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Analysis of a High Efficiency Boost-Inverter with Back-up Battery Storage in Fuel Cell

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Abstract:- This paper, proposes an analysis and design of a high efficiency boost-inverter with bidirectional back-up battery storage in fuel cell. When low-voltage unregulated fuel cell (FC) output is conditioned to generate AC power, two stages are required: a boost stage and an inversion one. In this paper, the boost-inverter topology that achieves both boosting and inversion functions in a single-stage is used to develop an FC-based energy system which offers high conversion efficiency, low-cost and compactness. The proposed system incorporates additional battery-based energy storage and a DC-DC bi-directional converter to support instantaneous load changes. The output voltage of the boost-inverter is voltage-mode controlled and the DC-DC bidirectional converter is current-mode controlled. The load low frequency current ripple is supplied by the battery which minimizes the effects of such ripple being drawn directly from the FC itself. Analysis, simulation results are presented to confirm the operational performance of the proposed system.

Keywords:- AC power, Boost inverter, Efficiency, Energy, Fuel cell

I. INTRODUCTION

In general, renewable energy systems based on Photo voltaic (PV) and fuel cell (FC) generation sources need to be regulated and in many applications must be supported through additional energy storage unit to achieve high quality supply of power [1] - [3]. When such systems are used to power AC loads or be connected with the electricity grid, an inversion stage is also required.

The typical output of any FC is low and variable DC voltage with respect to the load current. For instance, based on the current-voltage characteristics of a Proton Exchange Membrane FC (PEMFC) power module, the voltage varies between 26 to 43 VDC depending upon the level of the output current [5], [6]. Moreover, the slow response due to the natural electrochemical reactions required for the balance of enthalpy must be taken into account when designing the FC converter system [6], [7]. This is especially crucial, 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 demanded power to the load but also shut down or be damaged [6], [8]-[11]. For instance, when a load is added specific problems were founded such as fuel starvation phenomenon and slow increased oxygen flow for about 0.8s [10]. Therefore, the power converter needs to ensure that the demanded power remains within the limit of the maximum availability [10], [11].

A two-stage fuel cell power conditioning system to deliver AC power has been commonly considered and studied in many technical papers [2], [3], [8]-[14]. The system usually includes transformer type DC-DC boost converter stage and DC to AC inverter stage with auxiliary energy unit in Fig. 1 [8], [13], [14]. This type of power conditioning system has inevitable drawbacks such as being bulky, costly and inefficient because it actually has three power conversion stages (DC to high-frequency AC, then DC and low frequency AC) [3].

In order to minimize the problems with a two-stage fuel cell power conditioning system, a topology with reduced power processing and conversion stages is required. 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 [13]-[15]. The double loop control scheme of this topology has also been proposed for better performance even during transient conditions [14]-[15].

However, if such topology was to be used for an AC load to be powered by an FC, the FC would be exposed to a number of problems such as load variation, slow respond and current ripple. In this case, an energy storage back-up unit would be required to address the previously mentioned problems. The paper is organized in the following way. In Section II, the proposed FC energy system is introduced including the converter topology and the control algorithm of the boost inverter as well as the back-up unit and its power converter design. In Section III, analysis and simulation results are presented to validate the performance of the system.

II. PROPOSED FUEL CELL ENERGY SYSTEM

1. Description of the FC energy system

The objective of this paper is to propose an FC energy system with the lowest possible energy conversion stages. In particular, the proposed system, based on the boost-inverter with a back-up energy storage unit, solves the previously mentioned problems, i.e., the low and variable output voltage of the FC and its slow response. The boost-inverter utilizes two identical bi-directional boost converters and delivers in a single-stage boosting and inversion functions. This result in a high power conversion efficiency, reduced converter size and low cost. Additionally, the back-up unit supplies the low frequency current harmonics hence minimizing the stresses on the FC should it was to supply such currents. The control of the boost-inverter is moderately complex to handle and sliding- mode control [15] or double-loop voltage and current control schemes [11]-[12] may be adopted in this system.

Fig. 1 shows a popular FC energy system which includes two main power conversion stages between the FC and the load: a DC/DC boost converter and a DC/AC inverter. Due to stability considerations, high power applications and low input voltage have considered the two power stage approach. The proposed single main power stage should provide several advantages such as reduced number of components, high power conversion efficiency, and low cost if it is used in low power applications.

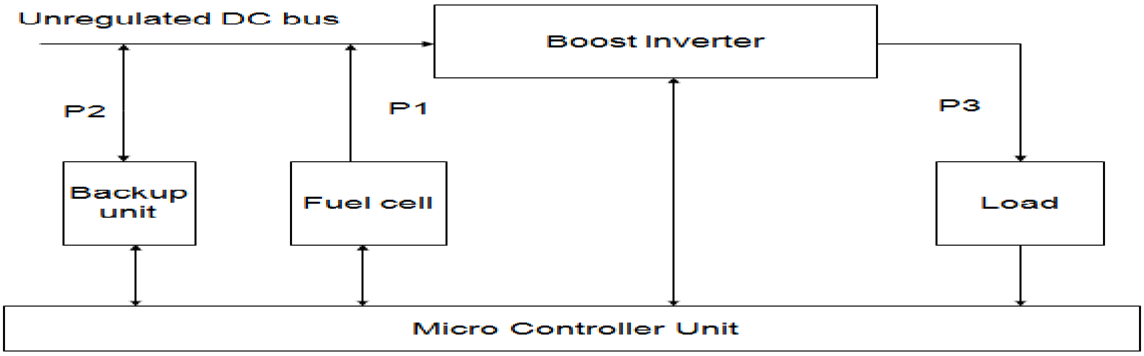

Fig.1 Block diagram for the proposed fuel cell energy system

The proposed FC energy system consists of two power converters: the boost-inverter and the back-up bi-directional unit as shown in Fig.1.

The output of the boost-inverter is connected to the load while the input side is supplied by the FC and the back-up unit, and both connected to the same unregulated dc bus. The back-up unit incorporates a current-mode controlled bi-directional boost converter with battery-based energy storage to support the FC power generation and two voltage-controlled boost converters making up the boost-inverter stage.

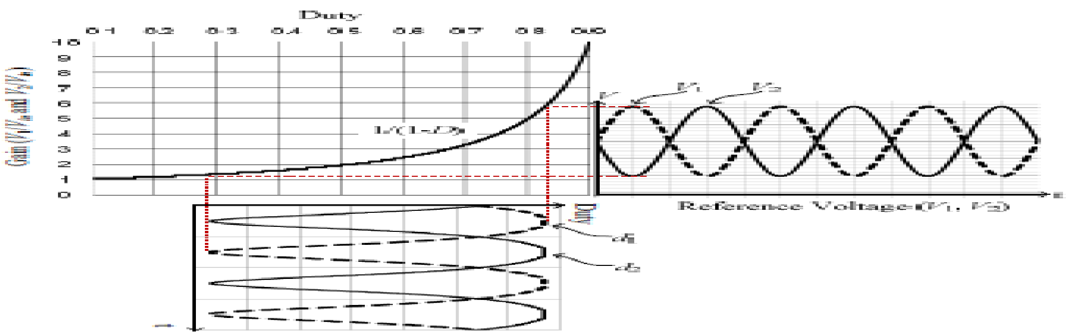

Fig 2. DC gain graph of the boost converter with reference voltages and duty cycles

The FC energy system must dynamically adjust to varying input voltage while maintaining constant power operation. Voltage and current limits need to be imposed at the input of the converter to protect the FC from damage due to excessive loading and transients. The power has to be ramped up and down so that the FC can react appropriately, avoiding transients and extending its life. The converter also has to meet the maximum ripple current requirements of the FC [6].

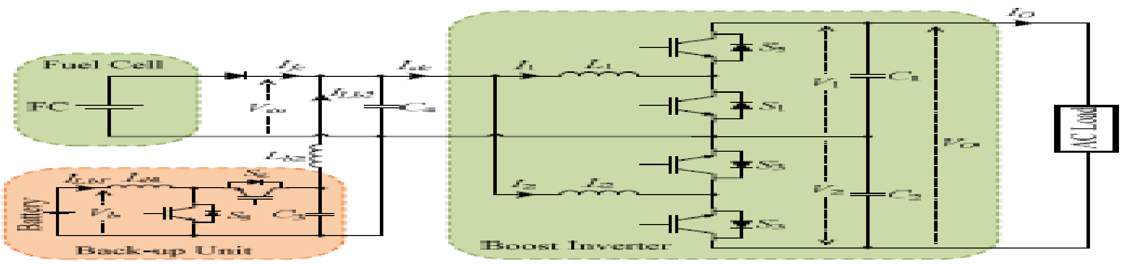

Fig 3. Proposed fuel cell energy system consisting of the boost-inverter and a back-up unit.

2. Boost-inverter

The boost-inverter consists of two bi-directional 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 (a dc-biased sinusoidal waveform as an output), so that each converter generates a unipolar voltage greater than the FC dc voltage with a variable duty cycle condition. Each converter output and the combined outputs are described by

$$V = V_C + {}_2 \cdot A_1 \cdot sin\theta \qquad V = V_C \qquad (1)$$

$$V_2 \cdot A_2 \cdot \sin\theta - 180 \qquad (2)$$

$$V_0 = V_1 - V_2 = A \cdot sin\theta, \text{ when } A = A1 = A2 \qquad (3)$$

where $V1$ and $V2$ are the output voltages of each boost converters and A is the peak amplitude of the boost-inverter output voltage, Vo. To increase the efficiency of the converter with variable input voltage the minimum dc-bias (Vdc) for the converters can be determined by

$$vdc > A + Vin \qquad (4)$$

where Vin is the input voltage as variable of the FC output voltage. From (3) & (4), it is observed that the required output is as desired, i.e. AC only. This concept and several control methods have been discussed in numerous technical papers Fig. 2 illustrates the relationship between the individual duty cycle and each output voltage reference signals. Based on the averaging concept for the boost converter, the voltage relationship for the continuous conduction mode (CCM) is given by

$$v1 = \frac{\theta 1}{1-d1}, v2 = \frac{\theta 2}{1-d2} \qquad (5)$$

$$\frac{v}{v1\theta 1} = \frac{1}{1-d1}, \frac{v}{v2\theta 2} = \frac{1}{1-d2} \qquad (6)$$

where $d1$ and $d2$ are the duty cycles of the boost converters respectively. Fig.2 also Illustrates that the zero output voltage of the boost-inverter is achieved at approximately $d1 = d2 = 0.72$. The reference signals are generated by the DSP unit itself as (1) and (2). After compensation, the duty cycles are calculated in every sampling time, Ts.

3. Control technique

The control algorithm for the two boost converters is presented in detail in Fig. 6. In this paper, a double-loop control scheme is chosen for the boost-inverter control being the most appropriate to control the individual boost converters covering the wide range of operating points. This control method is based on the averaged c o n t i n u o u s -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 the 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 [18]-[20].

The boost-inverter (Fig. 3) is based on a voltage-mode control. The voltages of the *C*1 and *C*2 are controlled by two PI regulators and the currents of the *L*1 and *L*2 are controlled to achieve a stable operation in special conditions such as sudden load change and unexpected short circuit.

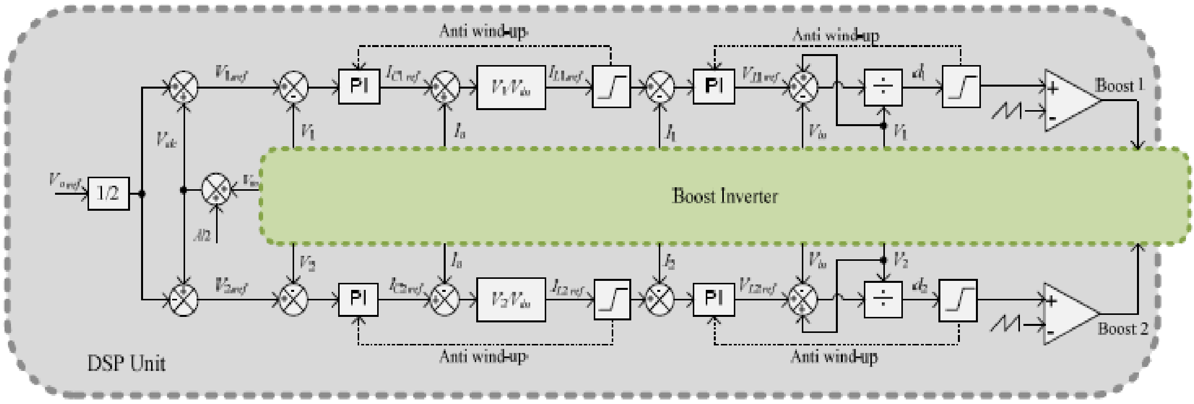

Fig 4. Block diagram for the boost inverter controller

The control block diagram for the boost-inverter is shown in Fig. 4. The output voltage reference is divided to generate the two individual output voltage references of the two boost converters with the dc-bias (*Vdc*). The dc- bias can be obtained by adding input voltage (*Vin*) to the half of the peak output amplitude. *Vdc* is also used to minimize the output voltages of the converters and the switching losses in the variable input voltage condition. The PI controller on the right side of the diagram is for inner current control loop that should be designed to allow at least 50°-phase margin and a high bandwidth. The left side PI controller is for controlling the outer output voltage control loop that should be designed with the same phase margin and lower bandwidth compared with the inner loop. The anti-wind-up is used for saturation and to limit the inductor current. The control block diagram in Fig. 4 including the digital PI controller with the anti-wind-up (Fig. 4) has been implemented in the DSP unit.

The output voltage reference is determined by

$$V_{o,ref} = A \cdot \sin 2\pi ft \quad , = 50Hz, = 100Hz \tag{7}$$

V

where *VO.ref* is the reference voltage and *f* is the fundamental frequency for the boost-inverter. Then *V*1.*ref* and *V*2.*ref* are calculated by (1) and (2). The digital PI controller in Fig. 7 has been implemented in the DSP unit and the equations are as follows:

$$m_i k = K_p \cdot T_s \cdot \varepsilon k + m_i \, k - 1 \tag{8}$$

$$m\,k = m_p k + m_i\, k$$
$$= K_I \cdot \varepsilon I(k) + m_i\, k \tag{9}$$

Where *εI(k)* represents the current error at instant *kTs* and *m(k)* is the output. *KP* and *KI* are the proportional and integral gains respectively. The PI controller is adapted by the anti-wind-up technique removing significant reduction of performance because of the well-known phenomenon of the integrator windup with saturation of the actuators.

3. Back-up unit

The back-up unit is designed to support the slow response of the FC and is shown in Fig. 3.The back-up unit comprises of a current-mode controlled bi-directional boost converter and a battery as the energy storage medium. F o r instance, when a 1kW load is added from a no-load condition, the back-up unit immediately provides the 1kW power from the battery to the load as shown in Table I.

Table I. Back-Up Unit Operations

P_3 Increase ($P_1+P_2 \longrightarrow P_3$)	P_3 Decrease ($P_1 \longrightarrow P_2+P_3$)	Normal ($P_1=P_3$)
Discharge ↓ Charge ↓ Normal	Charge ↓ Normal	Normal

On the other hand, when the load is disconnected suddenly, the surplus power from the FC could be recovered and stored into the battery to increase the overall efficiency of the energy system. Two generic 12 V lead-acid batteries are introduced in this unit for energy storage to deal with the need to provide fast response and a relatively low cost solution. The proposed back-up unit performs properly not only the support function for the FC module during transients but also is used as storage when any surplus power delivered by the FC is recovered.

In order to control the output current of the back-up unit, the inner current control loop of the boost-inverter is used. The reference of *ILb*1 is taken from *Idc* through a high-pass filtering and the demanded current I_{demand} relating the load change in Fig.5. Detecting only the ac component from the dc input current *Idc* for the current reference is used to eliminate ac ripple current into the FC power module while the dc component is used to determine the amount of demanded current. The elliptic 3rd order digital low pass filter (LPF) has been chosen and designed because of its narrow transition band and for being the most efficient of the IIR filters. The implementation has been integrated into the DSP.

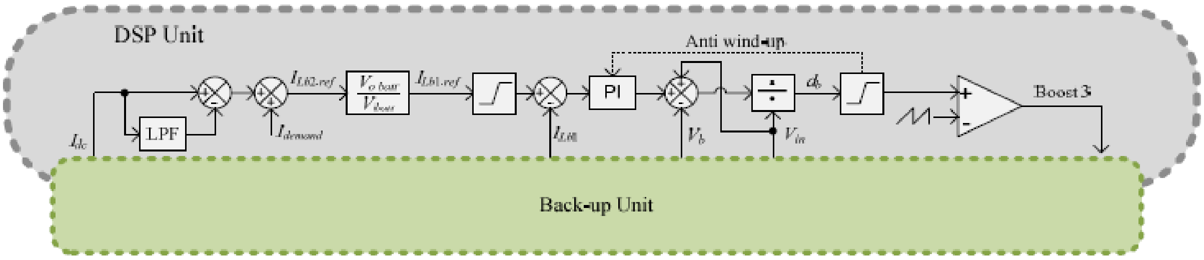

Fig 5. Block diagram for the controller of the back-up unit

Table II. Design Specifications

FC output voltage	26 – 43 V_{DC}
AC output voltage	100 V_{AC} RMS, Single phase, 50 Hz
Switching frequency	20 kHz
Output power	1.2kW
V_{in}	26V (min)
R_o (resistance of L_1 and L_2)	≈ 10$m\Omega$
V_1(t)	175.4V (max)
V_2(t)	36V (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)	8.3Ω (1.2kW)

4. Power component design

The power components of the proposed system where designed with the parameters given in Table II. To calculate the inductance of *L*1 and *L*2 the following equations are used [15] current, as calculated from (10) when the *V*1 is maximum and *V*2 is minimum. From (10) the minimum inductance is calculated as 177µH and 200µH which are the chosen values for *L*1 and *L*2. The ripple voltage of the *C*1 and *C*2 is given by [15] .

$$\Delta L t = (vg1 - R0 * iL) \Delta t1 L \quad (10)$$

Table III. Specifications for the Simulated System

Output voltage	Step down from 41 to 30 V_{DC}
AC Output voltage	100 V_{AC} RMS, Single phase, 50 Hz
Switching frequency	20 kHz
Output power	Step change from 40W to 500W

During transient conditions, the back-up unit should provide all the power required by the load. In this case, the maximum inductor current of the boost-inverter should appear in the inductor *Lb*2.Therefore, the maximum inductance of *Lb*2 can be calculated by (11) and $\Delta iL(t)max$ need to be larger than the maximum inductor current of the boost-inverter in order to track the maximum slope of the current. The maximum inductance is obtained from (11) as 51µH and the values of *Lb*1 and *Lb*2 are chosen to be 20µH. The values of the capacitors *C*3 and *C*4 of the back-up unit are chosen to be 30µF.

III. ANALYSIS AND SIMULATION RESULTS

The proposed FC energy system (Fig. 2), has been designed, simulated, to validate its overall performance. The simulations have been performed with the PSIM software to validate the analytical results. The simulation results show the operation of the boost-inverter and the back- up unit.

In particular, Fig. 6(a) illustrates the output voltages of each of the two boost converters (*V*1 and *V*2), the input voltage *Vin* same as the FC output voltage and the final output voltage of the boost-inverter *V*o.

The input currents of each boost converter flowing through the inductors *L*1 and *L*2 are shown in Fig. 6(c). shows the duty cycles (*d*1 and *d*2) of each boost converter that are varying between approximately 0.15 and 0.85.

Figs. 6(b), (d) and illustrate the waveforms of the dc total output current *Idc* (which is equal to the inverter input current), the FC output current *Ifc*, and the output current *ILb*2 of the backup unit respectively.

Fig. 6(d) also illustrate how the back-up unit supports the FC power in transients when the load is increased.

When full-load is required from the no-load operating point, the entire power is provided by the back-up unit to the load as shown in Fig. 6(e). Then, the power drawn from the battery starts decreasing moderately allowing gentle step-up to deliver power which should increase up to meet the demanded load power.

Moreover, the back-up unit protects the FC from potential damage by eliminating the ripple current due to the boost operation. If there was no back-up unit, the FC output current waveform should be the same as Fig. 6(e).

The high frequency output ripple current of the FC can be canceled by a passive filter placed between the FC and the boost- inverter.

Fig.6.a, Simulation results of boost-inverter output voltage

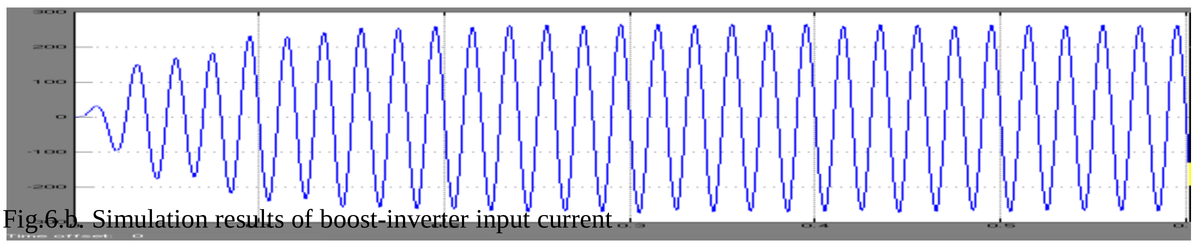

Fig.6.b. Simulation results of boost-inverter input current

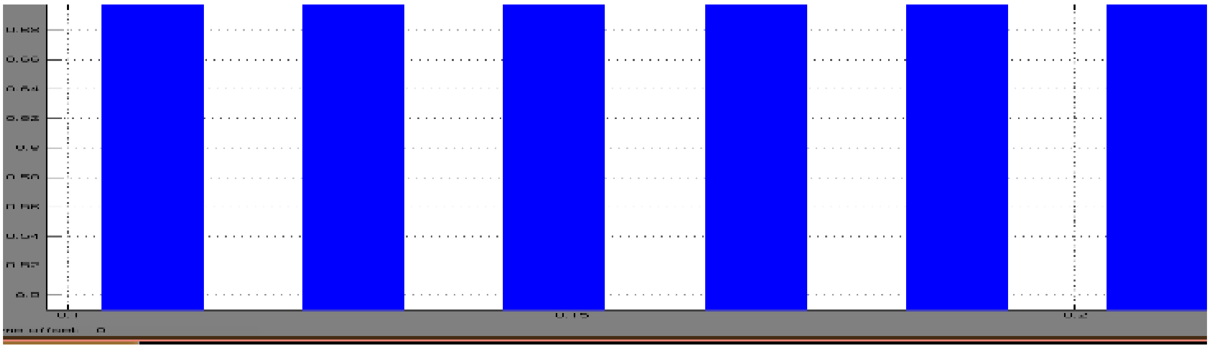

Fig6.c. Switching pulses of the boost-inverter current and voltages

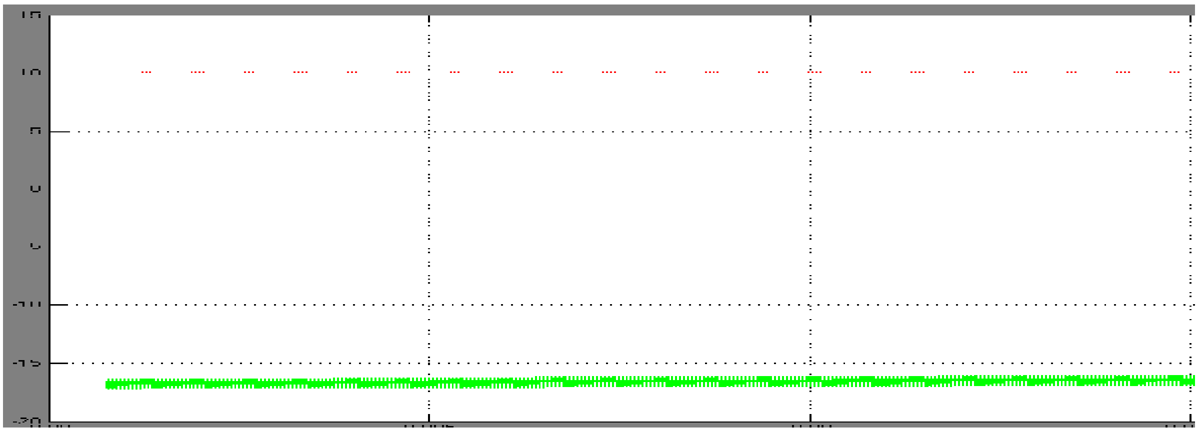

Fig.6.d Simulation results of back-up unit charging and discharging

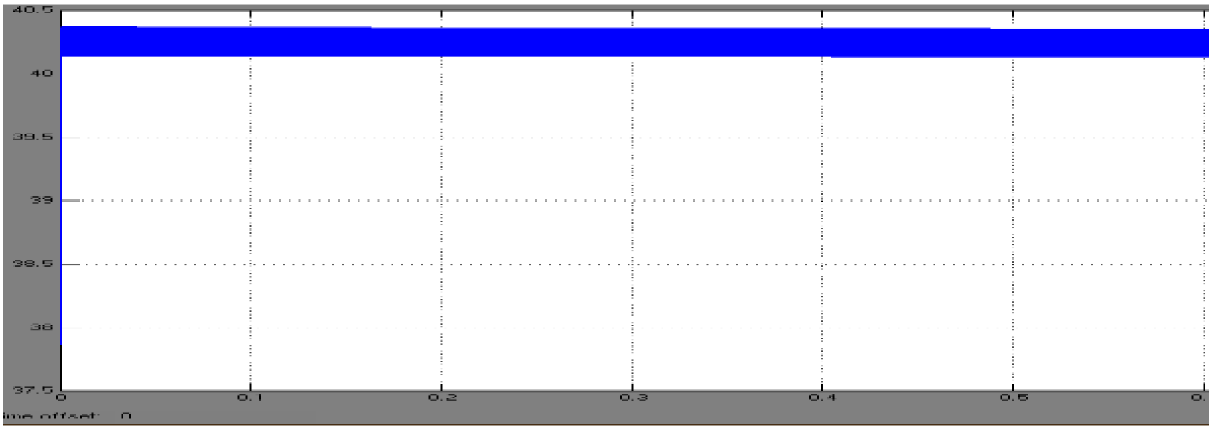

Fig.6.e. Simulation results of back-up unit charging

IV. CONCLUSION

Analysis and design of a high efficiency boost-inverter with back-up battery storage in fuel cell is proposed in this paper. In this paper, the boost-inverter topology that achieves both boosting and inversion functions in a single stage is used to develop an FC based energy system. The system incorporates additional battery based energy storage and a DC-DC bi-directional converter to support instantaneous load changes. The load low frequency current ripple is supplied by the battery which minimizes the effects of such ripple being drawn directly from the FC itself. The analysis and simulated results are presented in the paper have verified the operation characteristics of the proposed energy system. In summary, the proposed FC energy system has a number of attractive features, such as single main power stage with high conversion efficiency, simplified topology, low cost and stand alone operation.

REFERENCES

[1]. S.B. Kjaer, J.K. Pedersen, F. Blaabjerg, “A review of single-phase grid connected inverters for photovoltaic modules,” IEEE Trans. On Industry Applications, vol.41 no. 5, pp. 1292 – 1306, Sept.-Oct. 2005.

[2]. J.-S. Lai, “Power conditioning circuit topologies” IEEE Industrial Electronics Magazine, Vol. 3, 2, June 2009, pp. 24-34.

[3]. M.E. Schenck, J.-S. Lai and K. Stanton, “Fuel cell and power conditioning system interactions,” Proc. of the APEC 2005. vol. 1, pp. 114 – 120, 6-10 March 2005.

[4]. P. Thounthong, S. Rael, and B. Davat, “Utilizing fuel cell and super capacitors for automotive hybrid electrical system,” Proc. of the 2005 IEEE Applied Power Electronics Conference and Exposition (APEC05), Texas, 6-10 Mar. 2005, pp. 90-96.

[5]. Jung-Min Kwon, Student Member, IEEE, Eung-Ho Kim, Bong-Hwan Kwon, Member, IEEE, and Kwang-Hee Nam, Member, IEEE “High-efficiency fuel cell power conditioning system with input current ripple reduction” vol.56,March.2009.

[6]. M. W. Ellis, M. R. Von Spakovsky, and D. J. Nelson, “Fuel cell systems: efficient, flexible energy conversion for the 21st century,” Proc. of the IEEE, vol. 39, no. 12, pp. 1808-1818, Dec. 2001.

[7]. X. Yu, M. R. Starke, L. M. Tolbert, and B. Ozpineci; “Fuel cell power conditioning for electric power applications: a summary,” IET-Electric Power Appl., vol. 1, no. 5, pp. 643-656, Sept. 2007.

[8]. A.K. Raji and MTE Kahn,Cape Peninsula University of Technology, Cape Town ,”Overview of energy conversion systems for fuel cell technology: alternative energy generations” vol.26, August.2007.

[9]. Vazquez-Blanco, C. Aguilar-Castillo, F. Canales-Abarca and J. Arau-Roffiel, “Two-stage and integrated fuel cell power conditioner: Performance comparison,” Proc. of IEEE APEC 2009. vol 15-19, pp.452–458, Feb. 2009.

[10]. A. Kirubakaran, Shailendra Jain, and R.K. Nema, ”The PEM Fuel Cell System with DC/DC Boost Converter: Design, Modeling and Simulation” Vol1 no.3. May. 2009.

[11]. R. O. Cáceres and I. Barbi, “A boost dc-ac converter: Analysis, design,and experimentation,” IEEE Trans. Power Electron., vol. 14, no. 1, pp.134-141, Jan. 1999.

[12]. Arvindh Rajasekaran, Abhiman Hande, Dinesh Bhatia, “Buck-Boost Converter Based Power Conditioning Circuit for Low Excitation Vibrational Energy Harvesting:” Vol 2.15, no.3, pp. 134-142. October .1999.

[13]. Liuchen Chang, Zhumin Liu,Yaosuo Xue and Zhenhong Guo, “A Novel buck boost inverter for photovoltaic systems “ Vol 1.no.2.August.2004.

[14]. R. O. Cáceres and I. Barbi, “Sliding mode controller for the boost inverter, ”in Proc. IEEE CIEP’96, Cuernavaca, Mexico, Oct. 14-17,1996, pp. 247-252.