

Solid-Oxide-Fuel-Cell Performance and Durability: Resolution of the Effects of Power-Conditioning Systems and Application Loads

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Abstract—We describe methodologies for comprehensive and reduced-order modeling of solid-oxide-fuel-cell (SOFC) power-conditioning system (PCS) at the subsystem/component and system levels to resolve the interactions among SOFC, balance-of-plant subsystem, and power-electronics subsystem (PES) and application loads (ALs). Using these models, we analyze the impacts of electrical-feedback effects (e.g., ripple-current dynamics and load transients) on the performance and reliability of the SOFC. Subsequently, we investigate the effects of harmonics in the current, drawn from the SOFC by a PES, on the temperature and fuel utilization of the SOFC. We explore the impacts of inverter space-vector modulation strategies on the transient response, flow parameters, and current density of the SOFC during load transients and demonstrate how these two traditionally known superior modulation/control methodologies may in fact have a negative effect on the performance and durability of the SOFC unless carefully implemented. Further, we resolve the impacts of the current drawn by the PES from the SOFC, on its microcrack density and electrode/electrolyte degradation. The comprehensive analytical models and interaction-analysis methodologies and the results provided in this paper lead to an improved understanding, and may yield realizations of cost-effective, reliable, and optimal PESs, in particular, and SOFC PCSs, in general.

Index Terms—Power-conditioning system (PCS), power-electronics subsystem (PES), solid-oxide-fuel-cell (SOFC).

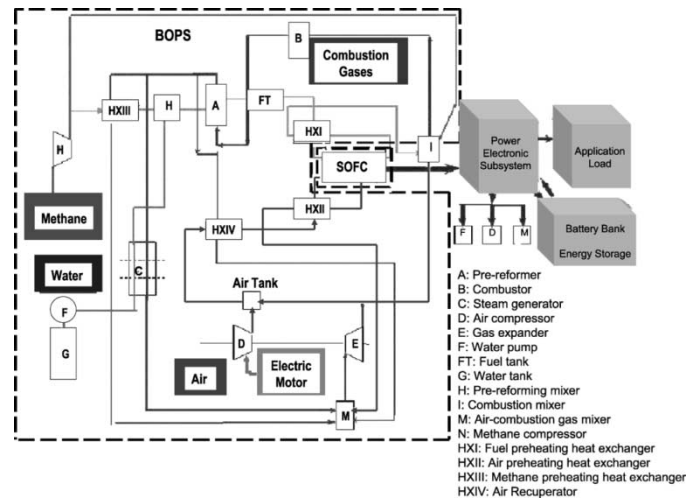


Fig. 1. Block diagram of a SOFC power-conditioning system (PCS). It shows the solid-oxide fuel cell (SOFC) stack, the power-electronics subsystem (PES) and application load (AL), and the balance-of-plant subsystem (BOPS).

I. INTRODUCTION

SOLID-OXIDE fuel cells (SOFCs) and SOFC power-conditioning systems (PCSs), as shown in Fig. 1, are expected to play a significant role in helping to meet the demands of power quality and reliability for distributed generation. However, certain challenges, including the issues of performance and durability of SOFC stacks (SOFCs), need to be resolved before SOFC PCSs can be applied to real-world applications. According to a recent Department of Energy estimate, for commercial viability, SOFC technology needs to demonstrate an operating life of greater than 40 000 h for stationary applications and greater than 5000 h for transportation applications. The factors, which could affect the lifetime and performance of the SOFCs may include transients in load current and steady-state ripple and harmonics, operating temperature, thermal cycling of SOFC material, and mechanical pressure fluctuations. Effects of high operating temperatures and high fuel utilization on the material properties of SOFC have been reported earlier [1]–[6]. These studies on SOFC reliability have primarily focused on studying the effects of material properties and electro kinetics of chemical reactions on its operating life and performance.

However, there is a need to study the effects of electrically-induced stresses imposed by the power-electronics subsystem

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(PES) on the performance of a SOFC. Development of high-performance and durable SOFCs and SOFC PCS requires knowledge of the electrical-feedback effects from the power-conditioning electronics and from the application loads (ALs), which may pass through or excite the PES. For example, a dc-dc converter imposes its own time-varying load on the SOFCS, apart from that due to variations in the ALs and other integrated dc-ac and dc-dc converters. High peak levels of the load-current can lead to low-reactant conditions within the SOFCS. It is, thus, important to develop analytical models and methodologies, which can be used to investigate the effects of electrical feedbacks from the PES and the ALs on the reliability and performance of SOFC systems for stationary and vehicular applications.¹ Achenbach [7], Hartvigsen *et al.* [8], Haynes [9], Haynes and Wepfer [10], and Hartvigsen [11] have demonstrated preliminary results on the impacts of linear electrical load impedance on the dynamics of a SOFC. Recently, Gemmen [12] attempted to estimate the effects of electrical loads and inverter current ripple on the durability and performance of PEM fuel cells using a simple first-order model of a PES. An understanding of the effects of dc-ac inverter loads on conditions near the electrolyte surface is achieved. Using a SOFC PCS model [13], Acharya *et al.* [14], [15] have demonstrated that, the behavior of a PES or AL has a direct impact on the performance and durability of the SOFCS.

There is, thus, a sustained need for resolving the issues of safe load-fluctuation and effective load-following and exploring how to optimally manage the response of the SOFC subsystems. Such analyses enables one to determine how much current and voltage ripples due to dc-dc converters the SOFC can acceptably withstand, how the frequencies of slow- and fast-scale ripples [16] affect the performance and life of a SOFC, and how a PES can be synthesized/developed and operated to mitigate these problems. In addition to the above effects, dc-ac inverter ripple currents have been reported to possibly degrade fuel-cell performance and reduce operating life if not adequately controlled [14], [15]. However, the effects of such feedback phenomena on SOFC performance and life are not completely understood and are required for further investigation. In the absence of proper understanding of the effects of ripple current on the SOFCS, bulky inductors or higher-order filters are typically specified to reduce ripple current to perceived low-risk levels. Therefore, understanding of the electrical impacts of PES topologies² on SOFCs may lead to reduction in the cost of inductor filtering, leading to more cost-effective power electronics for SOFC PCS without compromising the life of the SOFCS.

We also investigate the effect of electrically-induced thermal distribution on SOFC material property from the standpoint of SOFC durability. It has been shown in [1]–[5] that hydrogen uti-

lization and air-supply-pipe (ASP) temperature have a direct impact on the operating lifetime and performance of the fuel cell. In [6], it is shown that, the heating rate of the SOFC has a direct impact on its material properties including microcrack density. However, the effects of the current distribution of a SOFC on its stack parameters have not been demonstrated yet. Finally, we also investigate the impacts of modulation/control strategies in mitigating the effects of electrical perturbation on the SOFC. Because the heating rate of the ASP depends on the response of the SOFC (output current) to electrical-current perturbations, which in turn may depend on the modulation/control strategies, analysis of their effectiveness are of interest.

This paper, therefore, addresses the need for multiphysics (temporal and multiresolution spatial) models and interaction methodologies, which can be incorporated into a system tool to resolve the interactions among SOFC, PES and AL, and BOPS. Using these models and interaction-analysis methodologies, we investigate the impacts of electrical-feedback effects on the SOFC durability and performance. Without such analytical models and methodologies, realizations of cost-effective, reliable, and optimal PESs and their control/modulation strategy, in particular, and SOFC PCS, in general, are difficult.

II. MODELING AND ANALYSIS

The SOFC PCS (shown in Fig. 1) consists of three subsystems:

- 1) the SOFCS;
- 2) the PES and the AL;
- 3) the BOPS.

The chemical reactions responsible for producing electricity/electric power take place in the SOFCS. The PES is responsible for processing the SOFCS output to useful voltage and current levels to feed the AL. The BOPS acts as a fuel processor and converts hydrocarbon-based fuel to hydrogen. It is also responsible for maintaining the temperature of the fuel/air supply and their flow rates. Accurate steady-state and transient models of each of the above mentioned subsystems are critical to investigating the impact of the SOFC PCS on the performance and durability of the SOFCS.

A. SOFC Temporal Modeling

1) *Steady-State Model:* SOFCS steady-state and transient-models, based on fundamental electrochemistry (as opposed to curve-fit correlations and “black box” simplifications) are developed in [9]. The steady-state modeling technique is based on dividing the cell into a preset number of subdivisions. Mass and energy balance for fuel oxidation are made on each slice, which determines the equilibrium voltage, E_{slice} (known as the Nernst potential) of the slice

$$E_{slice} = \frac{1}{nF} \left\{ \Delta G_{\text{steam}, 1000^\circ\text{C}}^\circ - R_u T \ln \frac{p_{H_2O}}{p_{H_2} p_{O_2}^{\frac{1}{2}}} \right\} \quad (1)$$

where $\Delta G_{\text{steam}, 1000^\circ\text{C}}^\circ$ is the Gibb's free energy at 1000 °C, p_{H_2O} , p_{H_2} , and p_{O_2} are the partial pressures of water, hydrogen and oxygen respectively, R_u is the universal gas constant and

¹To overcome the lack of comprehensive analytical tools to model SOFC PCSs, manufacturers have so far implemented conservative (and expensive) schemes for managing stack response to electrical perturbations (e.g., controls tactics for delayed load-following to allow for balance-of-plant (BOP) response, and expensive inductor filtering.).

²Depending on its switching frequency and high-frequency rejection mechanisms, different PESs impose different electrically-induced stresses on the SOFC and hence, an in-depth understanding of the effects of the fast- and slow-scale ripples is necessary.

nF represents the charge flow across the cell. The equilibrium voltage represents the largest possible potential difference, from a thermodynamic standpoint. However as in any finite-rate process, the flows of ions and valence electrons generate several irreversibilities. In the case of SOFC, such irreversibilities include three types of polarization (activation, concentration, and ohmic), each of which causes a drop in the cell output voltage [10]. Activation polarization depends on the rates of chemical reaction in the fuel cell. High operating temperatures of SOFC cause extremely fast reaction kinetics; hence the voltage drop due to the activation polarization is small. The concentration polarization arises due to the transportation of the reactants from their respective streams to the fuel cell, while the voltage drop across the effective resistance of the fuel cell results in ohmic polarization. The output voltage can thus be expressed as $V_{\text{operate}} = E_{\text{slice}} - \Delta V_{\text{polarization}}$. The drop in output voltage due to polarization ($\Delta V_{\text{polarization}}$) is current dependent and has been extensively discussed in [10]. Once the current is estimated, constituent mole fractions and partial pressures for the next slice are calculated, based on the stoichiometric relationship between the current and reaction constituents (hydrogen, oxygen and steam) [10]. Successive slices are “marched” through until the current and power distributions for the entire cell are known. The total current and power are then calculated as accumulations of the slice values.

2) *Transient Model:* Although electrochemical transient responses are fast in comparison to thermal-hydraulic transients, finite electrical-transient effects still arise due to changes in constituent concentrations. Fig. 2, shows the hydrogen concentration profile along the fuel cell. The solid curve concentration profile corresponds to the cell’s initial steady state. At time, “ $t = 0^+$,” the operating voltage decreases to accommodate an increase in load demand. The reactant supply, however, is predicated on the prescribed fuel utilization and initial current. In accordance with Faraday’s law, there is a decline in reactant concentrations when the load increases. This decrease continues until a new electrical steady-state is reached (at $t = t_{ss}$). Transient analyses are facilitated by focusing attention on individual fluid elements as they travel along the cell; this method is called a Lagrangian approach. Fig. 3, illustrates the Lagrangian approach. During the cells’ transient response to load increase, each fuel element approaches the cell with the same inlet characteristics (It is assumed that both the supply and inlet properties of reactants remain invariant throughout the electrical transient). The exit properties of each fluid element, however, depend upon its location at the time of the load hike, $t = 0^+$. Element 2 of Fig. 3(a), for example, will have greater reactant depletion than element 1. This is because element 2 has longer exposure to electroactive area at the lower operating voltage. The electrical transient episode ensues until each fluid element approaching the cell again experiences an identical change in constituents. This occurs when element three reaches the end of the cell (note element three is at the beginning of the cell when the cell potential decreases). After element three, every subsequent fluid element (e.g., element four) enters at the new operating voltage; these elements then experience the same reaction phenomena. The time of the electrical episode is thus nearly the length of the cell divided by the fuel velocity. Depending on

fuel flow rate, the timeframe of the electrical transients is a fraction of a second. Note that fuel processors have response times of the orders of seconds (e.g., partial oxidation units) and minutes (e.g., steam reformers). In this model, the oxidant stream property variation is neglected. Air stoichiometric numbers, or inverse equivalence ratios, are typically greater than unity for conventional thermal management; this is especially the case when there is no internal reformation to absorb thermal energy from the cells. The oxygen mole fraction is thus more stable along the cathode. As an example, consider the operational extreme of a relatively low air stoichiometric number of three and an unrealistically high fuel utilization of unity. The inlet oxygen percentage is approximately 21%; the exit mole fraction would be nearly 15%. Simulations showed a current/power variation of only a few percent caused by such a difference in oxygen mole fraction; hence it can be neglected in the model.

The fluid elements involved in the transient episodes are computationally tracked. This is done via two-dimensional arrays containing field variable information (i.e., axial position and time). The Lagrangian basis is that a fluid element occupies a certain location at a given time

$$\eta_{\text{element,fluid}} = \eta(x, t) \quad (2)$$

where the symbol η represents the properties of the fluid element in question (e.g., constituent partial pressures) and x represents distance as shown in Fig. 3. The electrical power produced along the cell depends upon these properties. In accord with the Lagrangian methodology, the temporal discretization is compliant with the flows’ velocity and the axial discretization of the cell (i.e., slice lengths), as shown in Fig. 3(a)

$$\Delta t = \frac{\Delta x}{v} \quad (3)$$

where v is the fuel velocity. Combining (2) and (3), we obtain

$$\eta_{\text{fluid,element}}(t + \Delta t) = \eta(x + \Delta x, t + \Delta t). \quad (4)$$

The quasi-steady state electrochemistry assumption means that electrochemical phenomena occur as if at steady state, at the given instant. By applying a relation equivalent to the Reynolds transport theorem and utilizing the steady-state electrochemical model discussed in the earlier section, the current (and power) and heat generation is calculated

$$\begin{aligned} \dot{n}_{j,\text{int ermed}}(x + \Delta x, t + \Delta t) \\ = \dot{n}_{j,\text{entering,slice}}(x, t) + \Delta \dot{n}_j(x, t) \end{aligned} \quad (5)$$

where the subscript j represents hydrogen, oxygen, and steam, and (5) accounts for the temporal change in constituents due to electrochemical reactions. The temporal change in constituents due to shift reaction is given by

$$\begin{aligned} \dot{n}_k(x + \Delta x, t + \Delta t) \\ = \dot{n}_{k,\text{int ermed}}(x + \Delta x, t + \Delta t) + \dot{n}_{k,\text{shift,change}}(x, t) \end{aligned} \quad (6)$$

where the subscript k represents hydrogen, steam, carbon monoxide, and carbon dioxide. The shift reaction is modeled using equilibrium chemistry due to the hot fuel stream and nickel catalyst within the anode. These temporal expressions of

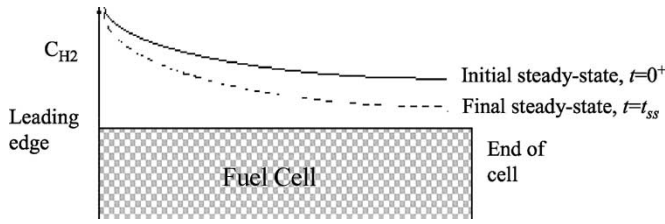


Fig. 2. Illustration of fuel stream transient dynamics.

mass conservation enable the transient electrochemical model to “march out” in time. Thermal transient effects are also considered.

3) Thermal Transient Model:

a) *Cell thermal response:* Thermal transport phenomena are illustrated in Fig. 4. The primary step in analyzing the thermal response of the fuel cell is to establish its time dependent thermal energy balance [10]

$$\dot{E}_{\text{stored,cell}} = \dot{E}_{\text{gen,cell}} - \dot{E}_{\text{out,cell}} \quad (7a)$$

$$\dot{E}_{\text{stored,cell}} = C_{\text{cell}} \frac{dT_{\text{cell}}}{dt} \quad (7b)$$

$$\dot{E}_{\text{out,cell}} = \dot{Q}_{\text{rad}} + \dot{Q}_{\text{TFD}} + \dot{Q}_{\text{cell,convect,ann}} \quad (7c)$$

$$\dot{Q}_{\text{rad}} = \varepsilon_{\text{ASP}} \sigma A_{\text{ASP}} (T_{\text{cell}}(t)^4 - T_{\text{ASP}}(t)^4) \quad (7d)$$

where $\dot{E}$ and $\dot{Q}$ represent the energy rate and heat, respectively, C_{cell} is the SOFC heat capacity rate, ε_{ASP} is the ASP emissivity, σ is the Stefan-Boltzmann constant and A is the surface area. The subscripts ASP and cell represents the ASP, and fuel-cell, respectively. $\dot{E}_{\text{stored,cell}}$, $\dot{E}_{\text{gen,cell}}$, and $\dot{E}_{\text{out,cell}}$ represent the stored-, Nernst-, and output-energy rates, respectively. $\dot{Q}_{\text{rad}}$ and $\dot{Q}_{\text{cell,convect,ann}}$ are the heat-rates due to radiation and convection, $\dot{Q}_{\text{TFD}}$ is the radiation from the cell to the ASP, and T_{cell} and T_{ASP} are the cell and air-supply-pipe temperatures.

Equation (7a) is the conservation of thermal energy applied to an unsteady (transient) system. The electrochemical model predicts the generation term. The volume of the SOFC and its reported volumetric heat capacity determine its overall heat capacitance. The first term on the right hand side of (7c) is the radiation from the cell to the ASP. The latter terms in this equation quantify heat convection from the cell to the oxidant in the annulus. The quasisteady state heat transfer assumption [9] is used to calculate

$$\dot{Q}_{\text{TFD}} = \dot{m}_{\text{air}} c_p (T_{\text{air,bulk,terminal}}(t) - T_{\text{air,exit,ASP}}(t)) \quad (8a)$$

$$T_{\text{air,bulk,terminal}}(t) = \theta_{\text{bi}} T_{\text{ASP}}(t) + \theta_{\text{bo}} T_{\text{cell}}(t) \quad (8b)$$

$$\dot{Q}_{\text{cell,convect,ann}} = N_u \frac{k_{\text{air}} \left(\frac{T_{\text{cell}}(t) + T_{\text{air,bulk,terminal}}(t)}{2} \right)}{D_h} \times A_{\text{ann,cell}} \times [T_{\text{cell}}(t) - T_{\text{air,bulk,terminal}}(t)] \quad (9)$$

where $\dot{m}_{\text{air}}$ is the air mass flow rate, c_p is the specific heat, θ is the temperature coefficient, N_u is the Nusselt number, k is the thermal conductivity, D is the diameter of the pipe and $A_{\text{ann,cell}}$ is the surface area of the annular region of the cell. $T_{\text{air,bulk,terminal}}$ and $T_{\text{air,exit,ASP}}$ are the temperature of air at the bulk terminal and the ASP exit, respectively. Equations

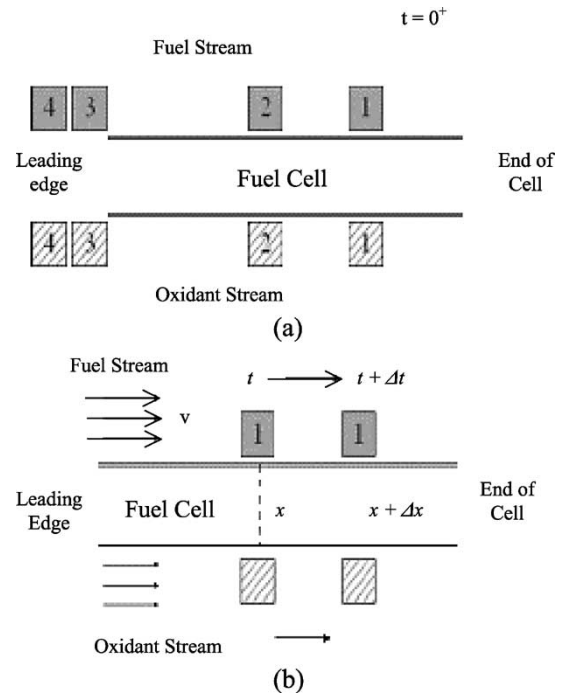


Fig. 3. (a) Individual fuel element locations at the time of the electrical change (Lagrangian approach) and (b) correlation between temporal and spatial discretizations.

Cutaway Section

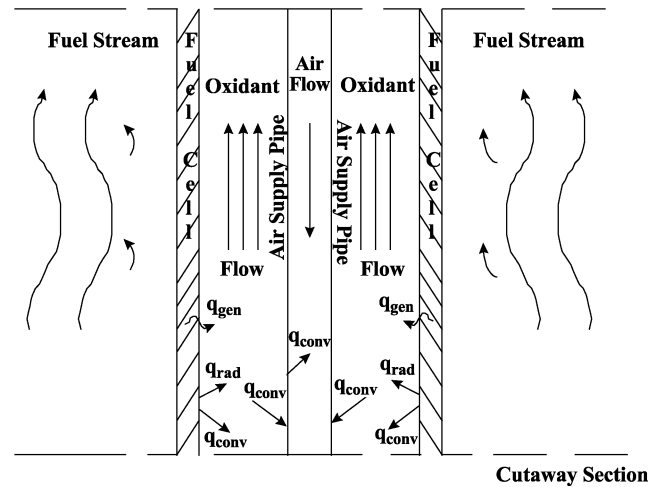


Fig. 4. Thermal transport phenomena within the interior of the cell.

(8) and (9) describe the convection within and beyond the annulus entrance. Fluid flow is presumed fully developed. Note the change in fuel-cell temperature is coupled to the ASP temperature both explicitly via radiation and implicitly via convection (the air entering the annulus is first preheated in the pipe). Resolving the temporal profile of the fuel cell's temperature then requires calculating the temperature response of the ASP as well.

b) *ASP temperature response:* Following (7), an energy balance is again developed as

$$\dot{E}_{\text{stored,ASP}} = \dot{E}_{\text{in,ASP}} - \dot{E}_{\text{out,ASP}} \quad (10a)$$

$$\dot{E}_{\text{stored,ASP}} = C_{\text{ASP}} \frac{dT_{\text{ASP}}}{dt} \quad (10b)$$

$$\dot{E}_{in,ASP} = \dot{Q}_{rad} + \dot{Q}_{cell,convect,ann} \quad (10c)$$

$$\dot{E}_{out,ASP} = \dot{Q}_{ASP \rightarrow air,inside} \quad (10d)$$

The heat capacitance term of (10b) is based on supply pipe volume and volumetric heat capacity data for alumina oxide. (10c) results from two considerations. The net heat radiated from the cell has to be absorbed by the supply pipe, since air is a nonparticipating medium. Additionally, the attainment of a terminal bulk temperature in the annulus entrance precludes heat gain by the fully developed flow. The convective heat from the cell to the oxidant stream thus continues convecting to the ASP.

Unlike the annular region, the fluid temperature inside the ASP has a profile that is nonuniform and initially exponential. In compliance with this axial variation of bulk temperature, convection within the ASP is modeled as a surface integral

$$\dot{Q}_{ASP \rightarrow air,inside} = \int_{length,ASP} [h(x)(T_{ASP}(t) - T_{bulk}(x,t))] P dx \quad (11)$$

where P is the power supplied by the fuel cell. The integrand of (11) is the product of convective heat flux and the supply pipe's inner perimeter. Note the time dependence of the convective heat transfer coefficient is negated. Here the fuel flows are presumed to be steady, and there is no change in flow regime (i.e., laminar-to-turbulent or vice versa). The thermodynamic models of the BOPS (which controls the ASP temperature) are outlined in Appendix B.

B. SOFC Spatial Modeling

Detailed spatial distribution of SOFC parameters are needed to gain an insight into the reliability of the SOFCS. Consequently, using the finite-element meshes, the co/counterflow model of the SOFC are developed, which are described in detail in [11]. It consists of a single cell repeat unit, which includes an electrolyte with anode and cathode, and two halves of a bipolar-biflow interconnect. Stack dimensions, representative material properties, and boundary conditions are shown in [11]. The "effective resistance" of each component (interconnect, anode, cathode, and electrolyte) is computed by the finite-element method from actual cell geometry- and temperature-dependent conductivity. The convective heat transfer coefficients are derived from the laminar flow Nusselt number for a rectangular duct. Current density is calculated at each electrolyte element from the local electrode potential, overpotential function (any function of local temperature, fuel composition, and current density may be input as an overpotential function), and local bulk gas chemical potential. Only areas directly exposed to fuel and air are electrochemically active; that is, the effects of diffusion under interconnect ribs are ignored. Finally, using the finite-element model, we couple the electrical- and thermal-conduction effects and rigorously compute the local electrical and chemical properties across the SOFC cross section. The fuel and air-stream inlet conditions for crossflow and co/counterflow are listed in Table I [11].

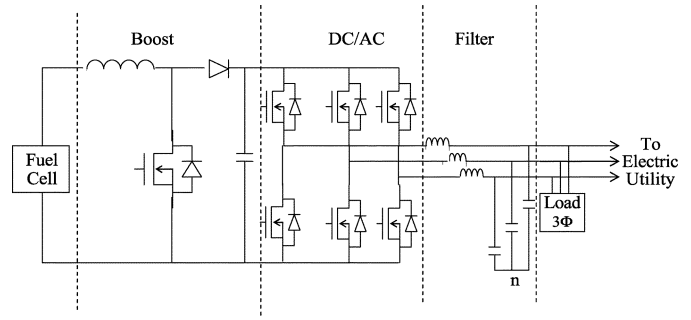


Fig. 5. PWM VSI topology used for studying the impact of power-electronics on the SOFCS, which provides the input voltage.

C. PES Modeling

SOFC based PESs are used to provide direct or alternating current (dc or ac) to satisfy application-specific power needs. The topological structures of the converters for PES (for SOFC PCS) can be vastly different from each other. For example, a PES for a stationary application can be a single-stage dc-ac inverter or even a two-/three-stage dc-dc-ac converter. In addition, the switching schemes in such power converters can be based on pulse-width modulation (PWM), resonant, quasiresonant conversion, soft-switching, or line-commutation. As such, the mathematical models of the PES may include ordinary/discontinuous/discrete/functional/impulsive/non-smooth differential equations. In addition, these models include system-level constraints. To model such PES, the traditional approach using average models [17], [18] is inadequate and may yield inaccurate results [16], [19]; this is because such averaged models neglect the switching frequencies and hence, cannot predict the dynamics on a fast scale [16], [20]. For the present study, dynamics of PES ripple on both fast and slow scales are important. As such, we use a switching-modeling framework, which can handle any type of dynamical system with varying levels of detail. Such a modeling framework is an indexed collection of dynamical systems along with a map for predicting transitions among them. A transition occurs whenever the state satisfies certain conditions, given by its membership in a specified subset of the state space. Hence, the entire system can be thought of as a sequential patching together of dynamical systems with initial and final states and with the transitions performing a reset to a different initial state of a generally different dynamical system whenever a final state is reached.

A typical PES for SOFC based applications consist of a dc-dc boost stage to step-up the SOFC voltage followed by a dc-ac stage. For this investigation, we use a pulse-width modulated (PWM) voltage-source inverter (VSI) [21] for the dc-ac conversion, as shown in Fig. 5.³ The switching frequency is determined by the PWM controller circuitry. The PES is rated to deliver a full-load output power of less than 5 kW. The PWM VSI topology is chosen because it imposes fast as well as a slow scale ripples on the SOFC and hence facilitates the investigation

³Other PES topologies such as line commutated current-source inverter and high-frequency-transformer-isolated cycloconverter are also used for SOFC applications.

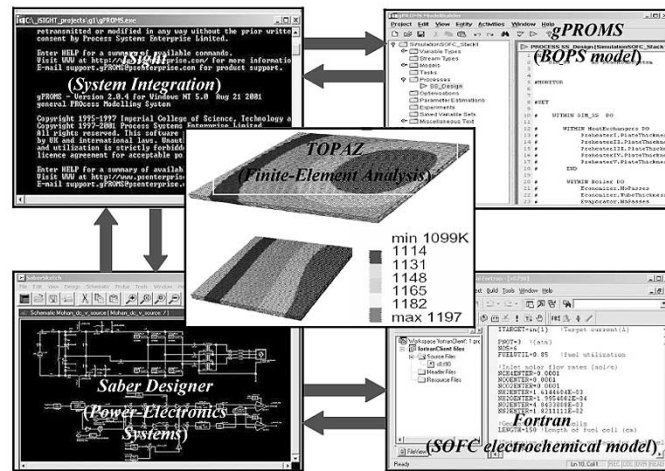


Fig. 6. Schematic shows the flow of data among the different software (model) packages. The arrows indicate the direction of data flow in the model. The TSOFC voltage and current information obtained using the comprehensive model is fed to the FEA tool to obtain the spatial distribution of TSOFC parameters.

of a wide range of electric-feedback effects on the SOFC. The parameters for the PES topology, illustrated in Fig. 5, are described in Table X.

D. BOPS Modeling

PES response to changes in electrical loads depends on the response of the SOFCS, which in turn depends on the BOPS response. Thus models of the BOPS⁴ must also be taken into account for accurate analysis of the overall SOFC PCS. In this paper, models of the BOPS are developed and are applicable for SOFC systems [22]. The BOPS consists of the fuel-processing subsystem (FPS) to convert natural gas to hydrogen gas, which is used as SOFC fuel, and thermal-management and power recovery subsystem to maintain fuel and oxidant temperature for efficient chemical reactions in the SOFC. These models are used to analyze the thermodynamic, kinetic, geometric, and cost characteristics of fuel-cell systems and components at full and part loads.

1) *Fuel-Processing Subsystem*: The fuel-processing subsystem (FPS), as shown in Fig. 1 consists of the prereformer, combustor, prereforming mixer, combustion mixer, and air-combustion gas mixer. The main objective of the FPS is to convert natural gas (methane) to hydrogen-rich reformat gas, which will provide hydrogen, required for SOFC operation. The necessary fuel feed, consisting primarily of methane is first compressed and then a part of it is supplied to the reforming line while the remaining fuel is used for combustion. The methane flowing down the reforming line is preheated by passing it through a compact plate-fin type heat exchanger and is then mixed with steam produced in a steam generator before entering the steam- and methane-reformer (SMR). The methane and steam is then sent to the SMR to reform the steam-methane mixture into hydrogen and carbon monoxide. The heat needed to drive the endothermic reforming reaction is provided by the combustion gases leaving the burner. The

reformat gases coming out of the steam reformer are stored in a tank, which then acts as an energy buffer between the BOPS and SOFCS. This allows almost immediate supply of fuel to the SOFCS, where the stack demand rate is larger than the reformer production rate. Before being delivered to the fuel cell stack, the hydrogen-rich reformat gas is brought to the desired anode inlet conditions using a heat exchanger.

The combustion mixture, supplied to the burner consists of air taken from the air-tank, the hydrogen-depleted anode exhaust gas, and the compressed methane that bypasses the reforming line. Burning the residual hydrogen in the stack tail gas translates to decreased consumption of additional methane in the burner and therefore, to increased efficiency of the configuration. Instead of air taken from the air-tank, air exhaust from the stack can also be used to increase efficiency by eliminating the compression stage. However, air coming from the stack is rich in nitrogen and its amount depends on the stack requirements; therefore, it depends on whether or not its heat capacity is enough to meet the thermal management necessities. After providing the required thermal energy for the endothermic reforming reaction, the combustion gases are split into three streams, the first preheats the methane, and the second is passed through the steam generator where it supplies the necessary heat for producing the steam consumed in the reforming process. The third is used to preheat the air flowing into the stack. Finally, the combustion gases are mixed together before being expanded and exhausted to the atmosphere.

2) *Thermal Management and Power Recovery Subsystems*: In the BOPS and the SOFCS, the temperatures of a number of critical components (particularly the SOFCS and the pre-reformer of the FPS) have to be carefully controlled, and the flow and utilization of heat from several sources within the configuration have to be managed efficiently in order to achieve high overall efficiency. Therefore, the thermal management subsystem (TMS) plays a significant role in the operation of the SOFC PCS. The TMS consists of the steam-generator, fuel preheating heat exchanger, air preheating heat exchanger, methane preheating heat exchanger, air-compressor, and gas

⁴Detailed mathematical models of the BOPS subsystems have been described in Tables II–VIII. The parameters used for the BOPS model are tabulated in Tables XI–XIV [22].

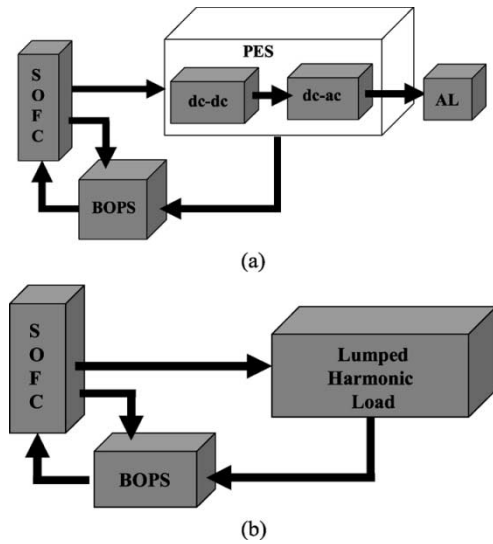


Fig. 7. Block diagrams of the (a) comprehensive and (b) reduced-order models for investigating the impact of electrical feedback effects on the SOFCS. For (b) the PES is replaced with a lumped harmonic load; the characterization for the latter is based on detailed simulation using (a).

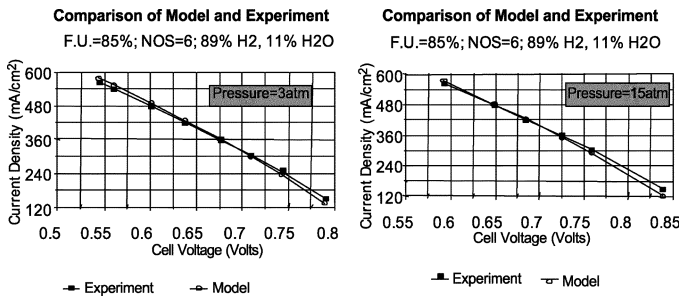


Fig. 8. Experimental validation of the SOFC model results. The model has the best performance (with an accuracy of around 5%) near the baseline condition, which is specified in Table IX. The accuracy of the model diminishes at higher cell potential/lower current-density settings, primarily because of the enhanced impact of activation polarization. F.U. is the fuel utilization and NOS is the ratio of actual oxidant (i.e., air) supply to the amount theoretically needed for complete oxidation of fuel supplied.

expander. Its major functions include maintaining the stack operating temperature in the appropriate range, bringing the hydrogen-rich reformat gas and compressed air to the desired anode inlet condition before exiting the FPS and the power recovery subsystem (PRS), respectively, and controlling the steam reformer operating conditions and the generation of steam required for the FPS. A number of high performance heat exchangers are used within the configuration in order to meet these objectives. Furthermore, since the SOFC operates at a high temperature, this high-grade waste heat is of important to precondition the streams coming into the stack. The mixed gases are expanded through an expander for energy recovery, i.e., to offset some of the parasitic power requirements. The work generated by the gas mixture is used to drive the air compressor, which in turn compresses the air to be used for the stack and the combustor. For most operating conditions, the work produced by the expander does not match the work required by the compressor. This additional work is supplied by an electrical motor which takes power from the SOFCS/PES.

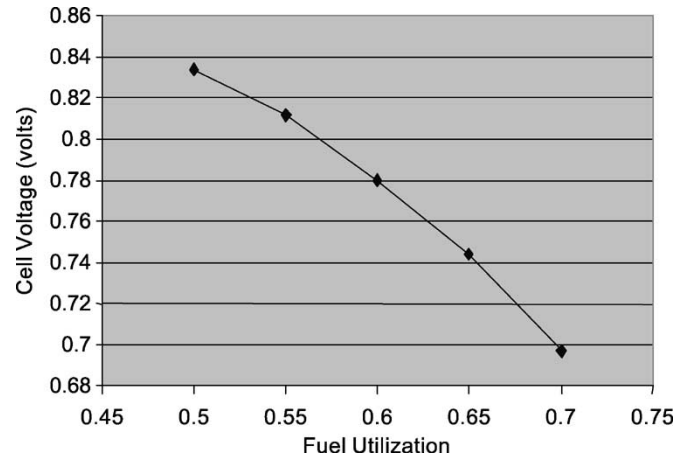


Fig. 9. Impact of initial fuel utilization upon fractional voltage drop due to "polarization curve" effect.

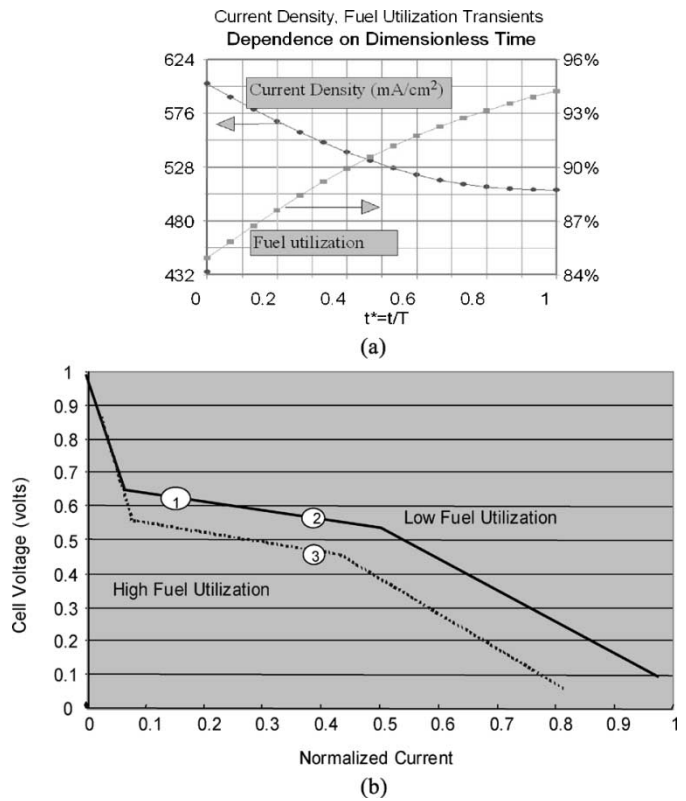


Fig. 10. (a) Current and fuel-utilization transients during transient episode, where T represents the time required for transition from the initial to the final steady state. In the given diagram, T is the cell length divided by the fuel velocity and has a value of 263 ms. It is on the order of milliseconds for the given SOFC tested, but is best considered a variable value subject to design constraints. (b) Cell potential drop due to polarization curve and fuel-depletion effects, where (1) is the initial steady-state operating point, (2) is the intermediate point representing an immediate ("step change") transition from (1) as a response to change in load current *before* fuel utilization effects are realized, and (3) is the final steady-state operating point.

E. SOFC PCS Modeling for Interaction Analyses

The problem of integrated-system design and optimization is complicated due to the necessity of examining a large number of alternate syntheses, designs, and control strategies at each level

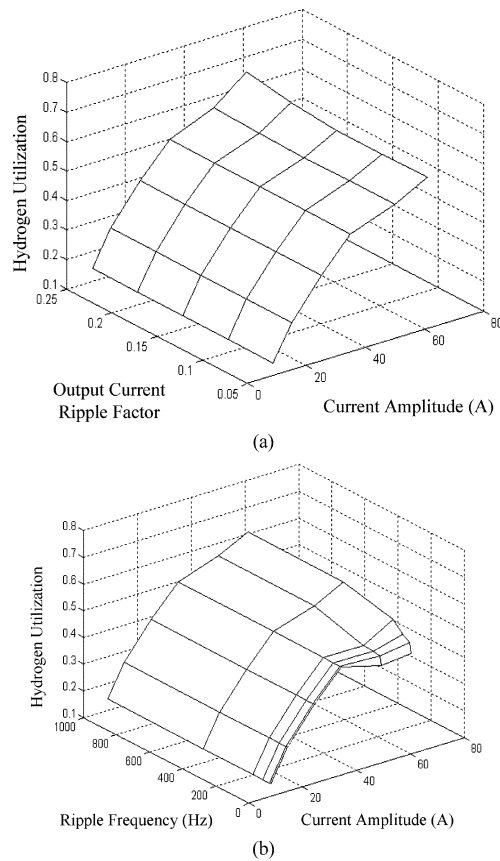


Fig. 11. (a) Hydrogen utilization and (b) air-supply-pipe temperature as a function of the dc current and the ripple currents (expressed as a percentage of the dc current) drawn from the SOFCS. Here, I is the average magnitude of the SOFCS output current, Δi is the variation of the steady-state current about this average value, and the ripple factor is the ratio of Δi over I .

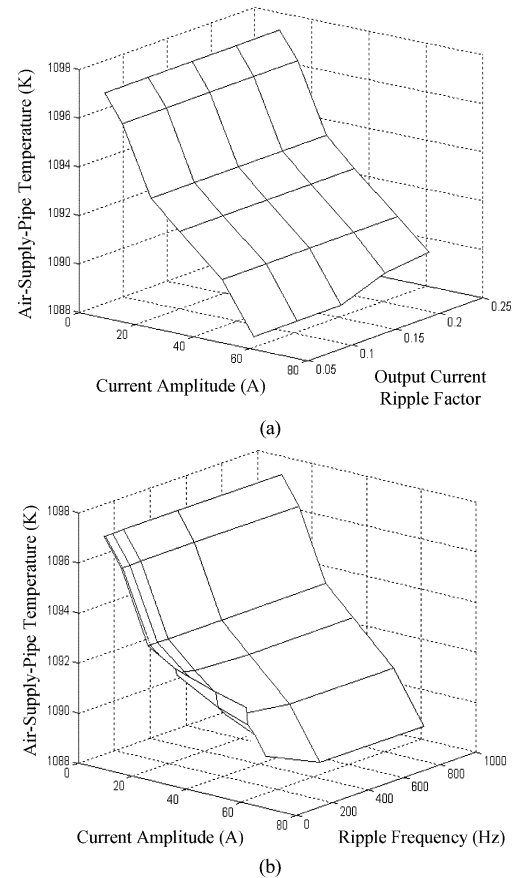


Fig. 12. (a) Hydrogen utilization and (b) air-supply-pipe temperature as a function of the dc current and the frequency of the ripple current drawn from the SOFCS. Here, I is the average magnitude of the SOFCS output current, Δi is the variation of the steady-state current about this average value, and the ripple factor is the ratio of Δi over I .

of the problem. SOFCS responds quickly to changes in load, because of their rapid electrochemistry. The PES also responds quickly to changes in AL or other variations. This is however not true for the thermal, mechanical, and chemical BOPS components and particularly for the fuel-processing subsystem, where load-following time constants are typically several orders of magnitude higher. Difference in response times of the electrochemical/electrical and thermal/mechanical/chemical subsystems of the overall SOFC PCS significantly increases the computational complexity. Hence, there is a need to develop efficient simulation techniques to model such systems.

1) *Comprehensive Integrated Model Using a Multisoftware Platform:* The PES models are implemented using SaberDesigner⁵ (developed by Synopsys, Inc.), while the SOFCS model is developed using Visual FORTRAN. Using the existing database on BOPS models and powerful decomposition techniques [22] for the integrated optimization of system and component synthesis/design and operation, the BOPS model is

implemented using gPROMS⁶ (developed by Process Systems Enterprise Limited). The PES and the SOFCS model are integrated on SaberDesigner simulator using dynamic link libraries (dlls). A comprehensive integrated model is developed to enable the use of software/package that is most suited to model any given subsystem. Fig. 6 illustrates the data flow among the various software packages of the comprehensive model, and the multisoftware simulation platform using iSIGHT⁷ (developed by Engineous software) [13], [14], respectively.

Such a tool enables dynamic simulation and modeling of the SOFC PCS. The transient and steady-state results thus obtained are fed to a FEA tool (TOPAZ) for spatial analyses of the effects of electrical feedbacks on the performance and durability of the SOFC. With these tools for dynamic simulation and modeling, it is possible to conduct parametric studies and optimizations for SOFC PCS subsystem interaction analyses and to determine control strategies (for stationary and/or transportation auxiliary power load profiles) and investigate their effects on the efficiency, power density, fuel utilization and

⁵Currently, among the commercially available simulators, *SaberDesigner* has the most extensive library of mathematical computer models in power-electronics components and systems, electromechanical-energy conversion, hydraulics, thermal, magnetic, control systems, and signal processing. *SaberDesigner* has its own programming language (MAST) for modeling but can accept codes written in C and Fortran as well.

⁶The kernel of *gPROMS* is written in C and, hence, the BOPS models developed in this environment will seamlessly integrate with *SaberDesigner*.

⁷iSIGHT integrates simulation codes and provides an interface between *SaberDesigner* and *gPROMS* [13], [14].

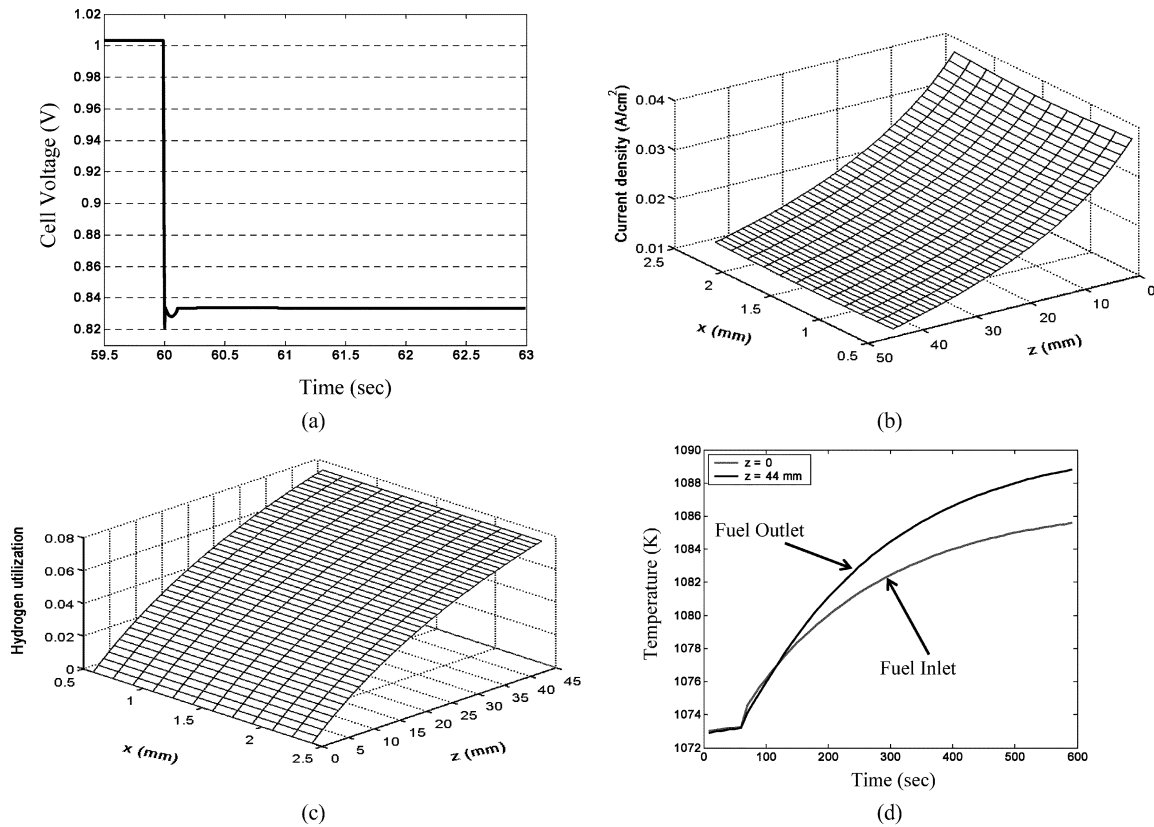


Fig. 13. (a) Load/current transient, which result in drop in SOFC output voltage, (b) and (c) spatial variation of current density and hydrogen utilization across the SOFC cross section using FEA after the load transient, and (d) mean variation of temperature at the extreme ends of the SOFC for a load transient.

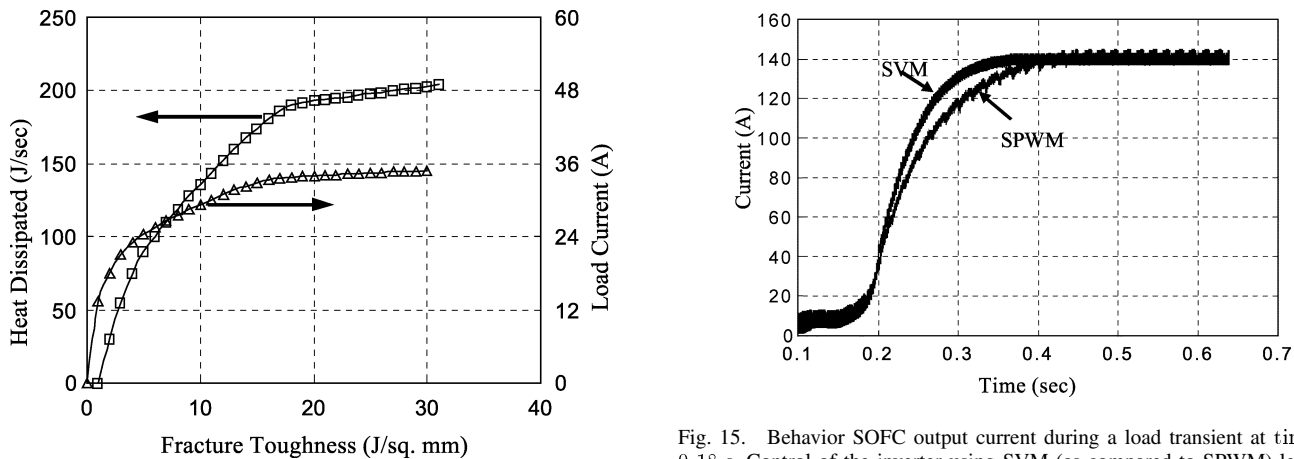


Fig. 14. Maximum allocable heat and current for a microcrack density of 30% as a function of fracture toughness.

Fig. 15. Behavior SOFC output current during a load transient at time = 0.18 s. Control of the inverter using SVM (as compared to SPWM) leads to faster recovery of SOFC output current. However, this may not always be useful as demonstrated in Fig. 24.

conversion, system response and configuration, and component design of SOFC systems.

2) *Reduced-Order Models to Resolve the Effect of Multiple Time Scales:* Significant differences in the response times of the electrochemical/electrical and thermal/mechanical/chemical subsystems of the SOFC PCS imply that simulations using the comprehensive model are extremely time consuming on a personal computer/SUN workstation. Hence, more efficient simulation techniques are needed for studying system interactions. Because a PES model comprises a number of switching functions, its real-time simulation using the comprehensive

model, outlined in the previous section, is extremely tedious. To reduce the complexity of the simulation, a two-step approach is taken. In the first step, simulations on different PES topologies are performed with an ideal voltage source as the input and the harmonic content of the PES input current is estimated. In the second step, the PES is replaced by a lumped load (with the harmonic content as estimated in the first step) in the reduced-order simulation platform as illustrated in Fig. 7(a) and (b). While developing the lumped load, it is ensured that all the harmonics are present and the magnitudes matched, so that the stresses imposed by the lumped load on the SOFC are

similar to those imposed by the PES. Next, the reduced order model is used to investigate the effect of the PES dynamics on the SOFCS life and performance. This model reduces the computational time for the simulation without sacrificing the performance.

3) *Methodology to Investigate the SOFC-PES Interactions:* Hydrogen utilization and thermal cycling of SOFCS material have a major impact on its reliability. Hydrogen utilization, U [11] is obtained from current drawn by the PES using the expression

$$U = \frac{I}{\dot{n}_{H_2}(nF)} \quad (12)$$

where I is the SOFCS output current, $\dot{n}_{H_2}$ is the hydrogen flow rate which is determined by the BOPS, and nF determines the charge flow between the anode and the cathode.

The heat dissipation in the SOFC is due to

- heat dissipated in the effective resistance of the fuel cell;
- heat dissipation due to the chemical reaction ($T\Delta S$).

It has been reported [6] that, heat dissipated by the fuel cell, if not managed properly, can have a significant impact on the microcrack density of the fuel cell. For a given material and spatial heat source, the microcrack density is directly proportional to the heat rate and increases beyond a certain threshold heating rate given by

$$q_{th} = \frac{3\pi^2 k r_o}{2\alpha} \sqrt{\frac{G_c \pi (1 - \nu)}{E_o b (1 + \nu)}} \quad (13)$$

where r_o is the length parameter that characterizes spatial nonuniformity of heat source, $k(= 5.84 \text{ J/(s m K)})$ is the thermal diffusivity, $\alpha(= 12.22 \times 10^{-6} \text{ /K})$ is the coefficient of linear thermal expansion, $G_c(= 9 \text{ J/m}^2)$ is the fracture toughness of the material, E_o is Young's elastic modulus of uncracked material, b is the crack size, and $\nu(= 0.3)$ is Poisson's ratio of the uncracked material.

The threshold current beyond which the microcrack density increases (for a particular fracture toughness of the SOFC electrolyte) is given by

$$I_{th} = \sqrt{\frac{q_{th} - q_{chemical}}{R_{SOFC}}} \quad (14)$$

where R_{SOFC} is the area-specific resistance of the SOFC and $q_{chemical}$ is the heating rate due to the chemical reaction of the SOFC.

SOFC temperature is obtained using basic thermodynamic equations and is outlined in [10]. These results are used to relate the SOFC output current to the stack temperature. Theoretical studies indicate interaction between the standard cathode, $(\text{La}_{0.85}\text{Sr}_{0.15})_{0.95}\text{MnO}_3$ (LSM) and the standard electrolyte (YSZ) above temperatures of 1000°C [3]. In long-term operation, an interlayer of LaZr_2O_7 forms, whose conductivity is

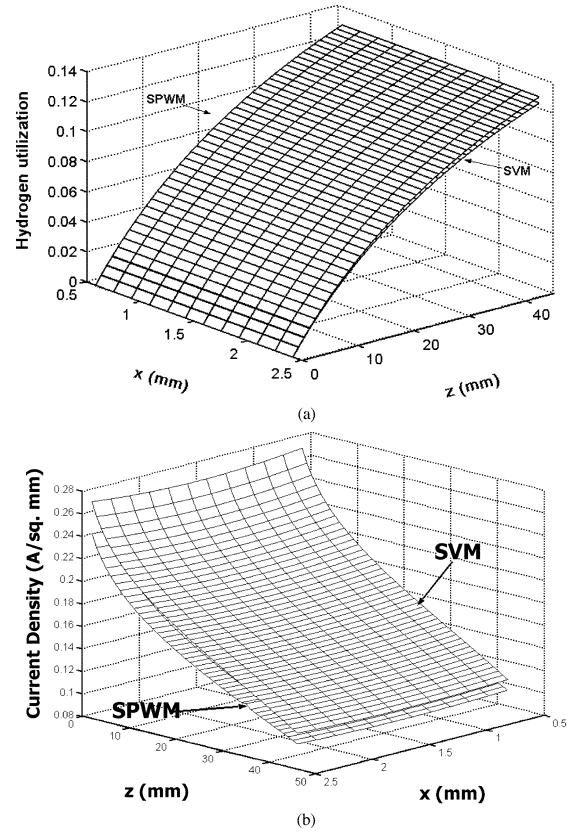


Fig. 16. (a) Hydrogen utilization and (b) current density across the cross section of the SOFC during a load-transient. It is obvious, that the better performance of SVM comes at the price of higher SOFC current density and higher fuel utilization. It is, therefore, important to recognize that modulation strategies such as SVM achieve superior performances for PES converter fed by a "stiff" dc voltage source, may require additional provisions for energy buffering devices to attain the same benefit. Such provisions may include, high-pressure fuel-storage tank in the BOPS, lower levels of initial fuel utilization, or alternate electrical-energy source just for the transient conditions.

TABLE I
INPUT OPERATING CONDITIONS OF FINITE-ELEMENT MODEL

Crossflow	
Hydrogen flow rate	6.0×10^{-5} mole/sec
Water flow rate	1.83×10^{-6} mole/sec
Oxygen flow rate	1.56×10^{-4} mole/sec
Nitrogen flow rate	6.3×10^{-4} mole/sec
Cell area	4.5 cm x 4.5 cm
Fuel/air inlet temperature	800°C
Co/counterflow	
Hydrogen flow rate	4.0×10^{-5} mole/sec
Water flow rate	1.22×10^{-7} mole/sec
Oxygen flow rate	1.04×10^{-5} mole/sec
Nitrogen flow rate	4.2×10^{-5} mole/sec
Cell area	4.5 cm x 0.3 cm
Fuel/air inlet temperature	800°C

much less than that of LSM and hence has an impact on the output voltage and current supplied by the SOFC.

TABLE II
GENERALIZED MODEL OF FUEL-PROCESSING SUBSYSTEM

Variable Description	Model Equation
$\dot{n}_{mix}$	Molar flow rate
$\dot{Q}_q$	Heating rate of q^h component
Q	Number of heat interactions
$\dot{W}$	Work done
E_{cv}	Control volume energy
m_{cv}	Control volume mass
h_{mix}	Specific enthalpy
h_p	Partial enthalpy
Δh_f°	Enthalpy of formation
$K(T)$	Equilibrium constant of reaction
$\Delta G^\circ(T)$	Gibb's free energy
$\Delta h^\circ(T)$	Enthalpy of reaction
$\Delta s^\circ(T)$	Entropy of reaction
ξ	Degree of reaction
ε	Reaction co-ordinate
$\frac{\dot{Q}_{max}}{T}$	Maximum possible heat transfer
C_p	Heat capacity

III. RESULTS

Table IX outlines the SOFC baseline conditions for analysis. We begin, with the responses of the SOFC under unslaved condition. The validation of the SOFC-stack model within an impressive accuracy of 3 to 5% (across a domain of pressure ratios) is shown in Fig. 8. The model transitions from small over predictions of current to slight under predictions as operating voltage increases; this is attributable to error in calculating polarization. For the same SOFC model, Fig. 9 shows the impact of variations in fuel utilization on the cell output voltage due to polarization-curve effect. The larger the initial fuel utilization, the more prevalent the reactant depletion effects that manifest via lowered Nernst potentials and limiting current densities [as shown in Fig. 10(a) and (b)]; hence, the “reactant depletion/accumulation” effect of hikes in current is substantially more influential. Fig. 10(a), illustrates the trends in current density and fuel utilization caused by an idealized step decrease in cell potential. Fig. 10(b), shows decreases in cell potential, as a result of progressive reactant depletion to attain a higher demand in current.

Figs. 11 and 12,⁸ illustrate the variations in the hydrogen utilization and the air-supply-pipe-temperature with the ripple, amplitude, and frequency of the current drawn by the PES from the SOFCS. It is clear from Fig. 11(a) that, to meet higher load-demands, the hydrogen utilization has to increase

⁸So far, we have focused at the cell level and on unslaved operation of the SOFC. For power delivery to the ALs, several of these cells are connected to form a SOFCS and then interfaced to the PCS. To resolve the electrical-feedback effects, the lumped harmonic model (Fig. 8), which replaces the PES and the AL, needs to account for low-harmonic as well as switching ripple frequencies.

TABLE III
KINETIC MODEL OF THE SMR REACTOR

Variable Description	Model Equation
ζ_{H_2}/CH_4	Steam-to-methane ratio
$\dot{n}_{CH_4,i}$	Inlet methane molar flow rate
$\dot{n}_{CH_4,o}$	Outlet methane molar flow rate
X_{CH_4}	Actual (kinetic) methane conversion
P_{CH_4}	Methane partial pressure
P_{SMR}	Reformate gas mixture pressure
T_{avg}^{SMR}	Average reformate gas temperature
Ra	Demethanation reaction rate
L_{SMR}	SMR reactor length for the design point

significantly. Fig. 11(b), illustrates the variation of the ASP temperature with variation in the load. Magnitude of the current ripple has a minimal impact at low loads. However at higher loads, an increase in current leads to an increase in the hydrogen utilization. However, the variation of the ASP temperature with current ripple is insignificant. Fig. 12(a) and (b) illustrates the variation of the hydrogen utilization and the ASP temperature of the SOFCS as a function of the dc current and the frequency of the ripple current drawn from the SOFCS.

The focus of Figs. 11 and 12 has been on electrical feed-backs during the steady state of the SOFC PCS. Another possibility of electrical perturbation is due to a sudden change in the magnitude of the AL. Fig. 13, illustrates the impact of such load-transients on SOFC temperature distribution. Fig. 13(a) shows, that with the increase in the output current of the SOFC, its output voltage decreases. This is accompanied by an increase in the temperature as shown in Fig. 13(d) on a large time frame. This plot is helpful in ascertaining the mean or the envelope of the temperature distribution; however, it cannot predict the spatial distribution (of the temperature), which requires spatial modeling using finite-element analysis. Fig. 13(b) and (c), reveal the spatial distribution of current density and hydrogen utilization across the SOFC cross section after the load transient. Clearly, the detailed spatial analyses reveals that the distribution of SOFC material properties is nonuniform and some sections may be more susceptible to failure than others under similar repetitive load transients [23], [24].

Increase in the ASP temperature and the accompanying heat generation have a degrading effect on the SOFC material properties. Basic thermoelectric equations governing SOFC material properties are discussed in [13] and a preliminary result showing a direct correlation between the current and the fracture toughness is established. Fig. 14, shows the variation of the maximum allocable heat and the maximum steady-state current that a fuel cell can handle for a 30% microcrack density [calculated using (13) and (14)]. Beyond these threshold values, high microcrack densities are expected which would significantly degrade the reliability of the SOFC.

An obvious question that arises out of these analyses is whether suitable choice of PES control and modulation strategies can mitigate the impact of electrical perturbation

TABLE IV
GEOMETRIC MODEL OF THE STEAM GENERATOR

Fixed Parameter Description	Value	Fixed Parameter Description	Value
t_w	Tube wall thickness (mm)	CTP	Tube count calculation constant
n_{passes}^{SG}	Number of passes	CL	Tube layout constant
Variable Description		Model Equation	
d_i^{SG}	Tube inner diameter	Assigned value	
n_{tubes}^{SG}	Number of tubes	Assigned value	
L_{SG}	Length	Assigned value	
d_o^{SG}	Tube outer diameter	$d_o^{SG} = d_i^{SG} + 2t_w$	
p_T^{SG}	Pitch	$p_T^{SG} = 1.25 d_o^{SG}$	
D_s^{SG}	Shell diameter	$D_s^{SG} = 0.637 \sqrt{\frac{CL}{CTP}} \sqrt{\pi n_{tubes}^{SG} (p_T^{SG})^2}$	
B	Baffle spacing	$B = 0.6 D_s^{SG}$	

TABLE V
GEOMETRIC AND HEAT TRANSFER MODELS OF A PLATE-FIN HEAT EXCHANGER

Variable Description	Model Equation
L_h	Hot-side length
L_c	Cold-side length
H	Height
n_{plates}	Number of plates
l_f	Fin length
V_p^h	Hot-side volume
V_p^c	Cold-side volume
A	Heat transfer area
A_o	Minimum free flow area
A_f	Finned area
A_p	Frontal area
η_f	Fin efficiency
η_o	Outside overall surface efficiency
$\dot{n}$	Mixture molar flow rate
j	Colburn factor
G	Maximum mass velocity
Pr	Prandtl number
h	Heat transfer coefficient
U	Overall heat transfer coefficient
C_{min}	Minimum heat capacity
C_{max}	Maximum heat capacity
C_r	Heat capacity ratio
NTU	Number of transfer units
ε	Effectiveness

$$H = b_h + 2a + n_{plates} (b_h + b_c + 2a)$$

$$l_f = \frac{b}{2} - l_f$$

$$V_p^h = L_c L_h b_h (n_{plates} + 1)$$

$$V_p^c = L_c L_h b_c n_{plates}$$

$$A = \beta V_p, A_c = \frac{D_s A}{4L}$$

$$A_p = LH, m = \sqrt{\frac{2h}{k_f l_f}}$$

$$\eta_f = \frac{\tanh(ml_f)}{ml_f}, \eta_o = 1 - (1 - \eta_f) \frac{A_f}{A}$$

$$G = \frac{\dot{n}}{A_c}$$

$$Pr = \frac{\mu C_p}{k}$$

$$h = j G C_p Pr^{-2/3}$$

$$C_{min} = \min(\dot{n} C_p^c, \dot{n} C_p^h), C_{max} = \max(\dot{n} C_p^c, \dot{n} C_p^h)$$

$$UA = \frac{1}{\frac{1}{(\eta_o A_h)_h} + \frac{1}{(\eta_o A_h)_c}}, C_r = \frac{C_{min}}{C_{max}}, NTU = \frac{UA}{C_{min}}$$

$$\varepsilon = 1 - \exp\left[-\left(\frac{1}{C_r}\right)(NTU)^{0.22} \left\{\exp[-C_r (NTU)^{0.78}] - 1\right\}\right]$$

on the SOFCS? For this paper, we investigate the effects of space-vector modulation (SVM) [25] strategy for the dc-ac inverter on mitigating the impacts of load transients on the SOFC. Spatial analysis (using FEA described in [11]) is also performed to observe the effect of load transient on SOFC temperature. We compare the effectiveness of the SVM with that of conventional sinusoidal PWM (SPWM). Fig. 15 illustrates the SOFC current for the SPWM and the SVM modulation schemes. For stiff voltage sources, SVM technique offers improved dc-bus utilization and hence improves the input current response. An apparent conclusion from this study is that SVM is better for the performance and life of the SOFC.

TABLE VI
HEAT TRANSFER MODEL OF THE ECONOMIZER

Variable Description	Model Equation
Re_{eco}	Tube-side Reynolds number
Pr_{eco}	Tube-side Prandtl number
$h_{H_2O}^{eco}$	Tube-side heat transfer coefficient
D_{eq}^{eco}	Shell-side equivalent diameter
A_s^{eco}	Bundle cross-flow area
G_s^{eco}	Shell-side mass velocity
h_{gas}^{eco}	Shell-side heat transfer coefficient
U_{eco}	Overall heat transfer coefficient
A_{eco}	Heat transfer area
ΔT_{lm}^{eco}	Log mean temperature difference
$\dot{Q}_{eco}$	Heat transfer rate

$$Re_{eco} = \left(\frac{4 \dot{n}_{H_2O}}{\pi d_i \mu_{H_2O} n_{tubes}^{eco}} \right), Pr_{eco} = \left(\frac{\mu_{H_2O} C_{pH_2O}}{k_{H_2O}} \right)_{eco}$$

$$\text{If } Re_{eco} \leq 2300 \quad h_{H_2O}^{eco} = 4.36 \left(\frac{k_{H_2O}}{d_i} \right)_{eco}$$

$$\text{otherwise} \quad h_{H_2O}^{eco} = 0.023 \left(\frac{k_{H_2O}}{d_i} \right)_{eco} (Re_{eco})^{0.8} (Pr_{eco})^{0.4}$$

$$D_{eq}^{eco} = \frac{4(p_T^{eco})^2 - \pi(d_o^{eco})^2}{\pi d_o^{eco}}$$

$$A_s^{eco} = \frac{D_s^{eco} (p_T^{eco} - d_o^{eco}) B_{eco}}{p_T^{eco}}, G_s^{eco} = \frac{\dot{n}_{gas}}{A_s^{eco}}$$

$$h_{gas}^{eco} = 0.36 \left(\frac{k_{gas}}{D_{eq}} \right)_{eco} \left(\frac{D_{eq}}{\mu_{gas}} \right)_{eco}^{0.55} \left(\frac{C_{p_{gas}} \mu_{gas}}{k_{gas}} \right)_{eco}^{1/3} \left(\frac{\mu_{gas}}{\mu_{wall}} \right)_{eco}^{0.14}$$

$$U_{eco} = \frac{1}{\frac{1}{h_{H_2O}^{eco}} + \frac{1}{h_{gas}^{eco}}}, A_{eco} = (\pi d_o L n_{tubes} n_{passes})_{eco}$$

$$\Delta T_{lm}^{eco} = \frac{(T_{gas,i} - T_{H_2O,o})_{eco} - (T_{gas,o} - T_{H_2O,i})_{eco}}{\ln \left[\frac{(T_{gas,i} - T_{H_2O,i})_{eco}}{(T_{gas,o} - T_{H_2O,o})_{eco}} \right]}$$

$$\dot{Q}_{eco} = \dot{n}_{gas} C_{p_{gas}} (T_{gas,i} - T_{gas,o}) = U_{eco} A_{eco} \Delta T_{lm}^{eco}$$

TABLE VII
HEAT TRANSFER MODEL OF THE EVAPORATOR

Variable Description	Model Equation
A_c^{evap}	Cross-sectional area
G_{tube}^{evap}	Tube-side mass velocity
Co	Convection number
Fr_{tu}	Froude number
Bo	Boiling number
h_{tu}	Heat transfer coefficient for the liquid phase
$h_{H_2O}^{evap}$	Tube-side heat transfer coefficient
D_{eq}^{evap}	Shell-side equivalent diameter
A_s^{evap}	Bundle cross-flow area
G_s^{evap}	Shell-side mass velocity
h_{gas}^{evap}	Shell-side heat transfer coefficient
U_{evap}	Overall heat transfer coefficient
A_{evap}	Heat transfer area
ΔT_{lm}^{evap}	Log mean temperature difference
$\dot{q}_{evap}^*$	Surface heat flux (single tube)

$$A_c^{evap} = \pi (d_i^{evap})^2, G_{tube}^{evap} = \frac{\dot{n}_{H_2O}}{\mu_{tube} A_c^{evap}}$$

$$Co = \left(\frac{1 - \chi}{\chi} \right)^{0.8} \left(\frac{\rho_{H_2O}}{\rho_{H_2O,i}} \right)^{0.5}$$

$$Fr_{tu} = \frac{(G_{tube}^{evap})^2}{(\rho_{H_2O,i})^2 g d_i^{evap}}$$

$$Bo = \frac{q_{evap}^*}{G_{tube}^{evap} h_{tu}}$$

$$h_{tu} = 0.023 \left(\frac{k_{H_2O}}{d_i^{evap}} \right) \left(\frac{G_{tube}^{evap} (1 - \chi) d_i^{evap}}{\mu_{H_2O,i}} \right)^{0.8} \left(\frac{\mu_{H_2O} C_{p_{H_2O}}}{k_{H_2O,i}} \right)^{0.4}$$

$$h_{H_2O}^{evap} = h_{tu} \left[C_{Co}^{0.1} (25 Fr_{tu})^{0.75} + C_{Bo}^{0.1} \right]$$

$$D_{eq}^{evap} = \frac{4(p_T^{evap})^2 - \pi(d_o^{evap})^2}{\pi d_o^{evap}}$$

$$A_s^{evap} = \frac{D_s^{evap} (p_T^{evap} - d_o^{evap}) B_{evap}}{p_T^{evap}}, G_s^{evap} = \frac{\dot{n}_{gas}}{A_s^{evap}}$$

$$h_{gas}^{evap} = 0.36 \left(\frac{k_{gas}}{D_{eq}} \right)_{evap} \left(\frac{D_{eq}}{\mu_{gas}} \right)_{evap}^{0.55} \left(\frac{C_{p_{gas}} \mu_{gas}}{k_{gas}} \right)_{evap}^{1/3} \left(\frac{\mu_{gas}}{\mu_{wall}} \right)_{evap}^{0.14}$$

$$U_{evap} = \frac{1}{\frac{1}{h_{H_2O}^{evap}} + \frac{1}{h_{gas}^{evap}}}, A_{evap} = (\pi d_o L n_{tubes} n_{passes})_{evap}$$

$$\Delta T_{lm}^{evap} = \frac{(T_{gas,i} - T_{H_2O,o})_{evap} - (T_{gas,o} - T_{H_2O,i})_{evap}}{\ln \left[\frac{(T_{gas,i} - T_{H_2O,i})_{evap}}{(T_{gas,o} - T_{H_2O,o})_{evap}} \right]}$$

$$\dot{q}_{evap}^* = \frac{\dot{n}_{gas} C_{p_{gas}} (T_{gas,i} - T_{gas,o})}{n_{tubes} A_{evap}} = \frac{U_{evap} \Delta T_{lm}^{evap}}{n_{tubes}}$$

Using Fig. 16, we show how deceptive this conclusion can be for SOFC energy source. Fig. 16(a) illustrates the hydrogen utilization across the cross section of the SOFC during the load transient. Nonuniform flow rates and nonuniform current density across the SOFC cross section, as shown in Fig. 16(b) are

TABLE VIII
HEAT TRANSFER MODEL OF THE SUPERHEATER

Variable Description	Model Equation
Re_{super} Tube-side Reynolds number	$Re_{super} = \left(\frac{4\dot{n}_{H_2O}}{\pi d_{super} \mu_{H_2O} n_{super}} \right), Pr_{super} = \left(\frac{\mu_{H_2O} C_{pH_2O}}{k_{H_2O}} \right)_{super}$
Pr_{super} Tube-side Prandtl number	
$h_{H_2O}^{super}$ Tube-side heat transfer coefficient	$h_{H_2O}^{super} = 0.023 \left(\frac{k_{H_2O}}{d_{super}} \right) (Re_{super})^{0.8} (Pr_{super})^{0.4}$
D_{eq}^{super} Shell-side equivalent diameter	$D_{eq}^{super} = \frac{4(P_t^{super})^2 - \pi(d_o^{super})^2}{\pi d_o^{super}}$
A_s^{super} Bundle cross-flow area	$A_s^{super} = \frac{D_{eq}^{super} (P_t^{super} - d_o^{super}) B_{super}}{P_t^{super}}, G_s^{super} = \frac{\dot{n}_{gas}}{A_s^{super}}$
G_s^{super} Shell-side mass velocity	
h_{gas}^{super} Shell-side heat transfer coefficient	$h_{gas}^{super} = 0.36 \left(\frac{k_{gas}}{D_{eq}} \right) \left(\frac{D_{eq} G_s}{\mu_{gas}} \right)^{0.55} \left(\frac{C_{p,gas} \mu_{gas}}{k_{gas}} \right)_{super}^{1/3} \left(\frac{\mu_{gas}}{\mu_{wall}} \right)^{0.14}$
U_{super} Overall heat transfer coefficient	$U_{super} = \frac{1}{\frac{1}{h_{H_2O}^{super}} + \frac{1}{h_{gas}^{super}}}, A_{super} = (\pi d_i L n_{tubes} n_{passer})_{super}$
A_{super} Heat transfer area	
C_{min} Minimum heat capacity	$C_{min} = \min(\dot{n}_{H_2O} C_{pH_2O}^{super}, \dot{n}_{gas} C_{pgas}^{super}), C_{max} = \max(\dot{n}_{H_2O} C_{pH_2O}^{super}, \dot{n}_{gas} C_{pgas}^{super})$
C_{max} Maximum heat capacity	
C_r Heat capacity ratio	$C_r = \frac{C_{min}}{C_{max}}, NTU = \frac{U_{super} A_{super}}{C_{min}}$
NTU Number of transfer units	
ϵ_{super} Superheater effectiveness	$\epsilon_{super} = \frac{2}{1 + C_r + \sqrt{1 + C_r^2}} \frac{1 + \exp(-NTU \sqrt{1 + C_r^2})}{1 - \exp(-NTU \sqrt{1 + C_r^2})}$

TABLE IX
BASELINE CONDITIONS FOR THE SOFC ANALYSIS

Pressure (atm)	3
Stoichiometric number	3
Fuel utilization (%)	85
Operating voltage (Volts)	0.6
Inlet methane mole fraction	5.e-5
Inlet hydrogen mole fraction	0.67
Inlet carbon monoxide mole fraction	0.22
Inlet steam mole fraction	0.11
Inlet carbon dioxide mole fraction	1.e-4

TABLE X
POWER-STAGE PARAMETERS FOR THE SELF-COMMUTATED-PWM-VSI TOPOLOGY

Parameters	Values
DC-AC Converter	
Filter Inductor	0.5 mH
Filter Capacitor	0.5 mF
Switching Frequency	10 kHz
DC-DC Converter	
Filter Inductor	1 mH
Filter Capacitor	1 mF
Switching Frequency	10 kHz

observed for both the modulation schemes. However, the current density of the SOFCS, when the inverter is operated with SVM, is higher. This may cause unequal heating across the SOFC cross section leading to degradation of the SOFC materials. In other words, superior performance (of the PES controller) alone is not sufficient to alleviate the impact of electrical perturbation on the SOFCS, which is not a stiff voltage source [26].

TABLE XI
FIXED PARAMETERS IN THE KINETIC MODELING OF THE SMR REACTOR

Fixed Parameter Description	Value
EA_{SMR} Arrhenius activation energy (kJ/kmol)	41900
k_o^{SMR} Arrhenius frequency factor (kmol/kg h)	0.0987
ρ_B^{SMR} Catalyst bulk density (kg/m ³)	1200
P_{amb} Ambient pressure (Pa)	101325
R Ideal gas constant (kJ/kmol K)	8.3145
d_i Tube internal Diameter (mm)	12
Z Tubes length (m)	0.4
n_t Number of tubes	15
N Number of discretization segments	20

TABLE XII
FIXED PARAMETERS IN THE PLATE-FIN HEAT EXCHANGER MODEL

Fixed Parameter Description	Value
D_h Hydraulic diameter (mm)	3.08
t_f Fin thickness (mm)	0.152
b Plate spacing (mm)	6.35
a Plate thickness (mm)	0.254
β Heat transfer area density (m ² /m ³)	1204
k_f Fin material thermal conductivity (W/mK)	35
N Number of discretization segments	10
ρ_M Metal density (kg/m ³)	7800

IV. CONCLUSION

Using a comprehensive modeling and analysis methodology, we show the effects of a solid-oxide fuel cell (SOFC) power-conditioning system (PCS) and electrical application load (AL) on the performance and durability of the SOFCS. We demonstrate that, on a short timeframe, fast-(switching) scale current ripple imposed by the power-electronics subsystem (PES) has negligible impact on the SOFC.

However, the impact of the switching ripple in a longer time frame (greater than 40 000 h for stationary applications and greater than 5000 h for transportation applications) needs further analysis and is a focus of our research currently. Low-frequency current ripple with large magnitudes result in electrically-induced thermal variations and variations in hydrogen utilizations, both of which have a direct impact on the performance and efficiency and life of a SOFCS.

TABLE XIII
FIXED PARAMETERS IN THE STEAM GENERATOR MODEL

Fixed Parameter Description		Value	Fixed Parameter Description		Value
t_w	Tube wall thickness (mm)	0.5	CTP	Tube count calculation constant	0.93
n_{passes}^{SG}	Number of passes	1	CL	Tube layout constant	1
Variable Description		Model Equation			
d_i^{SG}	Tube inner diameter (mm)	10			
n_{tubes}^{SG}	Number of tubes	20			
L_{SG}	Length (m)	0.35			
n	Number of discretization segments	100			

TABLE XIV
FIXED PARAMETERS IN THE COMPRESSOR AND EXPANDER MODELS

Fixed Parameter Description		Value
PR_C	Compressor design pressure ratio	3.4
γ_{air}	Air specific ratio	1.4
P_{amb}	Ambient pressure (Pa)	101325
γ_{gas}	Combustion gases specific ratio	1.33
ρ_M	Metal density (kg/m ³)	7800
T_{amb}	Ambient temperature (K)	295

Load transients, depending on severity, have a significant impact and lead to nonuniform thermal distribution. Depending on how high the temperature is at any spatial location within the stack/cell, it can have a negative impact on the material properties and microcrack densities of the SOFC and hence, on the durability of the SOFC.

We also demonstrate that, space-vector modulation (SVM), as compared to sine-wave pulse width modulation (SPWM), of the inverter, yields faster dynamic response under load-transients. While the superior dynamic-performance capability of SVM for three-phase inverters is well known, what is often overlooked in such analysis is the need for a stiff dc voltage source. As such, for SOFC, which is not a stiff dc voltage source, the enhanced performance of SVM comes at the cost of higher localized current densities and fuel-flow rates, both of which may be detrimental to the SOFCs. Nonuniformities during load transients will result in localized oxidation of SOFC electrolyte material, which could result in reduced conductivity because of the formation of $LaZr_2O_7$.

APPENDIX A

See Table I.

APPENDIX B

See Tables II–VIII.

APPENDIX C

See Tables IX–XIV.

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