# An Investigation to Resolve the Interactions among SOFC, Power-Conditioning Systems, and Application Loads

## Project Investigators


- **Sudip K. Mazumder, Kaustuva Acharya, and Rajni K. Burra**

(University of Illinois)

- **Michael von Spakovsky, Doug Nelson, Diego Rancruel, and Saravanan Subramanian**

(Virginia Tech)

- **Comas Haynes and Robert Williams**

(Georgia Tech.)

- **Joseph Hartvigsen and S. Elangovan**

(Ceramatec Inc.)

- **Dan Herbison and Chuck McKintyre**

(Synopsys Inc.)



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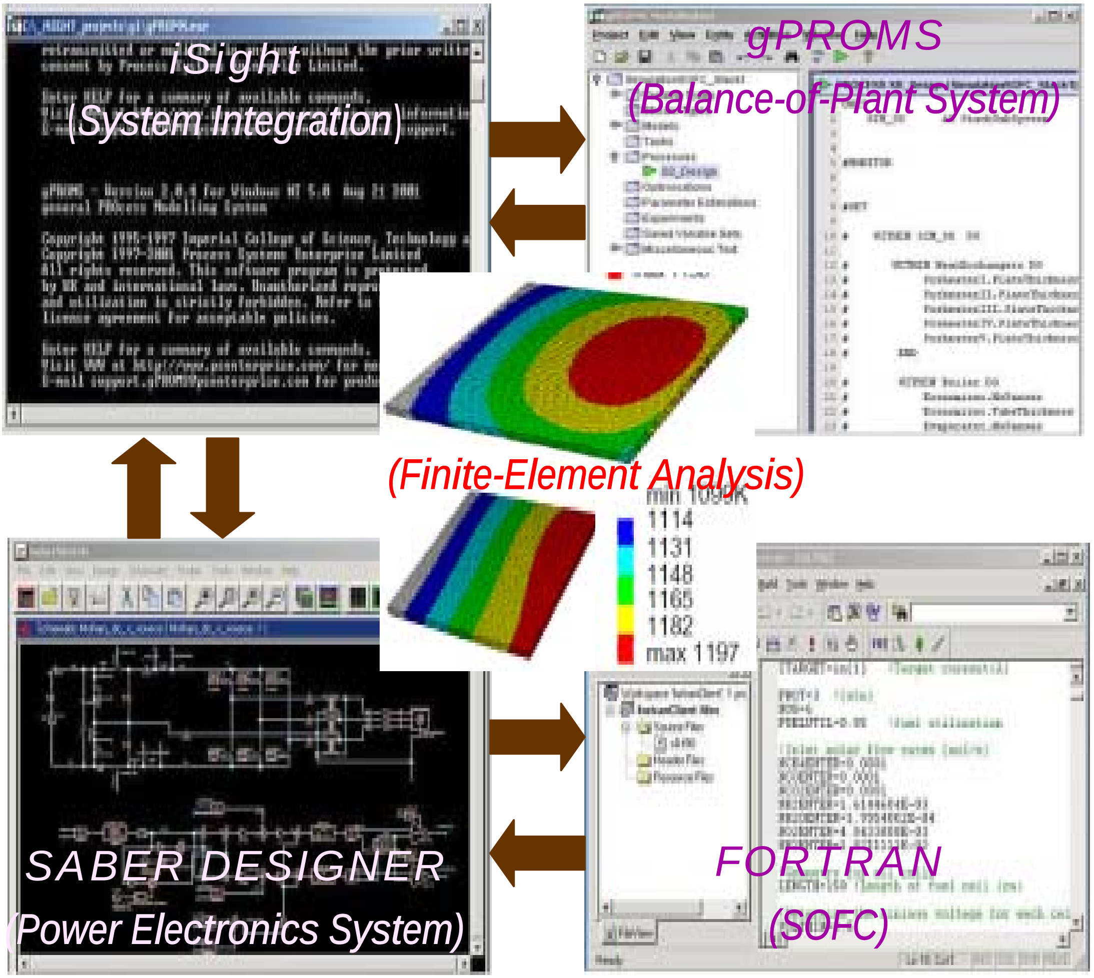
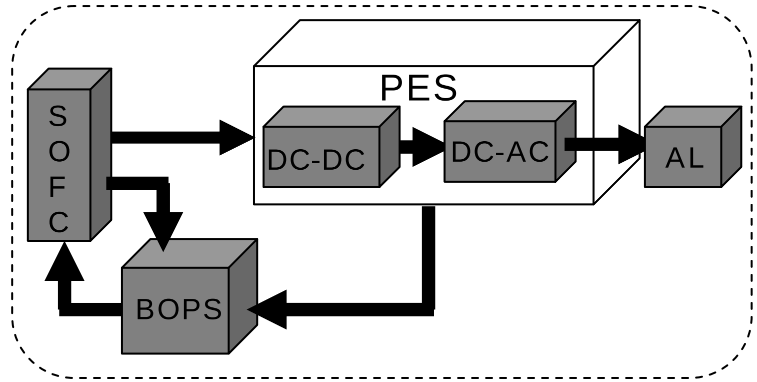
# SOFC Power-Conditioning System Modeling

## Multi-Software Simulation Platform

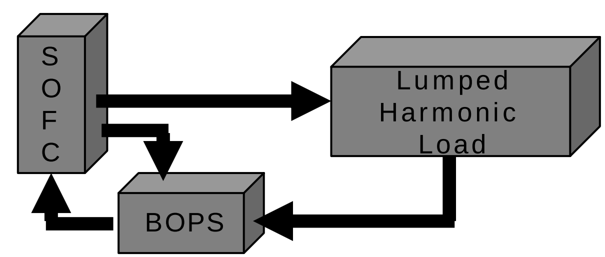



## Comprehensive System Model

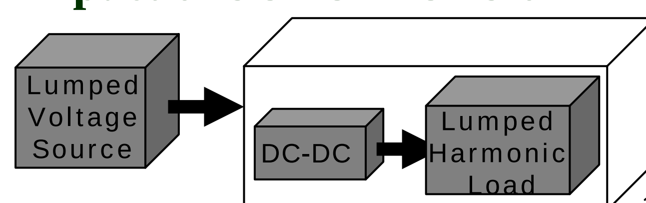



## Reduced-Order Models

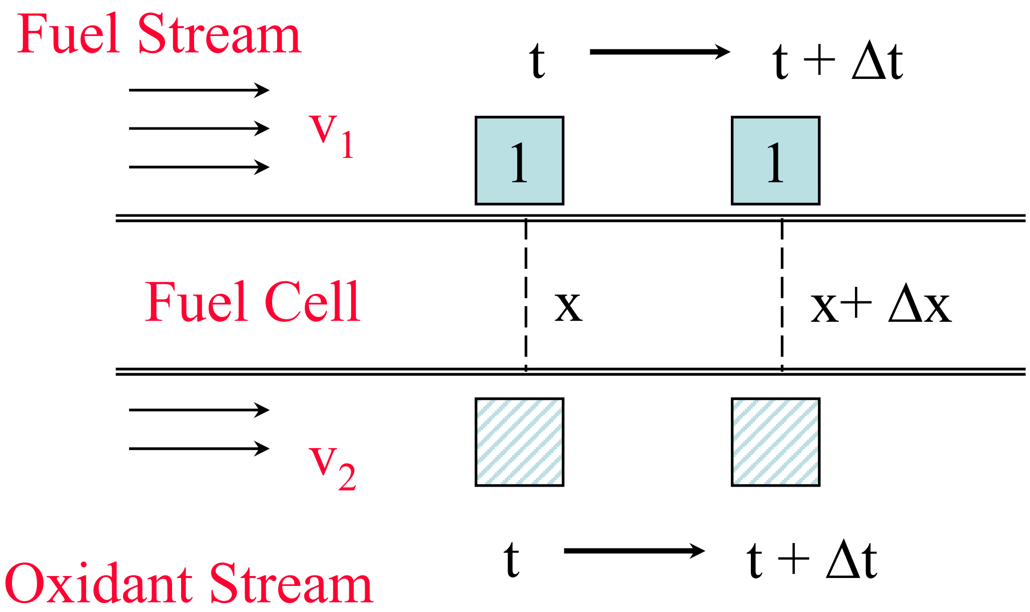
### Impact of PES on SOFC




### Impact of SOFC+BOPS on PES



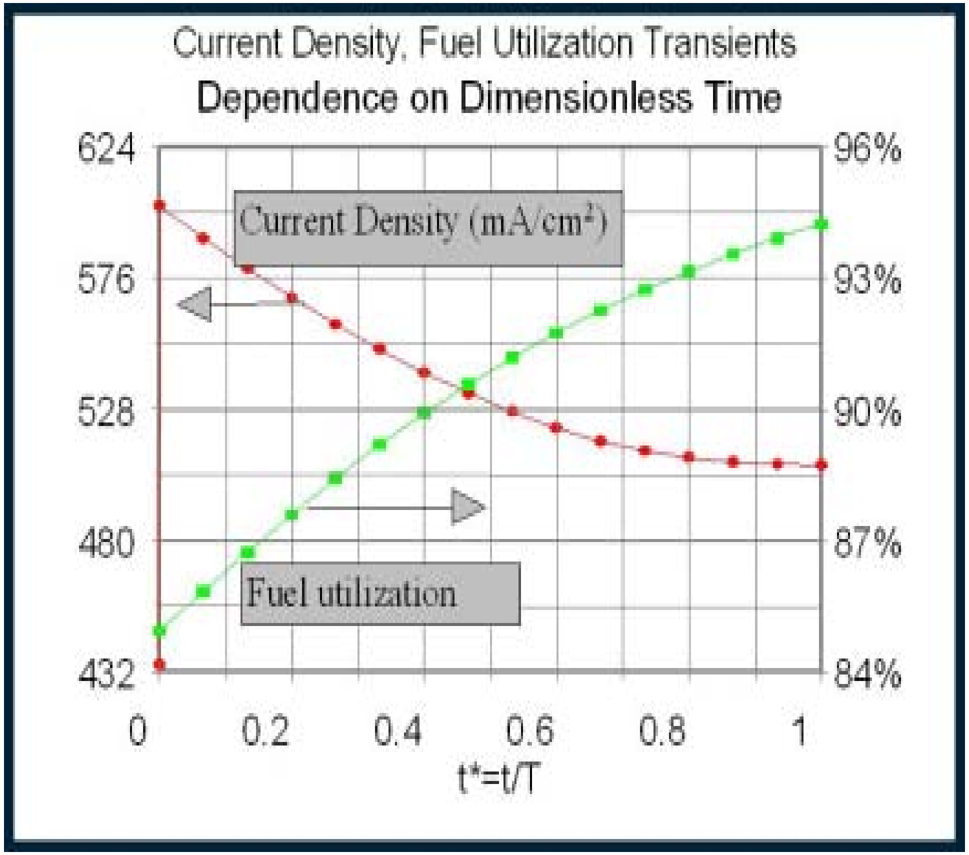
# Transient SOFC Response to Electrical Stimulus: Modeling Approach




$$\eta_{\mathbf{element}}(\mathbf{t}+\Delta\mathbf{t}) = \eta_{\mathbf{field}}(\mathbf{x}+\Delta\mathbf{x}, \mathbf{t} +\Delta\mathbf{t})$$

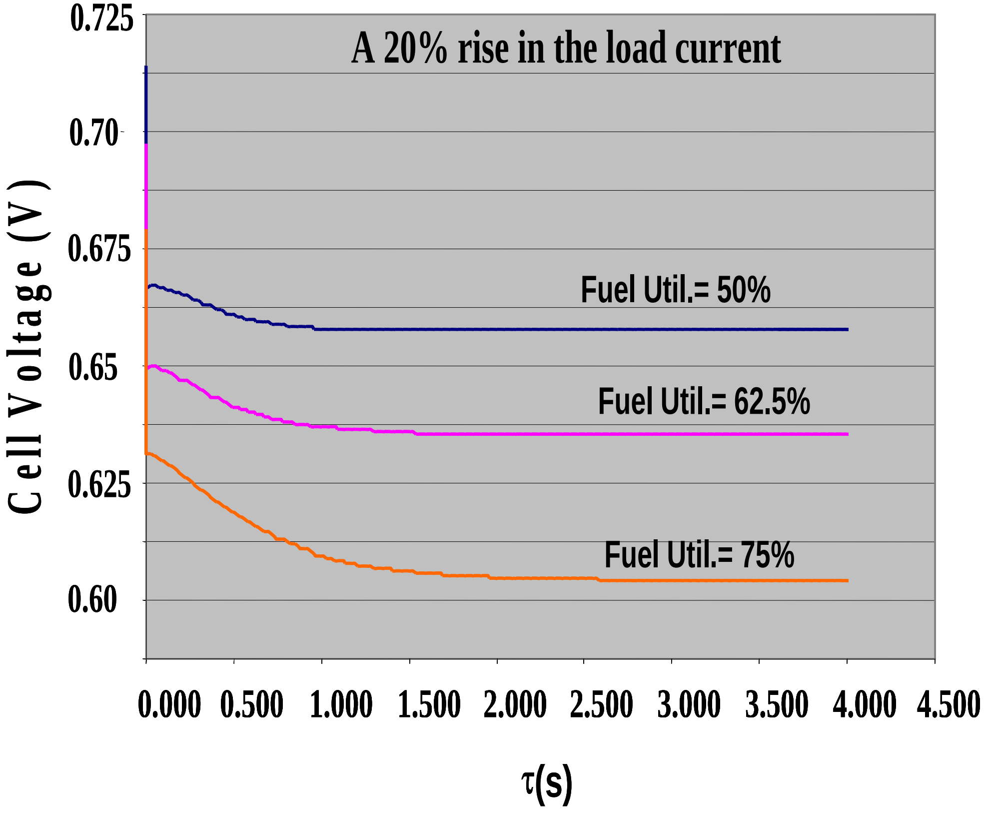
- Reactants' inlet flow rates and properties are invariant during relatively short transient episode
- Fuel stream effects are dominant
- Quasi-steady-state electrochemistry
- Lagrangian extension of validated steady-state model to track fuel parcels that travel over electroactive area

# Potentiostatic Control (Power Increase)



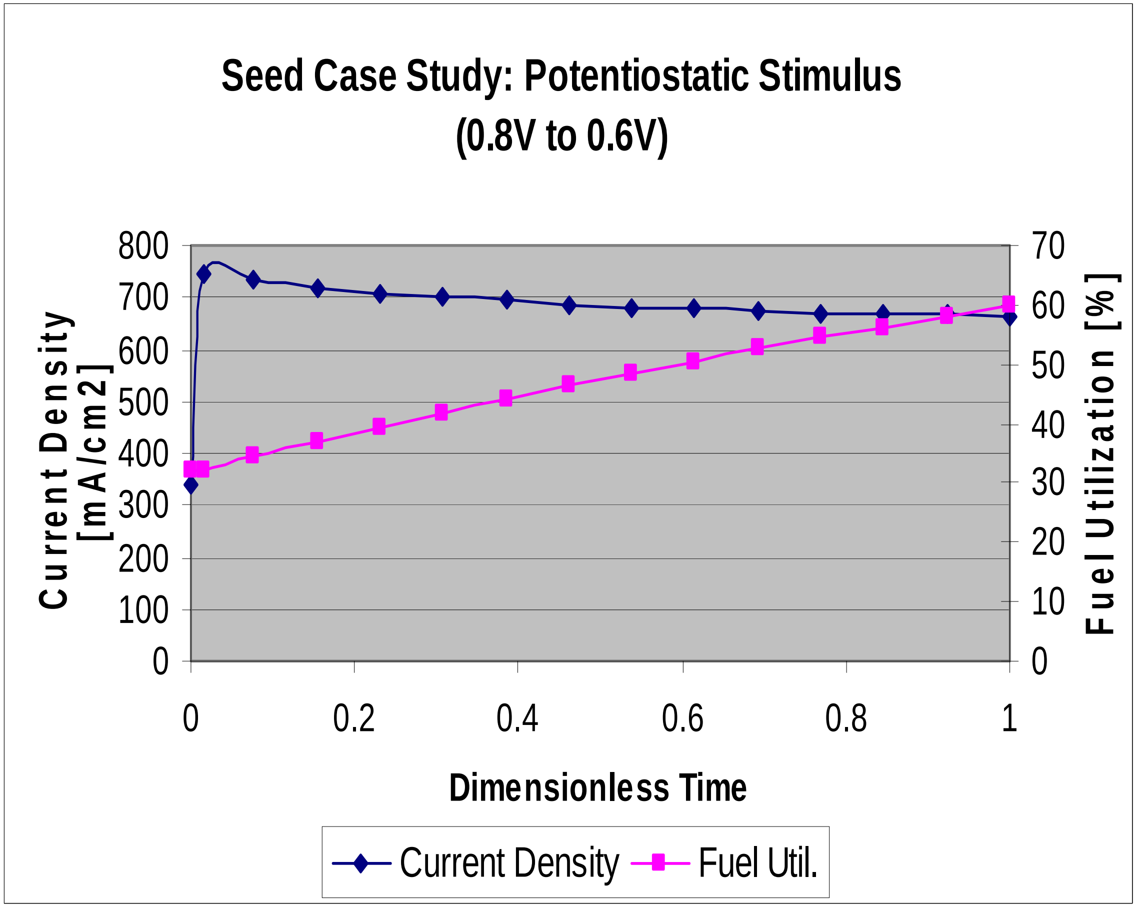

- **Current spikes up, yet the fuel supply remains invariant due to the *decoupling* of the cell**
- **Fuel utilization thus increases; this causes current (and power) to decrease from $t^*=0^+$ values, until a new steady state "match" occurs at the new voltage ($t^*=1$)**
- **Attainment of steady state at the time constant $\{T = L_{cell}/v_{fuel}\}$**

# Impact of Electrical Stimulus: Galvanostatic Control (Power Increase)




- **Duality of potential drop seen: *polarization curve effect* and *subsequent fuel depletion effect***
- **Multiple voltage reductions are "seen" by the reactant streams**
- **Transient is thus longer by multiples of the time constant**
- **Larger initial fuel utilizations prolong the relative transient due to enhanced fuel depletion effects**

# Leveraging Approach to Planar Cells




- Initial attempt at seed simulation of vertical team developmental cell {GE, SECA Annual Mtg., 4/03, 4 3/8" diameter cell}

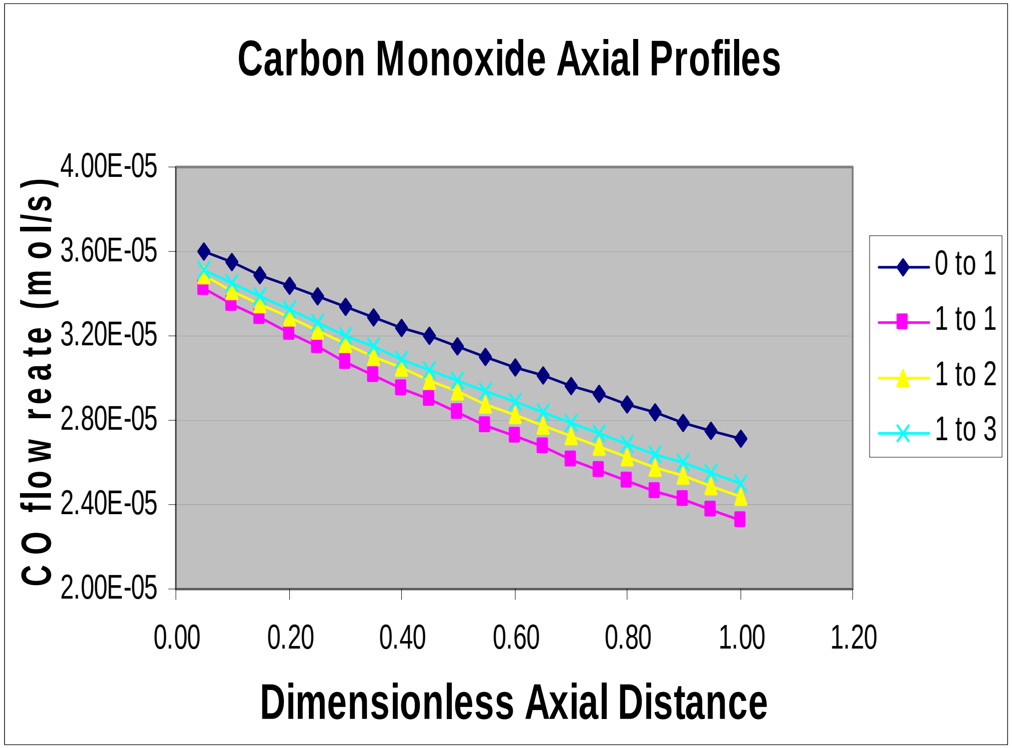
- Initial and final conditions match reported data

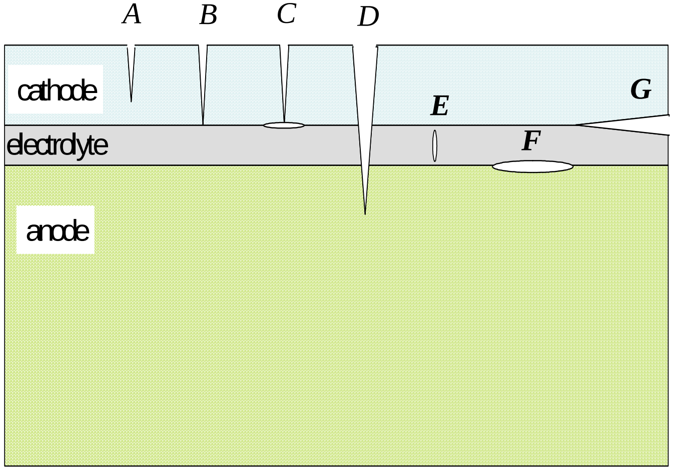
- Trends corroborate those of the tubular results

# RAM Issues of “Real World” Operating Conditions

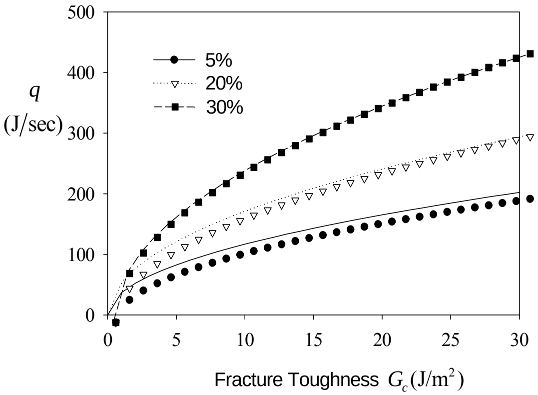
$$2CO \rightarrow CO_2 + C(s)$$

$$CO + H_2 \rightarrow H_2O + C(s)$$




**Microcrack Nucleation**




Maximum allowable heating rate for cracking vs fracture toughness

**Frozen CO electrochemistry promotes coking via heightened presence of CO along the anode.**

**Leverage of SECA Failure Analysis and Lab efforts into characterization of impact of electrical conditions upon cell electrochemistry**

# BOPS Modeling: Summary

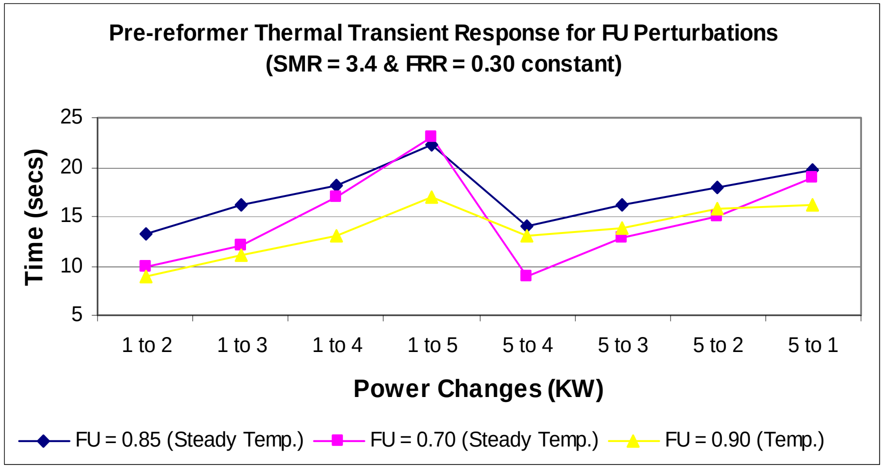
- Development of dynamic heat transfer, thermodynamic, kinetics, and physical models for each component of the BOPS:
  - ✓Compressor, expander, heat exchangers, steam generator, reformer, and fuel storage
- Implementation of models in a dynamic-programming environment using state-of-the-art transient numerical solver
- Integration of BOPS component models into a BOPS sub-system model
- Parametric studies (trade-off analyses) of best-practice control strategies for continuous operation and start-up and shut-down

# BOPS: PARAMETRIC STUDIES

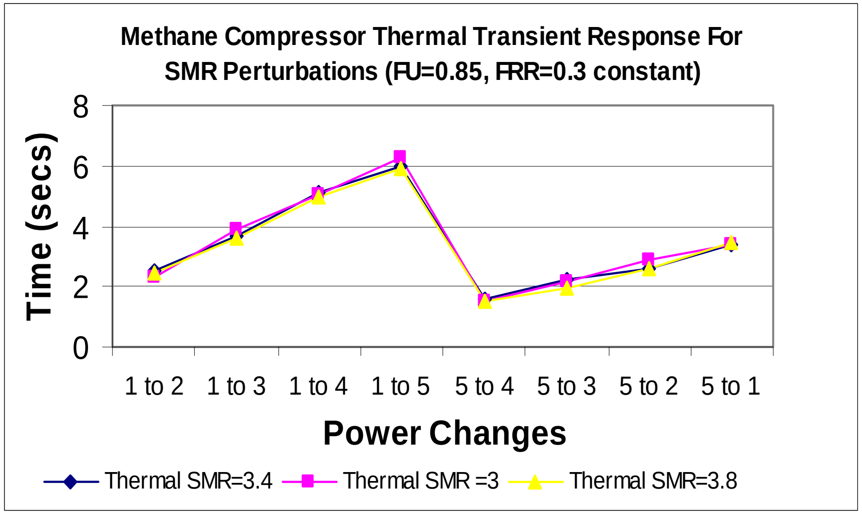
## Outline

- Power demand perturbation
- Power-demand and system-level parameter perturbations
- Small changes in power demand with floating fuel utilization
- Power demand perturbation with temperature control
- Total system efficiency analysis
- Start-up and shut-down

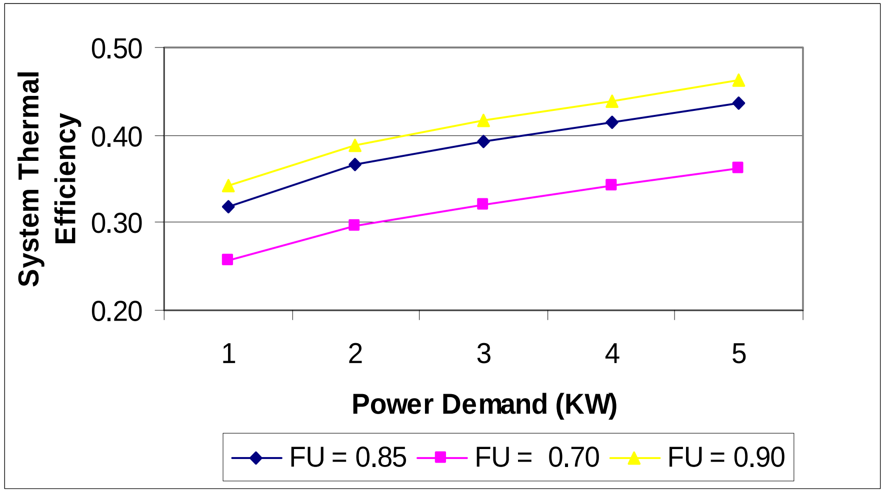
## Power-demand and system-level parameter perturbations




## Power-demand and system-level parameter perturbations

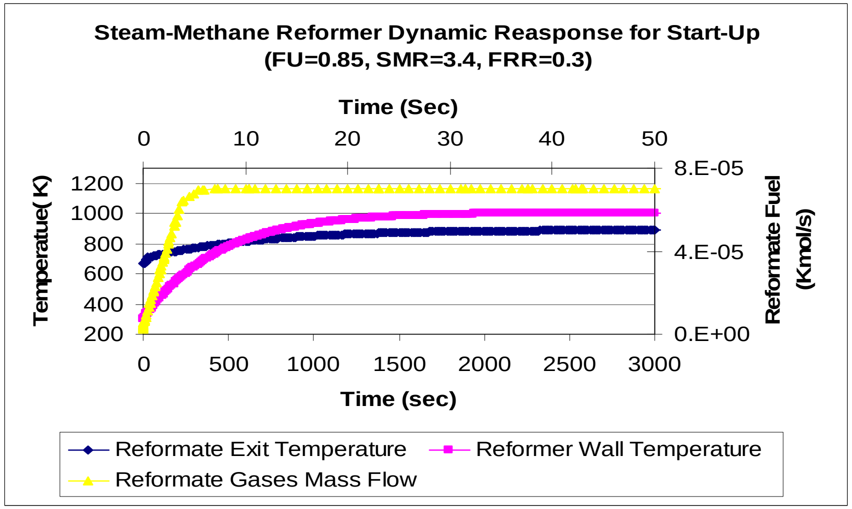



## Total system efficiency and power-demand and system-level parameter perturbations

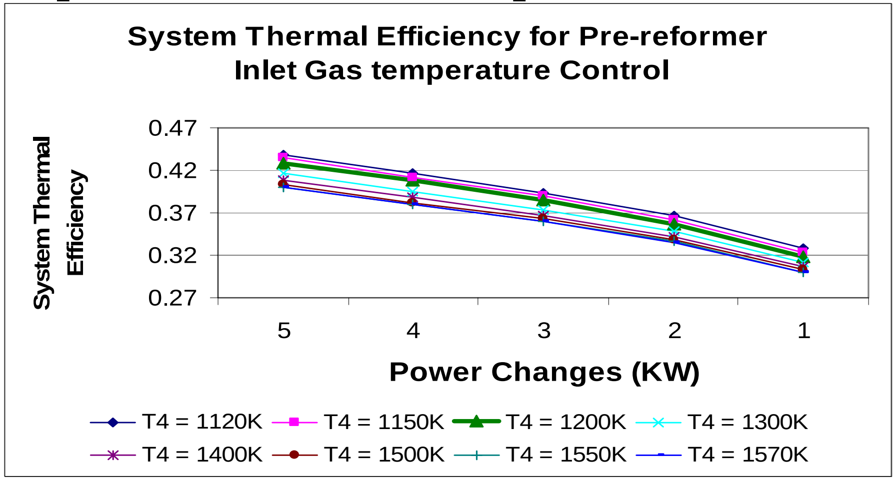


# BOPS: PARAMETRIC STUDIES

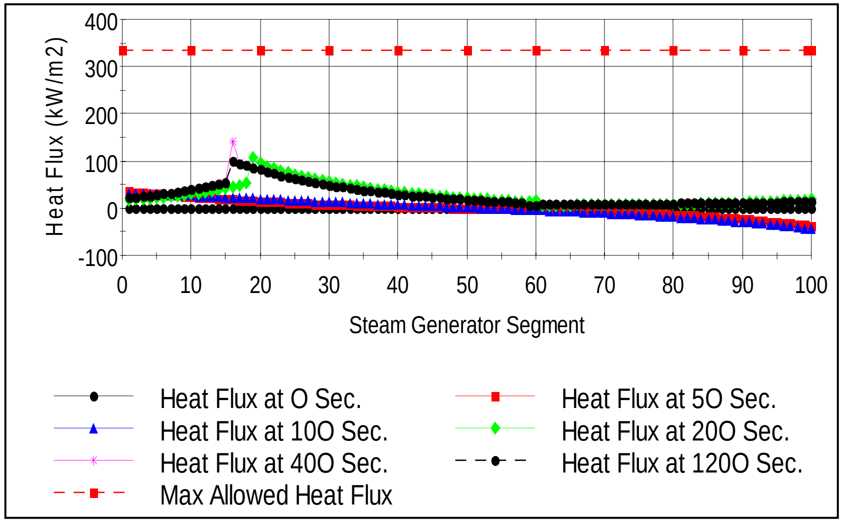
## Steam methane reformer start-up



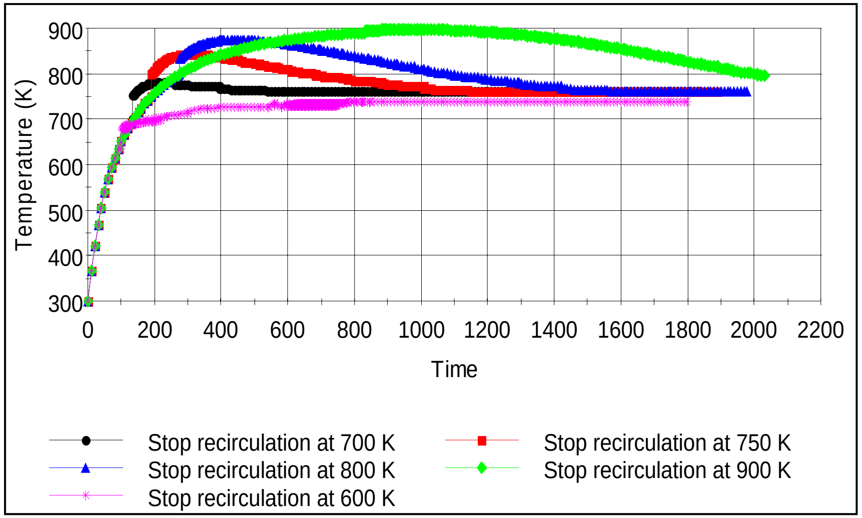

## Total system efficiency and power-demand perturbation with temperature control




## Steam generator heat flux




## Steam generator start-up

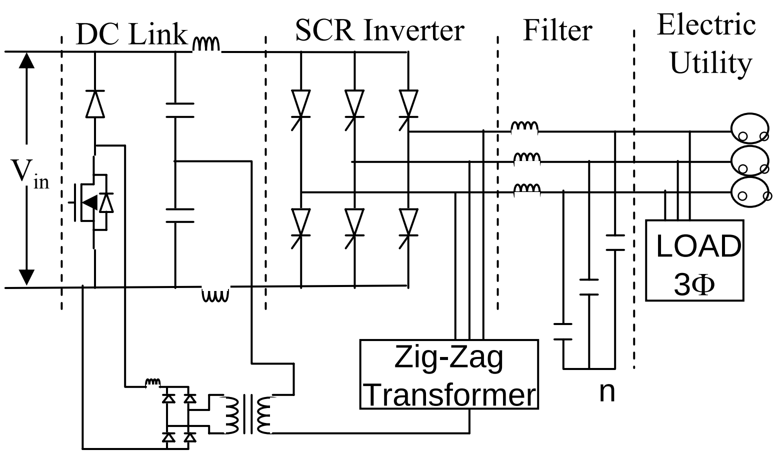


# PES Modeling and SOFC PCS System Interactions: Summary

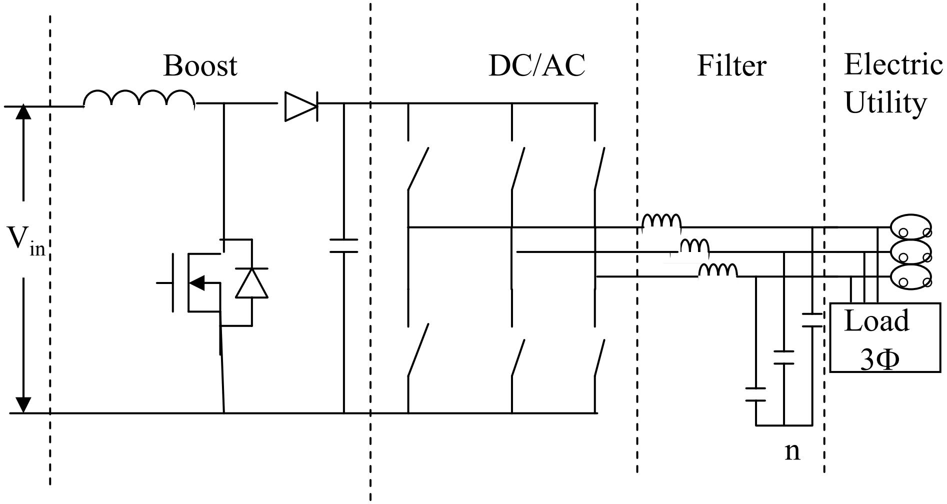
- Development of nonlinear switching models of PES
- Integration of SOFC, PES, and BOPS models to develop a comprehensive SOFC PCS model
- Development of  reduced-order models for fast and convergent simulations on a PC
- Investigated the impact of PES low- and high-frequency current ripples and the effects of load-transients on SOFC performance
- Analyzed the impact of SOFC-output-voltage variations on the dynamics and stability of PES using bifurcation analysis
- Investigated effects of PES control and modulation strategies on SOFC performance
- Conducted a preliminary trade-off study to determine the optimal size of a energy-storage device (*comprising a battery and a pressurized hydrogen fuel tank*) to cost-effectively improve PCS transient response
- Designed a (low-cost) novel zero-ripple, energy-efficient, reduced-voltage-stress, and direct energy-conversion PES

# PES Topological Models

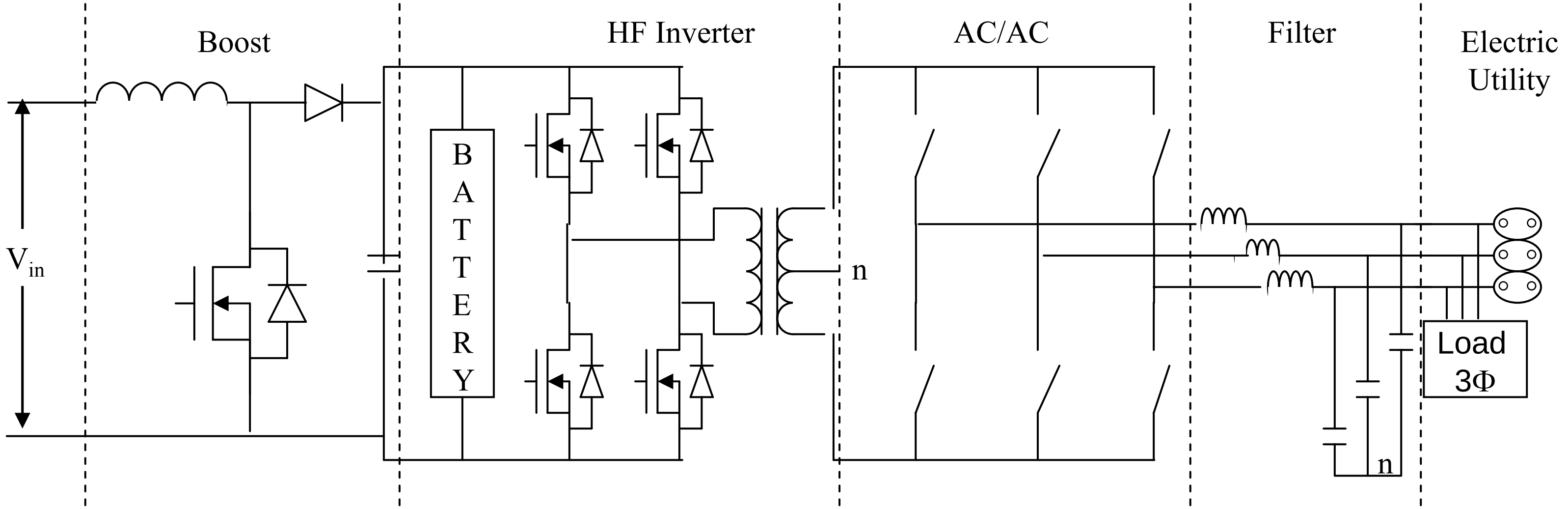
## Line-Commutated Current-Source Inverter




## Self-Commutated Voltage-Source Inverter

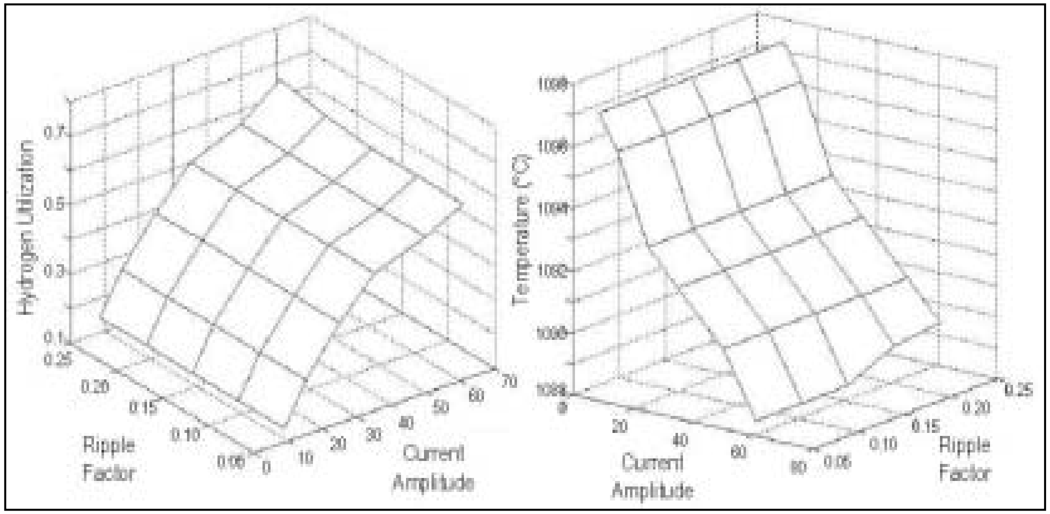



## High-Frequency Transformer-Isolated Topology

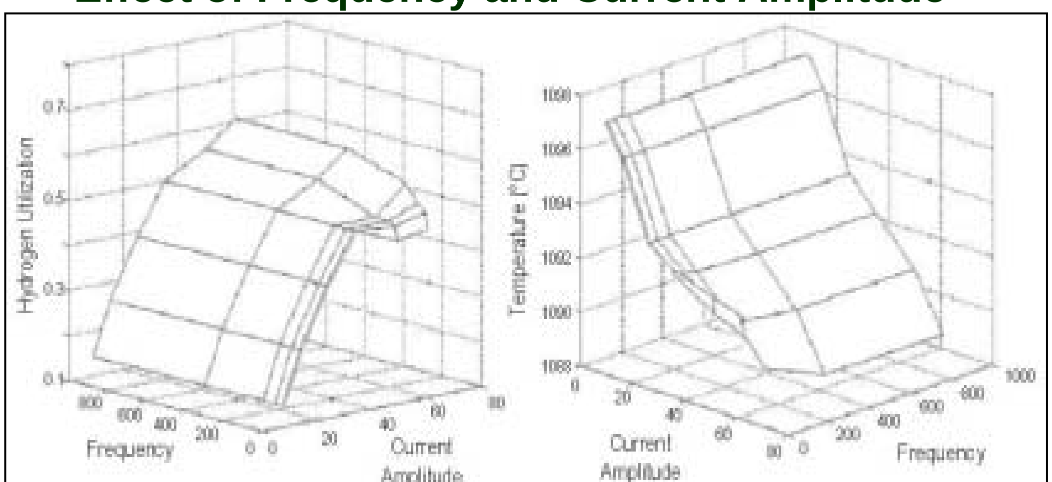


# SOFC PCS Steady-State Interaction Analyses

## Effect of Ripple Factor and Current Amplitude

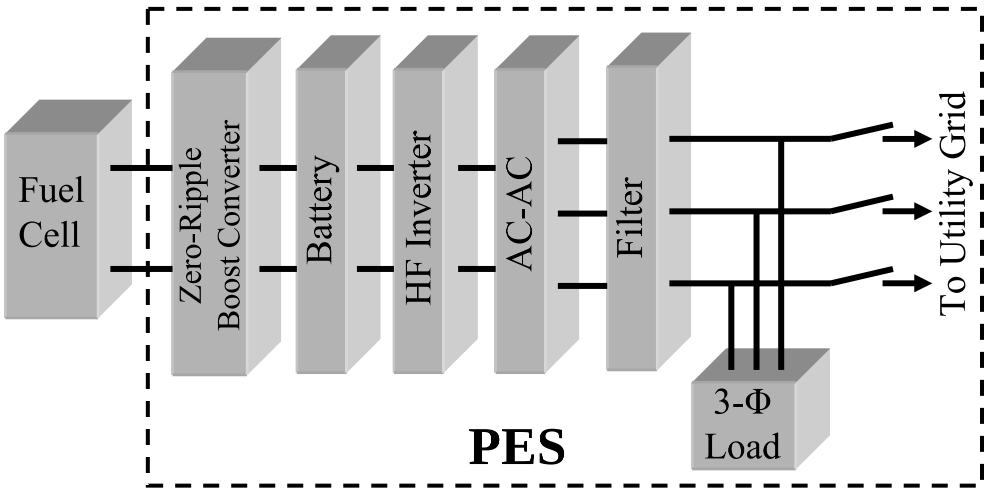


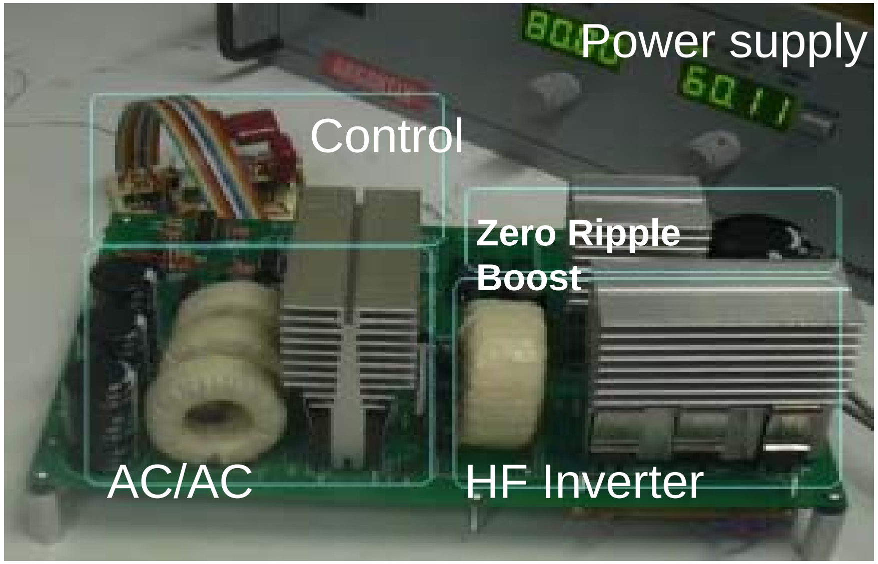

## Effect of Frequency and Current Amplitude



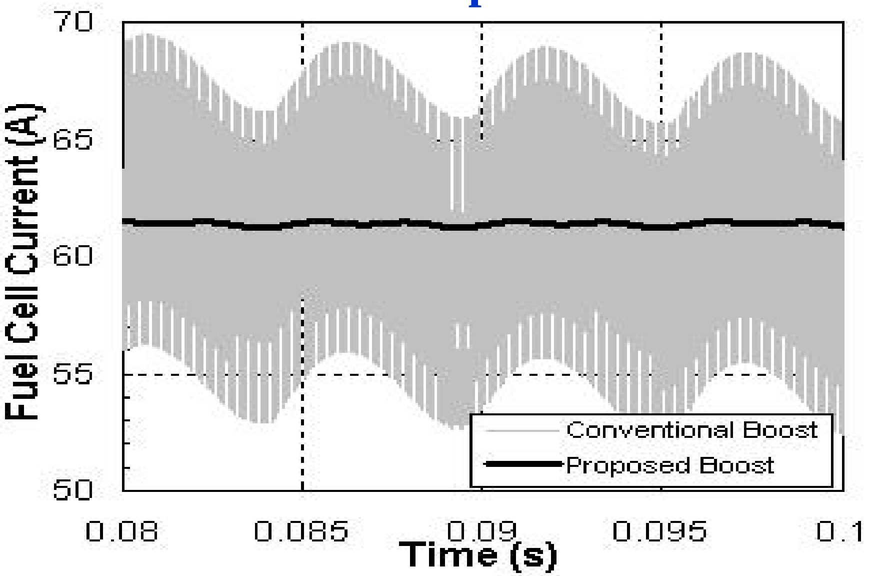

- Hydrogen utilization increases with the increase in load
- Current ripple has effect on the hydrogen utilization at high load conditions
- Low-frequency ripples do not necessarily lead to increased fuel utilization unless their magnitude is high
- For high loads, rise in the temperature observed at low frequencies (*high temperatures can cause interaction between SOFC electrolyte and electrodes leading to formation of high resistivity material and high microcrack densities*)

# Novel SOFC PES



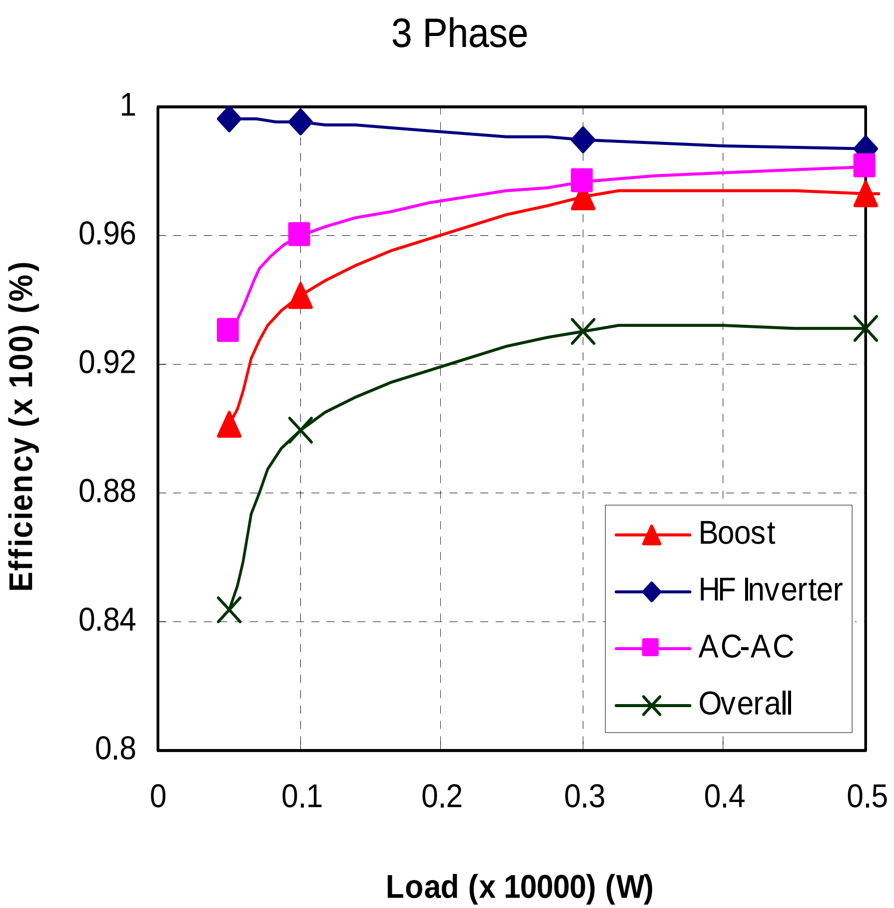

**SOFC Output Current**

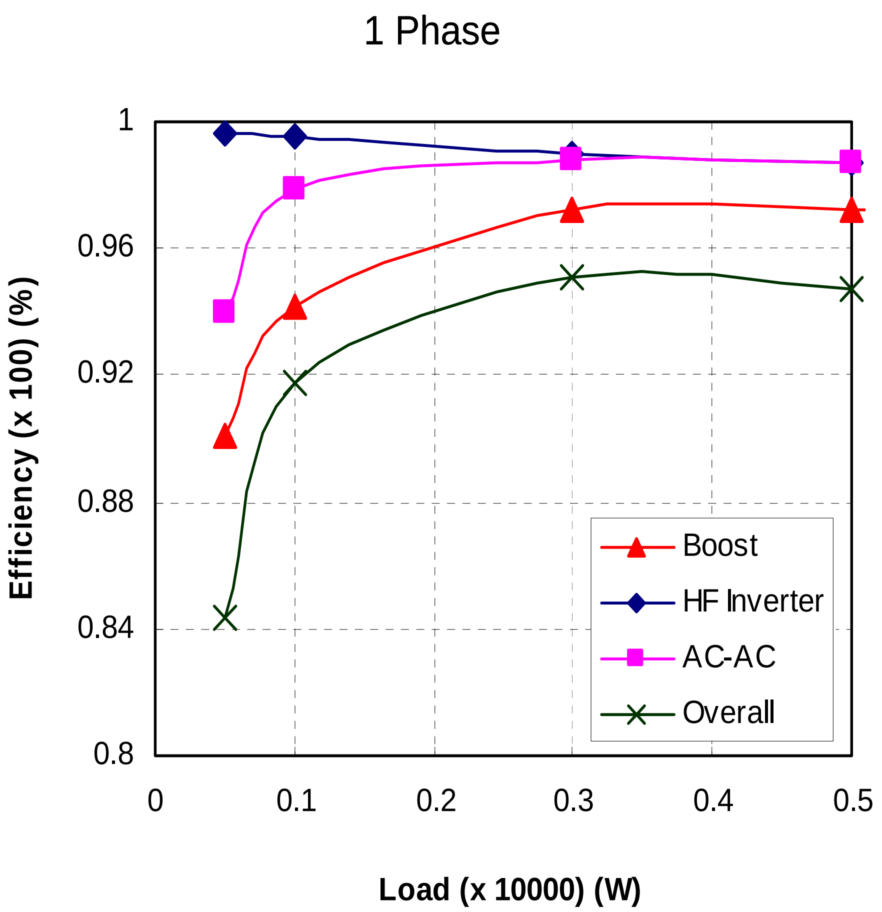



**FEATURES:**

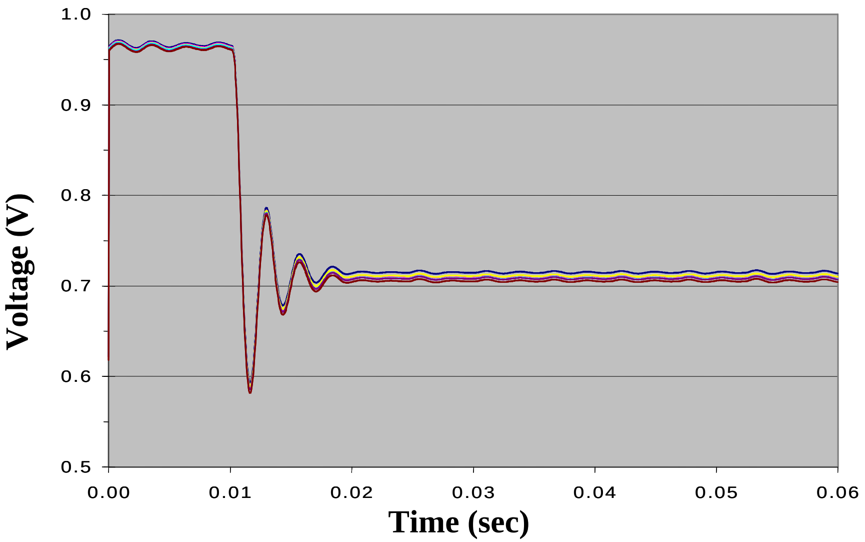
- Direct power conversion
- Reduced device voltage stress
- High energy efficiency
- Minimize SOFC output-current ripple
- Filter size and weight 50% less than conventional filter
- Cost effective

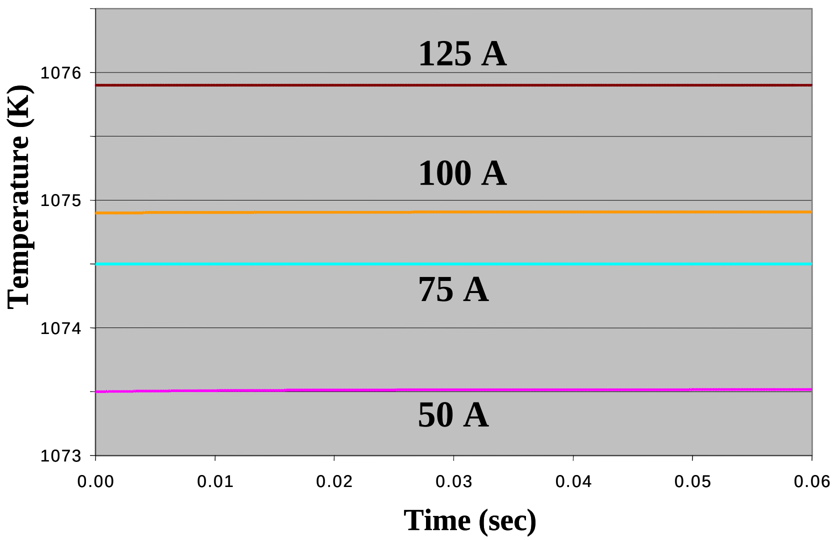
# Novel SOFC PES

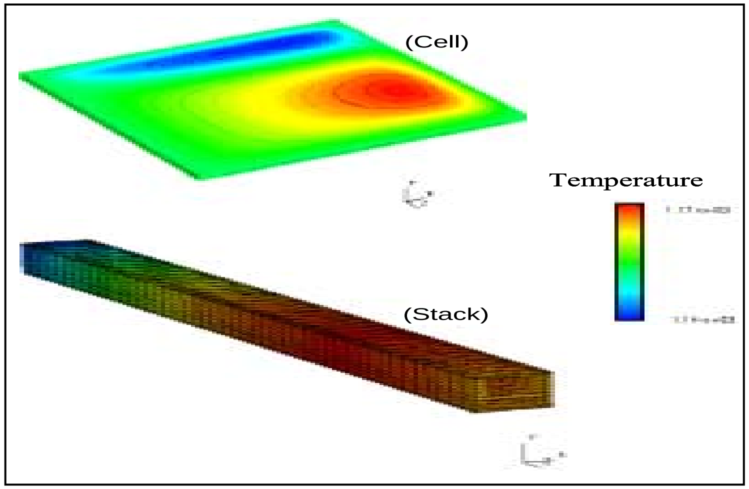


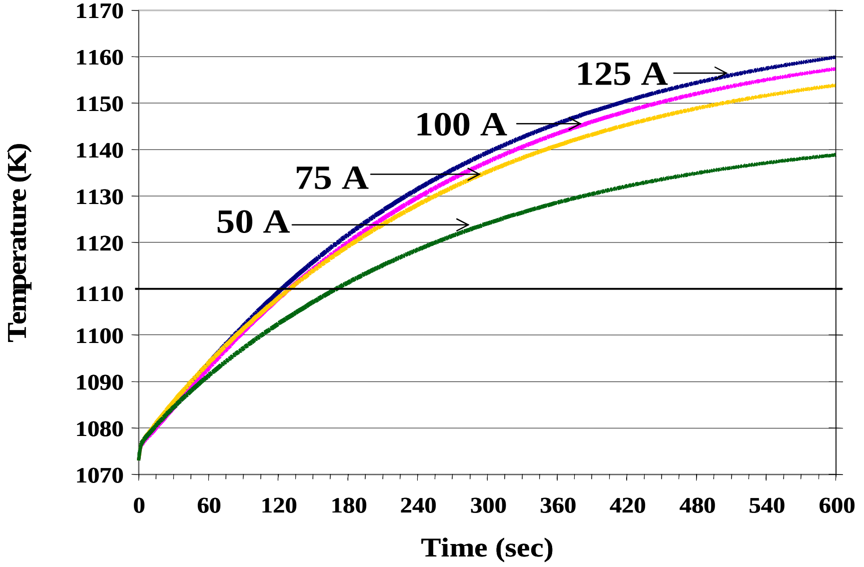



# SOFC PCS Load-Transient Interaction Analyses



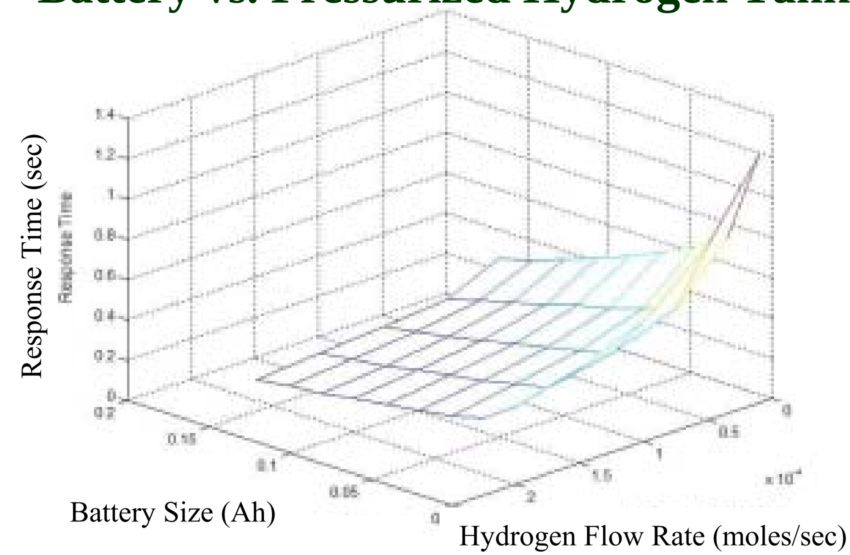



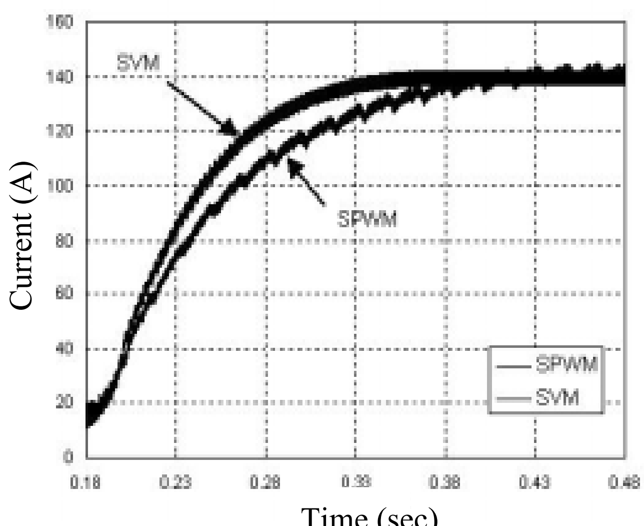
# Load-Transient Mitigation Techniques

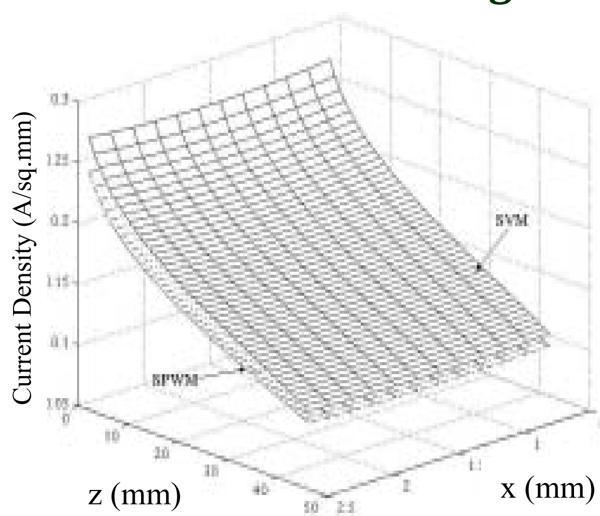
- **Pressurized Hydrogen Fuel Tank and Battery**
  - Instantaneous supply of additional energy requirement from SOFC stack
- **Inverter Modulation Strategies**
  - Space-vector modulation (SVM) vs sine-wave PWM (SPWM) used for the inverter
  - Battery acts as a stiff voltage source, providing additional energy requirements during transients
  - Slower boost converter voltage-controller response to prevent immediate change in SOFC energy demands

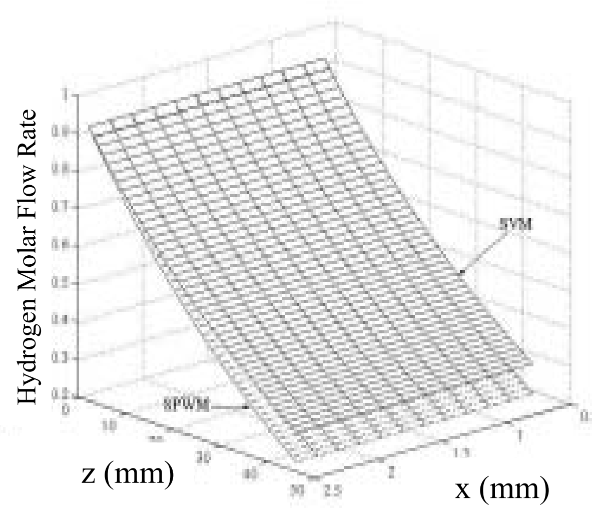
## Battery vs. Pressurized Hydrogen Tank



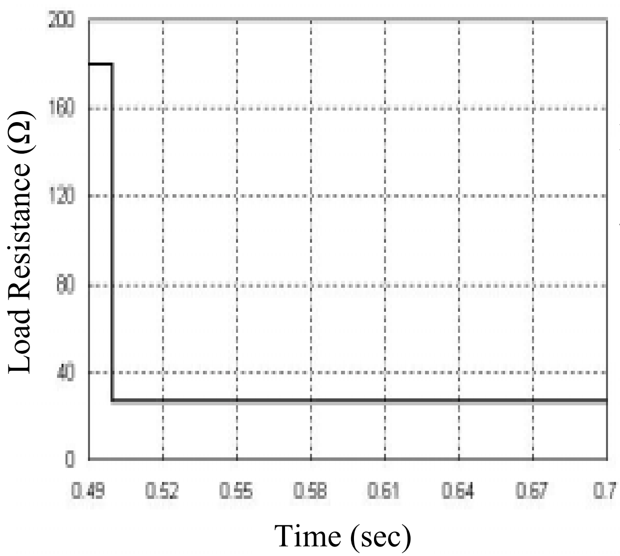

## Inverter Modulation Strategies

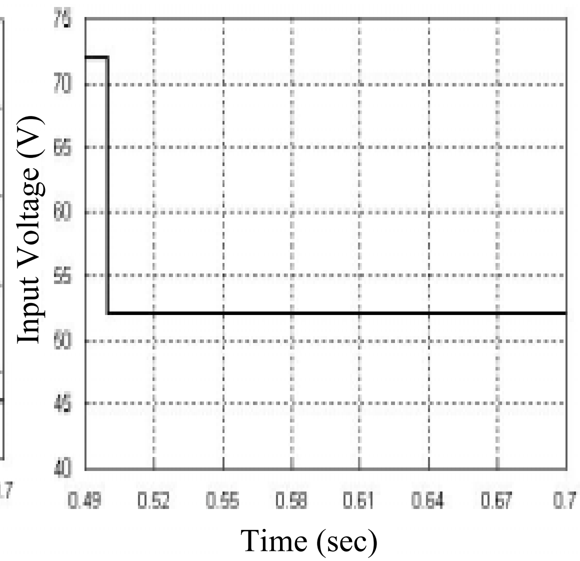


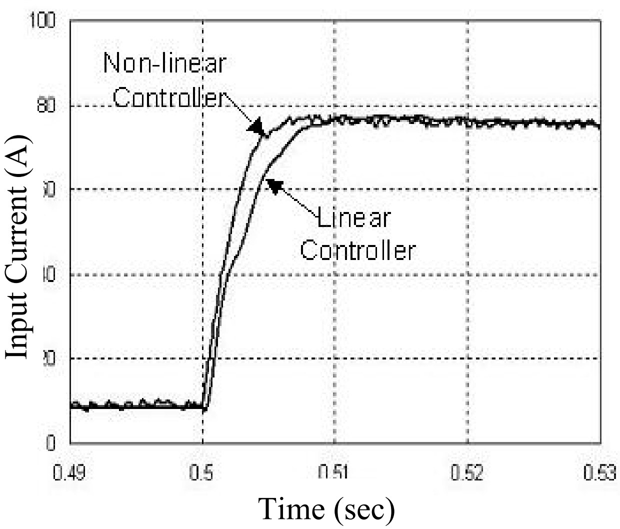



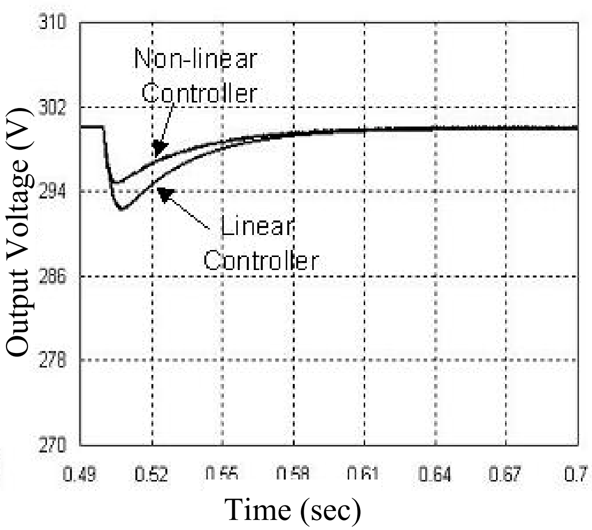



# Nonlinear Hybrid Controller for DC-DC Boost Converter




## ➢ FEATURES

- Hybrid control concept based on combining integral-variable-structure control (IVSC) scheme and multiple-sliding-surface control (MSSC)
- **Excellent steady-state and transient responses** even under parametric variations and under perturbations of SOFC stack voltage and load
- Controller eliminates the bus-voltage error with a **reduced control effort**
- Control scheme can **reduce the impact of very high-frequency dynamics due to parasitics** on an experimental closed-loop system

# Phase-II Objectives

- Develop and enhance fully transient nonlinear and temporal models for a variety of PES and BOPS components and for planar SOFC stacks
- Experimental validations of interaction-analyses results
- Develop capabilities for analyzing long-term performance and durability of SOFC planar and tubular stacks due to their system interactions with the PESs and application loads and the BOPSs
- Develop cost-effective optimal PES designs and design guidelines for (i) mitigation of electrical feedbacks on SOFC stack and (ii) technology transfer to SECA industry team
- Develop transient PES and PCS models and load profiles for vehicular APUs for performance and reliability analyses
- Develop optimal control and modulation strategies for robust PES and BOPS
- Develop decomposition techniques for optimizing PCS with respect to cost, reliability, size (power density), and response time

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