International Journal of Computer Applications (0975 – 8887)
Volume 94 – No 3, May 2014

Modeling and Simulation of Multi-input Bi-directional Boost Converter for Renewable Energy Applications using MatLab/Simulink

Ramya. S
Assistant Professor, ECE
P.A. College of Engineering and Technology,
Pollachi,
India

Gowthami. S
Assistant Professor, BME
Dr.NGP Institute of Technology, Coimbatore,
India

ABSTRACT
The objective of this paper is to propose a multi-input power converter for the hybrid system that interfaces two unidirectional ports for input power sources, a bidirectional port for a storage element, and a port for output load in a unified structure. The two input ports for simultaneously converting two different input power sources with low voltages to a stable output power with a high voltage. According to various situations, the operational states of the proposed converter can be divided into three states based on battery utilization .In order to ensure that the system operates with high efficiency, this paper proposes a power management control scheme, which controls the bidirectional converter operating under boost mode according to the operation condition of the PV/Fuel Cell , so that the battery can be charged or discharged. The integration of the hybrid renewable power system is implemented and simulated using MATLAB/SIMULINK.

Keywords
Photovoltaic (PV)/Fuel Cell/Battery Sources, State Of Charge(SOC), Bidirectional Power Flow, Boost DC-DC Converter,Power Converter

1. INTRODUCTION
The Energy consumption of the world is increasing dramatically with the rapid increase of population. Renewable Energy resources are holding the predominant place for satisfying the future Energy demand .Among the available renewable sources, Solar is predominant, since Solar have more advantages on production, maintenance, etc. when compared with others. The Surge for suitable alternative Energy sources is growing more intense than ever in order to reduce the heavy dependence on fossil fuels[1]. Fuel cells are another rapidly developing generation technology. Fuel cells have high efficiency, low carbon emissions, high reliability due to the limited number of moving parts and longer life . A Stand-alone Solar Energy system cannot provide a continuous power supply due to seasonal and periodical variations for stand-alone system. Batteries are usually taken as storage mechanism for smoothing output power, improving startup transitions and dynamic characteristics, and enhancing the peak power capacity [2]. Combining the photovoltaic generation with Fuel Cell, the instability of an output characteristic each other was compensated. Combining such energy source introduces a PV/Fuel Cell/Battery hybrid power system. In comparison with single-sourced systems, the hybrid power systems have the potential to provide high quality, more reliable, and efficient power. In these systems with a Storage Element, the Bidirectional Power flow capability is a key feature at the storage port. [3] Further, the input Power Sources should have the ability of supplying the load individually and simultaneously. Many Hybrid Power Systems with various Power Electronic Converters have been proposed in the literature up to now. However, the main shortcomings of these integrating methods are complex system topology, high count of devices, high power losses, expensive cost, and large size.[4]. In [5]–[8], three multi input converters are proposed based on structure of the DC-DC Boost Converter. The DC–DC Boost Converter in [5] is useful for combining several Energy sources whose power capacity or voltage levels are different. The Multi-input DC–DC Converter proposed in [9] has the capability of operating in different Converter topologies (Buck, Boost, and Buck–Boost) in addition to its Bidirectional operation and positive output voltage without any additional transformer. Further, phase-shift control method is used to manage the power flow among the three ports in addition to soft switching for all switches over a wide input range.[10] Although the circuit efficiency is greatly developed, the converter does not provide bidirectional functionality and is not able to boost the input voltage to a higher level. Moreover, the summation of duty ratios should be greater than one and the two input voltages should be in the same level in the dual-power-supply operation state.[11]. In [12] power control strategies designed manage the charge balance of the battery in order to regulate the output voltage.

2. PROPOSED SYSTEM
In this paper, combining the photovoltaic generation with Fuel Cell power generation, the instability of an output characteristic each other was compensated. The proposed system is applicable for hybrid power system. As shown in Fig. 1, the proposed converter interfaces two unidirectional ports for input power sources, a bidirectional port for a storage element, and a port for output load in a unified structure. The Input power source1 is Photovoltaic (PV) cell , power source2 is the Fuel Cell and the storage element is the battery. The converter is of current-source type at the both input power ports and is able to step up the input voltages. .The PV array and Fuel Cell work together to satisfy the load demand. When energy sources (Solar and Fuel Cell energy) are abundant, the generated power, after satisfying the load demand, will be supplied to feed the battery until it is full charged. On the contrary, when energy sources are poor, the Battery will release energy to assist the PV array and Fuel cell to cover the load requirements until the storage is depleted.

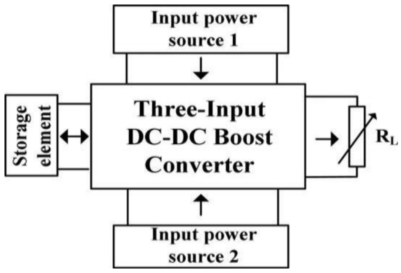


Fig 1 : Proposed System Overview

Supplying the output load, Charging or Discharging the Battery can be made by the PV and the Fuel Cell power sources individually or simultaneously. The Proposed Converter has the merits of including Bidirectional power at the Storage Port, Simple Structure, Low Power Components, Low weight and High level of Boosting.

3. STRUCTURE OF THE PROPOSED CONVERTER

The proposed Multi – Input power converter is shown in Fig. 2. The proposed converter Interfaces two Input power sources v_1 and v_2 and a battery as the storage element. v_1 and v_2 are two dependent power sources, their output characteristics are determined by the Input power sources. In the proposed circuit, two Inductors L_1 and L_2 make the Input power ports as two current type sources.

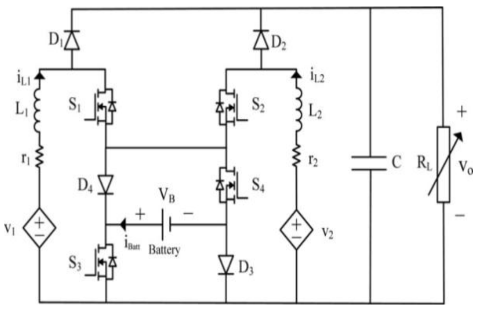


Fig 2 : Circuit topology of the Proposed System

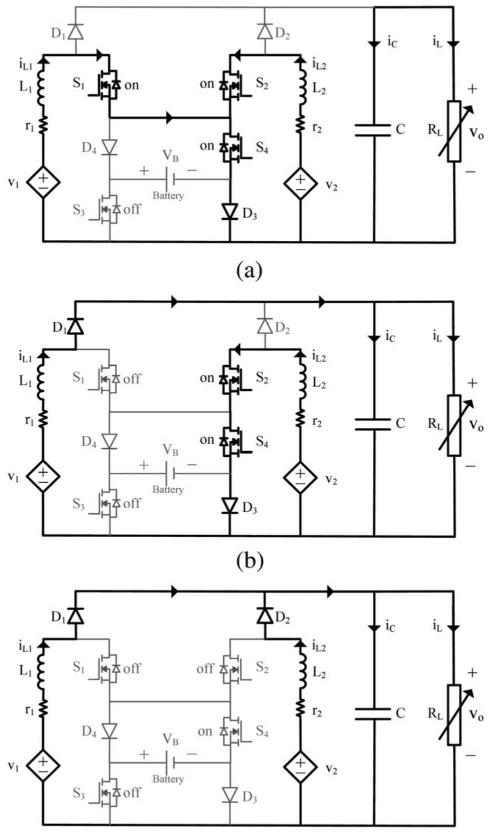
It results in drawing smooth currents from the sources. R_L is the load resistance and switches S_1 – S_4 are the main controllable element that controls the power flow of the hybrid power system. The d_1 – d_4 are the duty ratios controlling the switches S_1 – S_4 respectively. The diodes D_1 and D_2 conducts in complementary manner with switches S_1 and S_2. Turning ON S_3 and S_4, makes D_3 and D_4 to reverse bias by the V_{bat}. On the other hand, turn – OFF state of these switches makes diodes D_3 and D_4 able to conduct Input currents i_{L1} and i_{L2}. The steady states and dynamic behavior of the converter is observed in Continuous Current Mode (CCM).

4. MODES OF OPERATION OF THE PROPOSED CONVERTER

Utilization state of the battery defines three power operation modes of the converter. The assumptions for the operation modes are considered by utilizing sawtooth carrier waveform for S_1 – S_4 and considering d_3, $d_4 <$ min (d_1,d_2) in battery charge or discharge mode. d_1 is assumed to be less than d_2 in order to simplify the operation mode investigation. Further, the steady – state equations are obtained in each operation mode, assuming S_1 – S_4 to be Ideal.

4.1 First Operation Mode (Existence Of Sources v_1 and v_2 without Battery)

In this operation mode, the sources v_1 and v_2 supplies the load without battery. This is the Basic Operation mode of the converter. From the converter structure, there are two options to conduct Input – power sources currents i_{L1} and i_{L2} without passing through the battery, path1: S_4 – D_3, path2: S_3 – D_4. First path is chosen in this operation mode. Therefore, switch S_3 is turned OFF while turning ON Switch S_4 entirely in the switching period (d_4=1 and d_3=0). Thus, in one switching period, three different switching states of the converter are achieved. The switching states are shown in Fig. 3(a)–(c).



(a) (b) (c)

Fig. 3 :First operation mode :(a) Switching state 1: 0 < t < d_1 T. (b) Switching state 2: d_1 T< t < d_2 T. (c) Switching state 3: d_2 T < t < T

Switching state 1 ($0 < t < d_1$ T): At $t = 0$, switches S_1 and S_2 are turned ON and inductors L_1 and L_2 are charged with voltages across v_1 and v_2 , respectively [see Fig. 3(a)].

Switching state 2 (d_1 T $< t < d_2$ T): At $t = d_1$ T, switch S_1 is turned OFF, while switch S_2 is still ON (according to the assumption $d_1 < d_2$). Therefore, inductor L_1 is discharged with voltage across $v_1 - v_o$ into the output load and the capacitor through diode D_1, while inductor L_2 is still charged by voltage across v_2 [see Fig. 3(b)].

Switching state 3 (d_2 $T < t < T$): At $t = d_2 T$, switch S_2 is also turned OFF and inductor L_2 is discharged with voltage across $v_2 - v_o$, as like as inductor L_1 [see Fig. 3(c)].

Based on the balance theory, equations are

$$L_1 : d_1 T(v_1 - r_1 i_{L1}) + (1 - d_1)T(v_1 - r_1 i_{L1} - v_o)$$

$$= 0 \rightarrow v_o = \frac{v_1 - r_1 i L_1}{1 - d_1} \tag{1}$$

$$L_2 : d_2 T(v_2 - r_2 i_{L2}) + (1 - d_2)T(v_2 - r_2 i_{L2} - v_o)$$

$$= 0 \rightarrow v_o = \frac{v_2 - r_2 i_{L2}}{1-2} \tag{2}$$

$$C: (1 - d_1) T i_{L1} + (1 - d_2) T i_{L2} = T \frac{v_o}{R_L} \tag{3}$$

$$i_{Batt} = 0 \rightarrow P_{Batt} = 0 \tag{4}$$

In this mode, one of the Input sources is regulated with its corresponding duty ratios, while the other power source is utilized to regulate output voltage with its duty ratio.

4.2 Second Operation Mode (Existence Of Sources v_1 and v_2 with Battery Discharging)

In this operation mode, the sources v_1 and v_2 supplies the load with the battery discharging state. From the converter structure, turning ON switches S_3 and S_4 simultaneously causes i_{L1} and i_{L2} to conduct through the path of S_4, the battery and S_3 which results in discharging of the battery. However, discharging operations of the battery can last until S_1 and/or S_2 are conducting. So, the maximum discharge state of the battery depends on d_1 and d_2 as well as currents i_{L1} and i_{L2}:

$$P_{bat,dis}^{max} = v_B [d_1 i_{L1} + d_2 i_{L2}], \ S_3 = \text{ON}, S_4 = \text{ON}. \tag{5}$$

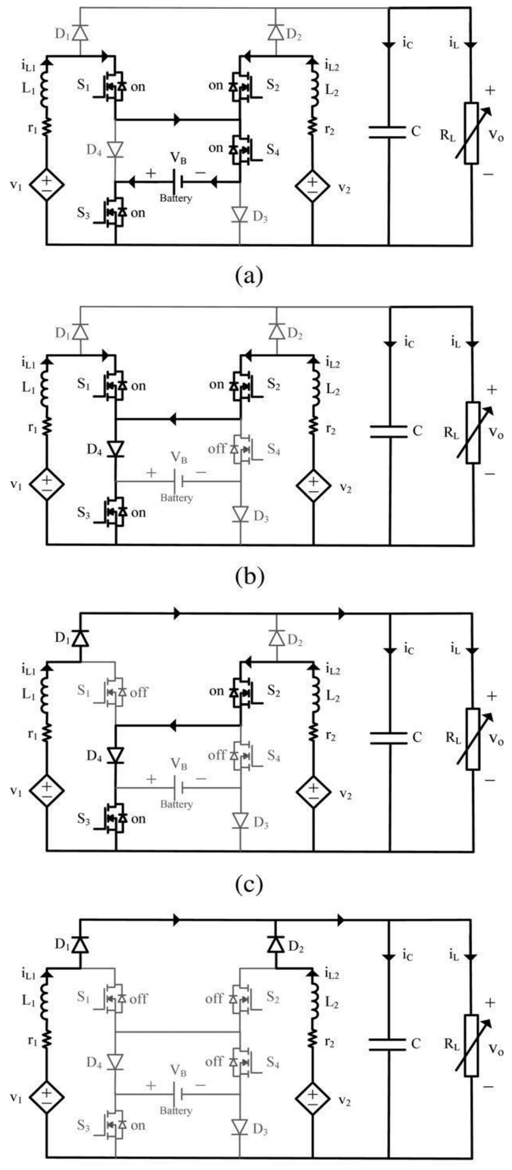
The discharging power of the battery below $P_{bat,dis}^{max}$ can be made by changing the state of only one of switches S_3 and S_4 before switches S_1 and S_2 are turned OFF. d_3 is controlled to regulate the discharging power of the battery. When S_4 is turned ON, it results in passage of currents of power sources through the battery; hence, battery discharge mode is started, and its turn OFF state starts D_4 to conduct and stops discharging mode of battery. The switching states are shown in Fig. 4(a)–(d).

Switching state 1 ($0 < t < d_4 T$): At $t = 0$, switches S_1, S_2, and S_4 are turned ON, so inductors L_1 and L_2 are charged with voltages across $v_1 + v_B$ and $v_2 + v_B$, respectively [Fig. 4(a)].

Switching state 2 (d_4 $T < t < d_1$ T): At $t = d_4 T$, switch S_4 is turned OFF, while switches S_1 and S_2 are still ON. Therefore, inductors L1 and L2 are charged with voltages across v1 and v2 respectively [see Fig. 4(b)].

Switching state 3 (d_1 $T < t < d_2$ T): At $t = d_1 T$, switch S_1 is turned OFF, so inductor L_1 is discharged with voltage across v_1- v_o , while inductor L_2 is still charged with voltages across v_2 [see Fig. 4(c)].

Switching state 4 (d_2 $T < t < T$): At $t = d_2 T$, switch S_2 is also turned OFF and inductors L_1 and L_2 are discharged with voltage across $v_1 - v_o$ and $v_2 - v_o$,respectively [see Fig. 4(d)].



(a) (b) (c) (d)

Fig 4: Second operation mode: (a) Switching state 1: $0 < t < d_4 T$. (b) Switching state 2: $d_4 T < t < d_1 T$. (c) Switching state 3: $d_1 T < t < d_2 T$. (d) Switching state 4: $d_2 T < t < T$.

Based on the balance theory equations are

$$L_1 : d_4 T(v_1 - r_1 i_{L1} + v_B) + (d_1 - d_4)T(v_1 - r_1 i_{L1})$$
$$+ (1 - d_1)T(v_1 - r_1 i_{L1} - v_o) = 0$$
$$= 0 \rightarrow v_o = \frac{v_1 - r_1 i L_1 + d_4 v_B}{1 - d_1} \tag{6}$$

$$L_2 : d_4 T(v_2 - r_2 i_{L2} + v_B) + (d_2 - d_4)T(v_2 - r_2 i_{L2})$$
$$+ (1 - d_2)T(v_2 - r_2 i_{L2} - v_o) = 0$$

$$= 0 \rightarrow v_o = \frac{v_1 - r_1 i_{L2} + d_4 v_B}{1-d_2} \tag{7}$$

$$C: (1-d_1)Ti_{L1} + (1-d_2)Ti_{L2} = T\frac{v_O}{R_L} \tag{8}$$

$$Battery \begin{cases} i_{Batt} = d_4(i_{L1} + i_{L2}) \\ P_{Batt} = -v_B[d_4(i_{L1} + i_{L2}) \end{cases} \tag{9}$$

In this mode, d_1 and d_2 regulates powers of the input sources, while d_4 is utilized to regulate output voltage through battery discharging.

4.3 Third Operation Mode (Existence Of Sources v_1 and v_2 with Battery Charging)

In this operation mode, the sources v_1 and v_2 supplies the load while the battery is in charging state. From the converter structure, switches S_3 and S_4 are turned OFF, by turning ON S_1 and S_2, currents i_{L1} and i_{L2} are conducted through the path of D_4, the battery, and D_3. Hence the condition of battery charging is provided. However, the charging mode of the battery prevails until S_1 and/or S_2 are conducting. So, the maximum charging of the battery depends on d_1 and d_2 as well as i_{L1} and i_{L2}.

Regulating charging power of the battery below $P^{max}_{bat.ch}$ can be made by change of state of switches S_3 and S_4 before turning OFF switches S_1 and S_2 (Assuming that d_3, d_4<min(d_1, d_2)). In order to regulate, the charging state of the battery, S_3 is controlled. The battery charging is not accomplished when S_3 is turned ON. In one switching period, Four different switching states obtained are shown in Fig. 5(a)–(d).

Switching state 1 ($0 < t < d_3 T$): At $t = 0$, switches S_1 , S_2 , and S_3 are turned ON, so inductors L_1 and L_2 are charged with voltages across v_1 and v_2 , respectively [see Fig. 5(a)].

Switching state 2 ($d_3 T < t < d_1 T$): At $t = d_3 T$, switch S_3 is turned OFF while switches S_1 and S_2 are still ON (according to the assumption). Therefore, inductors L_1 and L_2 are charged with voltages across $v_1 - v_B$ and $v_2 - v_B$, respectively [see Fig. 5(b)].

Switching state 3 ($d_1 T < t < d_2 T$): At $t = d_1 T$, switch S_1 is turned OFF, so inductor L_1 is discharged with voltage across $v_1 - v_o$, while inductor L_2 is still charged with voltage across $v_2 - v_B$ [see Fig. 5(c)].

Switching state 4 ($d_2 T < t < T$): At $t = d_2 T$, switch S_2 is also turned OFF and inductor L_2 as like as L_1 is discharged with voltage across $v_2 - v_o$ [see Fig. 5(d)].

Switching state 4 ($d_2 T < t < T$): At $t = d_2 T$, switch S_2 is also turned OFF and inductor L_2 as like as L_1 is discharged with voltage across $v_2 - v_o$ [see Fig. 5(d)].

$$P^{max}_{bat.ch} = -v_B[d_1 i_{L1} + d_2 i_{L2}],\ \ S_3 = \text{OFF},\ S_4 = \text{OFF}. \tag{10}$$

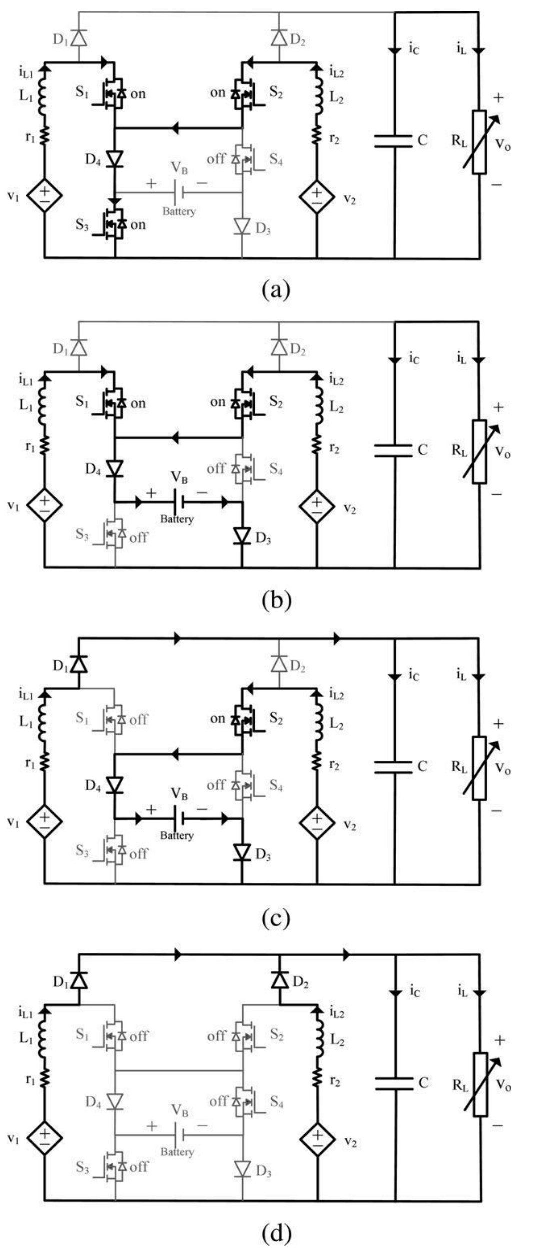


Fig 5 : Third operation mode : (a) Switching state 1: 0<t<d_3T (b) Switching state 2: d_3T< t<d_1T. (c) Switching state 3: d_1T<t <d_2T. (d) Switching state 4: d_2T <t<T.

Based on the balance theory, equations are

$$L_1: d_3T(v_1 - r_1 i_{L1}) + (d_1 - d_3)T(v_1 - r_1 i_{L1} - v_B) + (1-d_1)T(v_1 - r_1 i_{L1} - v_o) = 0$$

$$= 0 \rightarrow v_o = \frac{v_1 - r_1 iL_1(d_1 - d_3)v_B}{1-d_1} \tag{11}$$

$$L_2: d_2T(v_2 - r_2 i_{L2}) + (d_2 - d_3)T(v_2 - r_2 i_{L2} - v_B) + (1-d_2)T(v_2 - r_2 i_{L2} - v_o) = 0$$

$$= 0 \rightarrow v_o = \frac{v_2 - r_2 iL_2(d_2 - d_3)v_B}{1-d_2} \tag{12}$$

$$C: (1 - d_1) Ti_{L1} + (1 - d_2) Ti_{L2} = T \frac{v_o}{R_L} \quad (13)$$

$$Battery \begin{cases} i_{Batt} = -(d_1 - d_3)i_{L1} - (d_2 - d_3)i_{L2} \\ P_{Batt} = -v_B[(-d_3)(iL_1 + iL_2) + d_1 i_{L1} + d_2 i_{L2} \end{cases} \quad (14)$$

In this mode, d_1 and d_2 regulates powers of the Input sources, while d_3 is utilized to regulate output voltage through battery charging by the extra-generated power.

5. DETERMINATION OF OPERATION MODES

The proper operation mode should be determined based on availability of P_{Pv}^{max} , $P_{Fuel\ Cell}^{max}$, the output voltage value, and the battery charging necessity. In order to keep the battery voltage in allowable minimum and maximum voltages given by,

$$v_{Batt.Min} < v_{Batt} < v_{Batt.Max} \quad (15)$$

If the battery voltage is lesser than $v_{Batt \cdot Min}$, then the state of battery charging is required. The amount of the battery charging power depends on the capacity of the battery C_B, which is usually chosen to be less than $0.2C_BV_B$. On the other hand, battery discharging states, occurs when battery voltage is higher than $v_{Batt \cdot Min}$. The proper operation mode can be determined as follows:

5.1 First Operation Mode

Basic operation mode which takes place in the conditions that the summation of the PV and Fuel Cell powers can completely supply the load, without battery existence. Here d_1 is used to regulate PV source and d_2 is utilized to regulate output voltage.

5.2 Second Operation Mode

This mode takes place in the conditions that the output voltage cannot be regulated because summation of Fuel Cell and PV cannot completely supply the load and $v_{Batt.Min} < v_{Batt}$the battery discharging is accomplished. Here, d_1 and d_2 regulates powers of the input sources, while d_4 is utilized to regulate output voltage through battery discharging.

5.3 Third Operation Mode

This mode takes place in the conditions that summation of the Fuel Cell and PV powers can regulate the output voltage as like as first operation mode, while the battery is needed to be charged. In this mode d_1 and d_2 regulates power of the input sources, while d_3 is utilized to regulate output voltage through battery charging by the extra – generated power.

6. SIMULATION RESULTS AND DICUSSION

The Evaluation of the performance of the proposed converter is done by simulating all the three operation modes by MATLAB/SIMULINK software. The simulation parameters are $L_1 = L_2 = 6mH$,C=200µF,f_s=20KHZ $r_1 = r_2 = 0.4\,\Omega.R_L$ with average power of 2.5KW is supplied at the dc link in the proposed system. The dc-link voltage of the converter is regulated at v_o=350V which is a desired condition.Power of input sources and Load characteristics are discussed below for three modes.

6.1 First Operation Mode

In this stage(S=750 W/m^2), the load power required is P_L = 2.5 KW (R_L= 50 Ω), while the maximum available PV power is P_{pv}=1.7 KW and there is no need to charge the battery.

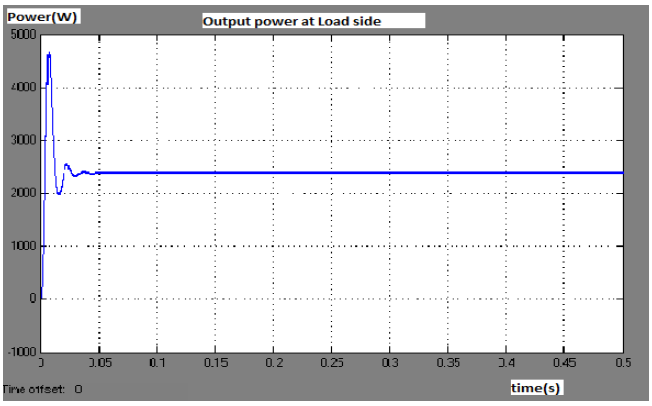


Fig 6 : Output Power at load side for mode 1

The Fuel Cell current is set on i_{L2} =4.57A by duty ratio $d2$ = 0.75 to regulate the output voltage, while the maximum power of the PV is elicited with the current of i_{L1}= 11.45A and adjusting the first duty ratio at $d1$ = 0.7,So that third and fourth duty ratios are set on $d3$ = 0 and $d4$ = 1, which result the battery power to be set on zero value.

6.2 Second Operation Mode

This stage occurs in a condition that solar power decreased certain value(S= 500W/m^2) in which the load requires P_L = 2.5 KW and the PV power is simultaneously decreased into P_{pv}=0.45KW From the maximum deliverable power of the PV, it is obviously understood that the PV is not able to completely supply the power deficiency. Thus, the remaining power should be supplied by the battery. Regulating its current at i_{L1}= = 5.3A and adjusting the first duty ratio at d1 = 0.71, the maximum power of is delivered at i_{L2} = 15.72A. Adjusting the second duty ratio at d2 = 0.73 and controlling the third and fourth duty ratios at d3 = 1 and d4 = 0.4 results in discharging the battery. Fig.7 indicates the operation of second operation mode.

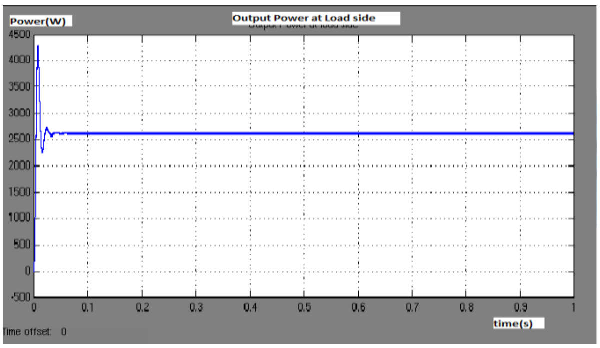


Fig 7 :Output power at load side for mode 2

6.3 Third Operation Mode
In this stage, a step change in the sun irradiation level ($S=1000W/m^2$), which results to increase the available maximum PV power into P_{pv}=1.7KW while the load power remains constant at P_L = 2.5 kW.

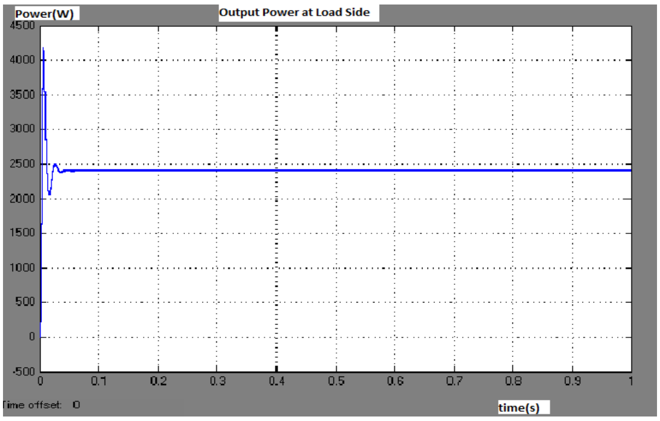


Fig 8: Output Power at load side for mode 3

In this condition, providing charging power of the battery in addition to power deficiency between the PV and the load can be accomplished. TheFuel Cell is regulated with duty ratio d2 = 0.79, while the maximum power of the PV source is tracked with regulating the PV current at i_{L1}= 4.4A and adjusting the first duty ratio at d1 = 0.73. Moreover, controlling the third and fourth duty ratios at d3 = 0.45 and d4 = 0, respectively, results in providing the charging power of the battery in addition to regulating the output voltage.

6.4 Result Analysis for Three modes
In Fig 9: Comparison of load power is shown below.The performance for three modes is given based on battery Operation. The demand Of Load Power is met in all Modes.

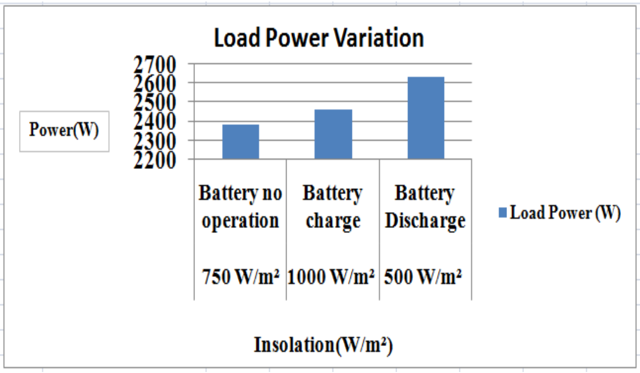


Fig 9 :Comparison of output power at load side for three modes

7. CONCLUSION AND FUTURESCOPE
This paper describes Renewable Energy Hybrid Fuel Cell-PV with Battery Energy storage system in three operation modes. A complete description of the hybrid system has been presented along with its detailed simulation results which ascertain its feasibility. The simulation results showed satisfactory performance of the hybrid system. The proposed system is a good alternative for the multiple- source hybrid power systems and has may advantages such as bidirectional power flow at the storage port , low power components, ,simple structure, centralized control, no need of transformer, low weight and also delivers constant and stepped up dc voltage to the load The future work will be to design the proposed hybrid system and implement in hardware. Also, the system has to be extended to higher ratings and solve for the synchronization issues.

8. REFERENCES
[1] J. L. Duarte, M. Hendrix, and M. G. Simoes, “Three-port bidirectional converter for hybrid fuel cell systems,” *IEEE Trans. Power Electron.*, vol. 22, No. 2, Mar. 2007.

[2] Y-C. Kuo, T-J. Liang, and J-F. Chen: *Novel Maximum-Power-Point- Tracking Controller for Photovoltaic Energy Conversion System, IEEE Transactions On Industrial Electronics, Vol.* 48, No. 3, June 2001

[3] F. Valencaga, P. F. Puleston, and P. E. Battaiotto, “Power control of a solar/Fuel Cell generation system without Fuel Cell measurement: A passivity/ sliding mode approach,” IEEE Trans. Energy Convers., vol. 18, No. 4, Dec. 2003.

[4] X. Huang, X. Wang, T. Nergaard, J. S. Lai, X. Xu, and L. Zhu, “Parasitic ringing and design issues of digitally controlled high power interleaved boost converters,” *IEEE Trans. Power Electron.*, vol. 19, No. 5, pp. 1341–1352, Sep. 2004.

[5] K. Rajashekara, “Hybrid fuel-cell strategies for clean power generation,” *IEEE Trans. Ind. Appl.*, vol. 41, No. 3, June 2005.

[6] K. N. Reddy and V. Agrawal, “Utility-interactive hybrid distributed generation scheme with compensation feature,” *IEEE Trans. Energy Convers.*, vol. 22, No. 3, Sep. 2007.

[7] H. Tao, J. L. Duarte, andM. A.M. Hendrix, “Three-port triple-half-bridge bidirectional converter with zero-voltage switching,” *IEEE Trans. Power Electron.*, vol. 23, No. 2, Mar. 2008.

[8] O. C. Onara,M. Uzunoglu, andM. S. Alam, “Modeling, control and simulation of an autonomous Fuel Cell turbine/photovoltaic/fuel cell/ultra capacitor hybrid power system,” *J. Power Sources.*, vol. 185, No. 2, Apr.2008.

[9] A. Khaligh, J. Cao, and Y. J. Lee, “A multiple-input DC–DC converter topology,” *IEEE Trans. Power Electron.*, vol. 24, no. 3, Mar. 2009.

[10] S. H. Hosseini, S. Danyali, F. Nejabatkhah, and S. A. K. Mozafari Niapour, “Multi-input DC boost converter for grid connected hybrid PV/FC/battery power system,” in *Proc. IEEE Elect. Power Energy Conf.*, 2010

[11] R. J. Wai, Ch. Y. Lin, J. J. Liaw, and Y. R. Chang, “Newly designed ZVS multi-input converter,” *IEEE Trans. Ind. Electron.*, vol. 58, No. 2, Feb. 2011.