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Fuel Cell for Standalone Application Using FPGA Based Controller

[1]K.Mahapatra, [2]K.C.Bhuyan

[1,2]ECE Department, National Institute of Technology, Rourkela, India, Pin-769008

[1]Email: kkm@nitrkl.ac.in

Abstract:

Recently, increase in energy consumption, uncertainty of crude oil price and universal environment changes has enforced researchers to focus more on new and renewable energy sources. Different renewable sources are available e.g. photovoltaic and wind energy; however each source has some limitations or other. One of the potential sources that can provide renewable energy is fuel cell which is better compared to other possible renewable sources of energy in certain terms. Solid oxide fuel cell (SOFC) is a more effective, environmental friendly renewable energy source. This paper focuses on standalone fuel cell power system (FCPS) using SOFC which can be used as a backup power source for household and commercial units. This backup power source will be efficient and will provide clean energy at an affordable per unit cost. Standalone fuel cell power system mainly comprises a fuel cell module, DC-DC converter and DC-AC inverter. This paper focuses on modeling, control of DC-DC converter and DC-AC inverter. Exhaustive simulation is conducted to validate our concepts and FPGA based experimental results confirm the same. Dynamic model of SOFC is developed to obtain output voltage, efficiency, various losses and power density of the fuel cell stack. This model contains the mathematical modeling and electrical features of the fuel cell system. It also describes the different types of possible losses i.e. i) Activation voltage loss, ii) Concentration voltage loss, and iii) Ohmic voltage loss. Detailed loss modeling facilitates accurate calculation of output voltage that ultimately drives further stages in a power supply scenario. Furthermore, it includes the calculation of the partial pressure of hydrogen, oxygen and water. In this investigation the output voltage of fuel cell is fed to a DC-DC converter to step up the output voltage. This converter steps up the output voltage that is a necessity as fuel cell normally provides a low output voltage at a reasonably high current. We first store energy in an inductor and that additional energy is then delivered at intervals through MOSFET acting as a switch regulated by PWM (Pulse width modulation) to a capacitor. The prototype of single phase fuel cell power system with Hysteresis Current Control (HCC) technique is developed. FPGA (Field Programmable Gate Array) implementation of HCC is done using NI -CompactRIO-9014. The HCC provides accurate pulse width modulation signal to drive the DC/AC inverter. This output wave form from the inverter indicates that the voltages are almost sinusoidal of frequency 50

Hz that is desirable for a specific load. Thus a fuel cell based standalone system is developed and its performance is evaluated.

Keywords: DC-DC Converter, DC-AC inverter, FPGA, NI-cRIO-9014, PI Controller, PWM-VSI Controller, SOFC

INTRODUCTION

- Limited supply of crude oil and fossil fuel, researchers are trying to generate electricity from renewable energy sources.
- Different renewable energy sources are solar, wind, hydrogen, tidal energy and biomass.
- Solar and wind energy has some practical limitations as it can only be installed at a proper geographic location.
- One of the promising renewable energy sources in Hydrogen energy where Hydrogen is used to generate electricity with the help of chemical process.
- The electrochemical process which converters hydrogen to electricity is non-polluting and efficient.
- One of the major advantages of a fuel cell system is that it can be placed at any site in a distribution system without geographic limitations to provide optimal benefit, and they are not intermittent in nature.
- Electro-chemical energy source is highly efficient, environmental friendly and requires low maintenance.

OBJECTIVES

- To develop multi-staged low cost digital controller for fuel cell power system

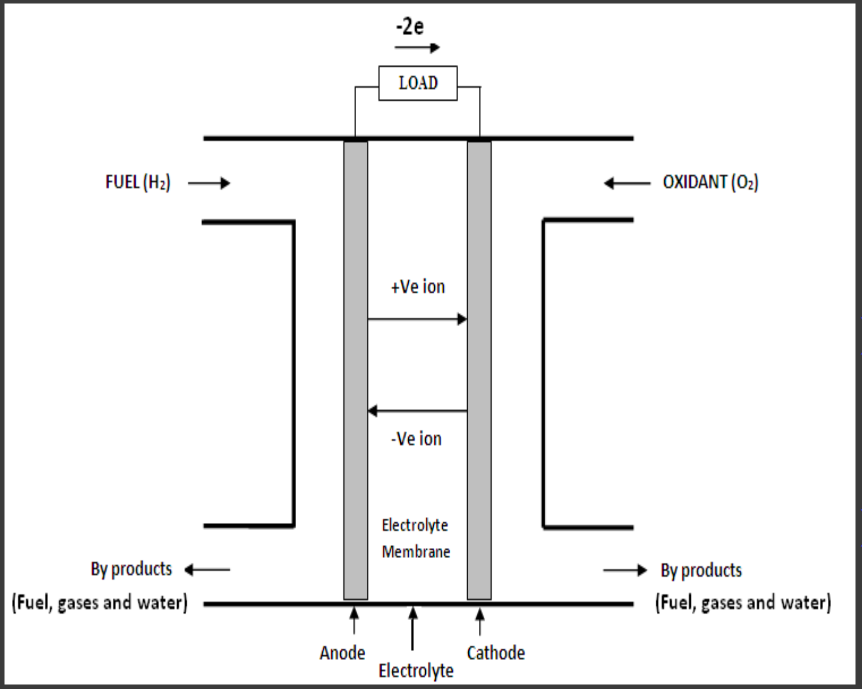
- Implement adaptive nonlinear control laws in controller

- Experimentally validate the simulated results

Fuel Cell

- A fuel cell is an electrochemical device that converts chemical energy of hydrogen gas and oxygen gas into electrical energy.
- Like a battery, a fuel cell consists of a pair of electrodes and an electrolyte.
- A fuel, usually hydrogen, is supplied to the fuel cell anode. At the anode, the fuel is oxidized, yielding electrons which travels through the external circuit.
- The anode and cathode reactions and the composition and the direction of flow of the mobile ion vary with the type of fuel.

Fuel Cell Operation



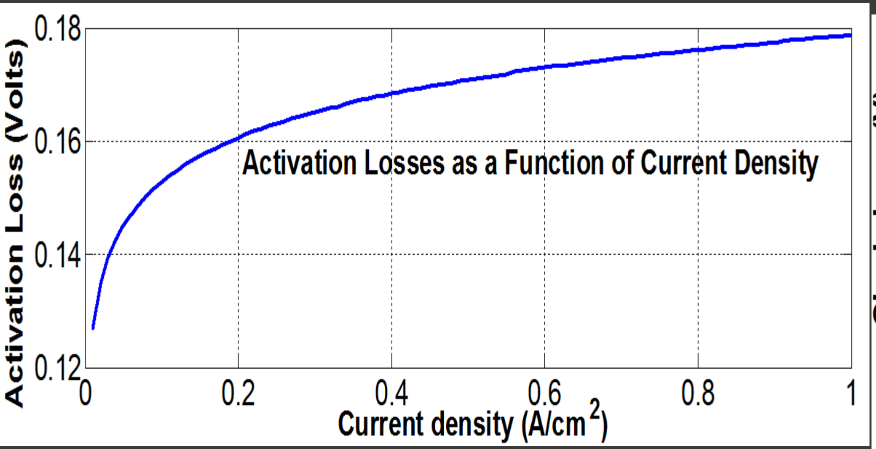
- Other side of cell, the oxidizer flows through the channels of the plate and it spreads through the electrode till it reaches the catalytic layer of cathode.
- The oxidizer used in model is air (oxygen).
- The oxygen is consumed with protons and electrons and the product, with liquid water, is produced with heat and electricity.

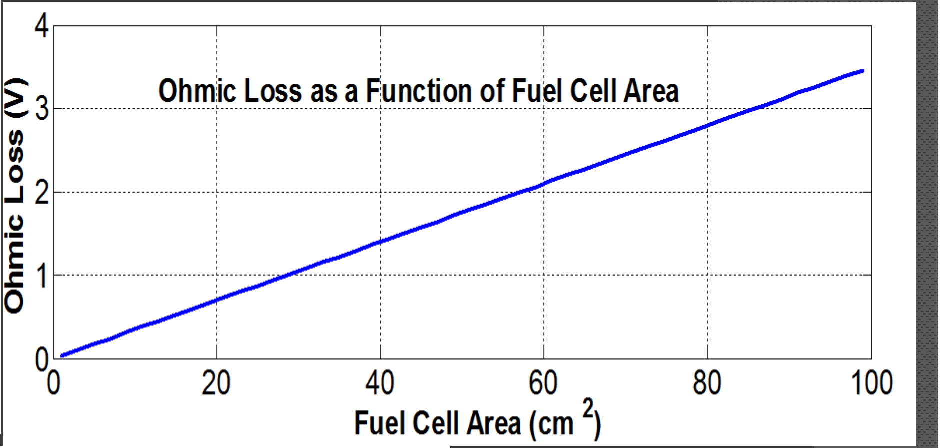
Advantages of Fuel Cell

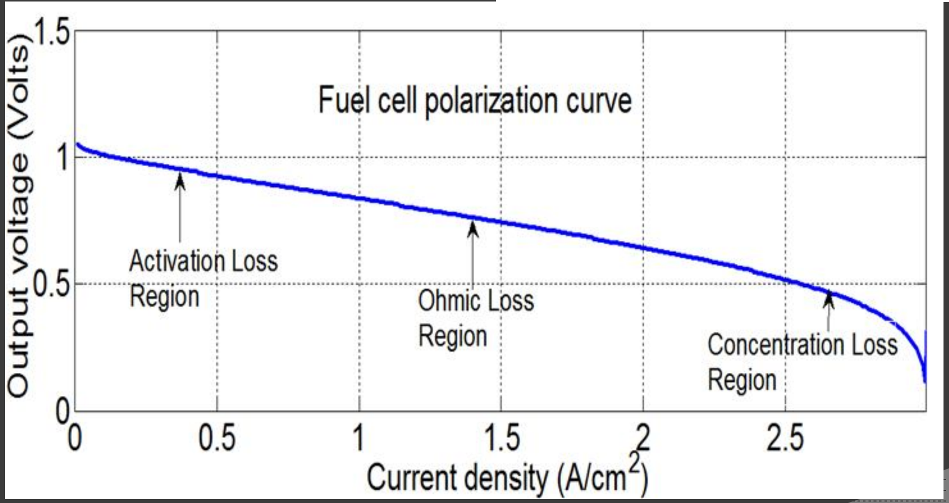
The major advantages of Fuel Cells are highlighted below:

- High energy conversion efficiency
- Modular design
- Cogeneration capability
- Rapid load response, relative to conventional power generation based prime movers
- Low environmental pollution and very low emissions
- Low noise
- High efficient power generation
- Reusability of exhaust heat
- Faster installation

V-I Characteristics of Fuel Cell

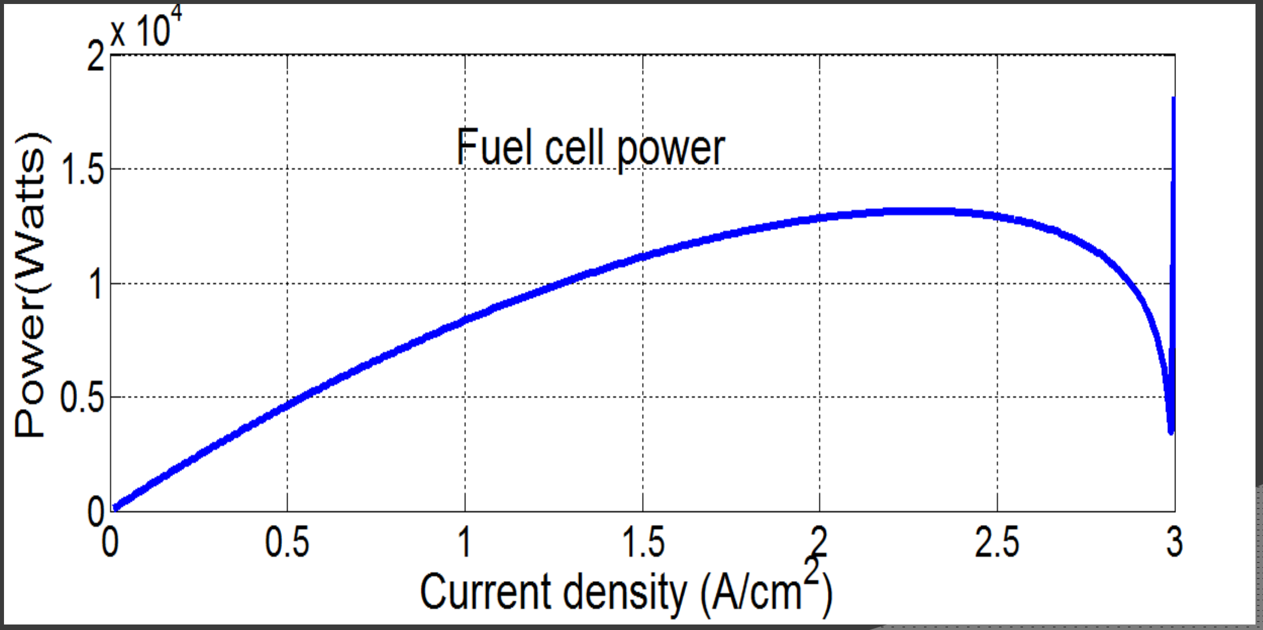






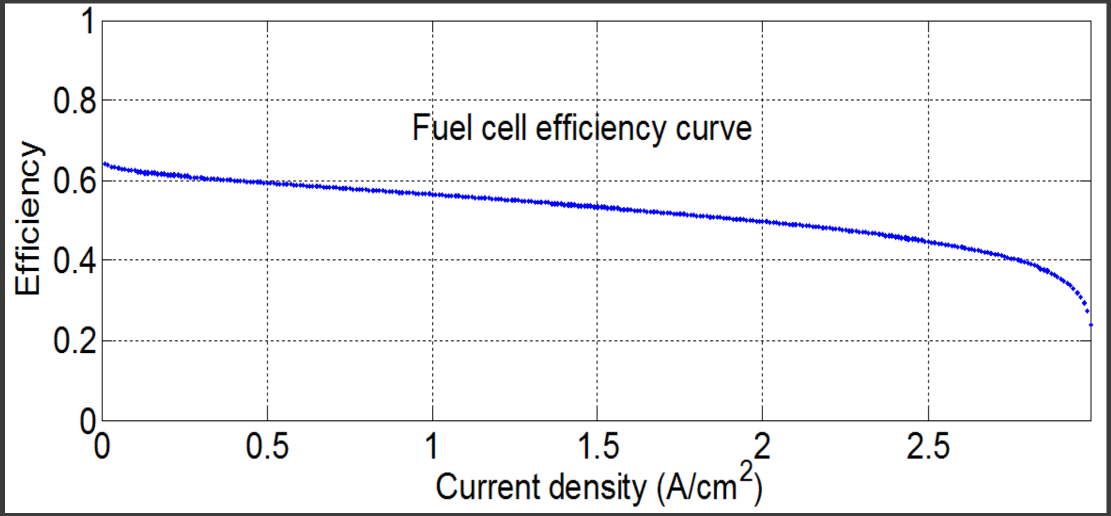
P-I Characteristics of Fuel Cell

- It is observed that the power output increases continuously with the increase in the value is attained, the power output falls rapidly due to the sudden increase in the ohmic and concentration (mass transportation) losses.



Efficiency of Fuel Cell

- The actual cell voltage is less than the ideal cell voltage because of the losses associated with cell polarization and the iR loss.
- The efficiency of the fuel cell can be written in terms of the actual cell voltage.

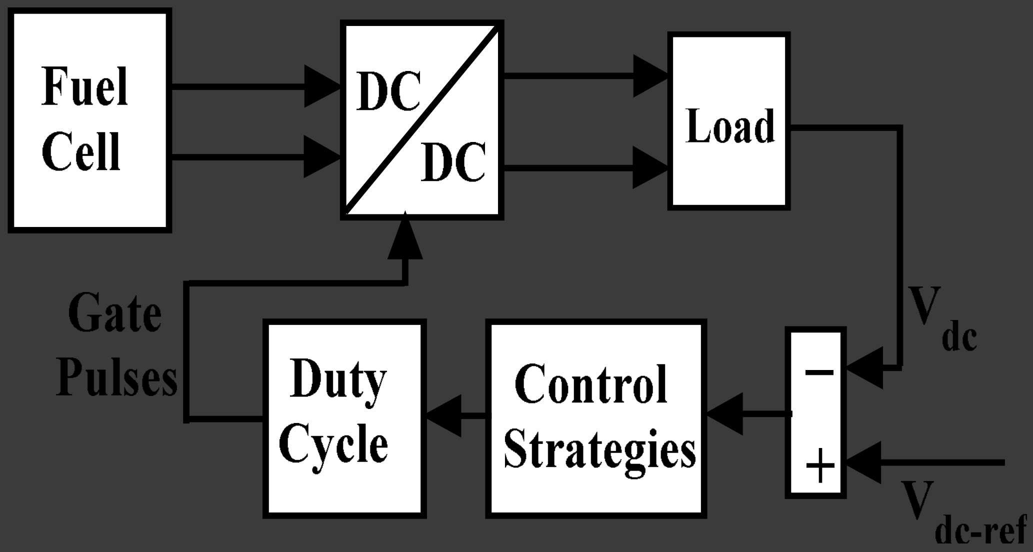


$$\eta = U_f \cdot \frac{V_{fc}}{1.48}$$

U_f is the utilisation factor and V_{fc} fuel cell output voltage.

- Fuel cells can convert high proportion of chemical energy in the form of fuel into DC electrical energy.
- It approaches the efficiency upto 60%, even without co-generation.
- Fuel cells contribute significantly to the cleaner environment. The by-products so produced are primarily hot water and carbon dioxide which are very small amounts.
- It has robust and modular structure. Due to their modularity, fuel cell can be placed near the load centres which results in a potential savings in transmission network expansion.

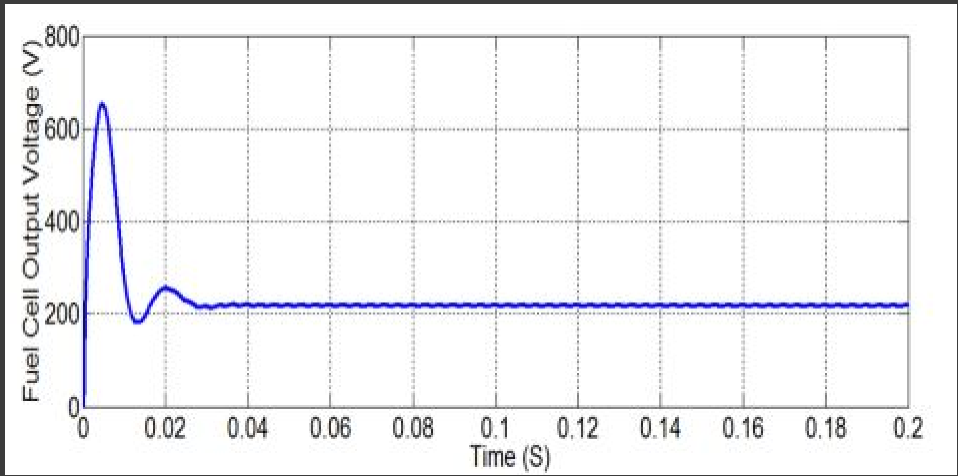
Fuel Cell With DC-DC Converter

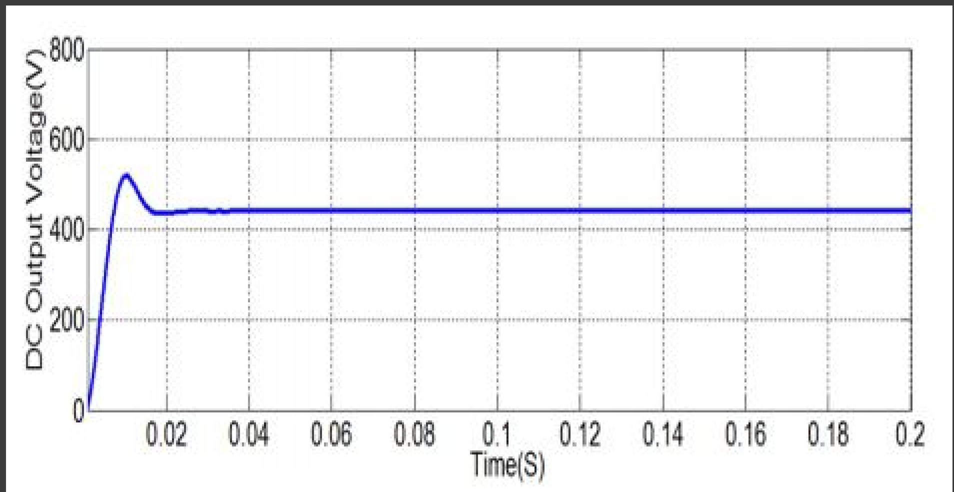


Different control strategy of DC-DC converter are simulated and analog and digital representation of controller are designed for experimental purpose.

- Voltage Mode Control
- Sliding Mode Control

Simulation Results

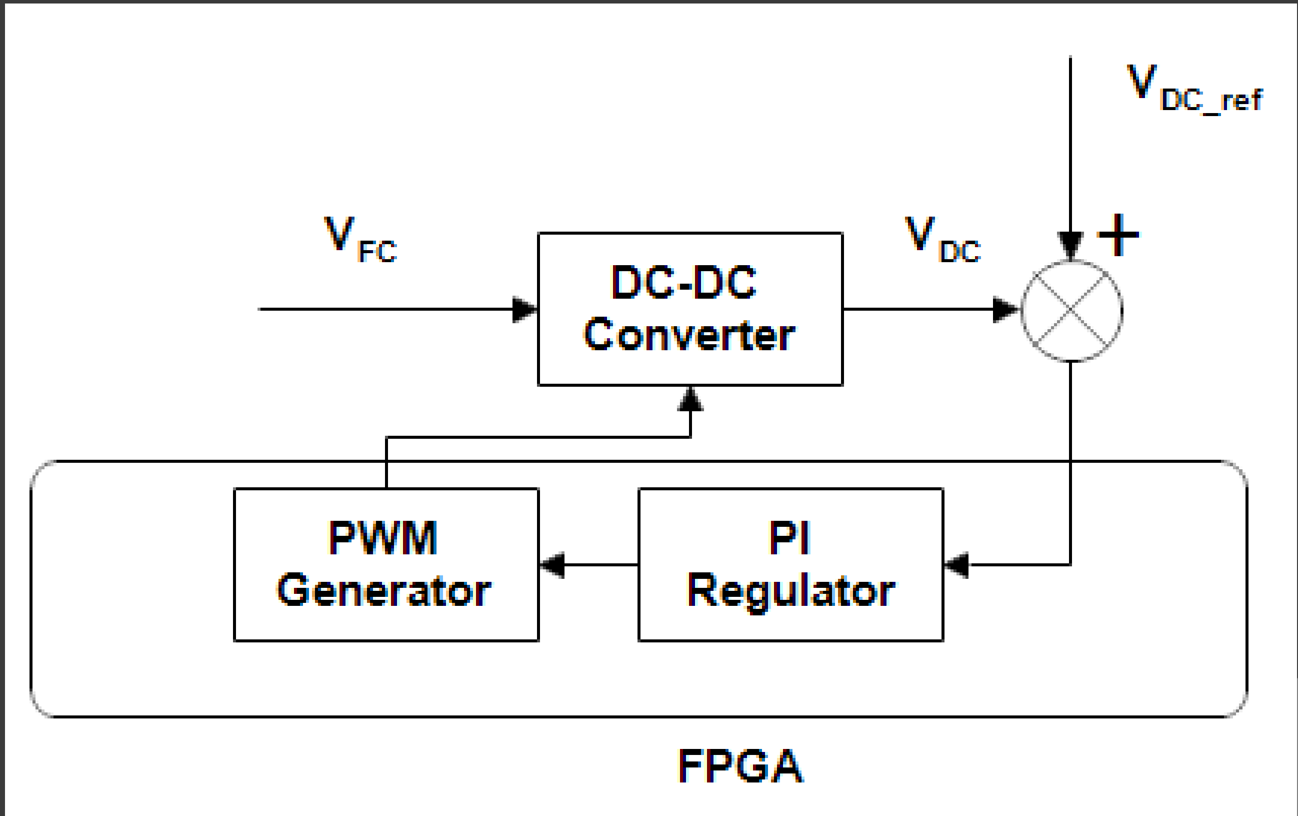




Parameters	Values
Voltage ripple	0.1%
Inductance: L	6 mH
Capacitance: C	1400 µF
Switching frequency : f_s	10 kHz
Desired DC output voltage	440 V

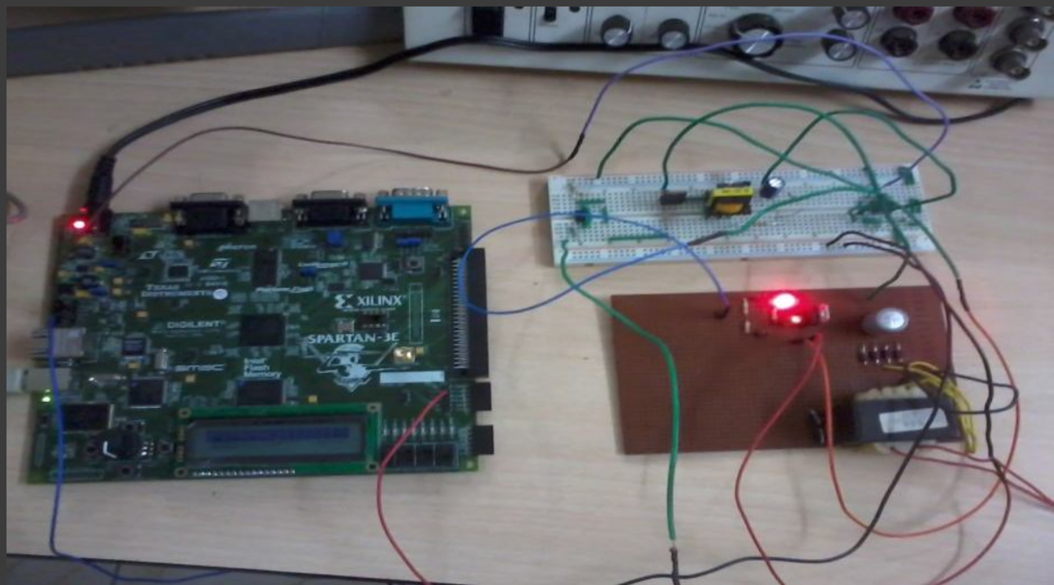
FPGA Implementation of PI Controller

- Fuel cell controller (PI in conjunction with PWM) is implemented in FPGA using VHDL.

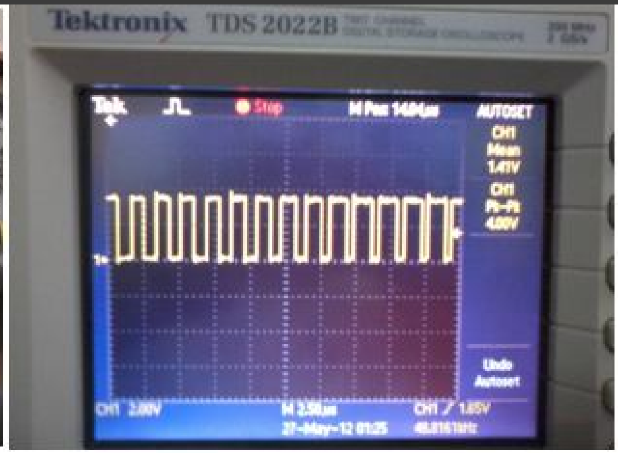


Prototype of Model DC-DC converter with FPGA based Controller

- Using PI modules, the error e(t) is minimised and PWM output is generated with its reference and output is taken from I/O pin F8 of XC3S500E board.
- Using opto-coupler (HCPL817), PWM signal is interfaced with the DC-DC converter. The opto-coupler provides isolation between the FPGA board and the power circuit.

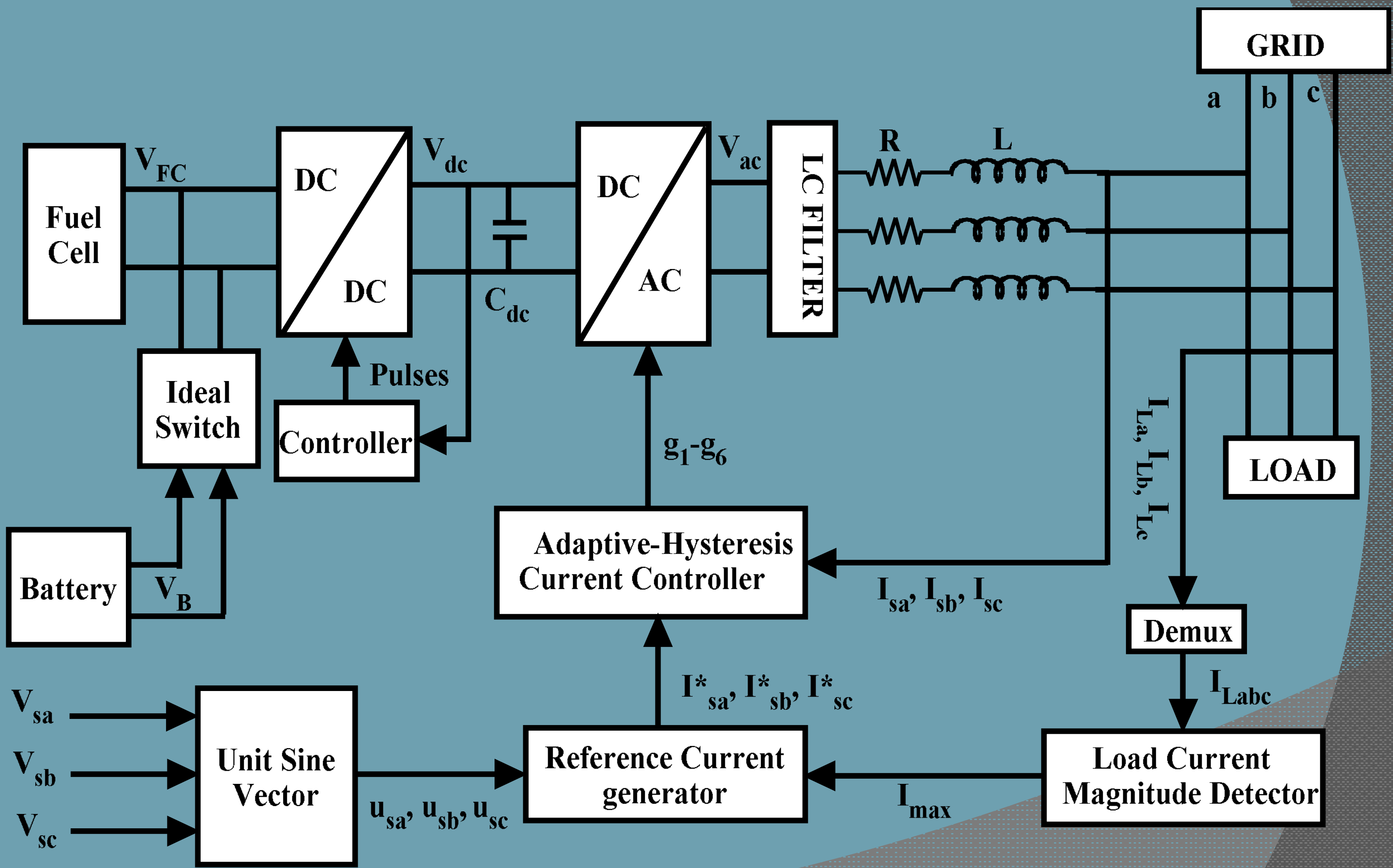


PWM switching pulse
with constant load



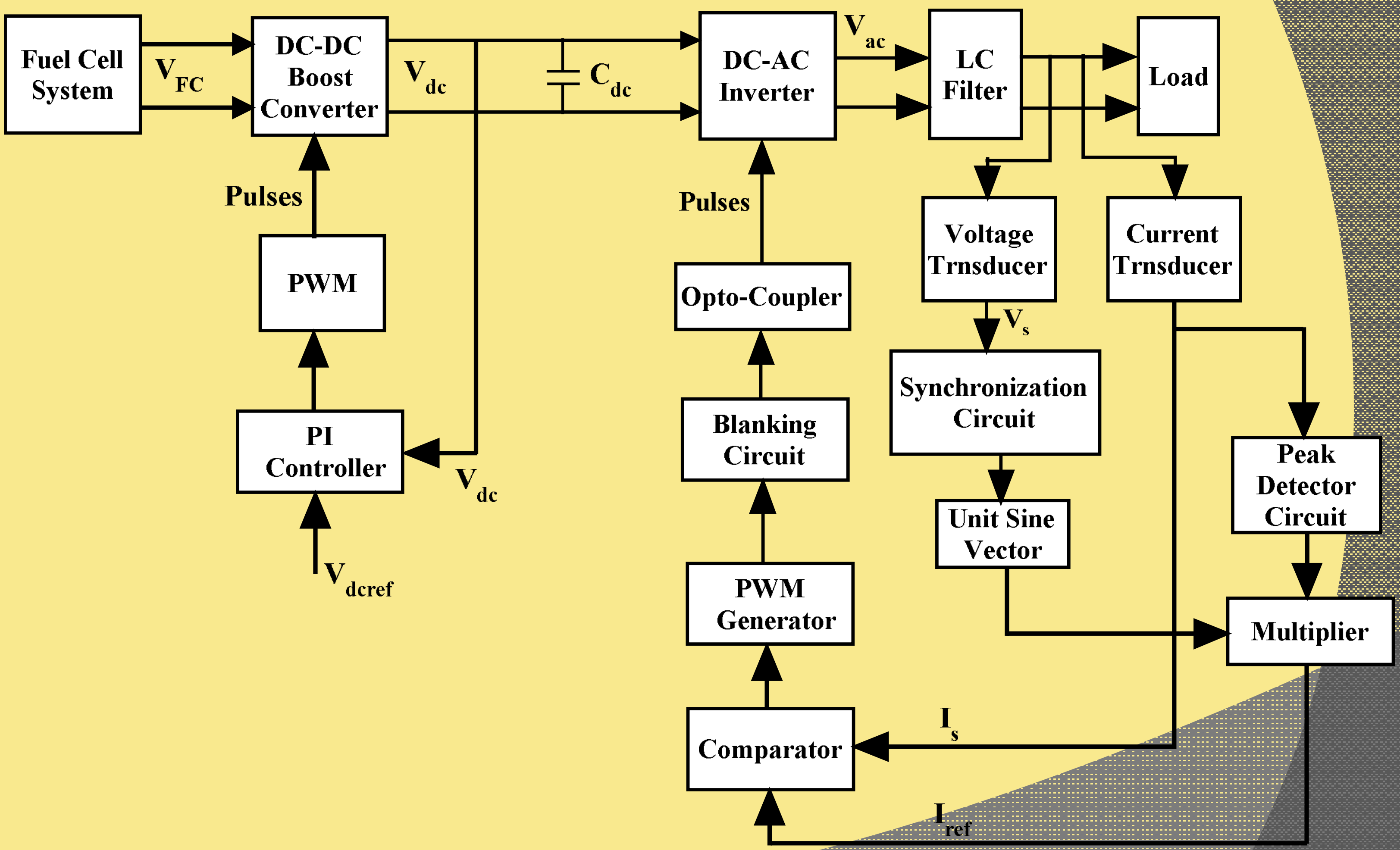
Duty cycle change with the
variation of load

Grid/Load Connected Fuel Cell Power System with Battery



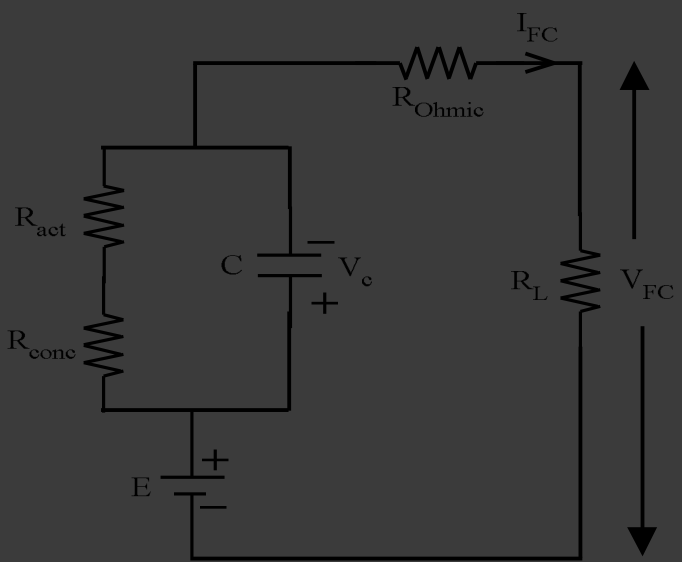
Simulation and Experimental Parameters

Parameters	Simulated Values	Experimental Values
Supply voltage/frequency	240 V / 50 Hz	154 V / 50 Hz
Resistor (R_L)	50 Ω	CFL Bulb (15 W)
Interface inductor (R_c, L_c)	1 Ω and 1.8 mH	5 mH
DC-link capacitance (C_{dc})	2200 µF	6800 µF
Reference voltage ($V_{dc, ref}$)	400 V	13 V
Voltage source inverter	--	SKM75GB063D IGBT module, TLP-250 for Gate driver circuit, Amplifier circuit, Separate Power supply for driver circuit.
Sensors	--	LEM make LV25-P for phase voltage, LA55-P for current transducer.
CCS for PC interface	--	XDS510PP JTAG Emulator

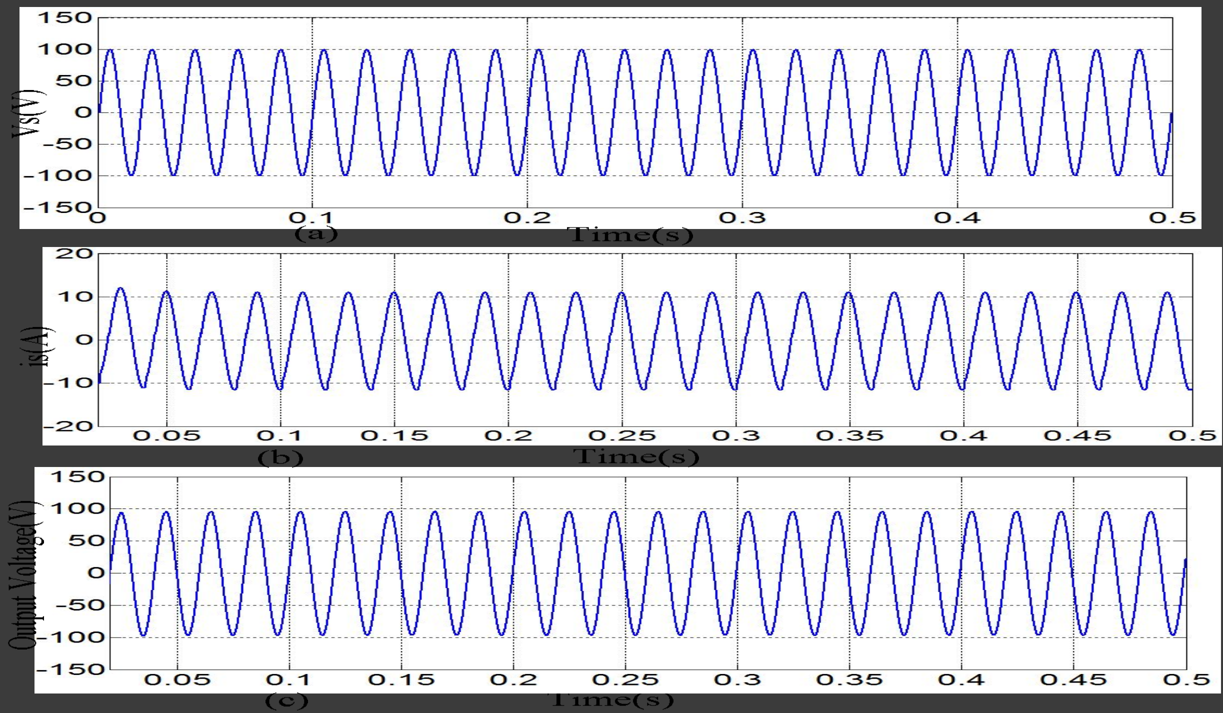


Fuel Cell System
V_{FC}
DC-DC Boost Converter
V_{dc}
C_{dc}
DC-AC Inverter
V_{ac}
LC Filter
Load
Pulses
PWM
PI Controller
V_{dc}
V_{dcref}
Pulses
Opto-Coupler
Blanking Circuit
PWM Generator
Comparator
Voltage Trnsducer
Current Trnsducer
V_s
Synchronization Circuit
Unit Sine Vector
Peak Detector Circuit
Multiplier
I_s
I_{ref}

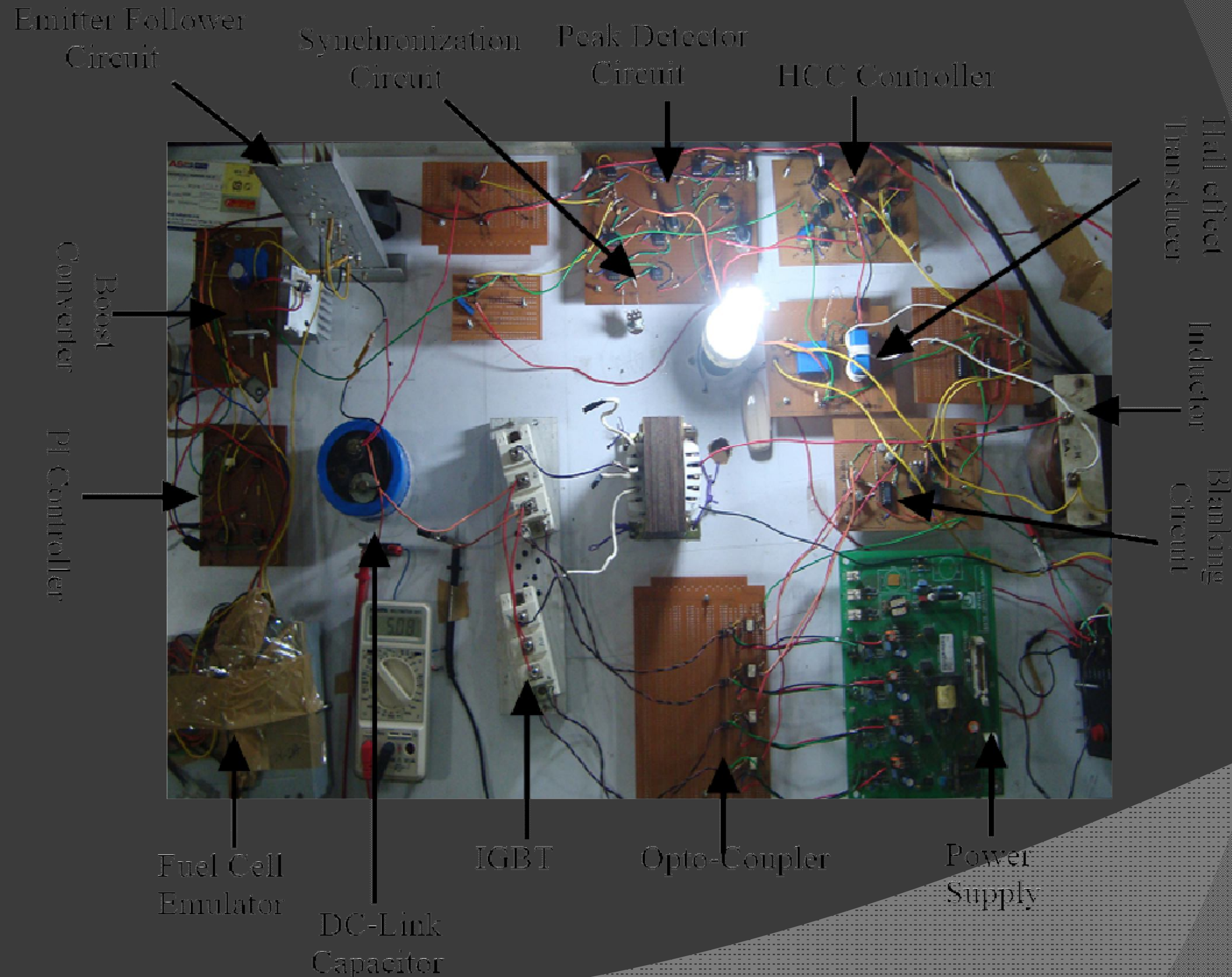
Electrical Equivalent Model of Fuel Cell



Simulation Results

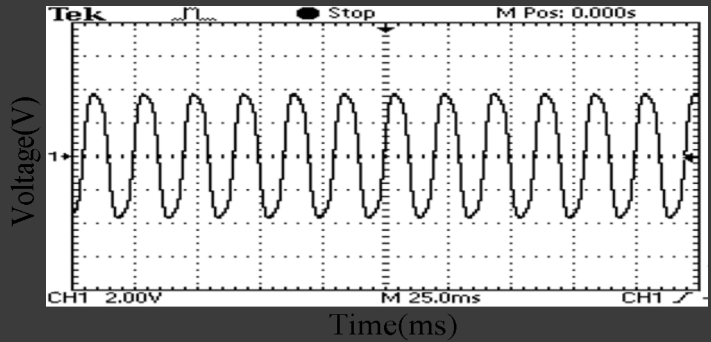


The waveform of the instantaneous single-phase balance supply voltage is shown in Fig.(a) and source current in Fig.(b).The simulation waveform of single phase inverter output is shown in Fig.(c) .

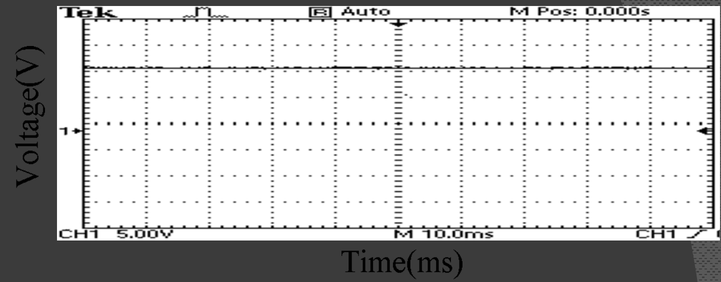


Emitter Follower Circuit
Synchronization Circuit
Peak Detector Circuit
HCC Controller
Hall effect Transducer
Boost Converter
Inductor
PI Controller
Blanking Circuit
Fuel Cell Emulator
DC-Link Capacitor
IGBT
Opto-Coupler
Power Supply

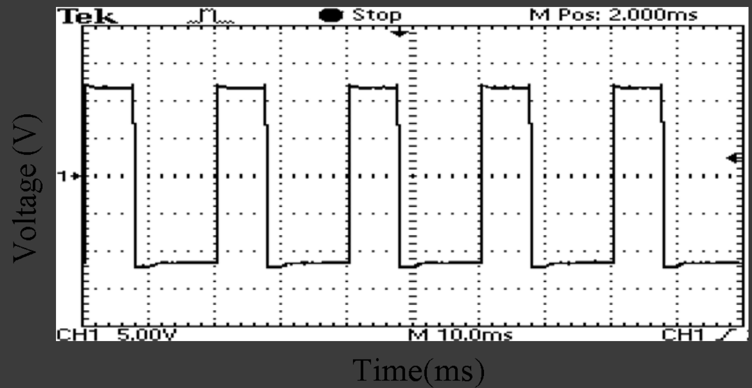
Experimental Results



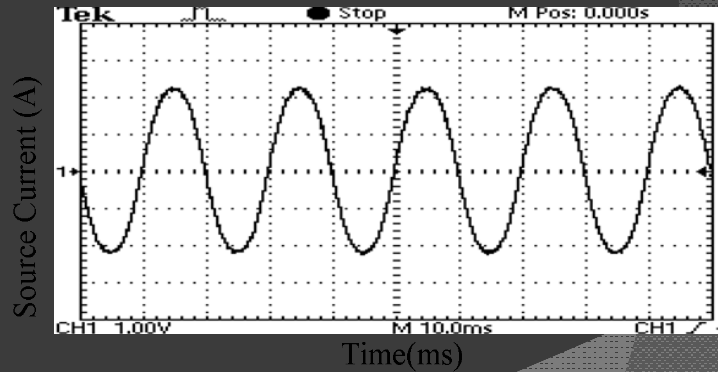
Waveforms of supply voltages



DC-link capacitor voltage

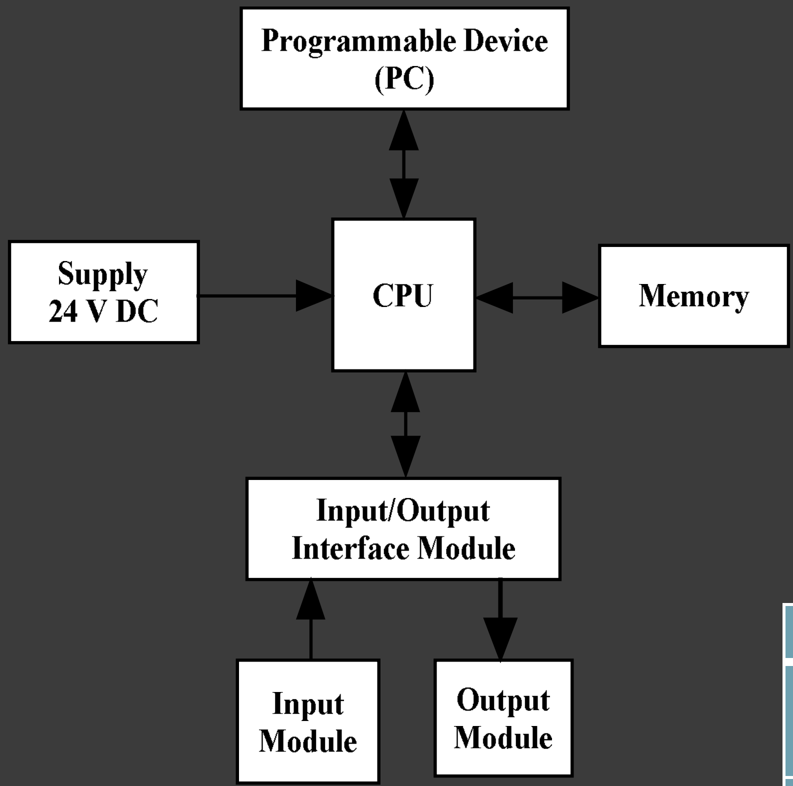


Inverter output before filter



Source Current

NI compactRIO-9014



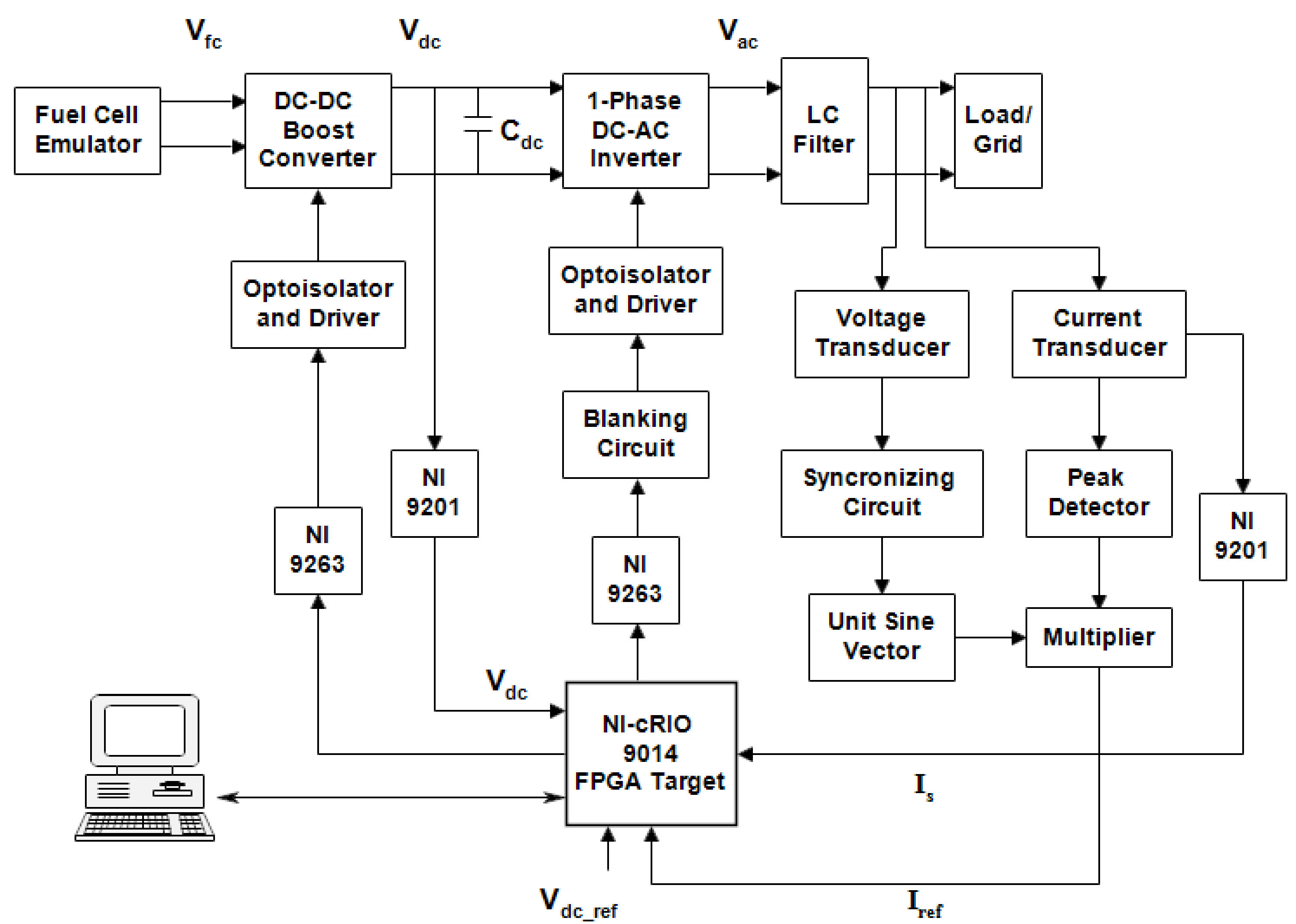
Block diagram of programmable controller

NI-compactRIO comprises of following modules:

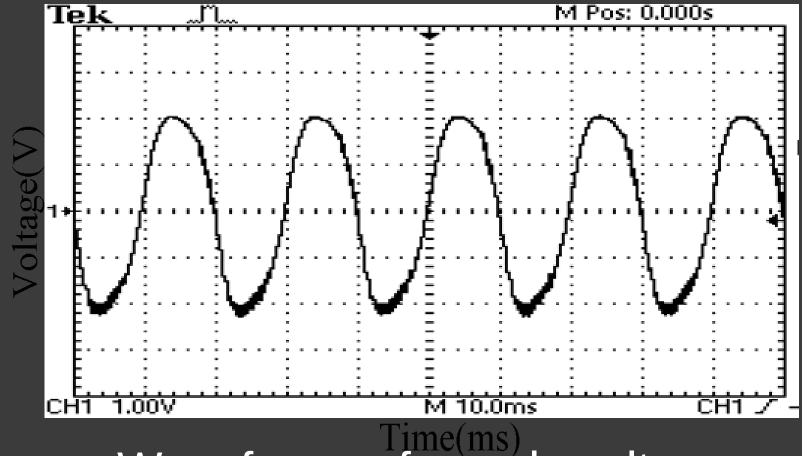
- 4 or 8-slots reconfigurable chassis
- Power supply
- Real time embedded processor
- Swappable industrial I/O modules

Slot	Module type	Description
	NI cRIO 9014	Real-Time Controller with 256 MB DRAM, 2 GB Storage
3	NI 9201	8-channel Analog Input Module
6	NI 9263	4-Channel, 100 kS/s, 16-bit, ±10 V, Analog Output Module

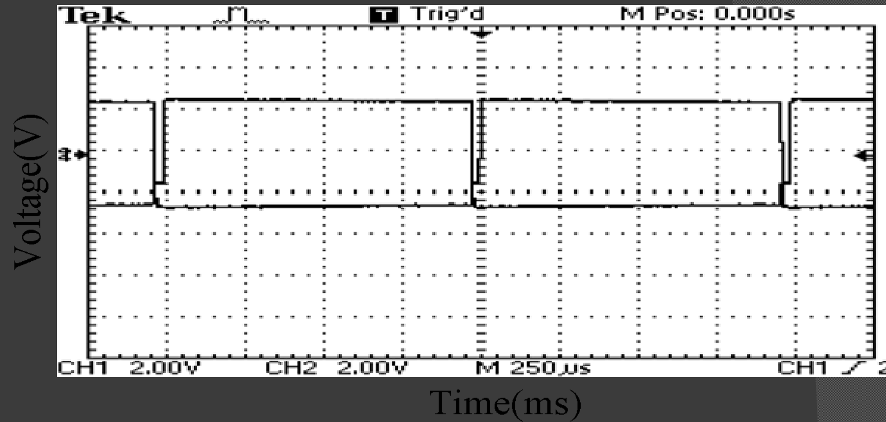
Hysteresis Current Control Using cRIO



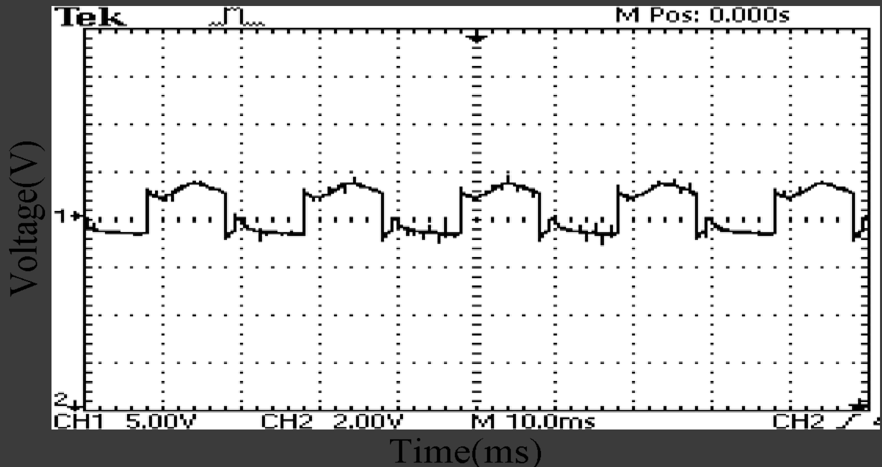
Experimental Results Using cRIO



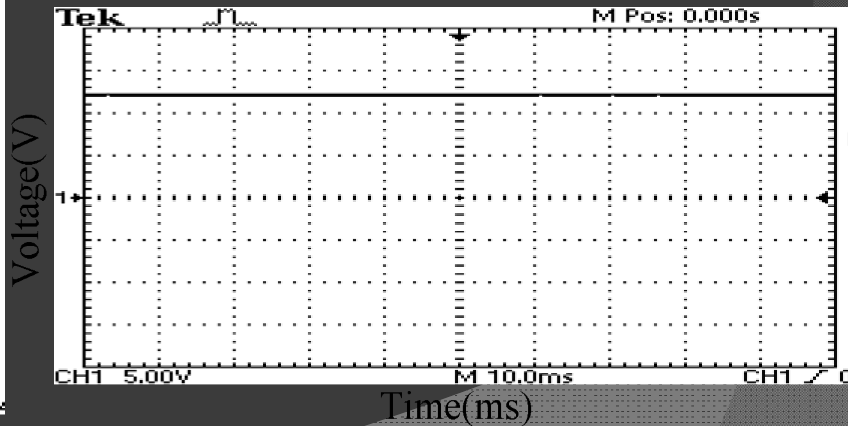
Waveforms of supply voltages



Delay waveform of blanking circuit



Inverter output before filter



DC-link capacitor voltage

Summary

- The single-phase fuel cell power system with HCC controller is experimentally validated.
- Hardware setup with hysteresis current controller is demonstrated. The result obtained from the experimental set up is presented.
- HCC technique reduces the switching power loses without compromising on performance.
- HCC technique for single phase fuel cell power system is implemented using National Instruments compactRIO-9014 and results are presented.
- FPGA based Adaptive-Fuzzy-HCC controller for three-phase fuel cell power system is designed and experimentally validated and results are presented.