Photovoltaic system connected Isolated Three port bidirectional DC-DC converter with Energy storage

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Abstract—The Project proposes a new isolated multiple input bidirectional DC-DC converter with power management. The proposed converter uses less number of switches with soft switching option for the main switch, which can be realized by using LCL converter circuit and hence ZCS can be achieved. It can manage the power with pv panel, rechargeable battery, and a load. The PV system is connected to unidirectional port and the battery is connected to bidirectional port. Isolated multiport converter which contain transformer is used and hence used for high voltage regulation ratio. The operating principle of battery, charging and discharging is explained by using different modes. The main objective is to regulate the output DC link voltage to a constant value and also to manage the power for the sources. MATLAB is used to stimulate the circuit and hardware prototype is of open loop.

Keywords—Bidirectional Dc-Dc Converter, Battery, Photovoltaic(PV), Multiport Converter, Soft Switching, Zero-Current Switching(ZCS).

I. INTRODUCTION

A multiport dc-dc converter has the advantage of using less number of components, lower cost, high power density and high efficiency. Multiport converters are of 2 types viz; non-isolated and isolated topologies. non-isolated multiport converters are used for low voltage regulation ratio whereas isolated multiport converters are used for high voltage regulation ratio, usually isolated converter with transformer is used.

It contains a new isolated three port bidirectional dc-dc converter. An LCL resonant circuit is used in order to achieve ZCS for the main switch. It consists of three switches and renewable energy is used to charge the battery and the battery is connected to the proposed converter circuit.

The simultaneous management of power takes place with the PV system and battery. The PV is connected to unidirectional port whereas battery is connected to bidirectional port of the converter.

II. TOPOLOGY AND OPERATION OF THE PROPOSED CONVERTER

Fig (1). Proposed isolated three port, bidirectional, DC-DC converter for a PV and battery system

A. Topology of the converter

The circuit consists of Low voltage side (LVS) and High voltage side(HVS). The LVS mainly consists of primary winding of transformer, LCL resonant circuit and energy storage capacitor. The HVS consists of secondary winding of transformer and a full bridge rectifier. It consists of three switches. S1 is called the main switch which controls the power generated by the source connected to port1(P1) and also changes the direction of current flowing through the transformer.

B. Single-Switch LCL-Resonant Converter

In a switching period, the voltages across C1 and Cs can be taken as constant values. Particularly, in the steady state, VCs = V1, where V1 is the output voltage of the PV panel. The converter has seven operating modes depending on the states of the switch S1 and the resonant circuit. Fig. 2 shows the equivalent resonant circuit in different modes. The differential equations of the resonant circuit in Mode k (k = 1, ..., 7) are

\[
\begin{align*}
\frac{dv}{dt} & = L_C \frac{di_1}{dt} + L_{\text{res}} \frac{dv}{dt} + \frac{1}{C} i_{\text{in}}(t) \\
\frac{di_1}{dt} & = C_r \frac{dv}{dt} + i_{\text{in}}(t)
\end{align*}
\]

(1)
where \( v \) represents the voltage of the capacitor \( C_r \); \( L_r(k) \) and \( i_r(k) \) represents the equivalent resonant inductance and the current through the equivalent resonant inductor in the \( k \)th (\( k = 1, \ldots, 7 \)) operating mode, respectively. Then \( v \) can be solved from (1) and has the following form.

\[
v(t) = A^{(k)} \cos \left[ \omega^{(k)} (t - t_k) \right] + B^{(k)} \sin \left[ \omega^{(k)} (t - t_k) \right] + V^{(k)}
\]

where

\[
\omega^{(k)} = \frac{1}{\sqrt{L_r^{(k)} \cdot C_r}}
\]

(3) is the resonant frequency in Mode \( k \); \( V(k) \) is the particular solution of equation (1) in Mode \( k \), and \( A(k) \) and \( B(k) \) are coefficients, which can be expressed as

\[
A^{(k)} = v(t_k) - V^{(k)}
\]

\[
B^{(k)} = \frac{I_1 - i_r(t_k) - i(t_k)}{\omega^{(k)} \cdot C_r}
\]

(5) where \( v(t_k) \), \( I_1 \), \( i_r(t_k) \), and \( i(t_k) \) represent the voltage across \( C_r \) and the currents of \( L_1 \) (\( i_1 \) can be viewed as a constant value \( I_1 \) because of a large \( L_1 \)), \( L_p \), and \( L_r \) at time \( t_k \), respectively. Equations (4) and (5) indicate that only \( \omega(k) \) and \( V(k) \) are required to determine the parameters of (2). The steady-state waveforms and equivalent circuits of the seven operating modes of the converter are shown in Figs. 3 and 4, respectively. To facilitate the explanation of the converter operation, define \( VT = n \cdot V_{dc} \) the equivalent output voltage of the converter referred to the primary side of the transformer.

Mode 1: \( t \in [t_1, t_2] \) (see Fig. 3). Prior to Mode 1, \( S_1 \) is off; the currents through \( L_r \) and \( L_p \) are zero and a positive value of \( I_1 \), respectively, i.e., \( i(t_1) = 0, i_p(t_1) = I_1 \). When \( S_1 \) is on, as shown in Fig. 4(a), \( L_r \) and \( L_p \) resonate with \( C_r \), the current of the inductor \( L_r \) increases and the voltage of the capacitor \( C_r \) decreases. Due to the existence of \( L_r \), the current through the switch \( S_1 \) increases slowly so that the switch is turned on under a low \( di/dt \) condition. The resonant frequency and the particular solution in this mode can be expressed as;

\[
\omega^{(3)} = 1/\sqrt{\left( L_r + L_p \right) \cdot C_r}
\]

\[
v^{(3)} = \frac{L_r}{L_r + L_p + L_n} \left( v_p - v_p^* \right)
\]

This mode terminates at time \( t_4 \) when the current of \( L_r \) decreases to zero, i.e., \( i(t_4) = 0 \).

Mode 2: \( t \in [t_2, t_3] \), during which \( S_1 \) is on, \( i(t) > 0 \), and \( i_p(t) = im(t) \), \( D_{s1} - D_{s4} \) are reverse biased such that \( i_T = 0 \). As shown in Fig. 4(b), \( L_m, L_p, \) and \( L_r \) resonate with \( C_r \). Since \( L_m >> L_p, L_m >> L_r \), then

\[
\omega^{(2)} = 1/\sqrt{\left( L_p + L_r \right) / L_n \cdot C_r}
\]

\[
v^{(2)} = \frac{L_r}{L_r + L_p + L_n} \cdot V_T - \frac{L_p}{L_r + L_p + L_n} \cdot V_1
\]

At the end of Mode 2, \( v_p(t_3) = -VT, v(t_3) = V_1 - VT, \) the diodes \( D_{s2} \) and \( D_{s4} \) begin to conduct. Mode 3: \( t \in [t_3, t_4] \), during which \( S_1 \) is on, \( i(t) > 0, v_p(t) = -VT, i_T < 0 \). As shown in Fig. 4(c), \( L_r, L_p \) resonate with \( C_r \), the energy stored in \( L_r \) is released to charge the capacitor \( C_r \); \( v_p \) is clamped to \( -VT \); and \( i_T \) is negative, which indicates the conduction of \( D_{s2} \) and \( D_{s4} \). Compared to Mode 1, the only difference in the equivalent circuit in this mode is the sign of \( v_p \). Thus, \( \omega^{(3)} = \omega^{(1)} \) and

\[
v^{(3)} = \frac{L_r}{L_r + L_p} \cdot v_p
\]

This mode terminates at time \( t_4 \) when the current of \( L_r \) decreases to zero, i.e., \( i(t_4) = 0 \).

Mode 4: \( t \in [t_4, t_5] \), during which \( S_1 \) is on, \( i(t) < 0, v_p(t) = -VT, i_T < 0, \) and \( D_{s2} \) and \( D_{s4} \) conduct. As shown in Fig. 4(d), a negative current flows through the internal diode of the switch \( S_1 \); the gate signal can be
removed to turn off the switch, e.g., at time t5, under the ZCS condition. The circuit equations are the same as those in Mode 3. Thus, ω(4) = ω(1), V(4) = V(3). At the end of Mode 4, i(t5) = 0 and the voltage across the switch S1 is the same as that across the capacitor Cr, i.e., vds1(t5) = v.

Mode 5: t ∈ [t5, t6], during which S1 is off, i(t) = 0, vp = −VT, and iT2 < 0. As shown in Fig. 4(e), Lr and the switch S1 can be neglected in the circuit. The inductor Lp resonates with Cr, and the direction of ip changes from negative to positive. The following can be obtained.

\[ \omega(5) = 1/\sqrt{L_p \cdot C_r} \]  
\[ V(5) = V_1 - V_T \]  

At the end of Mode 5, ip(t6) = im(t6), iT2(t6) = 0, and vp changes its polarity from negative to positive.

Mode 6: t ∈ [t6, t7], during which S1 is off, i(t) = 0, vp(t) = im(t), Ds1−Ds4 are reverse biased such that iT2 = 0. As shown in Fig. 4(f), Lm and Lp resonate with Cr, and Cr is charged. The following can be obtained.

\[ \omega(6) = 1/\sqrt{(L_p + L_m) \cdot C_r} \approx 1/\sqrt{L_p \cdot C_r} \]  
\[ V(6) = V_1 \]  

At time t7, vt(7) = V1 + VT and vp(t7) = VT.

Mode 7: t ∈ [t7, t8], during which S1 is off, i(t) = 0, vp(t) = VT, Ds1 and Ds3 conduct. As shown in Fig. 4(g), Lp resonates with Cr, the circuit equations are the same as those in Mode 5 except the sign of vp, then ω(7) = ω(5), and

\[ V(7) = V_1 + V_T \]  

Once S1 is turned on at time t8, Mode 7 switches to Mode 1. There are five inductances L1, L2, Lr, Lp1, and Lm in the proposed converter that need to be properly designed. Lm is designed based on the following critical inductance Lmc [18].

\[ L_m = \frac{V_T \cdot T}{4 \cdot I_{m,pk}} \]  

where T is the switching period of the switch S1; Im,pk is the peak current through the magnetizing inductor. In this paper, the root mean square (RMS) value of the magnetizing current is designed to be 2% of the RMS value of ip. Then Lm is designed to be larger than Lmc. Once the transformer is designed, the leakage inductance Lp of the transformer can be measured. Given the load resistance RL and the transformer’s turn ratio n, the quality factor Q of this LCL-resonant converter can be calculated [19];

\[ Q = \frac{8 \cdot n^2 \cdot R_s}{\pi^2 \cdot Z} \]  

where Z is the characteristic impedance of the resonant circuit defined below.

\[ Z = \sqrt{\frac{L_r/(L_p + L_s)}{C_r}} \]  

Given the desired value of Q and the value of RL, the value of Z can be calculated from (16). In this paper, Q is selected in the optimal range of [1.5, 5]. Specifically, the value of Q is 3.7 when the nominal load is applied. Then, given the resonant frequency, Cr can be calculated from (6) and (18). Considering the necessary condition Lp>Lr to achieve ZCS [20], Lr = Lp1 is selected such that the currents through the switch S1 and the transformer are close during the resonant stage. Then Lr and Lp1 can be calculated from (18) with the measured value of Lp. The values of L1 and L2 are designed according to their desired current ripples [10]. In this paper, it is expected that the current ripples are within 5% of their nominal currents.

Fig(4)Equivalent circuits for different operating modes

C. BUCK AND BOOST OPERATION OF BATTERY

It consists of Inductor L2, Switches S2 and S3 and Capacitor Cs.

When the available solar energy is more than the load requirement, S3 is switched off and S2 will be switched on hence act as a buck converter and some amount of energy is stored in the battery which is obtained from the PV panel.

If the available solar energy is less than the load demand then S2 will be off and S3 is switched on to form a boost converter and hence the battery is discharged to fulfill the load requirement.

III. POWER MANAGEMENT OF THE CONVERTER

The main objective is to regulate the output DC link voltage to a constant value and also to manage the power for the sources.

According to the availability of the solar energy there are 3 working scenarios of the converter:

- Scenario 1(p1>pout)- As shown in fig(a). If the available solar power is more than the load demand, the battery is charged and the PV panel supplies energy to the load.

ISSN (Online): 2347 - 2812, Volume-4, Issue -9, 2016

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**Scenario 2** \((0 < p_1 < p_{out})\): As shown in Fig(b), if the solar power is less than the load demand, the battery gets discharged. Both the PV panel and battery provide energy to the load.

**Scenario 3** \((p_1 = 0)\): As shown in Fig(c), if there is no solar power then the battery alone will discharge and supply energy to the load.

### Table 1: Parameters for simulation

<table>
<thead>
<tr>
<th>Components</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer turns ratio</td>
<td>5:14</td>
</tr>
<tr>
<td>(L_r)</td>
<td>3.3uH</td>
</tr>
<tr>
<td>(L_p)</td>
<td>3.5uH</td>
</tr>
<tr>
<td>(C_r)</td>
<td>0.22uF</td>
</tr>
<tr>
<td>Battery</td>
<td>7.5V, 0.16 ohm</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>100kHz to 170kHz</td>
</tr>
<tr>
<td>Resistive load</td>
<td>100 ohm</td>
</tr>
<tr>
<td>Input dc voltage</td>
<td>16-22v</td>
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<tr>
<td>Output dc voltage</td>
<td>50v</td>
</tr>
<tr>
<td>Output power</td>
<td>25W</td>
</tr>
</tbody>
</table>

D. Circuit diagram of simulation

E. Status of battery, voltage and current waveform.

**Scenario 1** \((p_1 > p_{out})\), **Scenario 2** \((0 < p_1 < p_{out})\), **Scenario 3** \((p_1 = 0)\).
V. CONCLUSION

This paper proposed a new isolated three port bidirectional DC-DC converter which uses very less number of switches and is used for simultaneous power management of multiple energy sources.

The voltage stress of the main switch can be reduced as soft switching is adopted.

The proposed converter is applicable to other types of renewable energy sources such as wind turbine generators.

REFERENCE


