Abstract – This paper investigates the performance of 3-Z-Network boost converter for a standalone Photovoltaic (PV) power generation system. This proposed converter integrates a single-switch with 3-Z-active Network by diodes, capacitors & inductors. The 3-Z structure of the converter improves the energy conversion efficiency with low switching losses and also reduces the shoot through problem. The different operating modes of this converter and the input-output responses have been analyzed. The Voltage gain (G_v) characteristic curve of this converter circuit has been studied for various duty cycle (D) and it is compared with conventional and Quadratic boost converters. The comparative result illustrates that the Voltage gain of the converter is more than the other boost converters. Further, this proposed converter is integrated with the Photovoltaic panel for promoting the green energy. The sun radiates more photons which are used to generate the electrical power. The solar energy has certain intermittency issues, not available at night and also during daytime there may be cloudy or rainy weather and partial shadow effects which affect the performance of the system. During, the Partial Shading Conditions (PSC) multiple peaks and multiple steps are accomplished in the photovoltaic characteristics curve. One way to improve the systems performance is by operating the PV system at its Maximum Power Point (MPP). Here, the Perturb and Observe (P&O), Incremental Conductance (IC) and Improved Incremental Conductance (IIC) algorithms have been incorporated and the simulations are carrying out under Psim-circuit environment to track the MPP. The simulation results show that the Improved Incremental Conductance algorithm overcomes the drawbacks of conventional algorithms where it fails to track the MPP effectively under PSC. The parameters of the PV module have been referred from the manufacturer datasheet (MS24250) for these analyzes.

Keywords - Photovoltaic (PV), 3-Z-Network boost converter, Maximum Power Point (MPP), Partial Shaded Condition (PSC), Perturb and Observe (P&O), Incremental Conductance (IC), Improved Incremental Conductance (IIC).

I. INTRODUCTION

Power origination from non-conventional energy sources like solar will have an important task in the recent electricity demand. Solar technology has been well grown and is one of the most assuring sources of non-conventional energies [1]. The performance of the solar system for extracting the maximum power depends on the solar irradiance (G), cell temperature (T) and the operating point of MPP (Maximum Power Point) with respect to working conditions. A major contest in using the PV electricity generation is to tackle it’s nonlinear I–V characteristics, which result in multiples of MPP on its PV curve. Fig. 1 indicates the block diagram of the proposed system.

Fig. 1. Block diagram of the proposed system.

The fundamental element of PV system is a PV cell. The PV array system has a combination of PV modules which are connected in series, parallel and series-parallel configurations also predominantly affect the performance of the Photovoltaic system. The PV panel has very low conversion efficiency therefore, a 3-Z-Network Boost Converter topology has been proposed to transmit solar power from the PV array to the load with high Voltage gain and results in better efficiency as the switching losses are minimized. Under uniform solar irradiance, PV system exhibits a single MPP in the Power-Voltage curve. Since the solar insolation continually changes with time, the MPP is subjected to constant variation. The PV system
is operated at the MPP at all times in order to achieve better performance. The MPPT control technique maximizes the resulting revenue of the PV modules by extracting maximum feasible energy. For this reason, MPPT control techniques have been grown. Many different algorithms have been developed to track the MPP. MPPT techniques are chosen depending upon the complexity, the required number of sensors, cost, performance, the convergence speed, and application area. Traditional algorithms do not prove efficient in tracking the MPP of multiple peaks and multiple steps. It results in high power loss [2]. Here the IIC algorithm has been implemented to track the MPP. The simulation work has been developed in Psim-circuit environment.

II. MODELING AND SIMULATION OF 3-Z-NETWORK BOOST CONVERTER

3-Z-Network boost converters are known for its application in renewable energy systems. The converter proposed here to use as a single-switch to boost the voltage which makes the converter as a boost converter which has three Z structure with active networks [3]. The use of a single-switch boost converter in the DC-DC energy conversion for renewable energy generation system provides solutions to many problems, such as reduces complexity, low cost, and high power density [4]. The proposed boost converter has only one active power switch that makes the converter have a very simple structure, low switching loss, a small volume, and less weight [5]. In addition to this, the converter provides high gain voltage by reducing their current ripple, the switching losses are very low, resulting in very high efficiency [6].

This converter differs from the traditional Z-source networks, which are normally designed with passive components. There are two modes at which the converter operates, they are Continuous Conduction Mode and Discontinuous Conduction Mode. In order to simplify the circuit analysis of the proposed boost converter, some assumptions follow:
1) All the components prototypical,
2) $L_1 = L_2$ and $L_3 = L_4$, and
3) The free-wheeling diode of the switch is neglected.

In the cyclic states (ON and OFF) of switch Q, the energy in the inductor is accumulated and released periodically. Similarly, the current in the inductor is also increased and decreased periodically. There are some cases in which the current decreases to zero and lasts for a time delay, which is said to be the discontinuous current conduction period of inductors. Different combinations of the inductances, the load, and the duty cycle result in continuous and discontinuous inductor current. The modes of operation of the proposed boost converter according to different states of the diodes and the currents of the capacitors and its six operational modes are analyzed. During Mode-1 operation $Q$, $(D_1&D_3)$, $D_4$, and $(D_6&D_8)$ are ON, $D_5$, $D_7$, and $D_9$ are OFF. In Mode-2 operation $D_2$, $D_5$, $D_7$, and $D_9$ are ON, $Q$, $(D_1&D_3)$, $D_4$, and $(D_6&D_8)$ are OFF. In Mode-3 operation $D_2$, $D_5$, and $D_9$ are OFF, $Q$, $(D_1&D_3)$, $D_4$, and $(D_6&D_8)$ are OFF. In Mode-4 operation $D_2$, and $D_5$ are ON, $Q$, $(D_1&D_3)$, $D_4$, $D_7$, and $(D_6&D_8)$ are OFF. During Mode-5 operation $D_2$ and $D_5$ are OFF, $Q$, $(D_1&D_3)$, $D_4$, $D_7$, $(D_6&D_8)$ are OFF. During Mode-6 operation $Q$, $(D_1&D_3)$, $D_4$, $(D_6&D_8)$, $D_2$, $D_5$, $D_7$, and $D_9$ are OFF.

2.1. Design of converter

The parameters of the proposed boost converter are designed according to the analyzes made through different modes of operation of the proposed boost converter in Continuous Conduction Mode. The output voltage $V_o$ is denoted as (1) and the voltage of capacitor $C_1$ can be expressed as (2).

$$V_o = V_{cap \, 2} = V_{in} \left( 1 + \frac{D}{1 - D} \right)^2$$  \hspace{1cm} (1)

$$V_{cap \, 1} = V_{in} \left( 1 + \frac{D}{1 - D} \right)$$  \hspace{1cm} (2)

The voltages of inductors ($L_1$, $L_2$, $L_3$ & $L_4$) can be attained from (3), (4), (5) & (6) respectively. $V_{L_1}$, $V_{L_2}$, $V_{L_3}$ and $V_{L_4}$ are referred to the average voltages across the inductances $L_1$, $L_2$, $L_3$ and $L_4$ during ON and OFF period of switch $Q$.

$$V_{L_1} = V_{L_2} = V_{in}, \text{ if } Q \text{ is ON}$$  \hspace{1cm} (3)

$$V_{L_1} = V_{L_2} = -V_{in} \left( \frac{D}{1 - D} \right), \text{ if } Q \text{ is OFF}$$  \hspace{1cm} (4)
\[ V_{L3} = V_{L4} = -V_{in} \left( \frac{1 + D}{1 - D} \right), \text{If } Q \text{ is ON} \]  
(5)

\[ V_{L3} = V_{L4} = -V_{in} \left( D \left( \frac{1 + D}{(1 - D)^2} \right) \right), \text{If } Q \text{ is OFF} \]  
(6)

As per the analysis of current in (7), it assumes that a lossless circuit leads to \( V_{in}I_{in} = V_oI_o \), where \( I_{in} \) and \( I_o \) are input and output currents, respectively. The currents of inductors \( L_1, L_2, L_3 \) & \( L_4 \) can be attained from (8) & (9).

\[ I_{in} = -I_o \left( D \left( \frac{(1 + D)^2}{(1 - D)^2} \right) \right) \]  
(7)

\[ I_{L1} = I_{L2} = -I_o \left( D \left( \frac{1 + D}{(1 - D)^2} \right) \right) \]  
(8)

Similarly, \( I_{L3} \) and \( I_{L4} \) can be denoted as

\[ I_{L3} = I_{L4} = I_o \left( \frac{D}{1 - D} \right) \]  
(9)

The parameter design of the inductor helps to estimate the value of rated current and inductance from the given preassigned variation range \( x_L \), an output voltage \( V_o \), an output current \( I_o \), and a switching period \( T \). The inductor ripple affects the stability of the converter. Therefore, the inductance must be designed in such a way that it can tolerate the ripples. The inductors in the proposed boost converter are designed based on (10), (11) & (12) respectively.

\[ L = \left( \frac{V_i dt_L}{x_L I_{L1}} \right) \]  
(10)

when the switch \( Q \) is ON, the \( dt_L \) is the current ripple of the corresponding inductor within the time delay \( (dt_L = DT) \) and the \( V_L \) represents the voltage of the inductor. The permissible error of \( I_L \) by \( dt_L \) is restrained by the preassigned variation range \( x_L \) as \( dt_L = x_L I_L \). Hence, the range of the inductance is found by varying the duty cycle, and the maximum value obtained is taken as the rated value of inductance.

\[ L_1 = L_2 = \left( \frac{V_o DT}{x_L I_{L1}} \right) \]  
(11)

\[ L_3 = L_4 = \left( \frac{V_o (1 + D) DT}{x_L I_o} \right) \]  
(12)

The parameter design of the capacitor estimates the rated voltage and capacitance from the given a preassigned variation range \( x_{cap} \), an output voltage \( V_o \), an output current \( I_o \) and a switching period \( T \). The capacitor ripple affects the stability of the converter, whose permissible variation range can be used to design the capacitance. Then, the value of capacitors in the proposed boost converter is designed from (13), (14) & (15) respectively.

\[ C = \left( \frac{I_{Cap} dt_{Cap}}{dV_{Cap}} \right) \]  
(13)

where \( I_{cap} \) is the current of the corresponding capacitor when the switch \( Q \) is ON, the \( dt_{Cap} = DT \) is the time delay of the switch \( Q \) as it is on, and \( dV_{Cap} \) is the ripple voltage corresponding to the capacitor within the time delay \( (dt_{Cap}) \). It denotes the permissible error of \( V_{cap} \) by \( dV_{cap} \). \( dV_{cap} \) is estimated by the tolerated variation range \( x_{cap} \) as \( dV_{Cap} = x_{cap} V_{cap} \) when the switch \( Q \) is ON, \( (I_{Cap1} = 2I_{L3}; \ I_{Cap2} = I_o) \).

\[ C_1 = \left( \frac{2I_{L1} DT}{x_{cap} V_{cap1}} \right) \]  
(14)

\[ C_2 = \left( \frac{I_{L2} DT}{x_{cap} V_o} \right) \]  
(15)

The design guidelines provide a proper tool to choose components and to ensure the appropriate operation of the proposed boost converter in an effective and efficient way. The simulation study of this proposed 3-Z boost converter is carried out in Psim-circuit environment with the design specifications as mentioned in Table-I. Fig. 3 shows the Psim-circuit diagram of 3-Z-Network boost converter. The relationships of the duty cycle \( D \) and Voltage gain \( G_v = \frac{V_o}{V_{in}} \) in conventional, Quadratic boost and 3-Z-Network boost converters are shown in Fig. 4. The graph indicates that the proposed boost converter gives much higher Voltage gain than the other two converters for the same \( D \). Fig. 5 and Fig. 6 show the simulation response of switching operation and the Input-Output waveform of proposed boost converter respectively.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage ( (V_{in}) )</td>
<td>100 V</td>
</tr>
<tr>
<td>Output Voltage ( (V_o) )</td>
<td>900 V</td>
</tr>
<tr>
<td>Inductor ( (L_1=L_2) )</td>
<td>100( \mu )H</td>
</tr>
<tr>
<td>Inductor ( (L_3=L_4) )</td>
<td>200( \mu )H</td>
</tr>
<tr>
<td>Capacitor ( (C_1) )</td>
<td>220( \mu )F</td>
</tr>
<tr>
<td>Capacitor ( (C_2) )</td>
<td>470( \mu )F</td>
</tr>
<tr>
<td>Switching Frequency ( (f_s) )</td>
<td>1000KHZ</td>
</tr>
<tr>
<td>Load Resistance ( (R) )</td>
<td>400( \Omega )</td>
</tr>
</tbody>
</table>
Fig. 3. Psim-circuit diagram of 3-Z Network boost converter.

Fig. 4. Voltage gain characteristics curve of boost converters for different values of the duty cycle (D).

Fig. 5. Simulation response of switching operation

Fig. 6. Simulation response of Input-Output waveforms of 3-Z Network boost converter.
III. MODELING AND SIMULATION OF PV ARRAY

The PV array (3x3 PV modules) has been modeled and simulated in Psim-circuit environment as shown in Fig. 7. It is very significant to the placement of bypass diodes and blocking diodes in a PV array under partial shading conditions. The by-pass diode protects the PV module against Hot-Spot and damage of cells. The bypass diode helps to reduce the reverse voltage across the sub-module, therefore prohibiting the shading voltage drop within the string to the normal voltage of one sub-module (-0.7V). During night times when illuminated light does not fall on the modules are get illuminated light energy, an energy storage (like a battery, supercapacitors) connected directly in series with the modules connected the cells forward biased. This might enhance a discharge of the energy storage. A blocking diode is connected in series with the PV module prevents the discharge from energy storage device. But during normal illumination level, this diode leads to significant power loss [7, 8]. In modern PV modules has internally attached bypass diodes. Here, the PV array system has a different operating condition (Table-II) and their P-V and I-V characteristics have been observed. The simulated response indicates the multiple peaks and multiple steps in the modular characteristics of PV array and it is plotted in Fig. 8 for the operating condition (pattern-II) respectively.

<table>
<thead>
<tr>
<th>PV array</th>
<th>Operating condition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pattern-I</strong></td>
<td>1000W/m², 25°C</td>
</tr>
<tr>
<td>Pattern-II</td>
<td>800W/m², 25°C</td>
</tr>
<tr>
<td>Pattern-III</td>
<td>1000W/m², 25°C</td>
</tr>
</tbody>
</table>

Table - II

<table>
<thead>
<tr>
<th>PV ARRAY UNDER DIFFERENT OPERATING CONDITION</th>
</tr>
</thead>
</table>

Fig. 7. Psim-circuit model of 3x3 PV array for Pattern-II.
IV. MAXIMUM POWER POINT TRACKING

The commonly used MPPT is the Perturb and Observe (P&O) method which is also known as a hill-climbing algorithm. This technique uses a simple feedback arrangement and needs a calculation of only a few parameters. In this approach, the array voltage is changed periodically for the given perturbation and comparison of the previous output power to the present output power is done to calculate the MPP [9, 10]. On contrast, this method does not track the sudden change in irradiation levels.

The MPPT method that is described here is Incremental Conductance (IC) method. It helps to find and adjust the array operating voltage to maintain MPP condition through simple incremental conductance and instantaneous conductance measurements [11, 12]. P&O and IC MPPT controllers have been employed along this proposed boost converter for comparing their performance analysis and efficiency. The Improved Incremental Conductance (IIC) MPPT algorithm is also illustrated in this research work where it initiated on the value of the derivative of the panel current over the panel voltage. Comparison of instantaneous conductance to the incremental conductance tracks the MPP. Based on it the reference voltage (V_{ref}) from the PV is increased or decreased with a small change in values to make the PV array operate at MPP. The knowledge of $V_{ref}$ makes the IIC implementation easier. Considerably, the tracking time of the algorithm is also reduced. The Fig. 9 shows the flowchart of IIC MPPT algorithm to locate MPP at different operating conditions.

$$V_{ref} = \alpha V_{oc}$$

The value of $\alpha$ varies from 0.73 to 0.80 depending upon the PV cell characteristics.

These are the important features of IIC,

- Real-time implementation becomes easy as computation burden is reduced.
- It tracks the MPP efficient at multiple peaks and multiple steps.
- Earlier knowledge reduces the tracking time of the algorithm.
- Maximum power loss is less in the proposed MPPT algorithm.
- The effectiveness of the IIC algorithm is more compatible and stable than the other two algorithms.

Fig. 10 shows Psim-circuit model of a PV array interfaced with the proposed boost converter using IIC MPPT algorithm for Pattern II. The duty cycle under the different operating condition is fed to the proposed boost converter for proper switching operation of the system at MPP. From the simulation results, it is
revealed that the proposed algorithm provides a higher percentage of maximum power tracking than other two methods.
The simulation responses have been illustrated in Fig. 11. Under PSC, PV modules belonging to the same string undergo different insolation and temperature. The resulting P-V characteristic curve becomes more complex and reveals multiple peaks. The presence of multiple peaks decreases the effectiveness of the system. Moreover, P&O and IC are not tracking the MPP effectively than IIC MPPT algorithm under these conditions. Table III shows the comparisons of the MPPT algorithms. The IIC tracks more power than other two algorithms.

<table>
<thead>
<tr>
<th>Pattern</th>
<th>MPPT</th>
<th>(P_m) (W)</th>
<th>(I_m) (A)</th>
<th>(P_o) (W)</th>
<th>(I_o) (A)</th>
<th>(\eta) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>P&amp;O</td>
<td>2269.1</td>
<td>20.22</td>
<td>2243</td>
<td>2.37</td>
<td>98.85</td>
</tr>
<tr>
<td></td>
<td>IC</td>
<td>2269.1</td>
<td>20.22</td>
<td>2244</td>
<td>2.37</td>
<td>98.89</td>
</tr>
<tr>
<td></td>
<td>IIC</td>
<td>2268.9</td>
<td>20.22</td>
<td>2247</td>
<td>2.37</td>
<td>99.04</td>
</tr>
<tr>
<td>II</td>
<td>P&amp;O</td>
<td>1291.8</td>
<td>10.81</td>
<td>1264</td>
<td>1.79</td>
<td>97.84</td>
</tr>
<tr>
<td></td>
<td>IC</td>
<td>1291.7</td>
<td>10.81</td>
<td>1273</td>
<td>1.79</td>
<td>98.55</td>
</tr>
<tr>
<td></td>
<td>IIC</td>
<td>1291.6</td>
<td>10.81</td>
<td>1279</td>
<td>1.79</td>
<td>99.02</td>
</tr>
<tr>
<td>III</td>
<td>P&amp;O</td>
<td>1133.7</td>
<td>15.05</td>
<td>1115</td>
<td>1.67</td>
<td>98.35</td>
</tr>
<tr>
<td></td>
<td>IC</td>
<td>1133.7</td>
<td>15.05</td>
<td>1116</td>
<td>1.67</td>
<td>98.44</td>
</tr>
<tr>
<td></td>
<td>IIC</td>
<td>1133.6</td>
<td>15.05</td>
<td>1119</td>
<td>1.67</td>
<td>98.70</td>
</tr>
</tbody>
</table>

V. CONCLUSION

The performance of 3-Z-Network boost converter for a standalone Photovoltaic (PV) power generation system under different shading patterns of solar irradiation has been investigated in this proposed work. The Voltage gain \(G_v\) characteristic curve of this converter circuit has been studied for various duty cycle (D) and it is compared with conventional & Quadratic boost converters. But, the 3-Z-Network boost converter provides good voltage gain ratio. The developed converter model and the Input-Output response have been analyzed under different operating modes. Further, this proposed converter is integrated with the Photovoltaic panel for the harvesting of solar energy. The modular characteristics of PV module under different irradiance level and temperature have been analyzed using Psim-circuit environment. During the PSC, multiple peaks and multiple steps are noticed in the P-V & I-V characteristics curves respectively. Here, the P&O, IC and IIC algorithms have been incorporated for finding the MPP under different operating conditions. The effectiveness of the IIC technique adopted in this work for finding MPP has been evaluated and the simulation results are compared with P&O and IC methods. The simulation results show that the IIC algorithm overcomes the drawbacks of conventional algorithms where it fails to track the MPP effectively under PSC. Moreover, the 3-Z structure of the converter improves the energy conversion efficiency of an integrated Photovoltaic system for promoting the green energy. In addition, this converter-PV system can be connected with suitable storage systems for meeting the power demand during night time and low irradiation conditions.

REFERENCES