# Power Balance Theory Control with Internal Model Controller Based Integrated Electronic Load Controller with Zig-Zag Transformer for Stand-Alone PEM Fuel Cell Feeding Three-Phase Four-Wire Non-Linear Load

Dipesh Kumar Karmakar [1] Laxman Dasari[1] N.G.S Raju [2]
1.M.Tech Student, EEE Department, GITAM University,Visakhapatnam, Andhra Pradesh-530045, INDIA
2.Assistant Professor, EEE Department, GITAM University,Visakhapatnam, Andhra Pradesh-530045, INDIA

**Abstract**
Fuel cell (FC) power generation has drawn attention to supply electricity to rural areas because of its portability, self- sustainability, high potential capability, modularity, environment friendliness, easy maintainence and less weight. This paper presents stand-alone Proton exchange membrane fuel cell (PEMFC) generating system with DC-DC boost converter, Integrated electronic load controller (IELC) feeding three-phase four-wire non-linear loads. The DC-DC boost converter contributes to the overall system electrical efficiency. The power balance theory (PBT) with internal model controller (IMC) is applied to estimate the reference load current to control the six-leg voltage source converter (VSC). The IELC is realized with zig-zag/three single-phase transformer and a six-leg insulated-gate bipolar-transistor-based current-controlled voltage source converter, a chopper switch and auxiliary load on DC bus. The fuel cell power generating system is modeled and simulated in MATLAB environment using Simulink and sim power system (SPS).
**Keywords**:Fuel cell (FC), Proton exchange membrane fuel cell (PEMFC), Power balance theory(PBT),Internal Model Controller(IMC), Integrated electronic load controller (IELC), Voltage source converter(VSC).

## I. Introduction

Energy is the most important necessity in today's world, its need is escalating , if emphasis is laid on the non-renewable energy generation in large scale then sustaining the growing energy demand is possible. The PEMFC is one safe, clean, economical, better technical efficiency and environmental friendly technique to address the growing load demands in a sustainable manner [1].

The fuel cell is electro-chemical instrument which derives DC electrical energy via electrochemical reaction between its anode and cathode. Among five various types of fuel cell, PEMFC is drawing the most attention because of its high energy density, simplicity, viability, quick start-up, simple structure, they produce water as residue, they operate at low temperature, they have high efficiency when compare to thermal generations, they employ solid polymer as electrolyte which requires less safety measures. The PEMFCs are being rapidly developed for both stand-alone as well as grid connected applications. The PEMFCs use hydrogen and oxygen as input fuel and generate dc power. The cell voltage decreases linearly as the load current increases. Therefore, the output voltage must be adjusted to an optimum value. To maintain the polarization characteristics at expected level, additional parameters such as cell temperature, air pressure, oxygen partial pressure and membrane humidity also needs to be taken into consideration. Power conditioning unit, it is necessary for FC based systems to condition its output dc voltage. It converts the dc voltage to ac voltage. The FC source is associated to the load or grid via inverter which must be properly interfaced with the grid in terms of voltage and frequency [7]. The DC bus voltage of the voltage source converter of integrated electronic load controller is less sensitive to load perturbation. The PBT based control of the proposed system is applied to derive the reference load currents to get power quality improvement [8][9]. The six-leg voltage source converter operates as harmonic eliminator and load balancer. The zigzag transformer eliminates zero-sequence currents and triplen harmonics in the primary winding itself by keeping the secondary winding free from triplen harmonics and zero-sequence currents. thereby reducing device rating of voltage source controller. This scheme is simulated under the MATLAB environment using simulink and power system blockset toolboxes, and the results are verified by implementation of control scheme. The performance of the proposed scheme is demonstrated through simulation results.

## II. Description of Fuel Cell

### A. *Reaction Process of PEMFC*

Proton exchange membrane fuel cell is such an equipment that converts hydrogen and oxygen to electricity via electro-chemical reaction[1]. The hydrogen in the anode release electrons and become hydrogen protons. The proton exchange membrane allows only proton to pass through, so the electrons is collected by external circuit and generate electric current. In the cathode, Protons combine with oxygen and form water [2].

$$2H_2 + O_2 = 2H_2O \quad (1)$$

*B. **Overview and Assumption***

The assumptions is made in this model

- Ideal and uniform distribution of gas.
- The gas is present in required amount for the high flow rate.
- Constant temperature in the fuel cell
- Parameter for individual cells can be lumped together to represent a fuel cell.

The model can be put into four parts

1. The circuits for internal potential (E)
2. The ohmic voltage drop (Vhom)
3. Activation loss (Vact)
4. Concentration voltage drop (Vcon).

A fuel cell output voltage is the function of the for part as shown in (2)

Vcell = E − Vhom − Vact – Vcon (2)

C. Equivalent Circuit for Internal Potential

According to Nernst Equation, a fuel cell systems internal potential is a function of PH2 , PO2 and PH2O2 as expressed in (3).

E = N[V0 + (RT/2F) ln(PH2 √PO2/PH2O2 )] (3)

N is the numbers of the fuel cell. V0 represents the reference potential at a standard state. PH2 is the H2 pressure in Anode. PO2 and PH2O2 is the oxygen and water pressure in the cathode.

*C. **Equivalent Circuit for The Activation Loss***

Activation polarization is due to the slow rate of reaction taking place in the cell. It differs depending upon the nature of the electrode, ionic interaction, ion-solvent interaction, and the electrode-electrolyte interface. The activation voltage is the addition of Vact1 and Vact2. Vact1 depends on temperature. Vact2 depends on load current as well as temperature. Vact1 expressed in (4), and Vact1 expressed in (5)

Vact1 = η0 + f(T) (4)

Vact2 = I・ f2(I, T) (5)

*D. **Equivalent Circuit for Ohmic Voltage Drop***

Ohmic polarization is engendered by the resistance of the polymer membrane to the transfer of protons and the resistance of the electrode and collector plates to the transfer of electrons. Expressed as (6).

Vohm = N・ I・ Rohm (6)

*E. **Equivalent Circuit for Concentration Voltage Drop***

Concentration polarization is caused by gas concentration changes at the surface of the electrodes. Concentration gradients can form during the reaction process; This is cause by mass diffusion from the gas flow channels to the reaction sites. Concentration voltage drop is expressed in the follow formula.

Vcon = N * m exp (n * I) (7)

Many attempts have been undertaken to develop and simplify mathematical model defining the behavior of a PEMFC. An accurate model can be obtained modifying equation and substituting the values of the different losses. This results in equation (8):

$V_{FC} = E_{rev} – (2.3*RT/ \alpha nF)\ln(I_{FC}/I_0) - R_{int}*I_{FC} – (RT/nF)\ln(1-I_{FC}/I_l)$ (8)

Where the different parameters are:

R = Universal gas constant (8.31451 J/(mol. K)),

F = Faraday's constant (96485 Coulomb/mol),

T = Stack temperature,

α = Transfer coefficient,

n = Number of electrons involved in the reaction,

$R_{int}$ =Sum of electrical and photonic resistances,

FC I =Fuel cell current,

0 I =Exchange current,

I =Limiting current of the fuel cell.

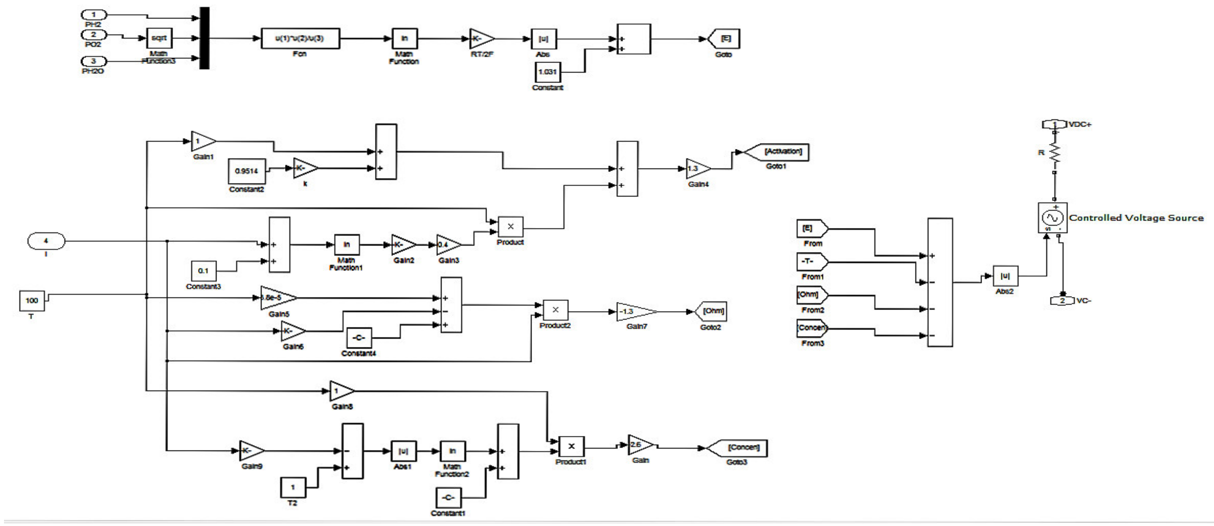



Fig. 1. Simulink Model of PEMFC

## III. Control Stratergy

The basic equations of this control algorithm are as follows

A. In-phase component of reference source currents

$$V_t = \{(2/3)\,(V_{sa}^2+V_{sb}^2+V_{sc}^2)\}^{1/2} \quad (9)$$

Where, $V_{sa}$, $V_{sb}$, $V_{sc}$ are the three phase voltages at load terminals.
The unit vector in phase with $v_a, v_b, v_c$ is calculated as

$$u_{sa} = v_a/V_t \quad u_{sb} = v_b/V_t \quad u_{sc} = v_c/V_t \quad (10)$$

Where, $u_{sa}$ , $u_{sb}$ , $u_{sc}$ are unit vector in phase.
The instantaneous active power of the consumer loads is derived as

$$P_L = (V_{sa}\, i_{La} + V_{sb}\, i_{Lb} + V_{sc}\, i_{Lc}) \quad (11)$$

The amplitude of the fundamental active power component of the load current is calculated as

$$I_{Lactive} = (2/3)(P_L/V_t) \quad (12)$$

The error in the dc bus voltage of the voltage source converter ($V_{dcer(n)}$) of the integrated electronic load controller at *n*th sampling instant is

$$V_{dcer(n)} = V^*_{dc(n)} - V_{dc(n)} \quad (13)$$

Where,
$V^*_{dc(n)}$ is the reference dc voltage
$V_{dc(n)}$ is the sensed dc-link voltage
The output of the internal model controller (IMC) [14] for maintaining the dc bus voltage of the voltage source controller of the integrated electronic load controller

$I_{loss(n)}$ = Output of internal model controller (IMC) (14)

Where $I_{loss(n)}$ is considered as part of the active-power component of the source current
Therefore, total an active power component of the load currents ($I^*_{active}$) and is calculated by adding to the DC component ($I_{Lactive}$) of the load currents and output DC link voltage controller, $I_{loss(n)}$

$$I^*_{active} = I_{Lactive} + I_{loss} \quad (15)$$

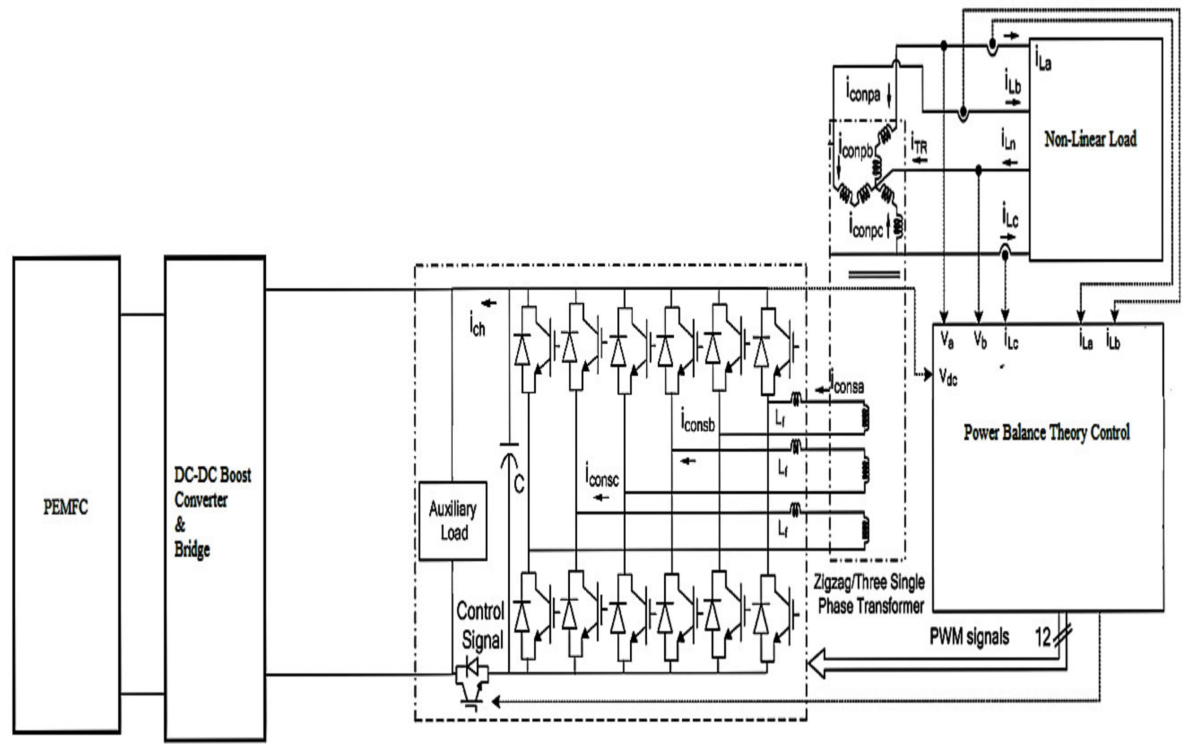



Fig. 2.Schematic configuration of PEMFC with DC-DC Boost converter and IELC

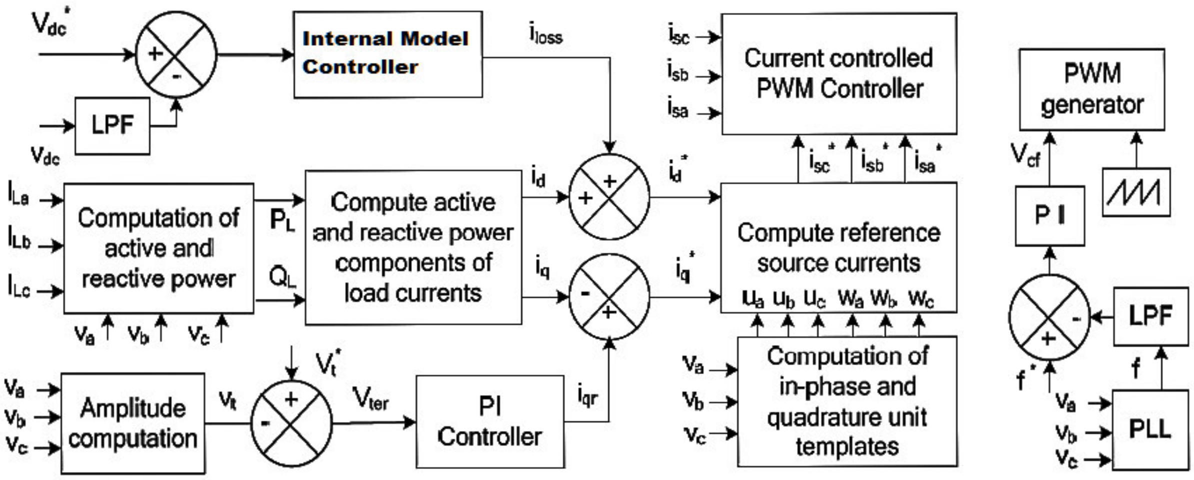



Fig.3. Power Balance Theory Control Algorithm

The fundamental components active-power of the reference instantaneous load currents in phase with PCC voltages are derived as,

$I^*_{sad} = I^*_{active} * u_{sa}$ $\quad I^*_{sbd} = I^*_{active} * u_{sb}$ $\quad I^*_{scd} = I^*_{active} * u_{sc}$ (16)

B. Quadrature Components of Reference Source Currents

The unit vector in quadrature with $v_a, v_b, v_c$ are derived using quadrature transformation of the in-phase unit vectors $u_{sa}$, $u_{sb}$, $u_{sc.}$

$$w_{sa} = -u_{sb}/\sqrt{3} + u_{sc}/\sqrt{3} \quad (17)$$

$$w_{sb} = \sqrt{3}\, u_{sa}/2 + (u_{sb} - u_{sc})/2\sqrt{3} \quad (18)$$

$$w_{sc} = -\sqrt{3}\, u_{sa}/2 + (u_{sb} - u_{sc})/2\sqrt{3} \quad (19)$$

The PI voltage controller is used to regulate the PCC voltage. The amplitude of terminal voltage ($V_t$) is derived in eq(9) and reference value ($V_{ref}$) is fed to the PI voltage controller. The voltage error is derived as,

$$V_{er(t)} = V^*_{tref(t)} - V_{t(t)} \quad (20)$$

The output of the PI controller, $I^*_{qr(n)}$ for maintaining the AC terminal voltage to a constant value at the $n^{th}$ instant is,

$$I^*_{qr(n)} = I^*_{qr(n-1)} + K_{pa}\{V_{er(n)} - V_{er(n-1)}\} + K_{ia} V_{er(n)} \quad (21)$$

Where,

$K_{pa}$ and $K_{ia}$ are the proportional and integral gain constants of the PI controller

$V_{er(n)}$ and $V_{er(n-1)}$ are the error in voltages of *n*th and (*n*-1)th instants.

$I^*_{qr(n-1)}$ is the amplitude of the quadrature component of the reference fundamental current at (*n*-1)th instant.

The instantaneous reactive power of the consumer load is derived as

$$Q_L = (1/3)\{(v_{sa} - v_{sb})i_{La} + (v_{sb}-v_{sc})i_{Lb} + (v_{sc}-v_{sa})i_{Lc}\} \quad (22)$$

This instantaneous reactive power consists of both DC and AC components.

The amplitude of fundamental reactive power of the load current is given by

$$I_{Lreactive} = (2/3)(Q_L/V_t) \quad (23)$$

The instantaneous quadrature component of the reference load currents are derived as,

$$I^*_{sad} = I^*_{active} * w_{sa},\ I^*_{sbd} = I^*_{active} * w_{sb},\ I^*_{scd} = I^*_{active} * w_{sc} \quad (24)$$

C. Reference source currents

The total reference source currents are the sum of the in-phase and the quadrature components of the reference source currents as

$$i^*_{sa} = i^*_{sad} + i^*_{saq} \quad (25)$$

$$i^*_{sb} = i^*_{sbd} + i^*_{sbq} \quad (26)$$

$$i^*_{sc} = i^*_{scd} + i^*_{scq} \quad (27)$$

These amplified current-error signals are compared with fixed-frequency (10-kHz) triangular wave to generate unipolar PWM switching signals to generate the gating signals for the six-leg VSC (each phase consists of three H-bridge VSCs) of the IELC. For switching on the H-bridge VSC of phase “a,” the basic logic is

$V_{cca} > V_{tri}$ (upper device of the left leg of phase a on)

$V_{cca} \le V_{tri}$ (lower device of the left leg of phase a on) (28)

$-V_{cca} > V_{tri}$ (upper device of the left leg of phase a on)

$-V_{cca} \le V_{tri}$ (lower device of the left leg of phase a on) (29)

Where, $V_{tri}$ is taken as the instantaneous value of the fixed- frequency triangular wave, and a similar logic is applied to generate the gating signals for the other two phases.

D. Chopper PWM Controller

The frequency error of the three-phase voltages at load terminal is defined as

$$f_{er}(n) = f^*_{(n)} - f_{(n)} \quad (30)$$

Where, f* is the reference frequency (50 Hz in the present system) and “f” is the frequency of the load voltage. The instantaneous value of *f* is estimated using the phase-locked loop over the ac terminal voltages ($v_a$, $v_b$, and $v_c$), as shown in Fig. 3.

At the *n*th sampling instant, the output of the frequency PI controller is

$$V_{cf}(n) = V_{cf(n-1)} + K_{pf}\{f_{re(n)} - f_{re(n-1)}\} + K_{if} f_{re(n)} \quad (31)$$

This output of the frequency controller $V_{cf(n)}$ is compared with the fixed-frequency triangular carrier wave (3 kHz in this case) to generate the gating signal of the insulated-gate bipolar transistor (IGBT) of the chopper of integrated electronic load controller.

## IV. MATLAB BASED MODELING

The load interface PEMFC power generating system is modeled using MATLAB/Simulink. The three-phase four wire non-linear load is connected to six- leg voltage source converter VSC through zigzag transformer along with PEMFC is simulated in MATLAB as shown in fig(2). The control algorithm for the power balance theory with internal model controller is also modeled in MATLAB. Three-phase reference non-linear load currents are derived from the measured PCC voltages ($V_{sa}$,$V_{sb}$,$V_{sc}$) and load currents ($I_{Lsa}$,$I_{Lsb}$,$I_{Lsc}$) and DC link voltage of the chopper ($V_{dc}$). The simulation of the proposed system is carried out on the MATLAB version 7.9.0 (R2009b) using the sim power system (SPS) toolbox and discrete step solver of 5e-6.

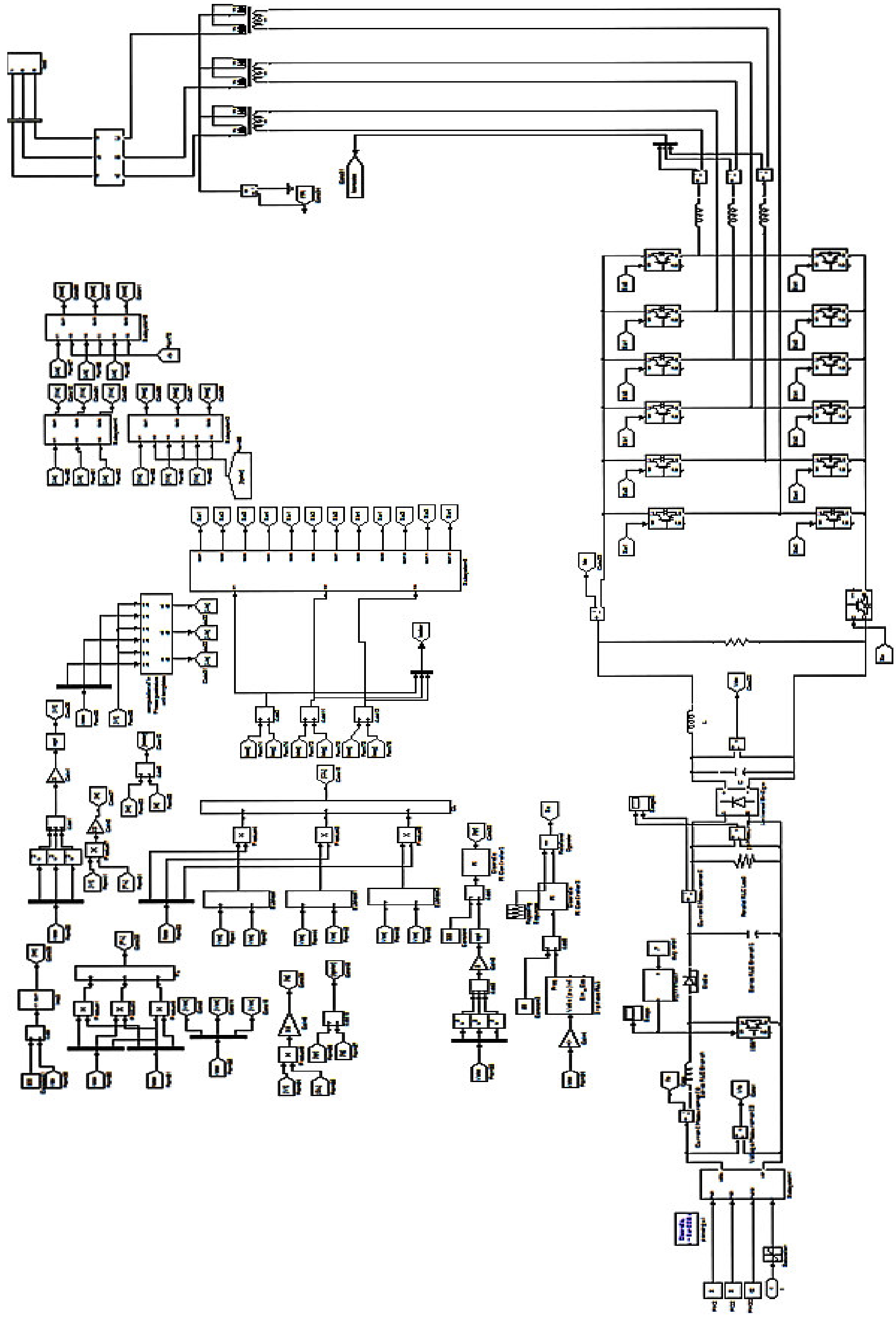
## V. RESULTS AND DISCUSSION

Simulation results of the PEMFC power generating system is shown in Fig.4a-4b. The PEM Fuel cell power generating system is controlled by power balance theory (PBT) for non-linear loads. Performance of the proposed system is represented in terms of fuel cell voltage ($V_{FC}$), DC bus voltage ($V_{dc}$) , DC bus current

($I_{dc}$),load current ($I_{labc}$), active (P)and reactive (Q) power, Fuel cell power ($P_{FC}$), Fuel cell current($I_{FC}$), load voltage ($V_{labc}$).

**MATLAB IMPLEMENTATION**



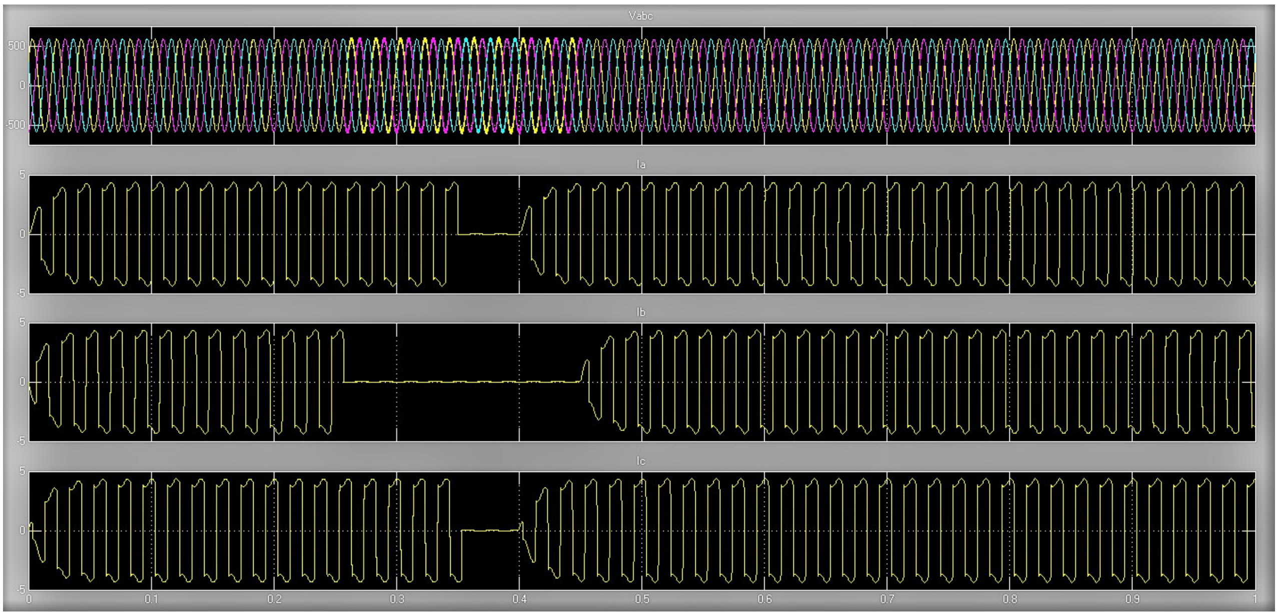


Fig. 4(a). Performance of the proposed system for non-linear load

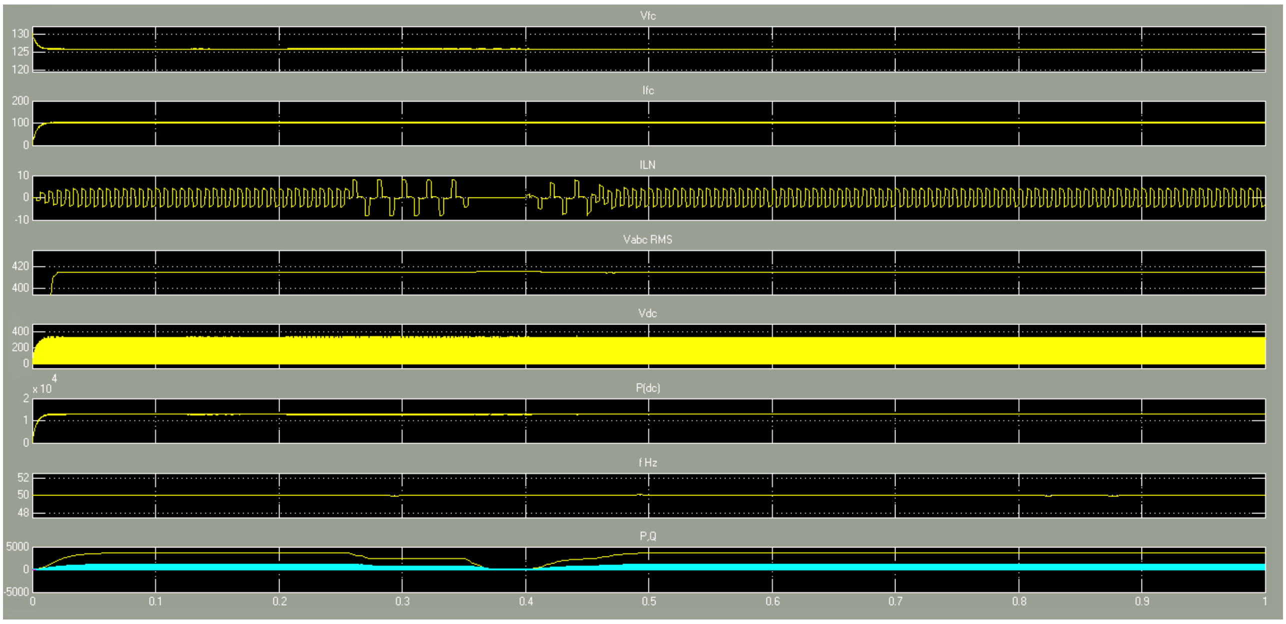



Fig. 4(b). Performance of the proposed system for non-linear load

## VI. Conclusion

The stand-alone PEMFC is modelled and simulated, its operation with power balance theory with internal model controller based control algorithm of an integrated electronic load controller is observed. The performance of the proposed system is studied under non-linear loading condition. It was observed that the system performance is satisfactory with proposed integrated electronic load controller employing PBT with IMC based control algorithm. This controller is simple to operate, easy to design and less sensitive to load perturbation.

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## BIBILOGRAPHY

**Dipesh Kumar Karmakar** born in 1991, in India. He received B-Tech degree in Electrical& Electronics Engineering from ANITS, ANDHRA UNIVERSITY, Andhra Pradesh, India in 2013. Currently he is a 2nd year M.Tech student at GITAM University in Power Systems & Automation (2014-2016). His research interest includes Applications of Power Electronics to Power Systems, Power Quality, Power System Operation & Control, Power System Stability & Analysis.

Laxamn Dasari born in 1991, in India. He received B-Tech degree in Electrical& Electronics Engineering Chaitanya engineering college, JNTUK, Andhra pradesh, India in 2012. Currently he is a 2nd year M-Tech student at GITAM University in Power Systems & Automation (2014-2016). His research interest includes Applications of Custom power devices to mitigate power quality problems.

N.G.S RAJU born in 1980, in India. He received B.E degree in Electrical & Electronics Engineering from College of Engineering, GITAM, ANDHRA UNIVERSITY, Andhra Pradesh, India in 2001 and M-Tech degree from College of Engineering, JNTU,Kakinada in High Voltage Engineering in 2008. Currently he is working as an Assistant Professor in GITAM Univeristy