IV.C.3 A Low-Cost Soft-Switched DC/DC Converter for Solid Oxide Fuel Cells

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Objectives

- Develop a low-cost DC-DC converter for low- to high-voltage power conversion as the standard interface between the solid oxide fuel cell (SOFC) source and the load-side DC-AC inverter.
- Develop a low-cost 5 kW DC-AC inverter with a minimum energy efficiency of 99% operating with >400 VDC input.
- Develop power management control strategies and demonstrate the ability to supply and consume reactive power while simultaneously supplying active power to the utility grid.
- Develop sensory and control logic to enable autonomous/semi-autonomous response to aid supporting grid voltage and frequency needs without nuisance tripping or disconnection of the fuel cell system.

Accomplishments

- Improved the peak efficiency of the 50 V V6 DC-DC converter to 97.3% by reducing the device turn-off loss with a smaller gate-drive resistance.
- Developed a precision power flow controller for a universal power conditioning system by incorporating an admittance compensation loop and advanced digital control technique.
- Developed a hybrid contactor for utility grid connection that allows zero current turn-on by a solid-state relay and zero connection loss by a mechanical contactor.
- Developed a new low-cost TMS320F2808 digital signal processor (DSP) based controller board for faster current loop and power flow control.

Introduction

The DC-DC converter that serves as the interface between the SOFC and the output stage DC-AC inverter has been the focus of the Virginia Tech Solid State Energy Conversion Alliance (SECA) project. The peak efficiency of the V6 DC-DC converter was reported at 96.5% with either 25 V or 50 V fuel cell voltage. Recently the 50 V level peak efficiency at the half-load was further improved to 97.3% by reducing the power metal oxide semiconductor field effect transistor (MOSFET) turn-off loss with a smaller gate-drive resistance. The efficiency at the 5 kW rated load is about 96.5%.

For the DC-AC inverter, the proposed soft-switching inverter shows 99% efficiency for the switching stage. After adding an inductor-capacitor-inductor (LCL) filter, the efficiency remains 98%. The problem is the originally used solid-state relay consumes another 1% loss, and in addition the relay itself requires separate heat sink and cooling. Recently we developed a hybrid contactor that combines the solid-state relay and a mechanical contactor to eliminate the loss and to maintain high efficiency operation.

The utility grid interface adopts an LCL filter that allows universal applications. In other words, it can operate in both standalone and grid-tie modes. In order to control such an LCL filter-based system, an admittance compensation technique was proposed to allow simple control design with well-defined control loop stability. A provisional patent has been filed through the Virginia Tech Intellectual Property office.

Approach

Figure 1 shows the hybrid contactor based grid-tie universal power conditioning system. For standalone mode, the output voltage needs to be filtered by inductor L_{o1} and capacitor C_o. For the grid-tie inverter, additional inductor L_{o2} is needed to reduce the output current ripple content. The hybrid contactor consists of a thyristor based solid-state relay (SSR) and a mechanical contactor. The SSR turns on and off at zero-voltage crossing to avoid any current transient. The mechanical contactor turns on after and off before the SSR turns on to eliminate the loss caused by the thyristor conduction.

Figure 2 shows the block diagram of the proposed admittance compensation method along with a proportional-resonant (PR) controller for the precise power flow control. The state-of-the-art controller design for LCL-based inverters is to make one equivalent

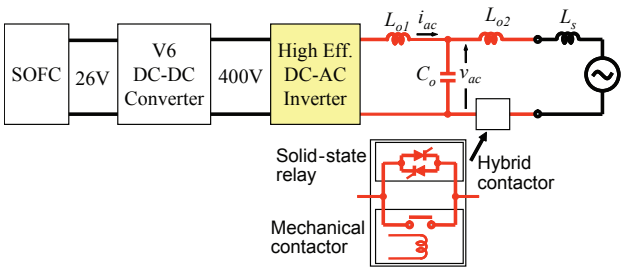

FIGURE 1. A Hybrid Contactor Based Grid-Tie SOFC PCS

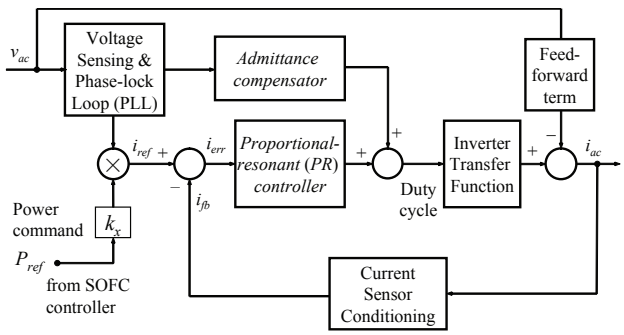

FIGURE 2. Block Diagram of a Grid-Tie SOFC PCS Using Admittance Compensator and PR Controller

circuit, which is a third-order system, and its original physical components, such as inductor current and capacitor voltage, disappear. Without knowing the physical term, the conventional controller cannot precisely control the power flow. The proposed admittance compensation is to solve the control design problem of the conventional LCL filter-based inverter, which has an undesirable feed-forward control term coming from the AC voltage source. The feed-forward term can produce a negative current command that reverses the power flow direction, and in low power commands, it can overcharge the DC bus capacitor voltage and results in catastrophe failure.

The admittance compensation method not only compensates the feed-forward term, but also avoids the use of a high-order filter circuit in controller design; instead, a second-order equivalent circuit can be used as the plant transfer function for standalone mode, and a first-order transfer function can be used for grid-tie mode. As a result, the controller design has well-defined frequency domain response, and the stability margins can be ensured. Additional benefit with the proposed admittance compensation technique is the placement of current and voltage sensors. Both standalone and grid-tie modes share the same sensing signals, thus allowing a potential cost saving on the sensors and their associated conditioning circuits.

The adopted PR controller is to replace the proportional-integral (PI) controller that has been widely used in DC-DC converters. The PI controller can eliminate the steady-state error for DC-DC converters but not for DC-AC inverters because the PI controller gain is not infinity at 60 Hz. With a finite gain at 60 Hz, the output can no longer follow the command, resulting in a significant command error.

For 50 V or higher voltage input V6™ converters, the Virginia Tech SECA team changed the switching device to a higher voltage rating and the transformer turns ratio to test the V6™ converter with a 50 V input. Initially the peak and full-load efficiencies were about the same as that obtained from 25 V level, but it was discovered that high-voltage switching tends to be slower than low-voltage switching, resulting in higher turn-off losses. Therefore, we added a small resistor and a blocking diode in the gate drive circuit to accelerate the turn-off speed. As a result, the switching between upper and lower devices was no longer overlapped, and the efficiency was improved over the entire load range. Without changing the existing circuit layout and design, this simple modification allows significant efficiency gain in a higher voltage system.

Results

In order to implement the proposed admittance compensation and PR controller, a DSP-based board has been developed, and the software program has been coded. As shown in Figure 2, a phase-locked loop (PLL), an admittance compensator, and a PR controller are all included in the DSP controller. The PLL is to obtain the grid synchronization signal and to produce the in-phase or orthogonal sine waves. These sine waves are multiplied with the real power command P_{ref} to obtain the reference control current i_{ref}. The comparison between i_{ref} and the feedback current i_{fb} results in a current error, which serves as the input to the PR controller. The duty cycle produced by the PR controller is compensated with the admittance compensator output to overcome the undesired feed-forward term that comes from the nature of the power circuit. The combination of admittance compensation and PR controller not only eliminates the steady-state error to control the power more precisely, but also avoids the current spike during startup and dynamic load changes [1,2].

Figure 3 compares the PR control results with and without admittance compensation at zero command operation. The PR controller allows elimination of steady-state error between the current command and actual current. Without admittance compensation, the PR controller produces a current spike under startup with zero command condition. Furthermore, the output current at zero command is not true zero. The rms current was measured at 1.34 A, and the output power was found to be –120 W. As mention before, without admittance compensation, such a negative power flow is not avoidable because of the feed-forward term. With the admittance compensation, the startup current spike

no longer exists. The measured power was found to be 4 W, which can be considered within the measurement error. The utility grid voltage for both cases is the same sinusoidal with 208 V rms.

For the DC-DC converter, the experiment is to compare the efficiency with different gate drive turn-off resistances. The turn-off voltage fall time was reduced from 270 ns to 200 ns by reducing the gate-drive turn-off resistor from 4.7 Ω to 2.2 Ω. Figure 4 compares the efficiency profiles with two different turn-off switching speed conditions. With a faster turn-off speed, the full-load (5 kW) efficiency is improved from 95.7% to 96.5%, and the peak efficiency at the half-load (2.5 kW) is improved from 96.5% to 97.3%. At 120% overload condition, the efficiency is improved from 95% to 96%. The total loss at 5 kW is 3.5% or 175 W. Note that the turn-on speed does not affect the efficiency because it is always under either zero voltage or zero current switching condition. A majority of the loss remains in conduction loss. Including the switch and transformer, the conduction loss is responsible for more than two-thirds the total loss. Therefore, it is possible that the V6™ converter efficiency will further go up if the fuel cell voltage goes higher. The question is how high the voltage should be? Because the MOSFET conduction loss is exponentially proportional to the blocking voltage level, and its switching loss is also increased with higher voltages, there should be a sweet spot for the V6™ converter input voltage, which remains a research issue.

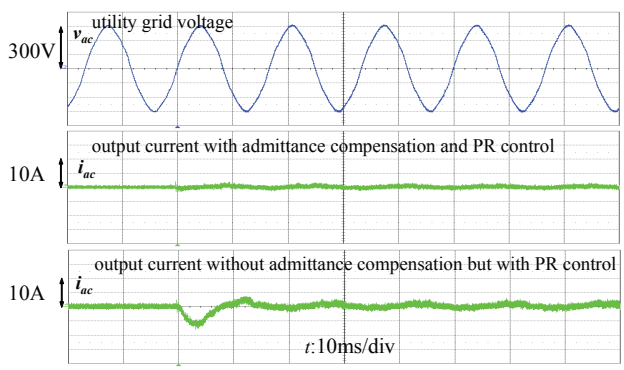

FIGURE 3. Experimental PR Controlled Voltage and Current Waveforms with and without LPAC under Startup with Zero Command Condition

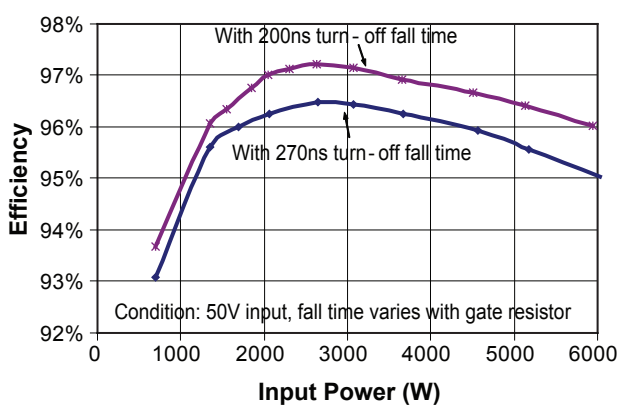

FIGURE 4. V6™ Converter Efficiency Test Results with 50 V Input Voltage

Conclusions and Future Directions

Major efforts have been focused on the precise power flow control and continuing improvement of PCS efficiency. A novel control system was developed to show its superiority to the conventional control methods. A simple modification of the gate drive circuit achieves further efficiency improvement. Major accomplishments are listed as follows.

- Developed a hybrid contactor that incorporates a solid-state relay to avoid switch current spike and a mechanical contactor to eliminate the contact conduction loss.
- Developed a control system that incorporates an admittance compensator and a proportional-resonant controller to precisely control the power flow. Test results indicated that not only the steady-state error is eliminated, but also the startup transient is avoided with the proposed controller.
- Modified and tested the V6™ DC-DC converter at 50 V input voltage with an efficiency gain of nearly 1%.

Future directions are:

- Test the V6™ DC-DC converter at a higher voltage to see if efficiency can increase further.
- Develop control system to comply with IEEE 1547 standard and California Rule 21.
- Test the entire PCS at EPRI-Solutions to show the performance of EMI and power quality under grid-tie control conditions.

Special Recognitions & Awards/Patents Issued

1. A U.S. provisional patent entitled "Control Method for a Universal Power Conditioning System" has been filed.

2. The V6™ converter was licensed to Hydra, Portland, OR and renewing the license to PEMDA Corp., Knoxville, TN.

FY 2007 Publications/Presentations

1. C. Liu, A. Ridenour, and J.-S. Lai, "Modeling and Control of a Novel Six-Leg Three-Phase High-Power Converter for Low-Voltage Fuel Cell Applications," *IEEE Transactions on Power Electronics*, September 2006, pp. 1292 – 1300.

2. J.-S. Lai, S.-Y. Park, S.-R. Moon, C.-L. Chen, "A High-Efficiency 5-kW Soft-Switched Power Conditioning System

for Low-Voltage Solid Oxide Fuel Cells", in *Proc. of Power Conversion Conference*, Nagoya, April 2007, pp. 463 – 470. Note: This paper received the Best Paper Award from the conference.

3. S.-R. Moon and J.-S. Lai, "Multiphase Isolated DC-DC Converter for Low-Voltage High-Power Fuel Cell Applications," in *Proceedings of IEEE APEC*, Anaheim, CA, February 2007, pp. 654 – 660.

4. S.-Y. Park, J.-S. Lai, C.-L. Chen, S.-R. Moon and T-W. Chun, "Current Loop Control with Admittance Compensation for a Single-Phase Grid-Tie Fuel Cell Power Conditioning System," in *Proceedings of IEEE APEC*, Anaheim, CA, February 2007, pp. 1010 – 1016.

5. S. Moon, S. Park, C. Liu, and J.-S. Lai, "Solid Oxide Fuel Cell Current Ripple Impact and Reduction Techniques," in *Proc. of IEEE PESC*, Jeju, Korea, June 2006, pp. 2037–2042.

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1. R. Teodorescu, F. Blaabjerg, U. Borup, and M. Liserre, "A new control structure for grid-connected LCL PV inverters with zero steady-state error and selective harmonic compensation," *Proc. of IEEE APEC*, Anaheim, CA, March 2004, pp. 580–586.

2. C.-L. Chen, S.-Y. Park, J.-S. Lai and S. Moon, "Admittance Compensation in Current Loop Control for a Grid-Tie LCL Fuel Cell Inverter," to be appeared in *Proc. of IEEE Power Electronics Specialists Conference*, Orlando, FL, June 2007.