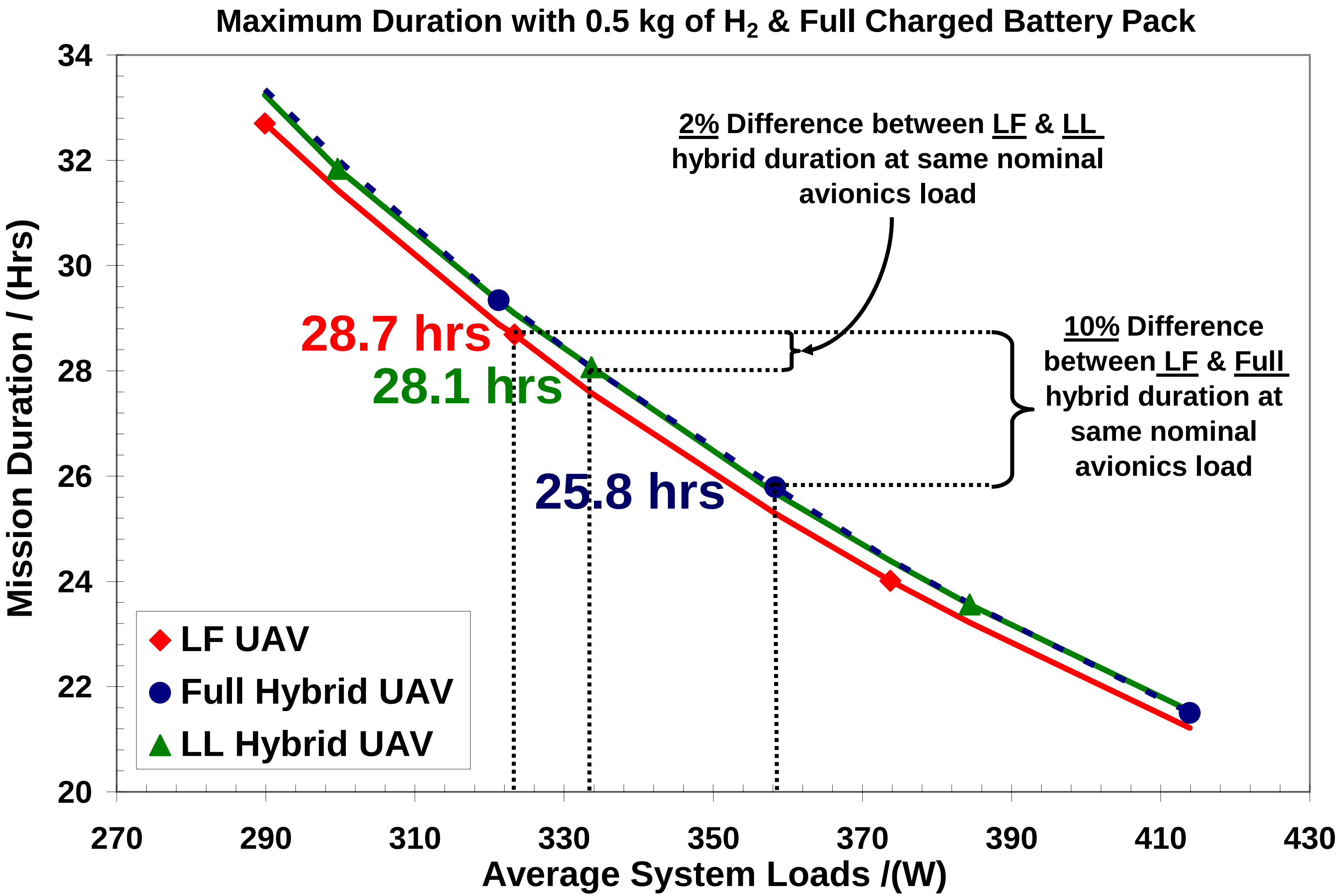
- **Propulsion Load Profile & System Weight Penalty:**
  - 20 mins Load Profile - Repeated to calculate the final duration of the system
  - Repeated Until - 0.5 k of H_2 is consumed and SoC% Battery ≤ 10%
  - Total weight penalty - Increase in propulsion power



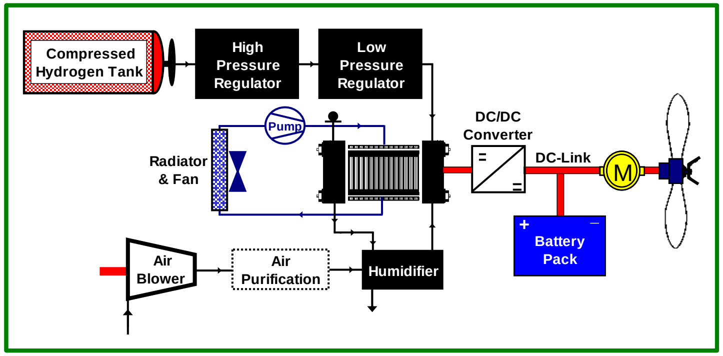
- **System Ancillary Loads:**
  - Zero Avionics + BoP
  - Nominal Avionics (cruise) + BoP
  - Maximum Avionics (peak) + BoP
- **DC-DC Converter Efficiency**
  - 90-93%
- **PEMFC System**
  - Nom. Power: 500 W
  - Peak Power: 550 W
  - Stack Temp : 50-55°C
  - Anode Stoich: 1.02
  - Cathode Stoich: ~ 2.5
- **Battery Pack: Lithium Ion**
  - Capacity: 2.3 Ah
  - Nom. Voltage: 3.3 volts
  - Initial SoC: 100%

UAV SYSTEM TYPES	FL	Full	LL
No of Cells of Lithium Ion	4	8	8
Increase in Battery Wt (g) (70g/cell)	0.0	280	280
Increase in Electronics Wt (g) DC-DC Converter/MOSFET/Diodes	0.0	100	112
Net Increase in System Weight (g)	0.0	380	392
Net Increase in Propulsion Power (W)	0.0	7.54	7.78

Max. Flight Endurance Results

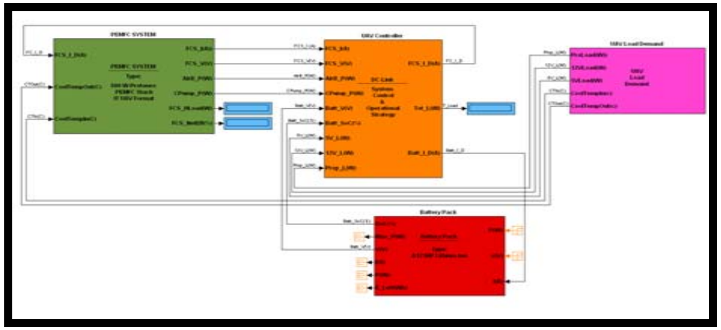


HiL Test System Operational Concept

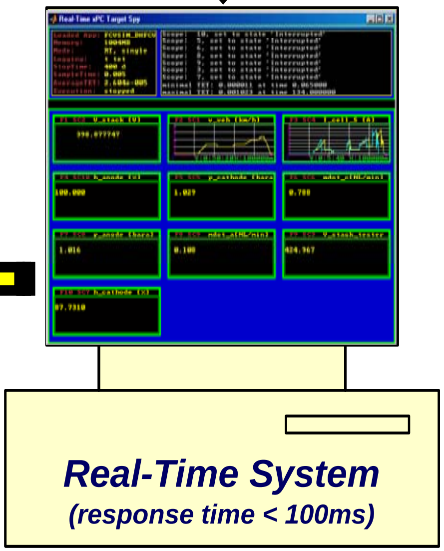


HPSys simulation

with load profile & control strategy



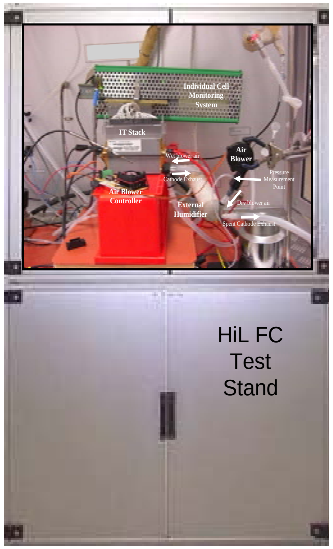
Download the simulation onto a real-time system



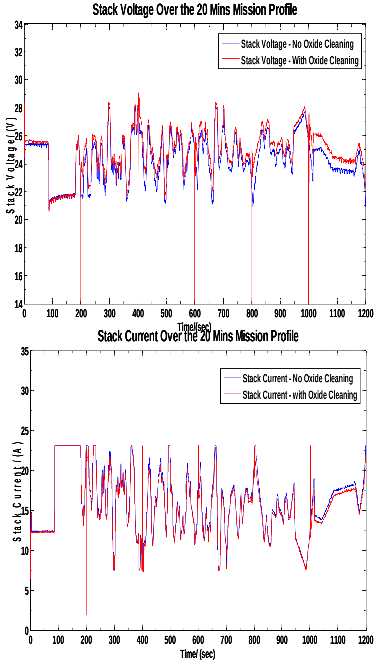
Set points are sent to hardware

Critical hardware component(s) placed under test

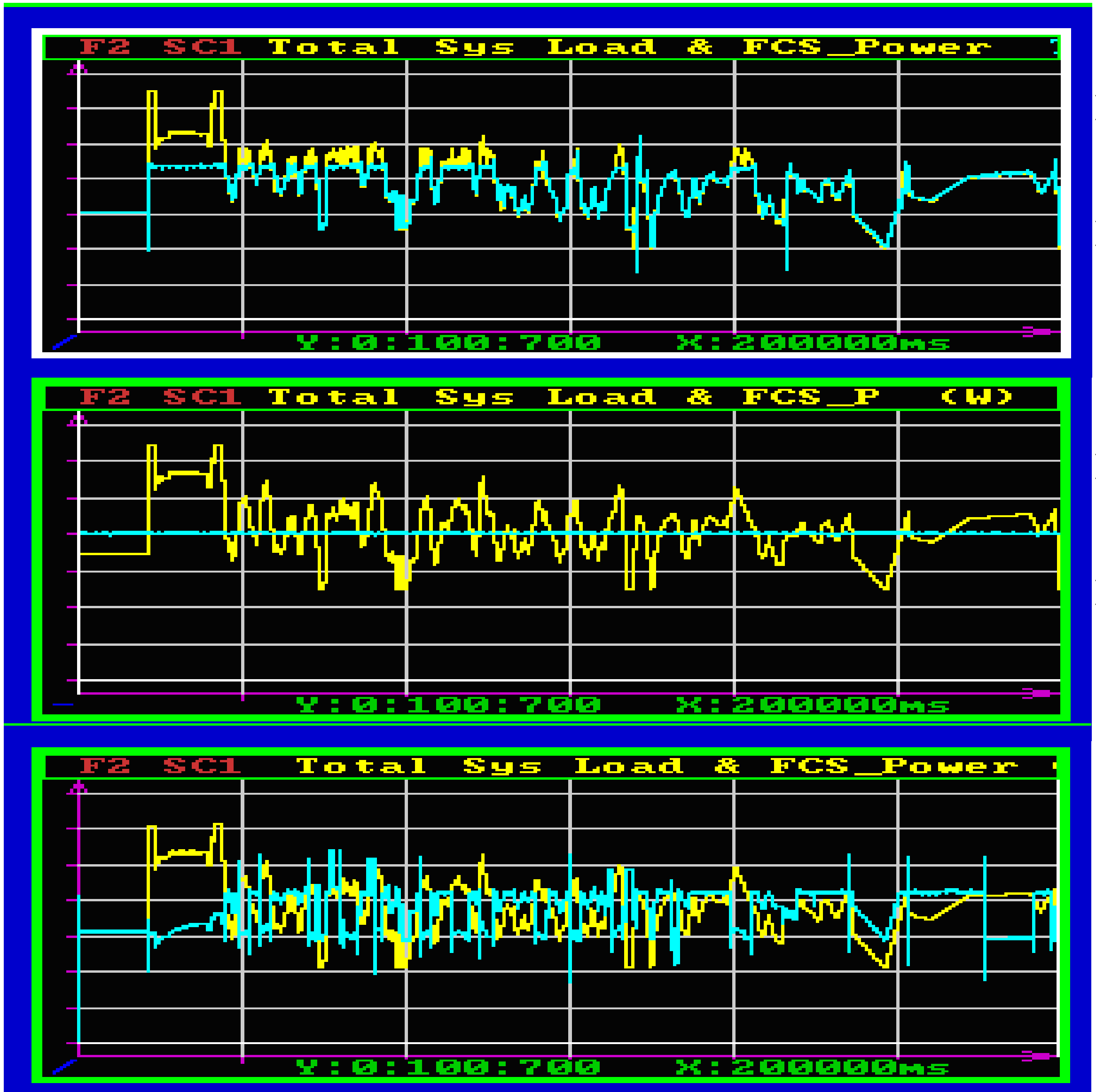
Actual values returned to real-time system



Dynamic Results



HiL Real Time Test Results under 20 mins Load Profile



LF UAV System

- Stack operates in highly dynamic mode
  - ⇒ Stack degradation over time
- Loss of stack performance
  - ⇒ ≡ 8% of flight duration
    ~ 2 hrs of flight duration

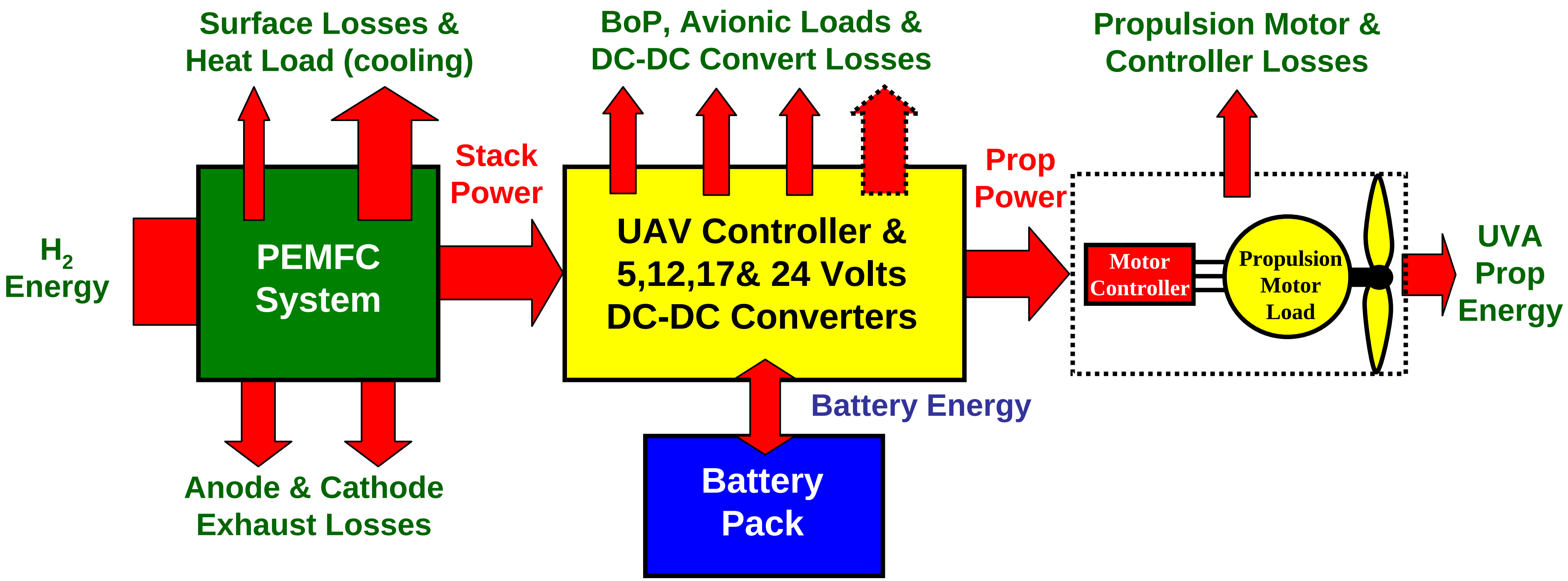
FH UAV System

- Stack operates in constant mode
  - ⇒ Battery provides high power
  - ⇒ Battery takes all dynamics
- At lower system demand the stack power used to charge battery pack

LL UAV System

- Stack operates in Parallel & LL Mode
  - ⇒ Peak power shared by both Stack and Battery
  - ⇒ Stack runs at high efficiency
- Stack dynamics reduced
  - ⇒ improves durability and life time of the stack

Energy Balance (kWh) – Over a 20 mins Real Time HiL Test



Assumptions:

1. Used actual stack current, voltage, cooling and cathode exhaust temperatures to estimate the cathode losses & heat load
2. Stack energy balanced was based on 98% H_2 utilization, 2.5 Air Stoichiometry and 75% Relative Humidity of Cathode
3. Surface radiation and convection losses were estimated assuming fuel cell as black body

Energy Balance

$$\frac{1}{3600} \times \left[\int_{t_1}^{t_2} P_{IN}\,dt - \int_{t_1}^{t_2} P_{OUT}\,dt - \int_{t_1}^{t_2} P_{LOSS}\,dt \right] = 0$$

Result Summary of UAV Systems Energy Balance (Wh)

Based on Peak Ancillary Loads & LHV of H2	LF UAV System				FH UAV System				LL UAV System			
	Energy In	%	Energy Out	%	Energy In	%	Energy Out	%	Energy In	%	Energy Out	%
	Wh	%	Wh	%	Wh	%	Wh	%	Wh	%	Wh	%
PEMFC System												
Anode Inlet H_2	**251**	**93%**			**264**	**91%**			**242**	**90%**		
Electrical Power			126	47%			135	46%			124	46%
Cathode Air Inlet	19	7%			22	8%			21	8%		
Anode Exhaust			5	2%			5	2%			5	2%
Cathode Exhaust			31	11%			28	10%			27	10%
Heat Load			**109**	**40%**			**118**	**41%**			**108**	**40%**
Battery Pack												
Battery Energy	[100% SoC]		**0.3**	**0.1%**	**4**	**1%**	[93% SoC]		**6**	**2%**	[89% SoC]	
System Loads												
5 V DCDC Load (Avionics & Sensor)			17	6%			17	6%			17	6%
12 V DCDC Load (Auto Pilot, Payload & Radiator Fan)			16	6%			11	4%			11	4%
17 V DCDC Load (Air Blower & Cooling Pump)			8	3%			8	3%			8	3%
24 V DCDC Load (Hybrid Battery Pack Charger)			**0**	**0%**			**12**	**4%**			**1**	**0.3%**
Propulsion Power			**90**	**33%**			**92**	**32%**			**92**	**34%**
Total	**270**	**100%**	**274**	**102%**	**290**	**100%**	**290**	**100%**	**268**	**100%**	**268**	**100%**

CONCLUSIONS

- **Three UAV PEMFC Systems analyzed with different degrees of hybridization**
  - Load Following (LF, non-hybrid)
  - Full Hybrid (FH, Full)
  - Novel Load Leveling Hybrid (LL, Partial)
- **LF UAV system**
  - High theoretical flight duration with new stack performance data
  - Loss of 8% (~ 2hrs) of flight duration with degraded stack performance
- **FH UAV Hybrid System**
  - Constant Power PEMFC stack operation
  - 10% in flight duration compared to LF UAV System
  - High system and PEMFC stack heat load losses
- **LL UAV Hybrid System**
  - Improved losses in flight duration to 2% compared to FH UAV System
  - Flexible modes of operations (Parallel ↔ Load Leveling ↔Load Following)
  - Reduced PEMFC stack dynamics and heat load losses
  - Consumed least amount of H_2 energy over a 20 minute UAV flight
  - Weight penalty due to extra control hardware

Acknowledgements

Project Supported by Office of Naval Research (ONR) Grants
Grant # N00014-10-1-0310
Grant # N00173-08-2-C008

Many Thanks
For
Your Attention