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A Single-Phase Grid-Connected Fuel Cell System Based on a Boost-Inverter

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***Abstract*— The boost-inverter topology is used as a building block for a single-phase grid connected fuel cell (FC) system, which is offering low cost and compactness. Fuel cells are different from batteries in that they require a constant source of fuel and oxygen to run, but they can produce electricity continually for as long as these inputs are supplied. In order to the meet the system operational and security requirements, fuel cell power systems need to be interfaced with the utility grid connected through a set of power electronic devices. Interconnecting a fuel cell power system with a utility grid is very important since the interface will not only affect the fuel cell system, but also the grid connected. In addition to that, the proposed system incorporates battery-based energy storage and a dc–dc bidirectional converter (Back-up unit) 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. A Simulink based model is developed and the simulation results for the proposed model applied to induction motor drive by using MAT LAB.**

***Index Terms*— Boost-inverter, DC–DC bidirectional converter, Fuel cell, Grid, Power conditioning system (PCS), PQ control, FC**

I. INTRODUCTION

This One of RECENTLY, energy sources such as wind power systems, photovoltaic cells, and fuel cells have been extensively studied in response to global warming and environmental issues. The fuel cell is an important technology for new mobile applications and power grid distribution systems. For power distribution, fuel cell system requires a grid interconnection converter to supply power to the power grid. A grid interconnection converter using an isolation transformer is preferable for power grid distribution systems in terms of surge protection and noise reduction. In addition, size reduction and high efficiency are essential requirements. One of the problems in the fuel cell system is that the lifetime is decreased by the ripple current. Therefore, in order to extend the lifetime, the fuel cell ripple current must be reduced in the grid interconnection converter. However, when a single-phase pulse width-modulated (PWM) inverter is used for grid connection system, the power ripple is twice the frequency of the power grid.

For Example, from the current–voltage characteristics of a 72-cell proton exchange membrane FC (PEMFC) power module, the voltage varies between 39 and 69 V. 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].

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 through the grid by the proposed PQ control algorithm using fast signal conditioning for single-phase systems [20].

II. FC ENERGY SYSTEM

A fuel cell is an electrochemical cell that converts a source Fuel into an electrical current. It generates electricity inside a cell through reactions between a fuel and an oxidant, triggered in the presence of an electrolyte. The reactants flow into the cell, and the reaction products flow out of it, while the electrolyte remains within it. Fuel cells can operate continuously as long as the necessary reactant and oxidant flows are maintained. Fuel cells are different from conventional electrochemical cell batteries in that they consume reactant from an external source, which must be replenished [1] – a thermodynamically open system. By contrast, batteries store electrical energy chemically and hence represent a thermodynamically closed system. Many Combinations of fuels and oxidants are possible. A hydrogen fuel cell uses hydrogen as its fuel and oxygen (usually from air) as its oxidant. Other fuels include hydrocarbons and

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alcohols. Other oxidants include chlorine and chlorine dioxide Fuel cells come in many varieties; however, they all work in the same general manner. They are made up of three segments which are sandwiched together: the anode, the electrolyte, and the cathode. Two chemical reactions occur at the interfaces of the three different segments. The net result of the two reactions is that fuel is consumed, water or carbon dioxide is created, and an electrical current is created, which can be used to power electrical devices, normally referred to as the load. At the anode a catalyst oxidizes the fuel, usually hydrogen, turning the fuel into a positively charged ion and a negatively charged electron. The electrolyte is a substance specifically designed so ions can pass through it, but the electrons cannot. The freed electrons travel through a wire creating the electrical current. The ions travel through the electrolyte to the cathode. Once reaching the cathode, the ions are reunited with the electrons and the two react with a third chemical, usually oxygen, to create water or carbon dioxide.

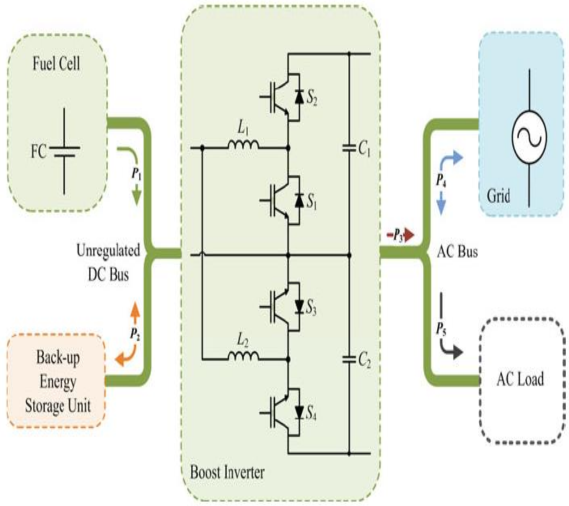

Figure 1 Proposed Block Diagram

In this block diagram the models 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. The representation of the power are mentioned as follows,

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.

FUEL CELLS

Fuel cells are also well used for distributed generation applications, and can essentially be described as batteries which never become discharged as long as hydrogen and oxygen are continuously provided. The hydrogen can be supplied directly, or indirectly produced by reformer from fuels such as natural gas, alcohols, or gasoline. Each unit ranges in size from 1-250 kW or larger MW size. Even if they offer high efficiency and low emissions, today's costs are high. Phosphoric acid fuel cell is commercially available in the range of the 200 kW, while solid oxide and molten carbonate fuel cells are in a precommercial stage of development. The possibility of using gasoline as a fuel for cells has resulted in a major development effort by the automotive companies. The recent research work about the fuel cells is focused towards the polymer electrolyte membrane (PEM) fuel cells. Fuel cells in sizes greater than 200 kW hold promise beyond 2005, but residential size fuel cells are unlikely to have any significant market impact any time soon. Figure 1 shows a block diagram of fuel cell system which consists of a reformer, fuel cell stack and a PCU.

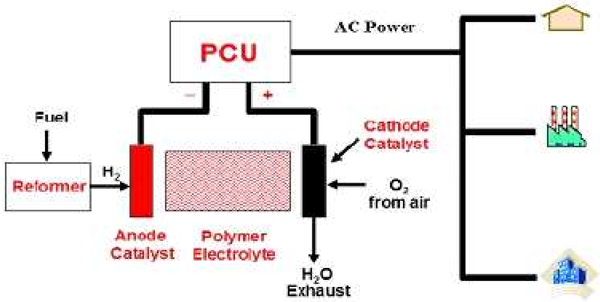

Figure 2 Basic Layout of FC System

Moreover, the scalability of fuel cells has allowed for applications in almost every field. Fuel cell systems can be easily placed at any site in a power system for grid reinforcement, thereby deferring or eliminating the need for system upgrades and improving system integrity, reliability, and efficiency.

Therefore, proper controllers need to be designed for a fuel cell system to make its performance characteristics as desired. Development of a standalone, reduced-order, dynamic model of fuel cell power plant connected to a distribution grid via dc/ac converter. The proposed model includes the electrochemical and thermal aspects of chemical reactions inside the fuel-cell stack but the dynamics model of DC/DC and DC/AC Converters are not considered. A novel hierarchical control architecture for a hybrid distributed generation system that consists of dynamic models of a battery bank, a solid oxide fuel cell and power electronic converter has been presented. The fuel cell power plant is interfaced with the utility grid and a three phase pulse width modulation (PWM) inverter. The second-order generalized integrator (SOGI) algorithm has been employed

III. BOOST INVERTER

Boost dc–ac inverter naturally generates in a single stage an ac voltage whose peak value can be lower or greater than the dc input voltage. The main drawback of this structure deals with its control. Boost inverter consists of Boost dc–dc converters that have to be controlled in a variable-operation point condition. The sliding mode control has been proposed as an option. However, it does not directly control the inductance averaged-current. This paper proposes a control strategy for the Boost inverter in which each Boost is controlled by means of a double-loop regulation scheme that consists of a new inductor current control inner loop and an also new output voltage control outer loop. These loops include compensations in order to cope with the Boost variable operation point condition and to achieve a high robustness to both input voltage and output current disturbances. As shown by simulation and prototype experimental results, the proposed control strategy achieves a very high reliable performance, even in difficult transient situations such as nonlinear loads, abrupt load changes, short circuits, etc., which sliding mode control cannot cope with.

A. GENERAL CIRCUIT

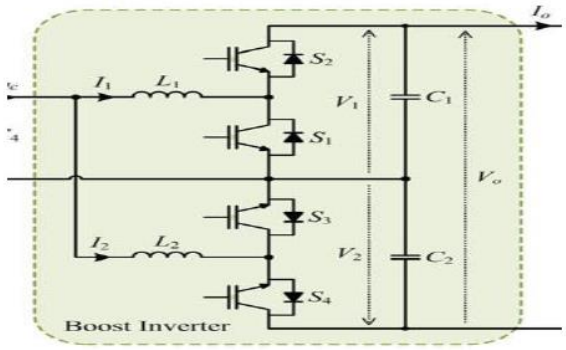

Figure 3 Circuit Diagram for Boost Inverter

B. CONTROL SCHEME

A double-loop control scheme is chosen for the boost inverter control being the most appropriate method to control the individual boost converters covering the wide range of operating points. This control method is based on the averaged continuous-time model of the boost topology and has several advantages with special conditions that may not be provided by the sliding mode control, such as nonlinear loads, abrupt load variations, and transient short circuit situations. Using this control method, the inverter maintains a stable operating condition by means of limiting the inductor current. Because of this ability to keep the system under control even in these situations, the inverter achieves a very reliable operation [16]. The reference voltage of the boost inverter is provided from the *PQ* control algorithm being able to control the active and reactive power. The voltages across *C*1 and *C*2 are controlled to track the voltage references using proportional-resonant (PR) controllers. Compared with the conventional proportional integral (PI) controller, the PR controller has the ability to minimize the drawbacks of the PI one such as lack of tracking a sinusoidal reference with zero steady-state error and poor disturbance

C. CONTROL BLOCK DIAGRAM

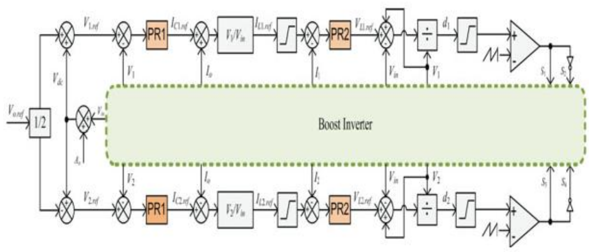

Figure 4 Control Block for Boost Inverter

D. BACKUP ENERGY STORAGE UNIT

The functions of the backup energy storage unit are divided into two parts. First, the backup unit is designed to support the slow dynamics of the FC. Second, in order to protect the FC system, the backup unit provides low-frequency ac current that is required from the boost inverter operation. The low-frequency current ripple supplied by the batteries has an impact on their lifetime, but between the most expensive FC components and the relatively inexpensive battery components, the latter is preferable to be stressed by such low-frequency current ripple. The backup unit comprises of a current-mode controlled bidirectional converter and a battery as the energy storage unit.

The backup unit controller is designed to control the output current of the backup unit in Figure 5. The reference of I_{Lb1} is determined by I_{dc} through a high-pass filter and the demanded current I_{demand} that is related to the load change. The ac component of the current reference deals with eliminating the ac ripple current into the FC power module while the dc component deals with the slow dynamics of the FC.

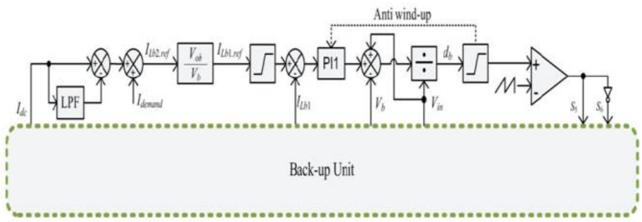

Figure 5 Backup Unit Control Block Diagram.

E. CONTROL OF THE GRID-CONNECTED BOOST INVERTER

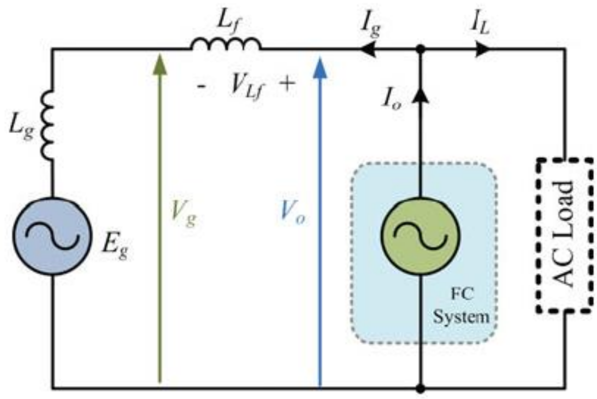

Figure 6 Circuit of the Grid-Connected FC System.

Fig. 6 illustrates 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

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

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

Where,

Lf is the filter inductance between the grid and the boost inverter.

The phase shift δ and voltage difference Vg – Vo between Vo and Vg affect the active and the reactive powers, respectively. Therefore, to control the power flows between the boost inverter and the grid, the FC system must be able to vary its output voltage Vo in amplitude and phase with respect to the grid voltage Vg.

IV. Modeling

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. The proposed model show in figure 7

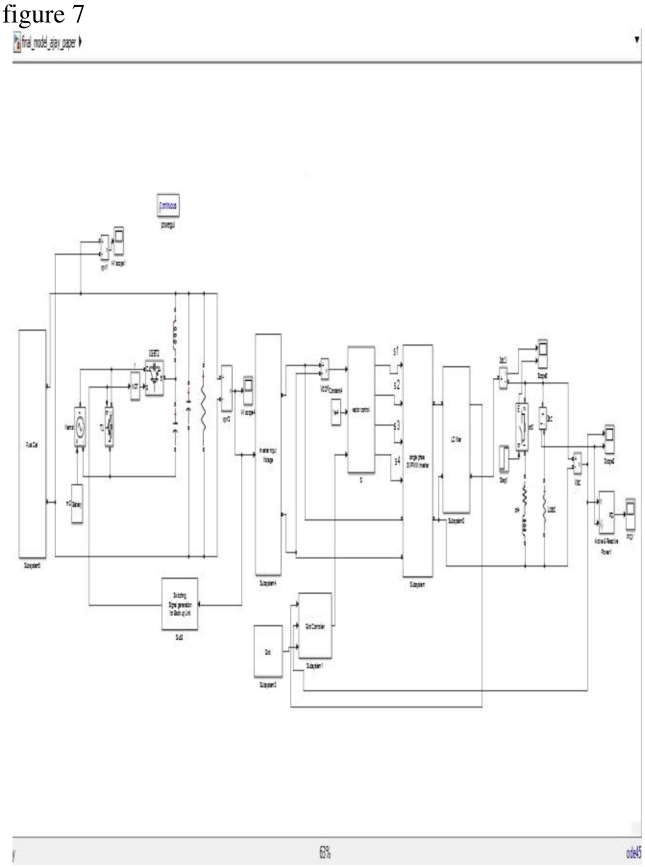

Figure 7 Main Model

Fuel cells are electrochemical energy converters. They directly convert the energy of a chemical reaction into electrical energy – without a thermal-electric intermediate step. Fuel cells consist of two electrodes that conduct electrons – the anode and the cathode. The electrodes are separated by an electrolyte that conducts ions. The main reason for the use of fuel cell is the increasing dependency on the use of fossil fuels. Fuel cell model shown in figure 8

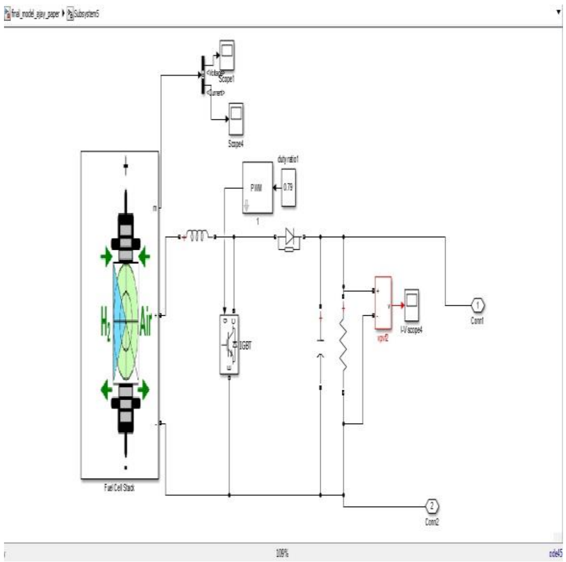

Figure 8 Fuel cell

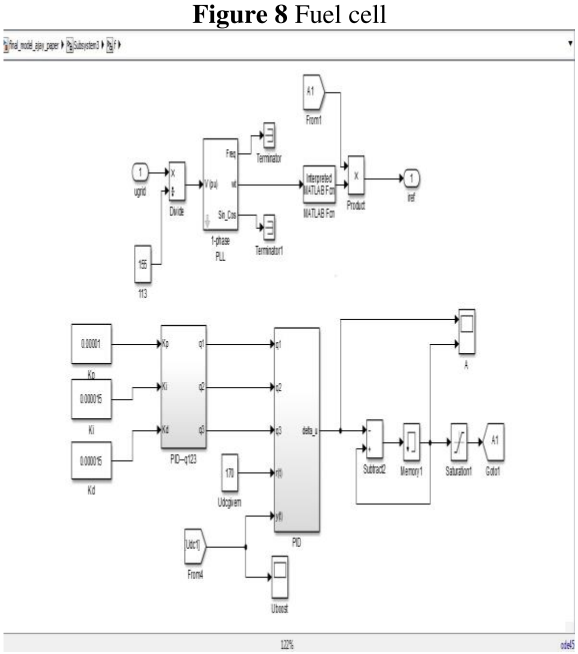

Figure 9 Grid Frequency Generators

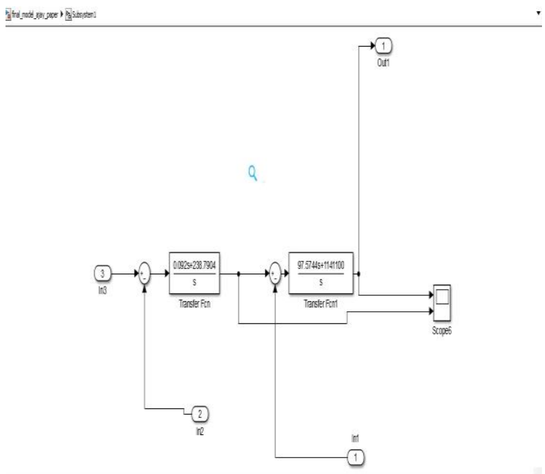

Figure 10 Grid Controller

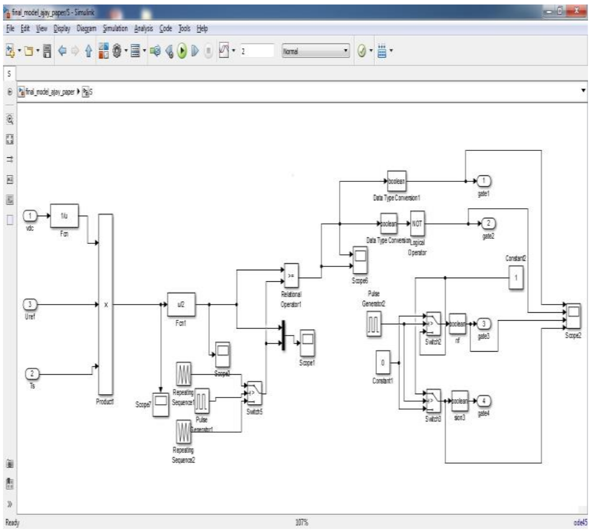

Figure 11 Vector Control

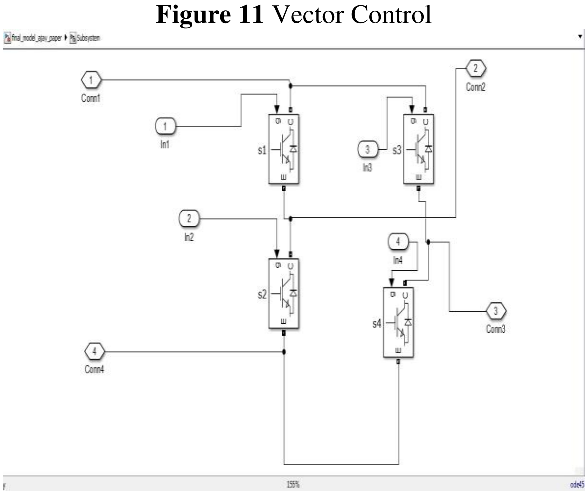

Figure 12 Single Phase SVPWM Inverter

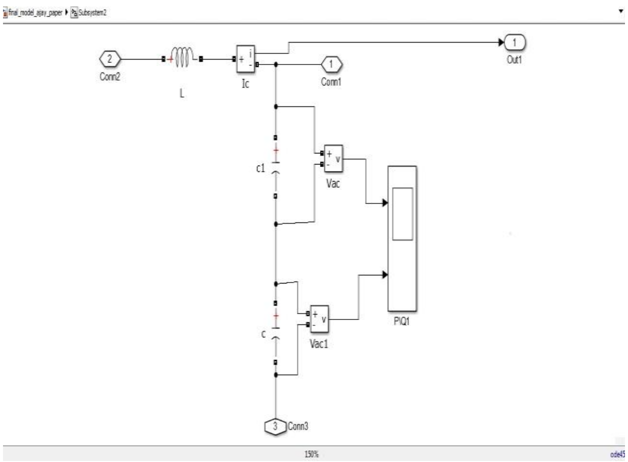

Figure 13 LC Filter

V. Results

The proposed single-phase grid-connected FC system has been developed as a laboratory prototype. In this thesis, a dc power supply is used to provide dc output between 43 and 69V, same voltage range as a 72-cell PEMFC. The power electronic stack consists of three insulated gate bipolar transistor (IGBT) modules that are used to build the boost inverter for two modules and backup unit for one module. The DSP controller unit has been used for a number of reasons such as low cost, embedded floating point unit, high speed, on-chip analog-to digital converter, and high-performance pulse width modulation unit. Experimental results presented below:

In figure 14 illustrates the performance of the fuel cell voltage. And the figure 15 show the performance of fuel cell stack voltage vs current and stack power vs current.

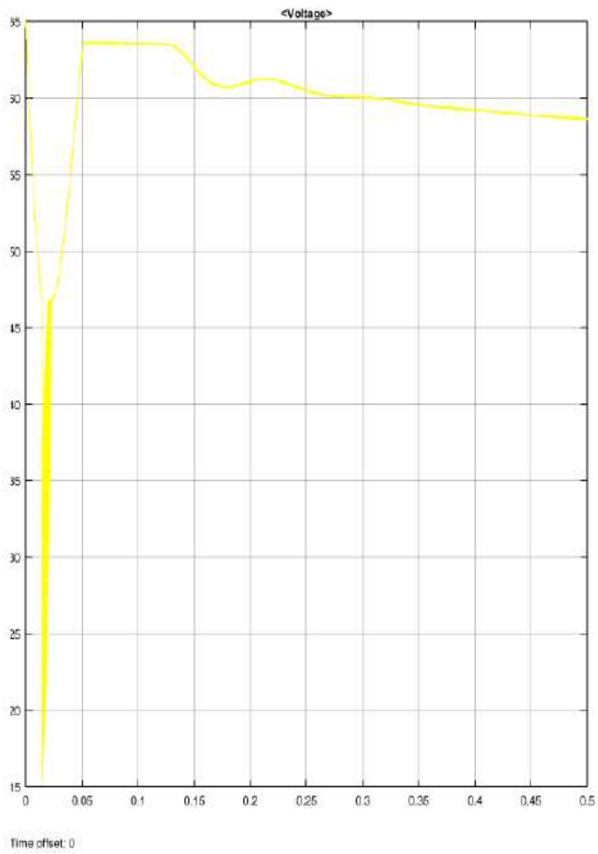

Figure 14 fuel cell voltages

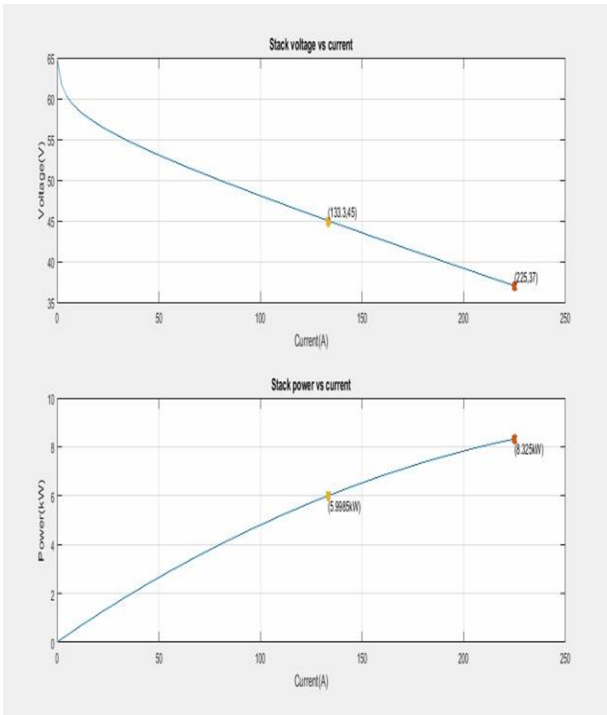

Figure 15 Fuel Cell Voltage Current/Power Current

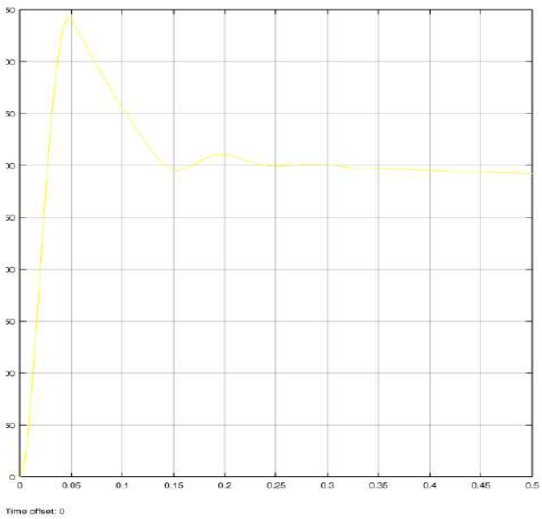

Figure 16 DC output voltages at storage

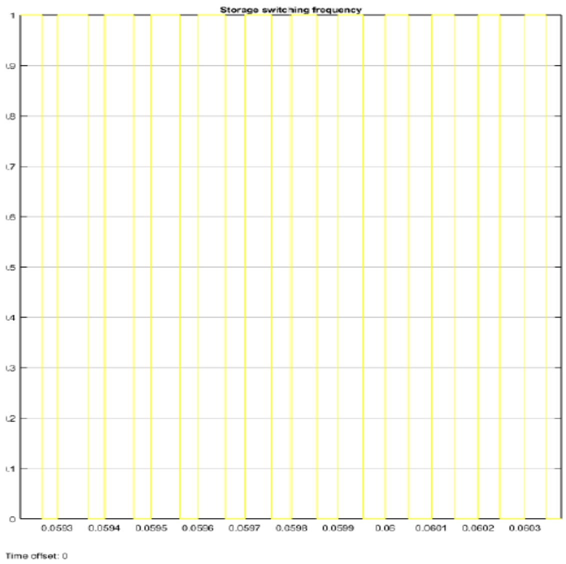

Figure 17 Storage Switching Frequency

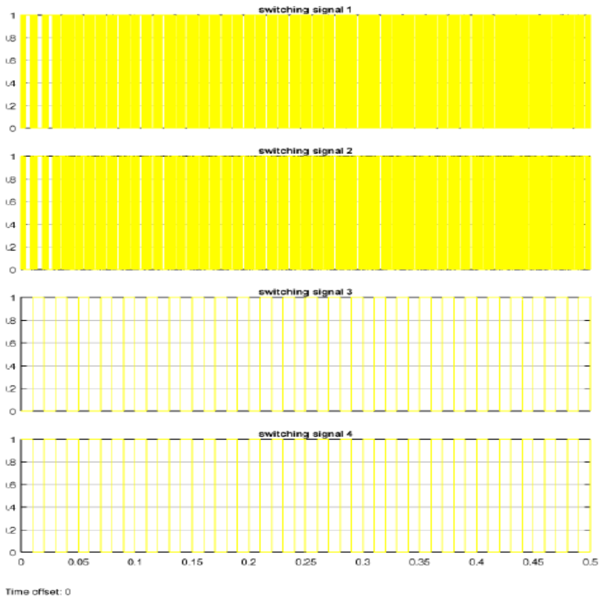

Figure 18 Inverter Switching Signals

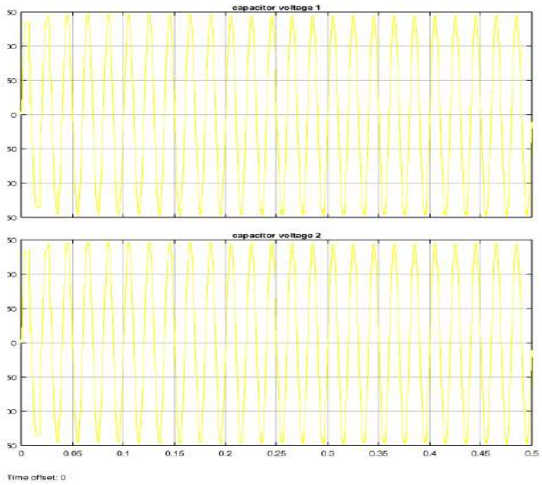

Figure 19 capacitor voltage

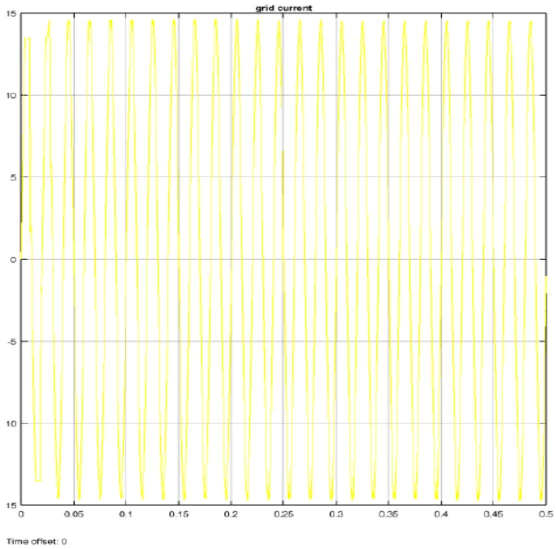

Figure 20 Grid Current

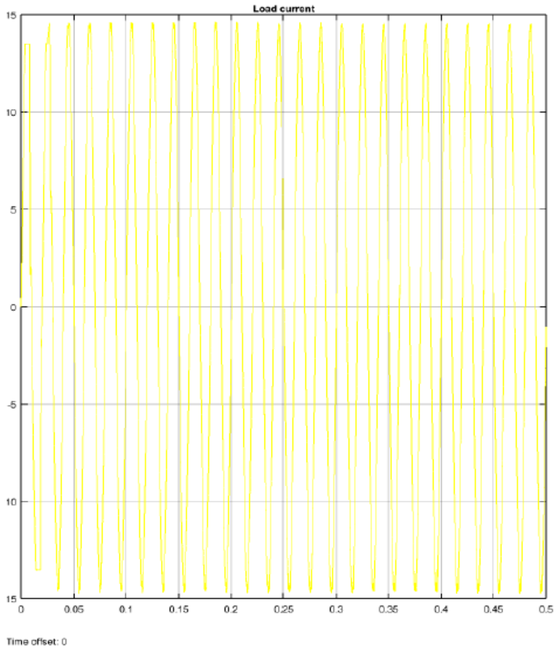

Figure 21 Load current

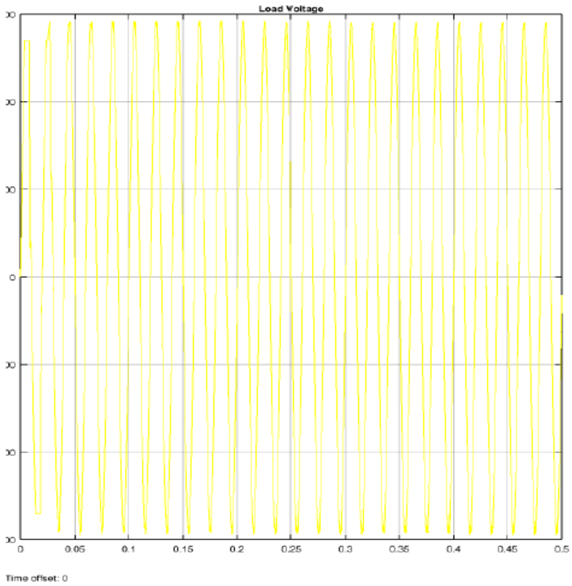

Figure 22 Load Voltage

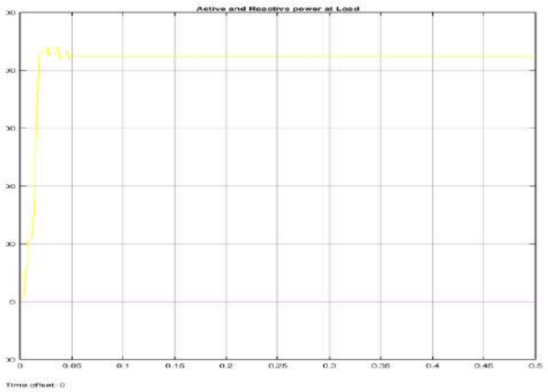

Figure 23 Active and Reactive power at Load

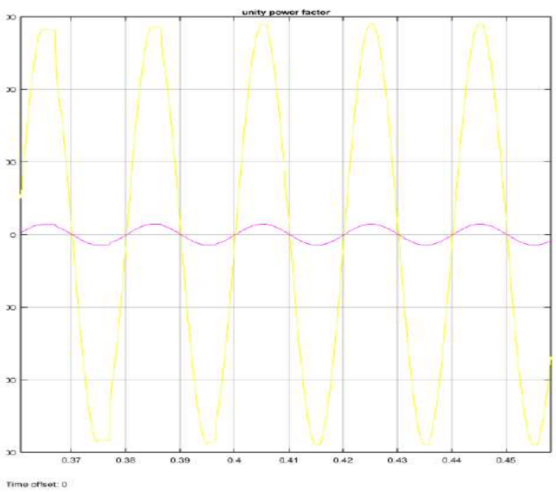

Figure 24 Unity power factor

VI. 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. 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

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