



# Load-following active power filter for a solid oxide fuel cell supported load

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## ABSTRACT

While the integration of base-load fuel cells into the built environment is expected to provide numerous benefits to the user, the steady-state and dynamic behavior of these stationary fuel cell systems can produce an undesirable impact on the grid distribution circuit at the point of connection. In the present paper, a load-following active power filter (LFAPF) is proposed to mitigate the grid impact of such systems and instead improve overall local power quality. To evaluate the strategy, the LFAPF is integrated into a SOFC system inverter with one-cycle control (OCC) to provide the fundamental benefits of a traditional active power filter (APF) while also damping out short-term line current transients. The LFAPF benefit is illustrated through simulation of an SOFC interconnected with the utility electric distribution system and a building electricity demand that is modeled as a dynamic non-linear load. Three installation cases are examined: (1) a load-following SOFC, (2) a base-loaded SOFC, and (3) an offline SOFC. Without LFAPF, the load-following SOFC causes load transients due to the finite SOFC response time, and the base-loaded SOFC case has transients that appear more severe because they represent a larger overall percentage of the grid-provided load. The integration of an LFAPF improves the steady-state behavior over the base case and mitigates voltage sags and step changes. Thus integrating an LFAPF can, by providing useful services to both the utility and the end-user, facilitate the integration of an SOFC into the distribution system.

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## 1. Introduction

The commercial deployment of large fuel cells (>200 kW) is accelerating to provide base-load power for a variety of applications including hotels, universities, food processing and industrial facilities, and waste water treatment plants. In California, for example, over 25 MW of commercial molten carbonate fuel cell (MCFC) and phosphoric acid fuel cell (PAFC) products are installed. Other types of fuel cell systems are under development. In particular, a number of manufacturers are developing solid oxide fuel cell (SOFC) product for commercialization in the near future.

While much research and development has been occurring on alternative energy technologies, a key aspect of the successful widespread deployment of distributed generation (DG) is a robust grid interconnection. This grid interconnection should ideally be designed to maximize overall DG benefits, increase power reliability for the customer, and improve grid functionality for the utility. An interconnection that does not meet these goals will inevitably create a barrier to either utility or customer acceptance. It is therefore important to understand and optimize the interconnection of DG, load, and the electric utility.

Power quality is a major issue for customers and the utility due to the increasing penetration of electric loads that are sensitive to harmonics and fluctuations in voltage and frequency. Incidentally, many of these sensitive loads, which include computers, electronics, and processing machinery, are simultaneously responsible for creating problems with power quality [1]. Thus, the utility cannot take full responsibility for providing optimal power quality, as the problems for a customer may arise as a result of that very customer's own equipment. One illustrative example of this occurs during sudden load changes. Load increases and decreases may occur during the start and stop of a large load with cycling behavior, such as an air conditioning compressor motor or arc furnace [2]. A voltage sag can accompany a sudden surge of inrush current, which may disrupt functionality or cause failure in delicate equipment on a neighboring circuit. This voltage sag can be greatly reduced or eliminated by supplying this current at the site of the load instead, since the voltage drop occurs locally and cannot be easily addressed by the grid due to the line impedance of the electric power distribution system.

An existing solution to power quality problems is the active power filter (APF). APF technology can compensate for current harmonics, balance phases, and provide reactive power compensation [3]. An APF essentially turns an unbalanced non-linear "troublesome" load into one that appears extremely "clean" from the utility perspective. The one-cycle control (OCC) method has been used to design and build a robust, simple APF in [4]. The addition of an APF

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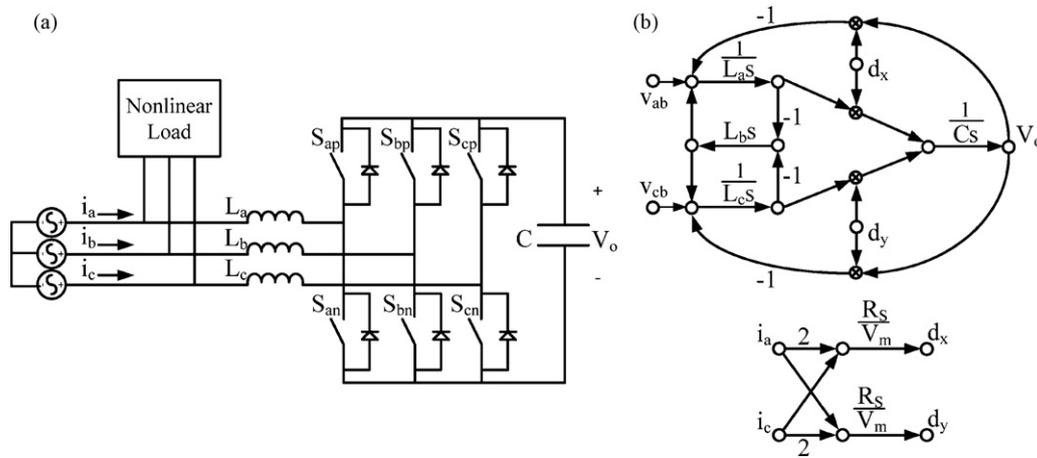


Fig. 1. OCC APF (a) power stage circuit diagram and (b) large-signal switching flow-graph model [6].

to the grid interconnection of a solid oxide fuel cell (SOFC) has been shown to allow the SOFC and inverter to supply grid-connected real power without perturbing the utility system by locally compensating for the harmonics and reactive power associated with practical building loads [5]. Thus, the APF provides benefits for power quality in the steady-state, but this does not guarantee that it will be effective for eliminating voltage sags or other transient-based power quality issues. The local DG could address the voltage sag issue by supplying power changes directly, but fuel cells lack the rotating inertia of large synchronous generators and are thus unable to buffer rapid load transients. Instead, the OCC APF is redesigned to provide local power buffering and thus provide dynamic protection against rapid voltage transients in addition to the established steady-state APF functions.

The two issues investigated in this paper are the APF capabilities in steady-state and load-following applications with an SOFC. The steady-state operation has already been verified in [6], but the control method is redesigned herein to allow for improvement of the dynamic operation to create a load-following active power filter (LFAPF). In Section 2, the benefits and theory of an OCC APF are summarized and dynamic models of the SOFC, inverter, and dynamic non-linear load are presented. In Section 3, the SOFC operation without APF is simulated. Section 4 expands on the model from Section 3 to demonstrate the operation of the LFAPF for the following conditions: (1) SOFC capable of load-following, (2) SOFC providing base-load power, and (3) SOFC offline (base case). A sensitivity analysis in Section 5 illustrates the dependence of the LFAPF overall effectiveness on the design parameters, and Section 6 presents the conclusions.

## 2. Dynamic physical models

### 2.1. Power electronics models

The two power electronics models used in this work are the one-cycle control (OCC) inverter and OCC APF. The description of the development and experimental verification of the OCC inverter is shown in [7], and the development, verification and application of the inverter model is described fully in [5,8,9]. The OCC APF design is originally developed and verified experimentally in [4,10,11], and the APF model is introduced in [6]. The OCC APF model uses the switching flow-graph method from [12], and is also incorporated with an inverter, SOFC, and load in [5]. The schematic of the power stage of the APF and the switching flow-graph model of the APF control are both presented in Fig. 1.

The overall control goal of the OCC APF is to maintain and match an input current to a reference voltage according to an emulated resistance. This control goal is shown in Eq. (1) where  $v_a$ ,  $v_b$ , and  $v_c$  are the line voltages,  $i_a$ ,  $i_b$ , and  $i_c$  are the grid currents, and  $R_e$  is the emulated resistance of the combination of the load and APF.

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = R_e \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (1)$$

The description of the OCC controller in [11] illustrates the entire 360° line cycle divided into 6–60° regions that can each be controlled by two active switch pairs, and the signals to each pair are complementary. Thus, for any region, the entire converter behavior can be defined by the duty ratios for two switches:  $d_p$  and  $d_n$ . The OCC controller uses the input voltages to select which switches are active and generates the duty ratios  $d_p$  and  $d_n$  by the key control Eq. (2), which is developed from the control goal (1) in [11].

$$V_m \cdot \begin{bmatrix} 1 - d_p \\ 1 - d_n \end{bmatrix} = R_s \cdot \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \cdot \begin{bmatrix} i_p \\ i_n \end{bmatrix} \quad (2)$$

$R_s$  is the sensing resistance and  $i_p$  and  $i_n$  are selected input currents.  $V_m$  is a compensated feedback parameter that is defined by (3), where  $V_o$  is the voltage across the APF DC capacitor.

$$V_m = R_s \cdot \frac{V_o}{R_e} \quad (3)$$

The behavior of the APF can be controlled by the determination of  $V_m$ , which is calculated by comparing the APF capacitor voltage,  $V_o$ , to the desired capacitor voltage,  $V_{ref}$ , through a PI gain. The design objective of the load-following APF is to inhibit changes in the magnitude of the line current, not to necessarily keep the capacitor voltage at a set value. Thus the PI control in the LFAPF is set to low values, so that the APF will subsequently not prioritize maintaining the capacitor voltage. The default proportional and integral values are  $P=1$  and  $I=0.2$ . To enhance the transient energy buffer capability of the LFAPF, the capacitor size can be increased to raise energy storage capability. The DC capacitor,  $C$ , has a default value of 300 mF, and the three inductors  $L_a$ ,  $L_b$ , and  $L_c$  are each 0.5 mH.

### 2.2. SOFC

SOFC technology is a type of high temperature fuel cell that is currently the subject of active research, development and investment for distributed and central power generation applications [13–17].

The SOFC dynamic model resolves physical, chemical and electrochemical dynamics of a fuel cell system in Matlab/Simulink® in

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