Soft switching and Efficiency Enhancement of Improved Multiple Input High Step-up Non-Isolated DC-DC Converters for Renewable Energy Applications

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Abstract: A Non Isolated Multi Input High Step up DC-DC converter is presented in this paper. This Multi Input DC-DC converter attains high voltage gain and low stress across the switches. This converter can be operated in bidirectional; with simple construction the controlling mechanism and generation of switching signals are easy. Principle of operation and analysis of the converter can be presented in detail. Multi Input High Step up DC-DC converter simulation with the closed loop controllers, PI and FUZZY logic controller are presented for getting stiff voltage regulation under sudden disturbances in load. Low Switching loss improves the converter performance.

Keywords: multi input dc-dc converter, pi controller, fuzzy logic controller, and voltage gain

1. Introduction:
Renewable energy sources requirement increase because of the echo friendly nature and exhaustion of the fossil fuels. Photovoltaic, fuel cells, wind energy etc all this are renewable energy sources. We need renewable sources because of the requirement of more demand at the same time reduction of Non renewable energy sources. These Photovoltaic modules contain Photovoltaic modules which are connected in parallel or in series. More number of the cells avoids because of divergence and also it causes the reducing of the output voltage [1]. With the isolated converters attain high step up ratios by implanting of transformer, which requires more turns ratio. These more turn ratio causes the leakage inductance during the secondary side of the transformer, voltage spike and current spike problems are arises that will reduce the performance of the converter. Pulsed input current is required for the isolated converter that is weak point for Photovoltaic modules as per the characteristics of the Photovoltaic cell [2]. So input side large filters are necessary. In case of Non isolated converters there is no transformer requirement and simple arrangement but less voltage gain. For improving these voltage gain different method are presented. With the tapped inductor high step up ratios can be obtain but voltage spike appear due to the leakage inductance which causes the high voltage stress lead to Electromagnetic Interference problems. Another method is Switched capacitors improves the voltage gain but it needs more number of the capacitors but switching loss and stress increases [3, 4]. Voltage lifting technique also improves the output voltage but controlling becomes difficult and complex also [5]. In this Multi input converter is discussed. These converters combine the different renewable sources which is available for reliability. This Multi input converters are simple in arrangement and it act as Bidirectional also with slight changes. In
previous one N number of Multi input converter is present [1], which is formed with the N number of conventional boost converters. The voltage gain of the converter is low when compared with the converter which is presented in this paper. Low voltage stress on switch in these Improved Multi Input boost converter.

2. Operational Principle
The arrangement of n-input high boost converter is as shown in Fig: 2.a. Multi input Converter combines various sources with various Voltage and current characteristics, to attain the power demand

The \( V_{in1} \), use capacitor, Two Inductors, 2 Switches and one diode, other inputs uses 1 switch, 1 inductor, 1 diode and one capacitor and capacitor is used at output side to filter \( V_o \). This three input version contain uni-directional switches those are MOSFET’S with Anti-parallel diode. Therefore during \( V_{in1} \)unit, the \( S_1, S_Q \) operates simultaneously. The three input:

- Figure 2.b contain four diodes, four inductors, four capacitors and four switches. Bi-directional converter operation can be possible by in 1st unit, the \( D_0 \& D_1 \) are replace as unidirectional switches.

3. Modes of Operation
Here three-inputs is considered for explanation. The switching method of three-input converter is shown in Fig3. The duty cycle of switches are considering as: \( D_{S1} = D_Q = d_1, D_{S2} = d_2 \) and \( D_{S3} = d_3 \).

A. Mode 1-[0-t1]
During this mode (time interval of \([0-t_1]\)), all the switches conduct. So, the energy of input sources is stored in the inductors. The \( L_{1a} \) is charged by \( V_1 \) through \( S_1 \) and the \( L_{1b} \) is charged by \( C_1 \) through \( S_1 \) and \( Q \) switches. For the other inputs the energy of \( V_i \) sources are stored in \( L_i \) inductors through \( S_i \) switches (i=2,3). The load power is supplied from output capacitor (Co) and none of the diodes conduct as shown in Fig 3.(a). Thus:
Fig 3(a) Equivalent circuit of First Mode
Inductor across voltages in mode one
\[
\begin{align*}
V_{L_{1a}} &= V_1 \\
V_{L_{1b}} &= V_{C_1} \\
V_{L_2} &= V_2 \\
V_{L_3} &= V_3
\end{align*}
\] (1)

B. Mode 2-[t1-t2]
In this mode, the $S_1$, $S_2$, $Q$ and $D_1$ conducts, but $S_3$ is off. The first input ($V_1$) charges the $L_a$, the $C_1$ charges the $L_b$ and the second input ($V_2$) charges the $L_2$. During this mode, the energy of third input ($V_3$) and $L_3$ is transferred to the $C_2$ through $D_2$ and $S_1$ as shown in Fig 3.(b)

Fig 3(b): Equivalent circuit second mode
Inductor across voltages in mode two
\[
\begin{align*}
V_{L_{1a}} &= V_1 \\
V_{L_{1b}} &= V_{C_1} \\
V_{L_2} &= V_2 \\
V_{L_3} &= V_3 - V_{C_2}
\end{align*}
\] (2)

C. Mode 3-[t2-t3]
In this mode the $V_1$ and $C_1$, charges the $L_a$ and $L_b$, respectively. The $V_3$ charges the $L_3$ through $S_3$. The $D_3$ goes off and $S_3$ turns on. So, the energy of $V_2$, $L_2$ and $C_3$ are transferred to $C_2$ through $D_2$, $Q$ and $S_1$ as shown in Fig 3.(c).

Fig 3.(c) Equivalent circuit third mode
Inductor across voltages in mode three.
\[
\begin{align*}
V_{L_{1a}} &= V_1 \\
V_{L_{1b}} &= V_{C_1} \\
V_{L_3} &= V_2 + V_{C_3} - V_{C_2} \\
V_{L_3} &= V_3
\end{align*}
\] (3)

D. Mode 4-[t3-t4]:
In this mode, $S_2$ and $S_3$ conduct but $S_1$ and $Q$ goes off. The $V_1$ and $L_a$ charge the $C_1$ through $D_1$. Also, the energy of $V_3$, $L_a$, $L_b$ and $C_2$ is delivered to the load through $D_1$ and $D_2$. The other sources charge their respective inductor Shown in

Fig 3.(d). Inductor across voltages in mode four
\[
\begin{align*}
V_{L_{1a}} &= V_1 - V_{C_1} \\
V_{L_{13}} &= V_{C_1} + V_{C_2} - V_0 \\
V_{L_2} &= V_2 \\
V_{L_3} &= V_3
\end{align*}
\]  \hspace{1cm} (4)

In this continuous conduction mode of analysis is considered. Waveforms of IL1, IL2, IL3, and IL1a, IL1b have been shown in Fig 4.

![Fig 4: current waveforms of inductors](image)

**4 Continuous Conduction Mode Analysis**

**Voltage gain:**

For calculate the gain of converter in Continuous Conduction Mode, according to the VOLT-SEC balance principle voltage across inductors is defined below

\[ V_{L_{1a}} = 0 \Rightarrow (d_1)(V_1) + (1 - d_1)(V_1 - V_{C_1}) = 0 \]  \hspace{1cm} (5)

\[ V_{L_{1b}} = 0 \Rightarrow (d_3)(V_{C_1}) + (1 - d_1)(V_{C_1} + V_{C_2} - V_0) = 0 \]  \hspace{1cm} (6)

\[ V_{L_2} = 0 \Rightarrow (d_1 + d_2 + d_3 - 2)(V_2) + (1 - d_3)(V_3) + (1 - d_2)(V_2 - V_{C_2} + V_{C_3}) = 0 \]  \hspace{1cm} (7)

\[ V_{L_3} = 0 \Rightarrow (d_1 + d_2 + d_3 - 2)(V_3) + (1 - d_2)(V_3) + (1 - d)(V_3) - (1 - d_3)(V_3) - (1 - d_1)(V_3) = 0 \]  \hspace{1cm} (8)

By simplifying above equations

\[ V_{c_1} = \frac{v_1}{1 - d_1} \]  \hspace{1cm} (9)

\[ v_0 = \frac{v_{c_2}}{1 - d_1} + v_{c_2} \]  \hspace{1cm} (10)

\[ v_{c_2} = \frac{v_2}{1 - d_2} + v_{c_2} \]  \hspace{1cm} (11)

\[ v_{c_3} = \frac{v_3}{1 - d_3} \]  \hspace{1cm} (12)

Replacing equations (9), (11) and (12) in (15), then the relationship in between input and output voltages is shown as

\[ v_0 = \frac{v_1}{(1 - d_1)^2} + \frac{v_2}{(1 - d_2)} + \frac{v_3}{(1 - d_3)} \]  \hspace{1cm} (13)

\[ \text{1}\text{st input D (duty cycle) of switch is denoted as } d_1. \text{ Input and } V_0 \text{ relations for the n number of sources are expressed as } v_0 = \frac{v_1}{(1 - d_1)^2} + \sum_{i=2}^{n} \frac{v_i}{(1 - d_i)} \]  \hspace{1cm} (14)

Consider Vin2, Vin3, ..... Vinn=V and d2,d3...dn=d then equation 14 can be expressed as

\[ v_0 = \frac{v_1}{(1 - d)^2} + \left(\frac{n-1}{1 - d}\right) \]  \hspace{1cm} (15)

For V=V and d=d then equation (15) can be represented as

\[ \frac{v_0}{v_{in}} = \left(\frac{n(1-d)+d}{(1-d)^2}\right) \]  \hspace{1cm} (16)

**5 Design Parameters**

**Inductance:**

The current ripple of inductor L_{1a} under CCM can be expressed by

\[ \Delta I_{L_{1a}} = \frac{V_{d1}}{L_{1a}f_s} \]  \hspace{1cm} (17)

Then, the inductance L can be determined by

\[ L_{1a} = \frac{V_{d1}}{\Delta I_{L_{1a}}f_s} = \frac{V_{d1}}{\Delta I_{L_{1a}}} = \frac{V_{d2}}{\Delta I_{L_{1b}}f_s} \]  \hspace{1cm} (18)

Where \Delta I_{L_{1a}} is the ripple tolerance of inductor current. Similarly, the inductances of L_{1b}, L_{2}, L_{3} can be defined by

\[ L_{1b} = \frac{V_{d1}}{(1-d_1)\Delta I_{L_{1b}}f_s} = \frac{V_{d1}}{(1-d_1)\Delta I_{L_{1b}}} \]  \hspace{1cm} (19)

\[ L_{2} = \frac{V_{d2}}{\Delta I_{L_{2}}f_s} = \frac{V_{d2}}{\Delta I_{L_{1b}}} \]  \hspace{1cm} (20)
\[ L_3 = \frac{V_3 d_3}{\Delta i_{L3} f_s} = \frac{V_3 d_3}{\Delta i_{L3} / i_{L3} f_s} \]  

Maximum inductor currents as follows

\[ i_{L1a, \text{max}} = \frac{V_o}{R(1-d_1)^2} + \frac{d_1 V_1}{2L_{1a} f} \]  
\[ i_{L2a, \text{max}} = \frac{V_o}{R(1-d_1)} + \frac{d_1 V_1}{2(1-d_1) L_{1b} f} \]  
\[ i_{L3, \text{max}} = \frac{V_o}{R(1-d_3)} + \frac{d_3 V_3}{2L_{3f} f} \]

Capacitance:
The capacitance of \( C_1, C_2, C_3, \) and \( C_0 \) can be defined by

\[ C_1 = \frac{i_o d_1}{\Delta V_{c1} f_s} \]  
\[ C_2 = \frac{i_o d_2}{\Delta V_{c2} f_s} \]  
\[ C_3 = \frac{i_o d_3}{\Delta V_{c3} f_s} \]  
\[ C_0 = \frac{i_o d_3}{\Delta V_{c0} f_s} \]

Where \( \Delta V_o \% \) is the ripple tolerance of capacitor voltage, the capacitances of \( C_0 \) should be large enough to keep the capacitor voltage constant.

Switching Components:
The maximum voltage appear across the switch or diode in its open condition is denoted as voltage stress Stress on switch in STEADY STATE Continuous Conduction mode is

\[ v_{s1} = v_{c1} \]  
\[ v_o = v_0 - v_{c3} \]  
\[ v_{s2} = v_{c2} - v_{c3} \]  
\[ v_{s3} = v_{c3} \]

I stress across the switches is represented as:

\[ i_{\text{stress-1}} = \frac{V_o}{R(1-d_1)^2} + \frac{d_1 v_1}{2L_{1a} f} \]  
\[ i_{\text{stress-2}} = \frac{V_o}{R(1-d_2)} + \frac{d_1 v_2}{2L_{1b} f} \]  
\[ i_{\text{stress-3}} = \frac{V_o}{R(1-d_3)} + \frac{d_3 v_3}{2L_{3f} f} \]

in this the \( V_o/V_{\text{in}} \) of two input improved converter is differentiate with the two input version multi input converter The voltage gain of the each converter is shown as:

6. Design of PI Controller
The best method of control the industrial drives is PI controller. Figure 5 represents the block diagram of PI control technique.

\[ (S) = [KP + (K_i/s)] \times e(s) \]

Fig. 5. Block diagram of proposed PI controller for converter

The error signal e(s) fed back to the PI controller and controlled output signal Q(s) is:

\[ (S) = [KP + (K_i/s)] \times e(s) \]
Design of FL controller

It is very simple in designing the FL controller which is shown in Fig 6.

1 Gaussian shaped
2 Signoidal shaped
3 Trapezoidal shaped
4 Π shaped
5 Triangular shaped

A. Fuzzification

Fig 6(a) shows the fuzzy membership function of error input variable with 7 linguistic terms as NB: Negative Big PB: Positive Big

NB: Negative Big NM: Negative Medium NS: Negative Small ZE: Zero

PM: Positive Medium PS: Positive Small

Fig 6(b) shows the fuzzy membership function of change in error input variable with 7 linguistic terms as

NB: Negative Big PB: Positive Big

NM: Negative Medium PM: Positive Medium NS: Negative Small PS: Positive Small

ZE: Zero

B. Rule Set

The processing is based on a collection of logic rules in the form of IF-THEN statements, where the THEN part is called the consequent and the IF part is called the antecedent. Basically fuzzy control systems have various rules.
In practice, AND is one popular definition, simply uses the minimum weight of all the antecedents, while or uses the maximum value. There is also a NOT operator that subtracts a membership function from 1 to give the complementary function. Table 1 gives the rules set for fuzzy controller.

**Table (a) Rule base table for the fuzzy controller**

<table>
<thead>
<tr>
<th>E</th>
<th>NB</th>
<th>MB</th>
<th>NM</th>
<th>NS</th>
<th>ZE</th>
<th>PS</th>
<th>PM</th>
<th>PB</th>
</tr>
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<tbody>
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<td>NB</td>
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<td>NB</td>
<td>MB</td>
<td>NB</td>
<td>MB</td>
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<td>MB</td>
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<td>NS</td>
<td>ZE</td>
<td>PS</td>
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<td>ZE</td>
<td>PS</td>
<td>PM</td>
<td>PM</td>
<td>PB</td>
<td></td>
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<td>PS</td>
<td>NS</td>
<td>ZE</td>
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<td>PM</td>
<td>PM</td>
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<td>ZE</td>
<td>PS</td>
<td>PM</td>
<td>PM</td>
<td>PM</td>
<td>PB</td>
<td></td>
</tr>
<tr>
<td>PB</td>
<td>ZE</td>
<td>PS</td>
<td>PM</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td></td>
</tr>
</tbody>
</table>

### 8 Comparison Of Improved Topology And Multi-Input Converter

Here \( V_1=V_2=V \) and \( d_1=d_2=d \) then the simplifying equations represented

\[
V_0^{\text{improved version}} = \frac{V_1}{(1-d_1)^2} + \frac{V_2}{(1-d_2)^2} \quad (39)
\]

\[
V_0 = \frac{V_1}{(1-d_1)^2} + \frac{V_2}{(1-d_2)^2} \quad (40)
\]

Here \( V_1=V_2=V \) and \( d_1=d_2=d \) then the simplifying equations represented as

\[
V_0^{\text{improved version}} = \frac{2-d}{(1-d_1)^2} V \quad (41)
\]

\[
V_0 = \frac{2}{(1-d)} V \quad (42)
\]

Fig 7 shows that range of duty cycle [0.5-0.85] , improved converter gain is more than multi input converter. For example \( d=0.7 \) then \( V0/Vin \) of improved multi input converter and multi- input converter are 14.45 and 6.67 respectively. At any \( D \) this multi-input converter contains more voltage gain. Finally gain of improved multi input high boost converter gain is very by changing the duty cycle.

![Fig 8: voltage gain of improved and topologies [11] voltage gain for \( V_1=V_2=V \) and \( d_1=d_2=d \)](image-url)
Table 1: parameters for Improved Multi-Input High Step-up DC-DC converter

<table>
<thead>
<tr>
<th>SPECIFICATION</th>
<th>VALUE</th>
<th>SPECIFICATION</th>
<th>VALUE</th>
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</thead>
<tbody>
<tr>
<td>D1</td>
<td>0.7</td>
<td>switchin. freq.</td>
<td>30 KHz</td>
</tr>
<tr>
<td>D2</td>
<td>0.7</td>
<td>Load resistance</td>
<td>390 Ω</td>
</tr>
<tr>
<td>D3</td>
<td>0.7</td>
<td>Capacitor C3</td>
<td>47 µF</td>
</tr>
<tr>
<td>V_{in1}</td>
<td>10 Volts</td>
<td>Output capacitor</td>
<td>220 µF</td>
</tr>
<tr>
<td>V_{in2}</td>
<td>10 Volts</td>
<td>Inductor L_{1a}</td>
<td>1.5 mH</td>
</tr>
<tr>
<td>V_{in3}</td>
<td>10 Volts</td>
<td>Inductor L_{1b}</td>
<td>1 mH</td>
</tr>
<tr>
<td>Capacitor C1</td>
<td>88 µF</td>
<td>Inductor L_{2}</td>
<td>2 mH</td>
</tr>
<tr>
<td>Capacitor C2</td>
<td>47 µF</td>
<td>Inductor L_{3}</td>
<td>2 mH</td>
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Table 2: parameters for pv panel

PV

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<td>V_{oc}</td>
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</tr>
<tr>
<td>I_{sc}</td>
<td>3.8A</td>
</tr>
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</table>

CONVERTER

<table>
<thead>
<tr>
<th>SPECIFICATIONS</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_{in}</td>
<td>10V</td>
</tr>
<tr>
<td>V_{out}</td>
<td>177V</td>
</tr>
<tr>
<td>Capacitor C_{2}, C_{3}</td>
<td>47 µF</td>
</tr>
<tr>
<td>Capacitor C_{0}</td>
<td>220 µF</td>
</tr>
<tr>
<td>Inductor L_{1a}</td>
<td>1.5 mH</td>
</tr>
<tr>
<td>Inductor L_{1b}</td>
<td>1 mH</td>
</tr>
<tr>
<td>Inductor L_{2}, L_{3}</td>
<td>2 mH</td>
</tr>
</tbody>
</table>

Switching frequency | 30Khz

Battery modeling:
For battery modeling parameters are \( V_b \) (terminal voltage) and State of Charge equation can be as follows

\[
V_b = V_o + i_b R_b - \frac{q}{q + \int i_b dt} + A \exp (B \int i_b dt) \tag{44}
\]

\[
SOC = 100 \left( 1 + \frac{\int i_b dt}{Q} \right) \tag{45}
\]

\( R_b \) = battery internal resistance

\( V_o \) = open circuit voltage

\( i_b \) = battery charging current

\( K \) = polarization voltage

\( Q \) = battery capacity

\( A \) = exponential voltage

\( B \) = exponential capacity
Simulation of improved multi-input high step-up dc-dc converter with pv panel and battery as input sources for pi controller:

**Fig 10:** MATLAB/SIMULINK circuit of improved multi-input high-step up converter with PI Controller

**Fig 10.1(a): PV model**

**Fig 11:** Input voltage, output voltage and current response of converter with pi controller
Fig 12: input voltage, output voltage and current response of converter for step change in load from 0.455A to 0.87A with pi controller

Fig 12: shows the input voltage 10V, output voltage 177V and load current from 0.455A to 0.87A with pi controller. Most of applications require a stiff voltage during sudden load conditions for that voltage controller is require.

11 Simulation of improved multi-input high step-up dc-dc converter with PV panel and battery as a input sources for fuzzy controller:

Fig 13: MATLAB/SIMULINK circuit of improved Multi-Input High Step up converter with fuzzy

Fig 14: input voltage, output voltage and current response of converter with fuzzy controller

Fig 14: shows the input voltage 10V, output voltage 177V and load current from 0.455A to 0.87A with fuzzy controller. Most of applications require a stiff voltage during sudden load conditions for that voltage controller is require.

Fig 15: input voltage, output voltage and current response of converter for step change in load from 0.455A to 0.87A with fuzzy controller

Fig 15: shows the input voltage 10V, output voltage 177V and load current from 0.455A to 0.87A with fuzzy controller. Most of applications require a stiff voltage during sudden load conditions for that voltage controller is require.
Table-3: comparison provides a performance of different controllers for a step change in load current from 0.455A to 0.87A at t=0.2 sec for constant input voltages of $V_1=10$, $V_2=10$, $V_3=10$

12. CONCLUSION

A improved multi-input high boost dc-dc converter has been describing in this paper. The proposed converter is compared with the previous multi–input high step-up dc-dc converter thus results shows that proposed topology gives high voltage gain with low voltage stress and simple structure, control mechanism and generation of switch signal be uncomplicated. Stiff voltage regulation is obtained in the power supply unit for a load voltage of 177V in opposition to the disturbances in the load applied at 0.2sec with an increment in current from 0.45A to 0.88 A in closed loop operation using the Proportional-Integral (PI) and FUZZY controllers, Study state analysis, operational principle have been presented. The three input version of multi input high boost converter has been simulated.
13. References


