Design and Implementation of Non-Isolated Three-Port DC/DC Converter for Stand-Alone Renewable Power System Applications

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Abstract: DC-DC Converters are those devices which have the ability to change one level of direct voltage/direct current to that of another level. Non-Isolated DC/DC three-port converters intermeddling the input source that is photovoltaic array, storage device like battery and the load is proposed in Stand-Alone Renewable system applications. In this application PV panel is not being connected to the grid but instead are used for charging the batteries. Each port is used for specific input or output, and its functions depend on the port; they are the renewable source, the battery set, and the output port. Three-Port Converters are brought into existence by introducing a bidirectional converter into Boost converter. Power flow path either from PV array to the load or from battery to the load is achieved in this project. Using four regulators accomplishing Maximum Power Point Tracking (MPPT) control of PV array, governs the charging battery and voltage control of the load. PWM scheme applied to the Three-Port Converter based on power relations among three ports. DC/DC Converter works in every operation mode and switch between different modes easily. Three-Port Converter has advantages of high efficiency, higher flexibility, reliability and lower cost. A proposed system is simulated using MATLAB/SIMULINK environment.

Keywords: PV array, DC/DC converter, Bidirectional converter, MPPT controller.

1. Introduction

Now a day's world population is increasing rapidly, the power demand is also increasing frequently. Conventional energy sources like oil, coal and so on (fossil fuels) are continuously depleting in the recent years in the universe, it is necessary to known various choice of energy sources in order to meet power demands. Hence renewable sources play an important role in generating power and achieve the load requirements. Advantages like low maintenance, almost nil harmful emissions, and renewable energy sources hold virtual role in satisfying the future load demand.

Applications of renewable energy sources may be different depending upon whether they are connected to the grid or not, also known as standalone system. Standalone system is also known as remote area power supply (RAPS), it is an off-the-grid electricity system for the locations that are not connected with an electricity distribution system. Standalone system includes electricity generation, energy storage and generation.

The renewable source like solar energy utilization has been looked upon by many researchers all around the world. It has been known that solar cell operates at very low efficiency approximately around 20% and thus a better control mechanism is required to increase the overall efficiency of the solar cell. In this field researchers have developed that are nothing Maximum Power Point Tracking (MPPT) algorithms [1].

PV array should be the main energy source in standalone application. Renewable sources like solar, wind are not regular in nature. Hence storage device like battery is required for stand-alone power system to improve overall dynamics of the system. Renewable energy sources have few disadvantages like fluctuation in output due to weather conditions, temperature irradiance. To overcome from these drawbacks battery is used as a storage element to improve dynamic characteristics.

The power management of power converter is required in order to meet output power. Three-Port DC/DC converter is best for standalone PV system applications. TPC has advantages of less component count, lower cost higher reliability and fewer conversion stages [2]-[4]. Due to considerable advantages of the TPC, a variety of topologies have been proposed in different fields, like hybrid electric vehicles [5]-[8]. PV system with battery backup [9]-[12].

2. Photovoltaic system

2.1 PV cell

PV cell is made of semiconductor material absorb light that is reflected on them and convert it directly into electricity. If electrical conductors are attached to the positive and negative sides, forming an electrical circuit, the electrons can be captured in the form of an electric current - that is, electricity.
2.1 PV module

Due to the low voltage generated in a PV cell (around 0.5V), several PV cells are connected in series (for high voltage) and in parallel (for high current) to form a PV module for desired output. Separate diodes may be needed to avoid reverse currents, in case of partial or total shading, and at night.

2.3 PV Array

The power produced by one module is not sufficient to achieve the load requirements; initially modules in a PV array are connected in series to obtain the desired voltages, and then individual modules are connected in parallel to produce current.

![PV cell, module and array.](image)

**Figure 2.2:** PV cell, module and array.

3. DC-DC Converter

Three-port DC/DC converter has the advantages of less component count, less conversion stages, lower cost and higher reliability. TPC has two categories: Non-isolated and isolated topologies. Non-isolated is better one compared to isolated one because in Non-isolated converter isolation is not required and non-isolated converter has advantages of compact design and higher power density.

Different types of non-isolated DC/DC converters are as follows:

3.1) Buck (Step down) converter.
3.2) Boost (Step up) converter.

3.1 Buck (Step down) converter

Buck converter is also known as step down converter because output voltage is less than that of input voltage. When switch is open, current through inductor is zero. When switch is closed, current through inductor is increases linearly and the inductor will produce an opposing voltage across its terminals in response to the changing current. This voltage drop counteracts the voltage of the source and therefore reduces the net voltage across the load.

![Buck converter](image)

**Figure 3.1:** Buck converter

\[
\frac{V_o}{V_{in}} = k
\]

* \(V_o\) is output voltage.
* \(V_{in}\) is input voltage.
* \(K\) is duty cycle.

3.2 Boost (Step up) converter

Boost converter is also known as step up converter because output voltage is greater than that of input voltage.

- When the switch is closed, current flows through the inductor is increases in clockwise direction and the inductor stores some energy by generating a magnetic field. Polarity of the left side of the inductor is positive.
- When the switch is opened, inductor current will be reduced as the impedance is higher. The magnetic field previously created will be destroyed to maintain the current flow towards the load. Thus the polarity will be reversed (means left side of inductor will be negative now). As a result two sources will be in series causing a higher voltage to charge the capacitor through the diode D.

![Boost converter](image)

**Figure 3.2:** Boost converter

\[
\frac{V_o}{V_{in}} = \frac{1}{1 - k}
\]

* \(V_o\) is output voltage.
* \(V_{in}\) is input voltage.
* \(K\) is duty cycle.

4. Block diagram

Non-isolated Three-Port (DC/DC) converters that is NI-TPC intermeddling PV array, the battery and the load. Non-isolated converters contain an inductor instead of a transformer (isolated). Power efficiency of all three ports power flow paths in the Boost (DC/DC) TPCs is higher.

![Three-Port Converter](image)

**Figure 4.1:** Three-Port Converter

As long as the Sun irradiation is high that is power produced by PV panel is greater than that of load demand. PV array feeds the load at the same time battery charges. When sun irradiation is low, battery discharges to the load because PV panel doesn’t have sufficient power to meet load demand.
MPPT controller is not mechanical tracking of the system. MPPT is electronic tracking of the system. The controller looks at the output of the Photovoltaic array and compares PV voltage to the battery voltage. It then figures out what is the best power that PV can put out to charge the battery.

Bidirectional converter is used to achieve power transfer between two dc power sources in either of direction. If battery connected with bidirectional converter results in improved system efficiency. Bidirectional converter increases battery life with proper control of charging and discharging of the battery.

When input power is lower than the load demand, battery should discharges to the resistive load, discharging of battery is controlled by switch $s_1$ which is introduced in the boost converter. Input source that is PV array and battery should not be connected in parallel hence diode $D_3$ is required. Here also the final circuit is Boost converter.

6. Operation mode analysis

Power in the input source is $P_{in}$, power in the battery is $P_b$, and power in the load is $P_o$. Consider that $P_b$ is negative when the battery charges and $P_b$ is positive when the battery discharges, neglecting the power loss. Input power and battery power is equal to battery power. That is:

$$P_{in} + P_b = P_o$$

Three different modes of operations are:

6.1 Dual Output (DO) mode.
6.2 Dual Input (DI) mode.
6.3 Single Input Single Output (SISO) mode.

6.1 DO mode

The TPC operates in DO mode when input power is more than that of the output power is shown in figure 8. In this mode input source and battery both works as outputs. Hence, named as dual-output mode. PV array supply the power to load and at the same time charge the battery. Power switch $s_3$ is off, input power is controlled by duty cycle $k_1$ and output power is controlled by $k_2$.

$$V_o = \frac{V_{in} - k_2 V_b}{1 - k_1 - k_2}$$

6.2 DI mode

The TPC operates in DI mode when input power is less than that of output power that is when sun irradiation is low. In this mode battery discharges to the load and PV array should not have sufficient power to meet load demand. Power $S_2$ is off in dual input mode. Input source and battery both works as inputs. Output power is controlled by $k_3$ instead of $k_2$. 
Net change in the inductor current over one complete cycle is zero in steady state. Therefore we have Output voltage is:

\[ V_o = \frac{(1 - k_2) V_{in} + k_2 V_b}{1 - k_1} \]

6.3 SISO mode

TPC operates in SISO mode when input power is zero that is during night time. In SISO mode battery power is supply to the load. Power switch \( S_2 \) is off. Here battery is serve as input and load as output.

\[ V_o = \frac{V_b}{1 - k_1} \]

7. Simulation

Design: The boost converter design is as follows

<table>
<thead>
<tr>
<th>Parameters</th>
<th>values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage</td>
<td>120v</td>
</tr>
<tr>
<td>Output voltage</td>
<td>230v</td>
</tr>
<tr>
<td>Battery voltage</td>
<td>0v</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>100kHz</td>
</tr>
<tr>
<td>Output power</td>
<td>500w</td>
</tr>
</tbody>
</table>

Conventional circuit for Dual-Output mode: (From figure 6.1)

Figure 6.2: DI mode

Figure 6.3: SISO mode

Figure 7.1: Simulation circuit of DO mode.
Battery in charging mode

Figure 7.1.1: Testing Battery State Of Charge (Charging)-Time (sec)

Conventional circuit for Dual-Input mode: (From figure 6.2)

Figure 7.1.2: Testing Battery State Of Charge (Discharging)-Time (sec)

Conventional circuit for Single-Input Single Output mode: (From figure 6.3)

Figure 7.2: Simulation circuit of DI mode

Battery in discharging mode

Figure 7.2: Simulation circuit of SISO mode.
Battery in charging mode

Conventional circuit for Dual-Output mode: (From figure 6.1)

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• Closed loop TPC

Figure 7.1.3: Testing Battery State Of Charge (Charging)-Time (sec)

Figure 7.4: Simulation circuit for TPC (From figure 4.2)

Figure 7.4.1: Solar irradiance initially 1000w/m² varies on weather conditions.

Figure 7.4.2: I-V and P-V characteristics for different irradiance at fixed 25°C temperature.

Figure 7.4.3: The required PWM signal used as the gate pulse for the MOSFET is shown above in the figure.

Figure 7.4.4: Battery charging voltage 40v

Figure 7.4.5: Output 230v DC voltage

8. Conclusion

Three-port DC/DC converter in renewable applications should be able to handle both the renewable source that is PV array and battery port; the renewable sources are not regular in nature it depends on climatic conditions, temperature and irradiance. Hence battery port is used; its utility period of life should be taken into consideration. Three-port DC/DC converters in this report are, one port is for PV array, the second port is for battery and finally the output port. Power may be obtained from both input voltages simultaneously or each one independently that is single stage power conversion between any two of the three ports can be accomplished. Battery port is used whenever it is required; this results in an increase the lifetime of battery. Also when the solar power is not available for example during night, the system automatically takes energy from battery port without any change, only when the MPPT optimize the renewable source.

Using four regulators MPPT control of input source, charging control of the battery and voltage control of the load is accomplished. Three-Port DC/DC converter operates in all DO, DI and SISO modes freely. PWM scheme is proposed based on power relations among three-ports. All three modes are simulated using MATLAB/SIMULINK environment.
References


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Rachana received the B.E degree in Electrical and Electronics Engineering from Guru Nanak Dev Engineering College Bidar in 2011 affiliated to VTU Bengaluru, and pursuing M.Tech in Power Electronics from The Oxford College of Engineering, Bangalore from 2013 to 2015 affiliated to VTU Bengaluru.