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CONTROL OF FUEL CELL GRID CONNECTED POWER SYSTEM NETWORK BASED ON BOOST INVERTER

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ABSTRACT:

In this paper, the boost-inverter topology is used as a building block for a single-phase grid-connected fuel cell (FC) system offering low cost and compactness. In addition, the proposed system incorporates battery-based energy storage and a dc–dc bidirectional converter to support the slow dynamics of the FC. The single-phase boost inverter is voltage-mode controlled and the dc–dc bidirectional converter is current-mode controlled. The low-frequency current ripple is supplied by the battery which minimizes the effects of such ripple being drawn directly from the FC itself. Moreover, this system can operate either in a grid-connected or stand-alone mode. In the grid-connected mode, the boost inverter is able to control the active (P) and reactive (Q) powers using an algorithm based on a second-order generalized integrator which provides a fast signal conditioning for single-phase systems. Design guidelines, simulation, and experimental results taken from a laboratory prototype are presented to confirm the performance of the proposed system.

Index Terms: Boost inverter, fuel cell, grid-connected inverter, power conditioning system (PCS), PQ control.

I.INTRODUCTION

Alternative energy generation systems based on solar photo voltaics and fuel cells (FCs) need to be conditioned for both dc and ac loads. The overall system includes power electronics energy conversion technologies and may include energy storage based on the target application.

However, the FC systems must be supported through additional energy storage unit to achieve high-quality supply of power [1]–[4]. When such systems are used to power ac loads or to be connected with the electricity grid, an inversion stage is also required. The typical output voltage of low-power FC is low and variable with respect to the load current. For instance, based on the current–voltage characteristics of a 72-cell proton exchange membrane FC (PEMFC) power module, the voltage varies between 39 and 69 V depending upon the level of the output current as show in Fig. 1 [5]. Moreover, the hydrogen and oxidant cannot respond the load current changes instantaneously due to the operation of components such as pumps, heat exchangers, and fuel-processing unit [6]–[8].

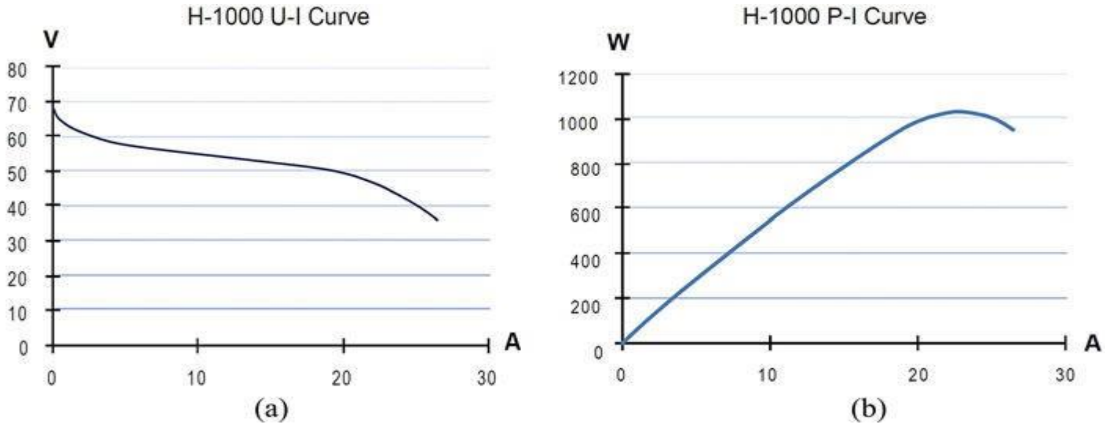
Caisheng et al. [9] presented the cold-start which takes more than few seconds. Thus, the slow dynamics of the FC must be taken into account when designing FC systems. This is crucial, especially when the power drawn from the FC exceeds the maximum permissible power, as in this case, the FC module may not only fail to supply the required power to the load but also cease to operate or be damaged [10]–[12]. Therefore, the power converter needs to ensure that the required power remains within the maximum limit [10], [12].

II. LITERATURE SURVEY

A two-stage FC power conditioning system to deliver ac power has been commonly considered and studied in numerous technical papers [3], [4], [7], [10]–[14]. The two-stage FC power conditioning system encounters drawbacks such as being bulky, costly, and relatively inefficient due to its cascaded power conversion stages. To alleviate these drawbacks, a topology that is suitable for ac loads and is powered from dc sources able to boost and invert the voltage at the same time has been proposed in [15]. The double loop control scheme of this topology has also been proposed for better performance even during transient conditions [16].

A single-stage FC system based on a boost inverter has been proposed in [17]. The single-stage system is able to minimize the problems with the two-stage FC power conditioning system [17]. The paper reported overall efficiency dealing with the single-stage and conventional two-stage FC systems. The total efficiency of the single-stage system has been improved around 10% over the range of the power rating and [17]. The paper illustrated the performance of a stand-alone FC system using the boost inverter with a bidirectional backup storage unit to support the slow dynamics of the FC and to cancel the ripple current that causes reduction of the lifetime and efficiency of the FC [17]–[19]. However, the performance and operating characteristics of such a system for grid applications is an important step forward that is yet to be reported in the technical literature.

The objective of this paper is to propose and report full experimental results of a grid-connected single-phase FC system using a single energy conversion stage only. In particular, the proposed system, based on the boost inverter with a backup energy storage unit, solves the previously mentioned issues (e.g., the low and variable output voltage of the FC, its slow dynamics, and current harmonics on the FC side). The single energy conversion stage includes both boosting and inversion functions and provides high power conversion efficiency, reduced converter size, and low cost [17]. The proposed single-phase grid-connected FC system can operate either in grid-connected or stand-alone mode. In the grid-connected mode, the boost inverter is able to control the active (P) and reactive (Q) powers



(a)
(b)

Fig. 1. Seventy-two-cell PEMFC system (Horizon H-1000, 1.0 kW). (a) Voltage–current characteristic showing the dc output voltage ranges from 39 to 69 V across the operating range. At rated power, dc output voltage and current are 43 and 23.5 A, respectively. (b) Power–current characteristic showing the output power ranges from zero when being idle to 1000 W at rated output power.

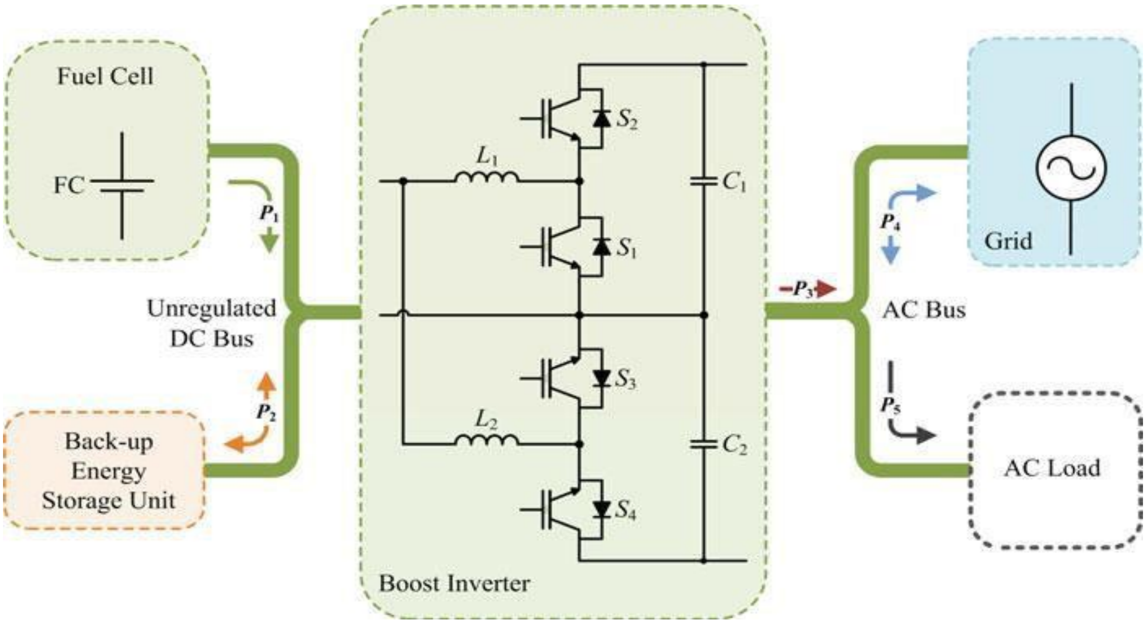


Fig. 2. Block diagram for the proposed grid-connected FC system.

The backup unit and the FC power module are connected in the unregulated dc bus and the boost-inverter output is connected to the local load and the grid. (P1: FC output power, P2: backup unit input/output power, P3: inverter output power, P4: power between the inverter and the grid, and P5: power to the ac loads). Through the grid by the proposed PQ control algorithm using fast signal conditioning for single-phase systems [20].

The remaining of this paper is organized as follows. In Section II, the proposed grid-connected FC system is introduced including the inverter topology, the control algorithm of the boost inverter, the backup energy storage unit, and the PQ control algorithm for a single-phase FC system. Design guidelines are also provided in Section II. In Section III, simulation and experimental results are presented to document the performance of the proposed system. Experimental results taken from a 1-kW laboratory prototype are presented to verify the overall performance of the proposed grid-connected FC system. Finally, the conclusions are summarized in Sections.

III. PROPOSED FC ENERGY SYSTEM

The block diagram of the proposed grid-connected FC system is shown in Fig. 2. Fig. 2 also shows the power flows between each part. This system consists of two power converters: the boost inverter and the bidirectional backup unit, as shown in Figs. 2 and 3. Fig. 4 shows the laboratory setup of the proposed FC system. The boost inverter is supplied by the FC and the backup unit, which are both connected to the same unregulated dc bus, while the output side is connected to the load and grid through an inductor.

The system incorporates a current-mode controlled bidirectional converter with battery energy storage to support the FC power generation and a voltage-controlled boost inverter. The FC system should dynamically adjust to varying input voltage while maintaining constant power operation. Voltage and current limits, which should be provided by the manufacturers of the FC stack, need to be imposed at the input of the converter to protect the FC from damage due to excessive loading and transients. Moreover, the power has to be ramped up and down so that the FC can react appropriately, avoiding transients and extending its lifetime.

The converter also has to meet the maximum ripple current requirements of the FC [6].

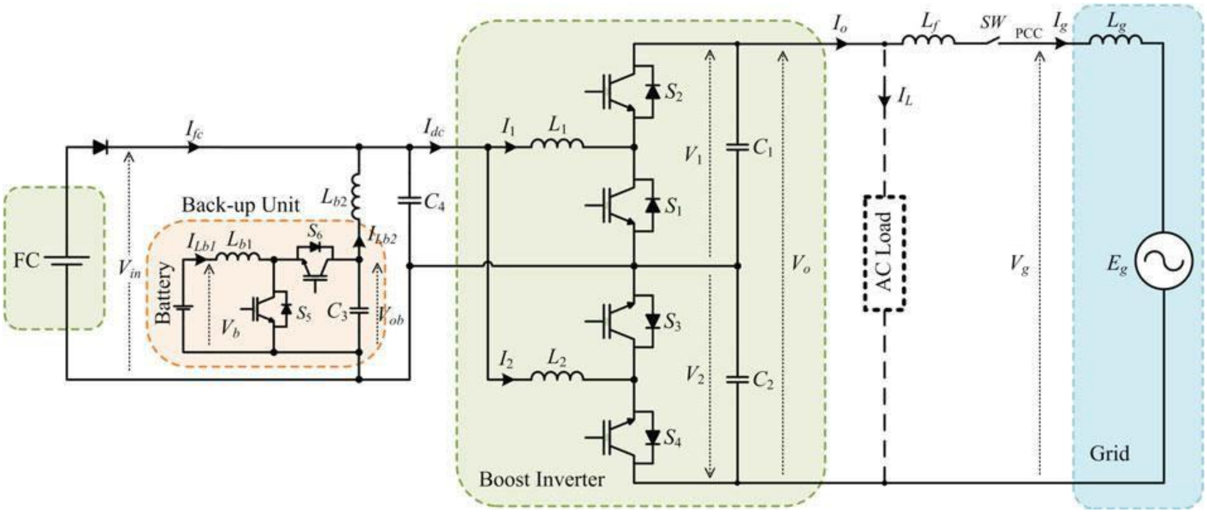


Fig. 3. General structure of the proposed grid-connected FC system.

The boost inverter consists of two bidirectional boost converters and their outputs are connected in series, as shown in Fig. 3. Each boost converter generates a dc bias with deliberate ac output voltage is calculated by using

$$V_1 = V_{\mathrm{dc}} + 1/2 \cdot A_1 \cdot \sin\theta$$

$$V_2 = V_{\mathrm{dc}} + 1/2 \cdot A_2 \cdot \sin(\theta - \pi)$$

$$V_o = V_1 - V_2 = A_o \cdot \sin\theta, \text{ when } A_o = A_1 = A_2$$

$$V_{\mathrm{dc}} > V_{\mathrm{in}} + \frac{A_o}{2}$$

The equivalent circuit of the grid-connected FC system consisting of two ac sources (*Vg* and *Vo*), an ac inductor *Lf* between the two ac sources, and the load.

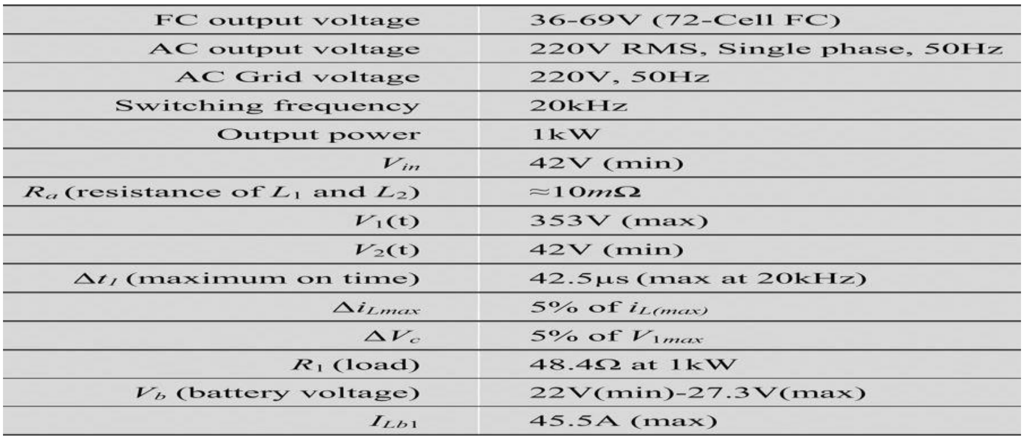
The boost inverter output voltage (including the FC and backup unit) is indicated as *Vo* and *Vg* is the grid voltage. The active and reactive powers at the point of common coupling (PCC) are expressed by [20] and [24]

$$P = \frac{V_g \cdot V_o}{\omega_o \cdot L_f} \sin(\delta)$$

$$Q = \frac{V_g^2}{\omega_o \cdot L_f} - \frac{V_g \cdot V_o}{\omega_o \cdot L_f} \cos(\delta)$$

Where L_f is the filter inductance between the grid and the boost inverte

TABLE I
DESIGN SPECIFICATION



FC output voltage	36-69V (72-Cell FC)
AC output voltage	220V RMS, Single phase, 50Hz
AC Grid voltage	220V, 50Hz
Switching frequency	20kHz
Output power	1kW
V_{in}	42V (min)
R_a (resistance of L_1 and L_2)	$\approx 10m\Omega$
V_1(t)	353V (max)
V_2(t)	42V (min)
Δt_I (maximum on time)	42.5μs (max at 20kHz)
Δi_{Lmax}	5% of $i_{L(max)}$
ΔV_c	5% of V_{1max}
R_1 (load)	48.4Ω at 1kW
V_b (battery voltage)	22V(min)-27.3V(max)
I_{Lb1}	45.5A (max)

IV SIMULATION RESULTS

The proposed FC system (see Fig. 3) has been analyzed, designed, simulated, and tested experimentally to validate its overall performance. The simulations have been done using Simulink/MATLAB and PLECS blockset to validate the analytical results. The ac output voltage of the systemwas chosen to be equal to 220 V, while the dc input voltage varied between 43 and 69 V.

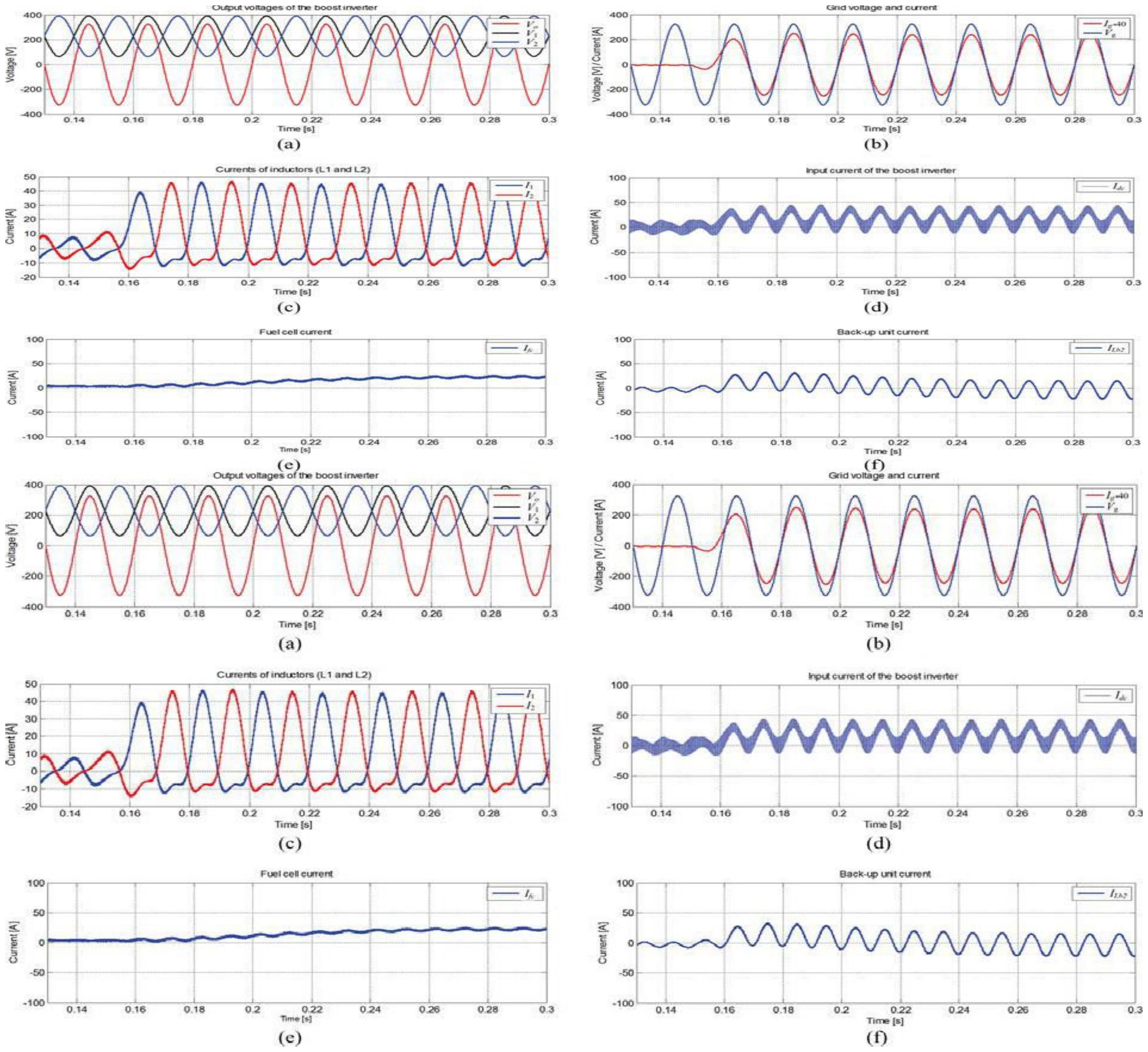


Fig. 10. Simulation results of the proposed FC system. (a) Output voltages of the boost inverter. (b) Grid voltage *Vg* and current *Ig* with full power feeding to the grid. (c) Current waveforms of *L*1 and *L*2 . (d) Input current of the boost inverter, *I*dc . (e) FC output current during transient, *I*fc . (f) Output current of the backup unit, *I*Lb

IV. CONCLUSION

A single-phase single power stage grid-connected FC system based on the boost-inverter topology with a backup battery based energy storage unit is proposed in this paper. The simulation results and selected laboratory tests verify the operation characteristics of the proposed FC system. In summary, the proposed FC system has a number of attractive features, such as single power conversion stage with high efficiency, simplified topology, low cost, and able to operate in stand-alone as well as in grid-connected mode. Moreover, in the grid-connected mode, the single-phase FC system is able to control the active and reactive powers by a *PQ* control algorithm based on SOGI which offers a fast signal conditioning for single-phase systems. However, it should be noted that the voltage-mode control adopted for the boost inverter may result in a distorted grid current (under given THD) if the grid voltage includes a harmonic component.

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