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 characteristic 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.
In the proposed converter, the waveform is designed to simplify the operation mode investigation. Further, charge or discharge mode for modes are considered by utilizing sawtooth carrier waveforms of the converter. The assumptions for 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: $S_4 - D_{k1}$ path2: $S_4 - D_k$. First path is chosen in this operation mode. Therefore, switch $S_4$ is turned OFF while turning ON Switch $S_3$ entirely in the switching period ($d_2 = 1$ 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).

![Fig 1: Proposed System Overview](image1)

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](image2)

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 $S_1$ and $S_4$ makes $D_2$ and $D_4$ to reverse bias by the $V_{bac}$. 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 $d_1, d_2 < \min (d_3, d_4)$ 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, some assumptions are made for

- **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 $S_3$ is turned OFF, while switch $S_2$ is still ON (according to the assumption $d_3 = d_4$). Therefore, inductor $L_1$ is discharged with voltage across $v_1 - v_2$ into the output load and the capacitor through diode $D_3$, while inductor $L_2$ is still charged by voltage across $v_2$ [see Fig. 3(b)].

- **Switching state 3 ($d_2 T < t < T$):**

![Switching state 3](image3)
Switching state 3 (d₁ ≤ t < d₂ T): At t = d₁ T, switch S₁ is also turned OFF and inductor L₁ is discharged with voltage across v₁ − vₒ, as like as inductor L₁ [see Fig. 3(c)].

Based on the balance theory, equations are

\[
L_1 : \frac{d}{dt} (v_1 - r_1 i_{L1}) + (1 - d_1) T (v_1 - r_1 i_{L1} - v_0) = 0 \quad \Rightarrow \quad v_0 = \frac{v_1 - r_1 i_{L1}}{1 - d_1} \\
L_2 : \frac{d}{dt} (v_2 - r_2 i_{L2}) + (1 - d_2) T (v_2 - r_2 i_{L2} - v_0) = 0 \quad \Rightarrow \quad v_0 = \frac{v_2 - r_2 i_{L2}}{1 - d_2} \\
C_1 : (1 - d_1) T i_{L1} + (1 - d_2) T i_{L2} = \frac{V_o}{R_{1}}
\]

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 v₁ and v₂ with Battery Discharging)

In this operation mode, the sources v₁ and v₂ supplies the load with the battery discharging state. From the converter structure, turning ON switches S₃ and S₄ simultaneously causes i₃ and i₄ to conduct through the path of S₄, the battery and S₁ which results in discharging of the battery. However, discharging operations of the battery can last until S₁ and/or S₂ are conducting. So, the maximum discharge state of the battery depends on d₁ and d₂ as well as currents i₃ and i₄:

\[
P_{\text{max, dis}} = v_o [d_3 i_{L1} + d_4 i_{L2}], \quad S_1 = \text{ON}, \quad S_4 = \text{ON}. \tag{5}
\]

The discharging power of the battery below \( P_{\text{max, dis}} \) can be made by changing the state of only one of switches S₃ and S₄ before switches S₁ and S₄ are turned OFF. d₃ is controlled to regulate the discharging power of the battery. When S₃ 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 D₄ to conduct and stops discharging mode of battery. The switching states are shown in Fig. 4(a)–(d).

Switching state 1 (0 < t < d₃ T): At t = 0, switches S₁, S₂ and S₄ are turned ON, so inductors L₁ and L₂ are charged with voltages across v₁ + vₒ and v₂ + vₒ, respectively [see Fig. 4(a)].

Switching state 2 (d₃ T < t < d₁ T): At t = d₃ T, switch S₃ is turned OFF, while switches S₁ and S₂ are still ON. Therefore, inductors L₁ and L₂ are charged with voltages across v₁ and v₂ respectively [see Fig. 4(b)].

Switching state 3 (d₁ T < t < d₂ T): At t = d₁ T, switch S₁ is turned OFF, so inductor L₁ is discharged with voltage across v₁ − vₒ, while inductor L₂ is still charged with voltages across v₂ [see Fig. 4(c)].

Switching state 4 (d₂ T < t < T): At t = d₂ T, switch S₂ is also turned OFF and inductors L₁ and L₂ are discharged with voltage across v₁ − vₒ and v₂ − vₒ, respectively [see Fig. 4(d)].
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 $S_2$. 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 $P^\text{max}_{\text{bat, ch}}$ 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 ($d_2 T < t < d_2 T$):** At $t = d_2 T$, switch $S_2$ is also turned OFF and inductor $L_2$ is discharged with voltage across $v_2 - v_o$ [see Fig. 5(d)].

Based on the balance theory, equations are

\( P^\text{max}_{\text{bat, ch}} = -v_B[d_1i_{L1} + d_2i_{L2}], \quad S_1 = \text{OFF, } S_4 = \text{OFF.} \) (10)

**Fig 5 : Third operation mode : (a) Switching state 1: $0 < t < d_3 T$ (b) Switching state 2: $d_3 T < t < d_1 T$. (c) Switching state 3: $d_1 T < t < d_2 T$. (d) Switching state 4: $d_2 T < t < T$.**

\[ L_1: \frac{d^2}{dt^2} (v_1 - r_1 i_{L1}) + (d_1 - d_2) \frac{d}{dt} (v_2 - r_1 i_{L1} - v_B) \\
+ (1 - d_1) (v_1 - r_1 i_{L1} - v_B) = 0 \]

\[ \Rightarrow 0 \to v_0 = \frac{v_1 - r_1 i_{L1}(d_2 - d_2) + \frac{R_1}{1-d_2}}{1-d_2} \] (11)

\[ L_2: \frac{d^2}{dt^2} (v_2 - r_2 i_{L2}) + (d_1 - d_2) \frac{d}{dt} (v_2 - r_2 i_{L2} - v_B) \\
+ (1 - d_2) (v_2 - r_2 i_{L2} - v_B) = 0 \]

\[ \Rightarrow 0 \to v_0 = \frac{v_2 - r_2 i_{L2}(d_2 - d_2) + \frac{R_1}{1-d_2}}{1-d_2} \] (12)
\[ C_i (1 - d_1) I_{L1} + (1 - d_2) I_{L2} = \frac{T_{eq}}{R_i} \]  

Battery:
\[ P_{Batt} = -v_B(-d_1)(i_L1 + I_L2) + a_1i_{L1} + d_2I_{L2} \]  

In this mode, \( d_1 \) and \( d_2 \) regulates powers of the Input sources, while \( d_1 \) 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 \( P_{PV} \), \( P_{PV}^{max} \), the output voltage value, and the battery charging necessity. In order to keep the battery voltage in allowable minimum and maximum voltages given by,

\[ v_{Batt-Min} < v_{Batt} < v_{Batt-Max} \]  

If the battery voltage is lesser than \( v_{Batt-Min} \) 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 \( 0.2C_Bv_{Batt} \). On the other hand, battery discharging states, occurs when battery voltage is higher than \( v_{Batt-Min} \). 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 the battery discharging is accomplished. Here, \( d_1 \) and \( d_2 \) regulates powers of the input sources, while \( d_1 \) 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 DISCUSSION

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 \( L_1 = L_2 = 6\mu H, C = 200\mu F, f_2 = 20\text{KHZ} \)

\[ r_1 = r_2 = 0.4 \Omega R_2 \] 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 \( v_B = 350\text{V} \) 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\( (S = 750\text{ W/m}^2) \), the load power required is \( P_L = 2.5\text{ KW} (R_2 = 50\Omega) \), while the maximum available PV power is \( P_{PV} = 1.7\text{ KW} \) and there is no need to charge the battery.

![Fig 6: Output Power at load side for mode 1](image)

The Fuel Cell current is set on \( I_{L2} = 4.57\text{A} \) by duty ratio \( d_2 = 0.75 \) to regulate the output voltage, while the maximum power of the PV is elicited with the current of \( I_{L2} = 11.45\text{A} \) and adjusting the first duty ratio at \( d_1 = 0.7 \). So that third and fourth duty ratios are set on \( d_3 = 0 \) and \( d_4 = 1 \), 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\( (S = 500\text{ W/m}^2) \) in which the load requires \( P_L = 2.5\text{ KW} \) and the PV power is simultaneously decreased into \( P_{PV} = 0.45\text{KW} \) 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 \( I_{L2} = 5.3\text{A} \) and adjusting the first duty ratio at \( d_1 = 0.71 \), the maximum power of is delivered at \( I_{L2} = 15.72\text{A} \). Adjusting the second duty ratio at \( d_2 = 0.73 \) and controlling the third and fourth duty ratios at \( d_3 = 1 \) and \( d_4 = 0.4 \) results in discharging the battery. Fig. 7 indicates the operation of second operation mode.

![Fig 7: Output power at load side for mode 2](image)
6.3 Third Operation Mode
In this stage, a step change in the sun irradiation level (=1000W/m²), 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](image)

In this condition, providing charging power of the battery in addition to power deficiency between the PV and the load can be accomplished. The Fuel 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 \( I_p = 4.4A \) 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](image)

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 many 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