ANALYSIS OF ISOLATED MULTI-PORT CONVERTER FOR INTEGRATING RENEWABLE ENERGY SOURCES BY USING SIMULATION SOFTWARE

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Abstract: In this paper, a new multi-port isolated SEPIC converter is analyzed for integrating with the renewable energy sources. This multi-port SEPIC converter provides the highest energy efficiency by utilizing only a single power stage. In this proposed structure, for input side a combination of Pulsating Voltage Cells (PVC) and Pulsating Voltage Source Cell (PVSC) are used. For output side, Pulsating Voltage Load Cell (PVLC) is used. Each PVSC connects with a common PVLC through a coupling capacitor, forming a complete SEPIC structure. It has two topologies, they are unidirectional and bidirectional. Thus, the SEPIC converter reduces the steady state error and maximum overshoot to zero. This multi-port SEPIC converter treats the whole system as a single-stage converter, and promises higher energy efficiency.

Keywords: DC/DC converter, Pulsating voltage source cell (PVSC), Pulsating Voltage Load Cell (PVLC).

1. Introduction

Nowadays the usage of power has increased day-by-day; however, the source of power is inadequate. Many micro sources such as batteries, fuel cells and PV [1-5], find extensive application in the case of distributed generation. Three-Port DC/DC converter is highly suitable for standalone PV system applications. Three-Port converter has advantages such as less component count, lower cost, higher reliability and fewer conversion stages [6][7]. Pulse Width Modulation (PWM) scheme is applied to the Three-Port converter based on power relations among three ports. DC/DC converter works in all operating modes and can easily switch between dissimilar modes, so that it has extra advantages such as high efficiency, higher flexibility, reliability and lower cost [8]-[9]. InCuk and SEPIC converter, the input current is continuous. While, in Buck-Boost converter the input current is not continuous. This leads to an advantage in better power factor. Another advantage of SEPIC converter is that it has non-inverting output, unlike, in Cuk converter and Buck-Boost converter. By this configuration, two sources can supply the load separately or simultaneously, depending on the availability of the sources. The embedded nature of this converter is that additional input filters are not required or mandatory to filter out high frequency harmonics, as CUK and SEPIC converters can filter out harmonic contents in a better way and can produce efficient outputs [10]. A SEPIC converter for higher power and higher gain application has been proposed in this paper. For relatively higher power applications, people prefer the use of interleaved Fly-back converter structures[1]. The Multi-port converter(MPC) is triggered by interconnecting multiple PVCs through DLIs. [12]. Power is generated by using a few renewable resources such as solar, wind and so on. [13]. Traditionally, renewable energy source is connected to the load through using DC-DC converter. There are five main types of DC-DC converters. They are: Buck, Boost, Buck-Boost, Cuk and SEPIC converter.[14].

The MPC is generated by interconnecting multiple PVCs through DLIs. PVCs can be of input, output and bidirectional type. As a result, a family of unique MPCs including multi-input converters, and bidirectional MPCs, are derived [15]. MPCs have attracted research interest recently with the rapid development of renewable power systems, electric vehicles, and DC distribution power systems, where multiple renewable sources, storages and loads are connected together. Compared to the conventional approach that employs multiple two-port (either unidirectional or bidirectional) converters, a MPC treats the whole system as a single-power converter and promises higher energy efficiency by utilizing only a single power stage [16]-[20].

This paper is organized as follows. In Section II, derivation of three-port isolated SEPIC converter and the
topology are proposed in detail. In Section III, Steady state analysis of Three-Port isolated Unidirectional SEPIC converter were proposed. In Section IV three-Port Bi-directional isolated SEPIC converter and small ripple approximation of both the topologies were proposed. In Section V simulation results are discussed in detail in both the topologies.

2. Derivation of Three-Port Isolated SEPIC Converter

2.1 Basic Idea for derivation of Multi-Port SEPIC Converter

Many isolated Three-Port DC-DC converters have been presented with different control and modulation methods. Some of them use only one inductor resulting in small sizes and further improvement of the power density, while others use two or three inductors. Since most of these converters are derived based on the traditional Boost, Buck, and Buck-Boost converters, the benefits of these converters are limited. To overcome this limitation, some Three-Port DC-DC converters.

In the multiport method, a single controller is used for multiple inputs and output ports. In this multi-port DC-DC power converter, there will be fewer power components, which implies that expense of the power converter will be lower than that of the conventional converter. Due to the presence of transformer in the circuit electric confinement is accessible, which is essential for safety. With the turn proportion of the transformer in certain topologies, it will be more effective to coordinate diverse renewable energy sources of distinctive voltage levels.

2.2 SEPIC Converter

In SEPIC converter, when the pulse is high, the switch $S$ on the input voltage, charges the inductor $L_1$, and the capacitor $C_1$ charges the inductor $L_2$. The diode $D$ is reverse biased, and the capacitor $C_2$ maintains the output. When the pulse is low, the switch $S$ is off, the inductors discharge through the diode to the load, and charges the capacitors. Increase in duty cycle charges the inductor longer, due to which more output voltage is available across the load. The converter is assumed to be loss-less with less switching ripples. The link between input and output voltage can be obtained both in Continuous Conduction Mode (CCM) and in Discontinuous Conduction Mode (DCM). CCM is preferable for higher efficiency and excellent utilization of passive components and converter switches. Therefore, the converter was designed to operate in CCM. For continuous load current, the load voltage $V_0$ can be obtained from equation, no.1.

$$V_0(\text{CCM}) = V \frac{D}{1-D}$$  \hspace{1cm} (1)

Figure 1. Generalized diagram of n-ports SEPIC converter

In this paper, four ports (two input ports and two output ports) SEPIC/SEPIC isolated converters are proposed. In topology 1, if both the sources are renewable dc source for example solar PV and fuel cell (FC) then the converter works as unidirectional converter as the energy flows from sources to load. When its output inductor is replaced by coupled inductors, further flexibility is achieved in the multiple-input isolated single ended primary inductor converter (MIISEPIC) thanks to its wider voltage transfer ratio ranges. With the coupled-inductors, an MIISSEPIC can possibly generate a high output voltage that matches the utility voltage level from low voltage distributed generation systems.

Table.1 shows the comparison of components used in proposed ‘n’ port isolated SEPIC/SEPIC multiport converter and conventional multiple input port converter. Here ‘n’ port refers to (n-1) number of source and one output port.
Table 1. Comparison of components of multi-port SEpic/sepic converter and multiple input SEpic converter

<table>
<thead>
<tr>
<th>Components</th>
<th>n port SEpic/sepic converter</th>
<th>(n-1) individual SEpic converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitors</td>
<td>n</td>
<td>2(n-1)</td>
</tr>
<tr>
<td>Inductors</td>
<td>n</td>
<td>2(n-1)</td>
</tr>
<tr>
<td>Diode</td>
<td>n-1</td>
<td>n-1</td>
</tr>
</tbody>
</table>

Figure 3. Three port unidirectional SEpic/sepic converter

2.4 Unidirectional power flow with two separate sources

Let us consider two separate sources (PV and Fuel cell) having different value of voltages $V_1$ and $V_2$. In order to use the sources effectively, the two sources operate at different duty cycle. The source with higher value, operate for lower duty cycle and the source with lesser value, operate for higher duty cycle. Assuming $V_1 > V_2$ and $D_1 < D_2$.

$D_1$ and $D_2$ are the respective duty cycles for source 1 and source 2.

3. Modes of operation

The operation is categorized in three modes as shown in Figure 4.

Mode 1: $S_1$ and $S_2$ ON, only $S_1$ conducts

In this mode although both $S_1$ and $S_2$ are on but $S_1$ only conducts as the voltage on the dc blocking capacitor $C_1$ is greater than the voltage on $C_2$. When $S_1$ is closed, $L_1$ starts charging, $C_1$, which is assumed to be pre-charged, discharges through the $S_1$, $L_2$ and $C_2$ are charged by $V_2$. $L_M$ is discharged through $C_1$. At the load side, capacitor $C$ supplies the output.

Mode 2: $S_1$ OFF and $S_2$ ON

Once the switch $S_1$ is open $S_2$ automatically starts conducting. The direction of flow of current is as shown in the Figure below. Here $C_1$ and $L_1$ are charged by $V_1$. Output voltage is maintained by the load side capacitor, $C$ and the diode is reverse biased.

Figure 4. Modes of operation of three port unidirectional SEpic/sepic converter

Where $D_{eff}$ is the effective duty of source 2, $D_{eff} = D_2 - D_1$, and $D_0$ is the duty for which diode conducts, $D_0 = 1 - D_2$.

Figure 5. Mode 1 of three port unidirectional SEpic/sepic converter
Figure 6. Mode 2 of three port unidirectional SEPIC/SEPIC converter

Mode 3: $S_1$ and $S_2$ OFF, D conducts

When both the switches are off then the diode becomes forward biased and behaves as short circuit. The inductors $L_1$ and $L_2$ discharge thus charging $C_1$ and $C_2$ respectively. $L_M$ also discharges through the load as shown in figure 7.

Figure 7. Mode 3 of three port unidirectional SEPIC/SEPIC converter

4. Steady state analysis of three port unidirectional SEPIC/SEPIC converter

Let us consider

- $i_1 = \text{Current through } L_1$
- $i_2 = \text{Current through } L_2$
- $i_{LM} = \text{Current through } L_M$
- $V_{C1} = \text{Voltage through } C_1$
- $V_{C2} = \text{Voltage through } C_2$
- $V_C = \text{Voltage through } C$

While doing the analysis the voltage and current ripples are assumed to be negligible. Writing the steady state equations of the voltages and currents:

Mode 1

$$L_1 \frac{di_{L1}}{dt} = V_1$$  \hspace{1cm} (2)

$$L_2 \frac{di_{L2}}{dt} = V_2 - V_{C_2} + V_{C_1}$$  \hspace{1cm} (3)

$$L_M \frac{di_{LM}}{dt} = V_{C1}$$  \hspace{1cm} (4)

$$C_1 \frac{dV_{C1}}{dt} = -(i_{LM} + i_{L2})$$  \hspace{1cm} (5)

$$C_2 \frac{dV_{C2}}{dt} = i_{L2}$$  \hspace{1cm} (6)

$$C \frac{dV_C}{dt} = -\frac{V_C}{R}$$  \hspace{1cm} (7)

Mode 2

$$L_1 \frac{di_{L1}}{dt} = V_1 - V_{C1} + V_{C2}$$  \hspace{1cm} (8)

$$L_2 \frac{di_{L2}}{dt} = V_2$$  \hspace{1cm} (9)

$$L_M \frac{di_{LM}}{dt} = V_{C2}$$  \hspace{1cm} (10)

$$C_1 \frac{dV_{C1}}{dt} = i_{L1}$$  \hspace{1cm} (11)

$$C_2 \frac{dV_{C2}}{dt} = -(i_{LM} + i_{L1})$$  \hspace{1cm} (12)

$$C \frac{dV_C}{dt} = -\frac{V_C}{R}$$  \hspace{1cm} (13)

Mode 3

$$L_1 \frac{di_{L1}}{dt} = V_1 - V_{C1} - nV_{C}$$  \hspace{1cm} (14)

$$L_2 \frac{di_{L2}}{dt} = V_2 - V_{C2} - nV_{C}$$  \hspace{1cm} (15)

$$L_M \frac{di_{LM}}{dt} = -nV_{C}$$  \hspace{1cm} (16)

$$C_1 \frac{dV_{C1}}{dt} = i_{L1}$$  \hspace{1cm} (17)

$$C_2 \frac{dV_{C2}}{dt} = i_{L2}$$  \hspace{1cm} (18)

$$C \frac{dV_C}{dt} = n(i_{L1} + i_{L2} + i_{LM}) - \frac{V_C}{R}$$  \hspace{1cm} (19)

Now simplifying the equations from 1 to 19 and rewriting again
\[ L_1 \frac{di_{L1}}{dt} = V_1 + (V_{C2} - V_{C1})D_{eff} - (V_{C1} + nV_C)D_D \]  
(20)

\[ L_2 \frac{di_{L2}}{dt} = V_2 - (V_{C2} - V_{C1})D_1 - (V_{C2} + nV_C)D_D \]  
(21)

\[ L_M \frac{di_{LM}}{dt} = V_{C1} D_1 + V_{C2} D_{eff} - nV_C D_D \]  
(22)

\[ C_1 \frac{dV_{C1}}{dt} = -(i_{LM} + i_{L2}) D_1 + i_{L1} (1 - D_1) \]  
(23)

\[ C_2 \frac{dV_{C2}}{dt} = (1 - D_{eff}) i_{L2} - (i_{LM} + i_{L1}) D_{eff} \]  
(24)

\[ C \frac{dV_C}{dt} = -\frac{V_C}{R} + n (i_{L1} + i_{L2} + i_{LM}) D_D \]  
(25)

At the steady state assuming
\[ L_1 \frac{di_{L1}}{dt} = L_2 \frac{di_{L2}}{dt} = L_M \frac{di_{LM}}{dt}, V_{C1} = V_1, V_{C2} = V_2 \]

and
\[ C_1 \frac{dV_{C1}}{dt} = C_2 \frac{dV_{C2}}{dt} = C \frac{dV_C}{dt} \]

So
\[ L_M \frac{di_{LM}}{dt} = V_{C1} D_1 + V_{C2} D_{eff} - nV_C D_D \]

Putting the steady state assumption in the above equation then the output voltage will become given in the equation no.26.

\[ V_C = V_o = \frac{D_1 V_1 + D_{eff} V_2}{n (1 - D_2)} \]  
(26)

The equation no.26 represents the output voltage expression of three port unidirectional SEPIC/SEPIC converter. On solving the steady state equations (20) to (25) by taking the left hand side as zero, the six state variables can be derived \((i_{L1}, i_{L2}, i_{LM}, V_{C1}, V_{C2} \text{ and } V_C)\).

\[ i_{L1} = I_1 = \frac{V_o D_1}{n D_2 R} \]  
(27)

\[ i_{L2} = I_2 = \frac{V_o D_{eff}}{n D_2 R} \]  
(28)

\[ i_{LM} = I_3 = \frac{V_o}{n R} \]  
(29)

\[ V_{C1} = V_1 \]  
(30)

\[ V_{C2} = V_2 \]  
(31)

\[ V_{C1} = V_o \]  
(32)

5. Three-port Bi-directional SEPIC/SEPIC Converter (Topology- 2)

If one source is renewable dc source and other one is battery then the circuit is called bi-directional converter as shown in Figure 3. Here if the source voltage is greater than the battery voltage then the battery starts charging through the other source. When the battery is charged to a pre-set value then the whole structure acts as a normal multiport SEPIC/SEPIC converter.

![Figure 8. Three port bidirectional SEPIC/SEPIC converter](image)

Here there are two cases:

a. \( V < E \), Discharging condition (Here both \( S_1 \) and \( S_2 \) work and battery discharges)
b. \( V > E \), Charging condition (Here \( S_2 \) remains off and battery gets charged by the source \( V \))

A. Discharging period

In this mode \( S_1 \) and \( S_2 \) operate for a duty cycle of \( D_1, D_2 \) respectively. The working principle of this mode is same as the Multi input single output SEPIC/SEPIC converter.

![Figure 9. Modes of operation of three port bidirectional SEPIC/SEPIC converter (discharging)](image)

Assuming \( D_1 > D_2 \), the output voltage equation is given by,

\[ V_c = V_o = \frac{D_3 E + D_{eff} V}{n (1 - D_1)} \]  
(33)

B. Charging period
When the battery voltage is less than the source voltage and the charge across the battery is less than a pre-defined value, battery starts charging. $S_2$ remains in off state throughout the charging period.

**Figure 10.** Modes of operation of three port bidirectional SEPIC/SEPIC converter (charging)

**Mode 1 (S₂ is always in off state)**

In this mode $S_1$ conducts for a period of $D_1$. $C_1$ discharges through the switch $S_1$ and the stored energy charges the capacitor $C_2$ and inductor $L_M$. The inductor, $L_2$ which is pre-charged discharges through the anti-parallel diode present across $S_2$ thus charges the battery and the capacitor $C_2$. At the output side the diode is reverse biased so the constant output voltage is maintained by the load capacitor $C$.

**Figure 11** Mode 1 of three port bidirectional SEPIC/SEPIC converter

**Mode 2**

In this mode both $S_1$ and $S_2$ are in open state for a period of $1-D$. The energy stored in the inductor $L_1$ discharges through the capacitor $C_1$ and charges it. The capacitor which was getting charged in the previous cycle discharges through the inductor $L_2$ and charges the battery. Inductor $L_M$ discharges through the load and makes the diode forward biased.

**Figure 12.** Mode 2 of three port bidirectional SEPIC/SEPIC converter

**C. Steady state analysis of three port bidirectional SEPIC/SEPIC converter**

Neglecting the voltage and current ripples and writing the steady state equations of the voltages and currents

**Mode 1**

\[
\begin{align*}
L_1 \frac{di_{L_1}}{dt} &= V \\
L_2 \frac{di_{L_2}}{dt} &= -E \\
L_M \frac{di_{LM}}{dt} &= V_{C_1} \\
C_1 \frac{dV_{C_1}}{dt} &= -(i_{LM} + i_{L_2}) \\
C_2 \frac{dV_{C_2}}{dt} &= -(i_{LM} + i_{L_1}) \\
C \frac{dV_C}{dt} &= -\frac{V_C}{R}
\end{align*}
\]

**Mode 2**

\[
\begin{align*}
L_1 \frac{di_{L_1}}{dt} &= V - V_{C_1} - nV_C \\
L_2 \frac{di_{L_2}}{dt} &= V_{C_2} - E - nV_C \\
L_M \frac{di_{LM}}{dt} &= -nV_C \\
C_1 \frac{dV_{C_1}}{dt} &= i_{L_1} \\
C_2 \frac{dV_{C_2}}{dt} &= i_{L_2} \\
C \frac{dV_C}{dt} &= n(i_{L_1} + i_L - i_{L_2}) - \frac{V_C}{R}
\end{align*}
\]

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D. Small Ripple Approximation of Multi-Port SEPIC/SEPIC converter

As the parameters used in both three port unidirectional SEPIC/SEPIC converter and three port bidirectional SEPIC/SEPIC are same so only topology 1 is considered for the calculation of those parameters. Here the current ripples through the inductors are assumed to be 0.5 Amp and the voltage ripples through the capacitors are assumed to be 0.5 V.

From these assumptions the optimised values of $L_1$, $L_2$, $L_1$, $C_1$, $C_2$, $C$ have been calculated. Let us Consider three modes (i.e. $D_1$, $D_{eff}$ and $D_3$) operating for $t_1$, $t_2$ and $t_3$ period respectively.

Here assuming $t_1 = D_1 T, t_2 = D_{eff} T, t_3 = D_3T$ for $t_1, t_2$ and $t_3$

In mode-1, the inductor $L_1$ current increases from a low level to high level, say $I_{L11}$ to $I_{L12}$ and in the next two modes, and then it current falls from $I_{L12}$ to $I_{L11}$. So the current ripple is considered to be $\Delta I_{L1} = I_{L12} - I_{L11}$.

$$L_1 \frac{di_{L1}}{dt} = V_1$$
$$L_1 \frac{\Delta i_{L1}}{t_1 + t_2} = V_1$$
$$I_1 = \frac{V_1 D_2}{f L_1}$$
$$L_1 = \frac{V_1 D_2}{f I_1}$$

(46)

Similarly the voltage ripples can be assumed for capacitor voltage. The capacitor voltage $C_1$, decreases from a high level, say $V_{C12}$ to low level $V_{C11}$ during the period $t_3$. So the voltage ripple is considered to be $\Delta V_{C1} = V_{C12} - V_{C11}$.

$$\Delta V_{C1} = \frac{1}{C_1} \int_{0}^{t_3} i_{L1} dt = \frac{1}{C_1} \int_{0}^{t_2 + t_3} i_{L1} dt$$

$$C_1 = \frac{I_1 (D_{eff} + D_3)}{f \Delta V_{C1}}$$

(47)

The inductor $L_2$ current increases from a low level to high level, say $I_{L21}$ to $I_{L22}$ and then it current falls from $I_{L22}$ to $I_{L21}$. So the current ripple is considered to be $\Delta I_{L2} = I_{L22} - I_{L21}$.

$$L_2 \frac{di_{L2}}{dt} = V_2$$
$$i_{L2} = \frac{V_2 (t_1 + t_2)}{L_2}$$
$$I_2 = \frac{V_2 D_2}{f L_2}$$
$$L_2 = \frac{V_2 D_2}{f I_2}$$

(48)

The capacitor $C_2$, voltage decreases from $V_{C22}$ to $V_{C21}$ in the period. So the voltage ripple is considered to be $\Delta V_{C2} = V_{C22} - V_{C21}$.
Let us consider the ripple in the current across the inductors is 0.5 amp and ripple in the voltage across the capacitor is 0.5v. Assuming $D_1=40\%$, $D_2=70\%$, $V_1=25v$, $V_2=15v$ the circuit parameters obtained are shown in Table 2.

### Table 2. Circuit parameters of three port SEPIC/SEPIC converter

<table>
<thead>
<tr>
<th>Components</th>
<th>Circuit values</th>
<th>parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_1$</td>
<td>700$\mu$H</td>
<td></td>
</tr>
<tr>
<td>$L_2$</td>
<td>420$\mu$H</td>
<td></td>
</tr>
<tr>
<td>$L$</td>
<td>540$\mu$H</td>
<td></td>
</tr>
<tr>
<td>$C_1$</td>
<td>159.46$\mu$F</td>
<td></td>
</tr>
<tr>
<td>$C_2$</td>
<td>182.328$\mu$F</td>
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</tr>
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</table>

### 6. Simulations and Results

In three port unidirectional SEPIC/SEPIC converter the sources 1 and 2 are of 25 V and 15 V respectively. Switch 1 and switch 2 are given a pulse width of 40% and 70%. From the simulation the output voltage of 95 V is obtained is shown in the fig.30. The current and voltages through the inductors and capacitors for sources 1 and 2 are shown in fig.29. In three port bidirectional SEPIC/SEPIC converter source 1 is 15 V and source 2 is battery voltage of 25 V with the state of charge of the battery is 80% in the discharging condition. As the voltage magnitude of battery is more than the source 1 voltage the battery discharges. A constant output voltage of 120 V is obtained for a duty cycle of 70% shown in figure 30 and 31.

For the charging case source 1 is 25 V and the voltage of battery is 15 V with the state of charge of the battery is 20%. As the voltage magnitude of battery is less than the supply voltage the battery charges. A constant output voltage of 68 V is obtained for a duty cycle of 70%. From the state of charge of the battery it can be concluded that the battery is charging by the other source shown in fig.32 and 33.
Figure 16. Output voltage and current waveforms of three port Uni-directional SEPIC/SEPIC converter

Figure 17. Waveforms of voltage and current of components of source 1 and source 2

Figure 18. Output voltage and current waveforms of Three-port bidirectional SEPIC/SEPIC converter

Case-1 (Discharging) Three-port bidirectional SEPIC/SEPIC converter

Figure 19. State of charge, battery current and battery voltage

Case-2 (Charging)

Figure 20. Output voltage and current waveforms of three port bidirectional SEPIC/SEPIC converter
Figure 21. State of charge, battery current and battery voltage

Table 3. Simulated and estimated value of output voltage for different set of supplies in three port unidirectional SEPIC/SEPIC converter

<table>
<thead>
<tr>
<th>V₁</th>
<th>V₂</th>
<th>D₁</th>
<th>D₂</th>
<th>Vo (simulated)</th>
<th>Vo (est)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>12</td>
<td>30</td>
<td>70</td>
<td>78</td>
<td>80</td>
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<tr>
<td>30</td>
<td>15</td>
<td>30</td>
<td>60</td>
<td>64</td>
<td>67.5</td>
</tr>
<tr>
<td>25</td>
<td>20</td>
<td>30</td>
<td>50</td>
<td>43.3</td>
<td>46</td>
</tr>
<tr>
<td>30</td>
<td>20</td>
<td>40</td>
<td>70</td>
<td>117.5</td>
<td>120</td>
</tr>
<tr>
<td>36</td>
<td>24</td>
<td>40</td>
<td>60</td>
<td>95</td>
<td>96</td>
</tr>
</tbody>
</table>

7. Conclusion

Multiple energy sources can be connected to the system with a lot of flexibilities and compactness. Further flexibility is achieved by connecting a battery system to provide uninterrupted power supply. The charging and discharging of the battery can be controlled, and the system efficiency can be improved. The simulation results have been provided to show the effectiveness of the system and are compared with the results obtained from the mathematical analysis.

References
