AN ISOLATED THREE-PORT BIDIRECTIONAL DC-DC CONVERTER FOR PV BATTERY APPLICATION

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Abstract—In this paper an isolated three-port bidirectional DC-DC converter for Photovoltaic (PV) battery application is presented. This converter is capable of parallel power management of various renewable energy sources. The proposed converter is designed for controlling power of photovoltaic panel, load and rechargeable battery. The advantage of this converter is it utilizes less number of controllable switches and provides soft switching for converter primary switch. This is achieved by an inductor-capacitor-inductor resonant circuit. This converter has ability to control the battery power when there is a low and extra power according to load, and also to control maximum power point tracking for PV system. MATLAB Simulink software is used for simulation studies. Simulation results shows that irrespective of variation in solar radiation this converter is capable of maintain constant output DC link voltage by managing power between two sources.

Keywords—Photovoltaic(PV), Soft switching, Multiport Converter, battery.

I. INTRODUCTION

Now days, there is increasing interest in producing electricity from renewable energy sources due to environmental concern, progress in technology and highly reducing cost of manufacturing [1]. However, it is difficult to promote clean energy sources because discontinuity of renewable energy sources and dynamic load demand [2]. Therefore it is required to connect several renewable energy sources to satisfy load demand against challenge of discontinuity of renewable energy sources and dynamic load demand.

Traditionally, for connecting multiple renewable energy sources to grid or load multiple DC-DC converters are used [3]. So this system has many disadvantages such as less efficiency because of using independent DC-DC converter for each source, big architecture, lower power density and costly. So to overcome above drawbacks multiport DC-DC converters are used [4]. This converter has many input ports for combining various DC energy sources so it has advantages of low losses, high power density, compact structure and cheap cost.

The multiport DC-DC converter has two types based upon their connections, isolated multiport converters and non-isolated multiport converters. A non-isolated DC-DC converter has low cost and they are used in low voltage applications. In non-isolated converters there is no electrically separation between input and output terminal [5]. An isolated DC-DC converter has high cost and they are used in high voltage appliances. In an isolated DC-DC converter output and input terminals are electrically separated [6].

A mostly used isolated multiport converter includes half-bridge isolated converter topology [7]. This uses $2n+2$ controllable switches, where $n$ denotes number of input ports of the DC-DC converter. An isolated multiport converter which consists of isolated full bridge utilizes four switches for each input source [8]. Therefore these multiport DC-DC converters are composed of full bridge and half bridge cartographies uses too many switches and make difficult controlling of circuit. In some isolated multiport topologies uses only one switch for each input source but does not include any bidirectional port [9]. Bidirectional port is required for connecting storage element to the system. In many applications continuous power is required and without storage system there is no proper utilization of renewable energy sources.

This paper introduces an isolated three-port bidirectional DC-DC converter for PV battery application. The proposed converter is built for parallel power management of PV panel, battery and a load. It provides zero current switching for converter primary switch which is achieved by resonant circuit which comprises of two inductors and one capacitor.
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(LCL). This converter is controlled by using only three switches. A Perturbation and Observation MPPT control algorithm is used for getting maximum power from solar panel. This converter is capable of charging battery when excess energy is available and discharging of battery when there is energy inadequacy according to the load. For proper control of battery power charge and discharge controllers are designed.

The circuit description and general working of proposed converter is discussed in sectionII and III respectively. Controlling and component designing of the converter are detailed in section IV. Section V discusses Simulation model and simulation results of the proposed converters. Section VI summarizes a paper with conclusion.

II. CIRCUIT CONFIGURATION

Fig.1. Circuit Diagram

Fig.1 illustrates circuit diagram of proposed system. This comprises of high frequency transformer, primary of transformer is low voltage-side (LVS) circuit and secondary is high voltage side (HVS) circuit. Low voltage side circuit consist of two ports, capacitor $C_s$ which is for energy storage, LCL resonant circuit made up of inductors $L_r, L_p$ and capacitor $C_r, L_p$ consists of $L_p1$ and $L_p'$. $L_p$ and $L_p'$ is added inductance and transformer leakage inductance respectively. High voltage side circuit contains full bridge rectifier comprises of diodes $D_{s1}, D_{s2}, D_{s3}$ and $D_{s4}$. $N_p$ and $N_s$ denotes primary andsecondary turns of transformer respectively. In above circuit $S_1$ is referred as primary switch because it controls power produced from the source and also reverse direction of current in the transformer.

III. GENERAL WORKING OF PROPOSED CONVERTER

Two controllers are required to maintain power flow in the low voltage side. Their aim is to maintain constant DC-link output voltage to a specific value by managing power between two sources. Depending on solar radiation and availability of solar energy, the converter works in three scenarios. The working scenarios of proposed converter are given below:

Scenario 1 ($P_1 \geq P_{out}$): When power produced from PV panel is greater than load demand. Working of multiport converter is illustrated in Fig.2, the power required by load is provided by PV panel which operates in MPPT mode and extra power is utilized to charging of battery so DC link output voltage is keep at fix value.

Scenario 2 ($P_1 \leq P_{out}$): When power produced from PV panel is lesser than load demand. Working of multiport converter is illustrated in Fig.3; power required by load is supplied by both PV panel which operates in MPPT mode and battery. Here lack of power required by load is provided by the battery so DC link output voltage is keep at fix value.

Scenario 3 ($P_1 = 0$): When there is no power produced from PV panel. Working of multiport converter is shown in Fig.4, the whole power is required by load is supplied by the battery. Here continues discharge of battery takes place so DC link output voltage is keep at fix value.
For working of converter in different scenarios two controllers are required. One of them is MPPT controller for solar panel and other is bucks boost converter for control battery power (charging and discharging).

IV. CONTROLLING AND PARAMETERS DESIGN OF CONVERTER

In this section for working of converter in different scenarios and for achieving soft switching various controllers are discussed.

A. An inductor capacitor inductor (LCL) resonant circuit for photovoltaic panel.

In steady state condition, voltage across capacitor $C_s (V_{cs})$ is equal to PV panel output voltage ($V_1$). LCL resonant circuit includes two inductors $L_r$ and $L_p$ and capacitor $C_r$. This converter operates in seven distinct modes based on resonant circuit and position of $S_1$ [10]. Fig. 5 illustrate equivalent diagram of resonant circuit in distinct modes. The differential equations of this circuit in mode k are:

$$v = L_r^{(k)} \frac{di_r^{(k)}}{dt}$$

$$i_1 = C_r \frac{dv}{dt} + L_r^{(k)}$$

Where $v$ denotes voltage across capacitor $C$, $i_r^{k}$ and $L_r^{k}$ denotes current flowing in the resonant inductor and the equivalent resonant inductance in the $k^{th}$ mode of operation.

When switch $S_1$ is on, inductors $L_p, L_r$ are resonates with capacitor $C_r$, the current through $L_r$ is increases, and voltage across $C_r$ decreases. Due to presence of $L_r$ current flowing through $S_1$ is gradually increases and switch $S_1$ operates in poor $di/dt$ condition. So resonant frequency is expressed as follows:

$$\omega_1 = \frac{1}{\sqrt{(L_r/L_p)C_r}}$$

There are five inductances in the converter for smooth operation of converter proper design of the inductances is required. $L_m$ is calculated according to critical inductance $L_{mc}$ [11]. The value of $L_m$ is greater than $L_{mc}$, $L_p$ can be measured when designing of transformer is completed.

The quality factor (Q) of inductor capacitor inductor (LCL) resonant converter is expressed as [12]:

$$Q = \frac{8. n^2. R_L}{\pi^2. Z}$$

Where $n$ is transformer turns ratio, $R_L$ is load resistance and $Z$ is resonant circuit impedance given as follows:

$$Z = \sqrt{\frac{L_r / (L_p + L_p)}{C_r}}$$

The value of Q is lies between range of [1.5, 5]. If the value of Q is selected 3.7 and load resistance value is known then value of Z is calculated from (4).
The values of \( C_r \) and resonant frequency are calculated from (3) and (5). By assuming required condition for zero current switching \( L_p > L_r \) [12], \( L_r = L_p \) is selected. Then \( L_r \) can be derived from (5). The values of \( L_1 \) and \( L_2 \) are derived which is based on their ripples of current [9].

B. MPPT controller for solar panel.

Whenever there is availability of solar radiation, the converter must operate in MPPT mode. Therefore, to get maximum power from solar panel, MPPT algorithm is used. Here, perturbation and observation algorithm is used for maximizing PV panel efficiency as shown in Fig. 6. It is the easiest method of MPPT control. In this output power of system is observed by changing the supplied voltage. If increase in voltage cause increase in power then increase duty cycle (\( \delta \)) else decrease duty cycle. If decreasing in voltage cause increasing output power then decrease duty cycle. This is continuous till maximum power point (MPP) is achieved. As illustrated in Fig. 6, the Perturbation and Observation MPPT algorithm is realized by frequency modulation method [13].

![Flowchart of P&O MPPT algorithm](image)

C. Buck and Boost Converter for Battery

For charging and discharging purposes, the battery is required to form buck and boost converter. The buck and boost converter is comprised of inductor \( L_2 \), switches \( S_2 \) and \( S_3 \), and capacitor \( C_s \). When power produced from PV panel is greater than the load demand, \( S_3 \) is off and \( S_2 \) is on so it forms buck converter. Extra produced power from solar panel is stored in battery. When power obtained from solar panel is lesser than load demand, \( S_2 \) is off and \( S_3 \) is on and it forms boost converter. Discharging of battery takes place to charge \( C_s \) which supply energy deficiency of load and fulfill the load demand.

The current in the battery is controlled by proportional integral (PI) controller. Separate PI controllers are used for charging and discharging respectively. For every current in the battery, PI controller produce duty cycle for switches \( S_2/S_3 \) by using input of current error. When current in the battery is less than or equal to zero, charge PI controller is chosen, then duty cycles are \( d_3 = 0 \) and \( d_2 \geq 0 \). When current in battery is more than zero, discharge PI controller is chosen, then the duty cycles are \( d_2 = 0 \) and \( d_3 > 0 \).

V. SIMULATION RESULTS

MATLAB Simulink software is used for simulation of this proposed converter and results are discussed below. The parameters of the converter are given in the TABLE I.

### TABLE I

<table>
<thead>
<tr>
<th>Components</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer turns ratio (( n ))</td>
<td>5:14</td>
</tr>
<tr>
<td>Inductors</td>
<td>( L_r ) 3( \mu )H, ( L_p ) 3.5( \mu )H</td>
</tr>
<tr>
<td>Capacitor</td>
<td>( C_r ) 0.22( \mu )F</td>
</tr>
<tr>
<td>PV panel open circuit voltage(( V_{oc} ))</td>
<td>22V</td>
</tr>
<tr>
<td>PV panel short circuit current (( I_{sc} ))</td>
<td>3.15A</td>
</tr>
<tr>
<td>On time of ( S_1 ) (( t_{on} ))</td>
<td>3( \mu )s</td>
</tr>
<tr>
<td>Load resistance (( R_L ))</td>
<td>100( \Omega )</td>
</tr>
<tr>
<td>Switching frequency range</td>
<td>100-170 kHz</td>
</tr>
<tr>
<td>DC link voltage</td>
<td>50V</td>
</tr>
<tr>
<td>Nominal load power</td>
<td>25W</td>
</tr>
</tbody>
</table>

Fig. 7 shows simulation model of proposed converter with different controllers. To check converter operation with controllers in different scenarios, step change of radiation is given to PV panel as illustrated in Fig. 8 (a). When there is no solar radiation, the power generated by solar panel is zero as illustrated in Fig. 8 (b). This is the case of converter operates in scenario 3. All the required power by load is provided by the battery so discharging of battery...
takes place; Fig.8(c) shows that constant 50V DC link voltage.

When solar radiation is varies from zero to 400W/m$^2$, then power generated by solar panel is also changes to 20W are illustrated in Fig.8 (b). Power generated by solar panel is less than load demand (25W). This is the case of converter operates in scenario 2. Therefore battery is used to fulfill the load demand and DC link voltage reaches to constant voltage of 50V is illustrated in Fig.8(c).

When solar radiation is reaches to 600W/m$^2$, then power produced from solar panel also increases to 32W is illustrated in Fig.8 (b). Power generated by solar panel is greater than load demand which is 25W. This is the case of converter operates in scenario 1. Therefore extra generated power by solar panel is used to charge the battery and DC link voltage is keep at fix value of 50V is illustrated in Fig.8(c).

To check the usefulness of the converter for various controllers like MPPT control the system is simulated by using data from National Renewable Energy Laboratory (NERL). Fig. 9 illustrates the results of simulation by utilizing data from NERL. Fig.9 (a) illustrates generated PV power by utilizing MPPT control algorithm which is same as ideal MPP. Fig.9 (b) illustrates output DC link voltage which is maintained at steady 50 V value.

![Fig.8. step responses: (a) solar radiation, (b) PV power, (c) DC link voltage.](image)

![Fig.7. Simulation model of proposed system](image)

![Fig.9. Simulation results using data from NREL: (a) generated PV power (b) DC link voltage](image)
VI. CONCLUSION

This paper introduced an isolated three-port bidirectional DC-DC converter for PV battery application, which is controlled by less number of switches. This converter is capable of parallel power management of various energy sources like PV panel, battery etc. This converter provides MPPT control to PV panel and low voltage stress on converter primary switch. Simulation results shows that irrespective of variation in solar radiation this converter is capable of maintain constant output DC link voltage by managing power between two sources.

REFERENCES


