Analysis of PV Array coupled Active Network Converter Employing Fuzzy Logic Based Maximum Power Point Tracking Control Strategies

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Abstract - This paper investigates the performance analysis of coupled inductor Active Network Converter (ANC) for photovoltaic (PV) energy harvesting system. The proposed converter has an integrated with two coupled inductors in a single magnetic core which reduces the size of magnetic components and provides high step-up Voltage gain (Gv) without requiring an extreme Duty ratio (D). The voltage conversion ratio of ANC is high and has low switching losses due to the low voltage and current stress of power switches. The Voltage gain characteristic curve of this converter circuit with different turn’s ratio (n) has been studied for various duty cycle. The efficiency of this converter is about to 98.73%. Further, this proposed converter is integrated with the PV panel for the harvesting of solar energy. 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 Maximum Power Point (MPP) with respect to working conditions. Here, the Incremental Conductance (I&C) algorithm and Fuzzy Logic Control (FLC) method are incorporated for finding the MPP under different operating conditions. The comprehensive PV modeling and simulation of PV arrays are explained in [1-4] various literature works. The Fig.1 shows the Block diagram of the proposed system.

Since, the PV panel has very low conversion efficiency and the proposed integrated coupled inductor Active Network Converter topology transmits solar power from the PV array to the load with high step-up voltage gain without requiring an extreme duty ratio which improves the better efficiency by it minimizing the switching losses.

2. MODELING AND SIMULATION OF ACTIVE NETWORK CONVERTER

High step-up DC–DC power conversion has become one of the important technologies in the modern renewable energy fields. Active Network Converter is a DC-DC converter which increases a low voltage level to a relatively high voltage. As a matter of fact, when the output voltage is high, it is important to reduce the voltage stress on the active switch and output diode; otherwise, it will cause high conduction loss and switching loss. By connecting the coupled inductor to the active network converter, voltage gain can be increased. Furthermore this is explained in [5-10]. Active Network Converter consists of two switches...
which can MOSFET, two coupled inductors which can be integrated into one magnetic core, six diodes, one clamping capacitor, and one capacitor as filter in the output side. The Fig. 2 shows the circuit diagram of proposed coupled inductor Active Network Converter.

2.1. Modes of operation of ANC Converter

The performance of converter circuits has been explained in four operating modes as below:

Mode-I operation: During Mode-I the power MOSFET switches of S1, S2 are turned ON. The current through the diodes of D1b and D2b decrease to zero at the time of t0. The inductors of L1a and L2a are charged by the source current and the filter capacitor C releases energy to the load.

Mode-II operation: At the time of t1, the power switches of S1 and S2 are turned OFF; the diodes of D2a, D1a, and D2a start to conduct. Affected by the leakage inductor, the currents through the inductors of iL1a and iL2a are limited; and as a result of iL1a > iL2a, iL1a decrease slowly than iL2a. The current iC could be expressed as iC = iL2a - iL1a < 0, clamp capacitor Cc has been discharged. Since iL1a - iL1b > 0, iL2a - iL2b > 0, D1b and D2b remain conducting during this stage.

Mode-III operation: During this stage, the switches of S1, S2 are in OFF state. At the time of t2, the current through D1c and D2c decrease to zero; the inductors can supply the energy to the load. Since the difference of the leakage inductors, iL2b larger than iL2b, clamp capacitor Cc has been charged.

Mode-IV operation: The switches of S1 & S2 start to conduct at the time of t3; the output diode Dc become reverse-biased; the inductor current iL1a and iL2a increase slowly; the current in the inductors of iL1b and iL2b decrease slowly. The diodes of D1c and D2c keep conducting during this time period.

2.2. Performance analysis of converter

During the ON-state, the inductors of L1a, L1b, L2a, L2b are charged by the dc source, respectively, while, during the OFF State, the inductors are discharged in series. The derived voltage gain is expressed as,

\[ G_V = \frac{1 + 2D}{1 - D} \]  

D is the duty ratio of switches S1 and S2. Obviously, we can conclude that all the inductors are sharing the same operating modes, therefore, L1a, L1b, L2a, L2b can be integrated into one magnetic core, as shown in Fig. 4. In this condition, we can change the turns ratio of L1a/L1b to 1:n (n > 1). When the switches are ON, L1a and L2a are charged by the dc source through D1b and D2b. Since the voltage of L1b and L2b is higher than L1a and L2a, D1a and D2a are reverse biased. When the switches are OFF, L1b, L1b, L2a, and L2b are series connected to transfer the energy to output. Due to the circuit symmetry of the proposed converter, it is reasonable to consider L1a = L2a = Lc, L1b = L2b = Lb, and the turn ratio of two coupled inductors are equaled to 1:n, the performance analysis of the circuit is illustrated as follows:

2.2.1 Voltage-Conversion Ratio

In an ideal condition, the leakage inductance is zero; the operating mode can be simplified to Mode-I and Mode-III.

During the Mode-I, the voltage across the inductors can be expressed as equation (2.1) & (2.2)

\[ V_{L1a} = V_{L2a} = V_i \]  

\[ V_{L1b} = V_{L2b} = nV \]  

During the Mode-III, the voltage across the inductor is expressed as equation (3.1, 3.2 & 3.3)

\[ V_{L1a} = V_{L2a} = \frac{V_o - V_o}{2(n + 1)} \]  

\[ V_{L1b} = V_{L2b} = \frac{n(V_o - V_o)}{2(n + 1)} \]  

\[ V_{Cc} = \frac{(V_o - V_o)}{2} \]  

By simplifying (3.3), the voltage of clamp capacitor Cc is expressed by equation (4)

\[ V_{Cc} = V_o \frac{(n + 1)D}{1 + (2n + 1)D} \]  

By varying the duty cycle (D), Voltage gain of the converter is also varied. According to the turn’s ratio,
higher the value of turns gain, the voltage becomes too high (Fig.3). The voltage conversion ratio can be extended by increase $n$.

![Duty Cycle(D) vs Voltage gain (V)](image)

**Fig.3. Voltage gain characteristics curve of ANC converter for different turn ratio ($n$).**

The voltage-conversion ratio of the proposed CL-ANC is

$$G_{CCM} = \frac{V_o}{V_i} = \frac{1 + (2n + 1)D}{1 - D} \quad \ldots \quad (5)$$

### 2.2.2 Effect of Leakage Inductance on Voltage Gain

According to the analysis, the leakage inductor may cause duty-cycle loss and reduce the voltage conversion ratio. Taking the leakage inductor into consideration, the voltage gain is derived as below:

$$G'_{CCM} = \frac{V_o}{V_i} = \frac{1 + (2n + 1)D}{1 - D} \left( 1 - \frac{8n^2 L_i F_v P_o}{1 - D} \right) \quad \ldots \quad (6)$$

### 2.2.3 Voltage and Current Stress of the Power Devices

The voltage stress of the diode $D_{1a}$ and $D_{2c}$ can be expressed as below:

$$V_{stress} - D_{1a} = V_{stress} - D_{2c} = nV_i \quad \ldots \quad (7)$$

The voltage stress of the diode $D_{1b}$ and $D_{2b}$ can be expressed as below:

$$V_{stress} - D_{1b} = V_{stress} - D_{2b} = \frac{n(V_o - V_i)}{2(n + 1)} \quad \ldots \quad (8)$$

The on-state average current of $D_{1c}$, $D_{2c}$ can be expressed as equation (9),

$$I_{2c} = \frac{I_o}{1 - D} \quad \ldots \quad (9)$$

According to the flux balance on the coupled inductor, the primary current and turns can be expressed by equation (10),

$$N_1 I_1 = (N_1 + N_2) I_2 \quad \ldots \quad (10)$$

Where $N_1$, $N_2$ is the number of turns of $L_a$, $L_b$, which can be expressed by equation (11),

$$N_2 = nN_1 \quad \ldots \quad (11)$$

From (7) & (8) the on-state average current of $D_{1b}$, $D_{2b}$ can be expressed as equation (12),

$$I_1 = \frac{(1 + n)I_o}{1 - D} \quad \ldots \quad (12)$$

The RMS current through the switches can be obtained by assuming the inductor current ripple of $D_{1b}$, $D_{2b}$ which can be expressed by equation (13)

$$\Delta i_L = K_i I_L \quad \ldots \quad (13)$$

$$I_{RMS} = \frac{1}{T_s} \int_{0}^{T_s} (I_L - \frac{1}{2} \Delta i_L + \frac{\Delta i_L^2}{DT_s})^2 \, dt \quad \ldots \quad (14)$$

$$= \frac{(1 + n) \sqrt{D}}{V_o} \sqrt{\frac{1}{12} - K_i^2 + 1} \quad \ldots \quad (15)$$

The proposed Active Network Converter is simulated in Matlab-Simulink environment with the design specifications for $(n=1:1)$ as mentioned in Table-I.

**TABLE –I DESIGN SPECIFICATIONS OF ACTIVE NETWORK CONVERTER**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage $(V_{in})$</td>
<td>21 V</td>
</tr>
<tr>
<td>Output voltage $(V_{out})$</td>
<td>200V</td>
</tr>
<tr>
<td>Output power $(P_{out})$</td>
<td>200W</td>
</tr>
<tr>
<td>Switching frequency $(f_s)$</td>
<td>50KHZ</td>
</tr>
<tr>
<td>Coupled inductors $(L_1, L_2)$</td>
<td>330 $\mu$ H</td>
</tr>
<tr>
<td>Clamping capacitor $(C_c)$</td>
<td>3 $\mu$ F</td>
</tr>
<tr>
<td>Capacitor</td>
<td>1 $\mu$ F</td>
</tr>
</tbody>
</table>

Fig. 4 shows the Matlab-Simulink diagram of Active Network Converter. Fig. 5 depicts the simulation response of Input-Output waveforms of Active network Converter.
Fig. 4. Matlab-Simulink model of proposed Active Network Converter

Fig. 5. Simulation response of Input-Output waveforms of Active Network Converter
Table-II shows the analysis of proposed converter for the changes in input voltage levels. The proposed converter is analyzed with the different input voltage. As the output voltage of the converter increases the output power also increases. The power output from the proposed converter with input DC source is nearly 200W.

3. MODELING AND SIMULATION OF PV ARRAY

The comprehensive PV module has been developed and simulated in Matlab-Simulink environment. The PV module (MS24250) used in this research work has been referred from manufacturer PV module datasheet. The I-V and P-V characteristics curve of a PV module for different irradiances (1000W/m², 800W/m² & 600W/m²) and temperature of 25°C & 30°C have been simulated and plotted in Fig.6 and Fig.7 respectively. The change in irradiation significantly affects the photovoltaic current and change in temperature significantly affects the open circuit voltage and results in the performance of the PV system & Maximum Power Point gets affected [11].

3.1 MPPT- Incremental Conductance (I&C) algorithm

The IC MPPT method purpose is to find and adjust the array operating voltage by maintaining MPP condition through simple incremental conductance and instantaneous conductance measurement. P&O and IC MPPT controllers are one of the well-known methods which have been employed along this proposed boost converter for comparisons [12]. The Incremental Conductance algorithm (Fig.8) computes Maximum Power Point by comparison of the conductance (dI/dV) to the panel conductance (I/V) when these two are the same (I/V = dI/dV) the output voltage is the MPP voltage is to the right side curve of the MPP and positive when it is to the left side curve of the MPP.

![Flowchart for I&C algorithm](image)

Fig.8. Flowchart for I&C algorithm

This algorithm has advantages over P&O in that it can determine when the MPPT has reached the MPP, where P&O oscillates around the MPP. Also, incremental conductance can track rapidly increasing and decreasing temperature or irradiance conditions with higher precision than Perturb & Observe. The output voltage and current tapped from PV module are given to the MPPT controller and the controller provides an appropriate pulse signal to the power switches in the converter circuit in order to adjust the turn-ON and turn-OFF periods.

3.2 Fuzzy Logic Control (FLC) algorithm

Fuzzy logic based MPPT control technique has been incorporated with ANC converter to study the performance of the PV system. It is relatively simple to design since they do not require the awareness of the exact model. Moreover, it overcomes the conventional MPPT methods of solar power extraction with nonlinearity behavior of the solar
system. The important points should keep in the mind while framing the Rule base of the fuzzy controller [13, 14].

The error (E) and change in error (CE) are the two FLC input variables and the respective duty ratio (D) is referred as fuzzy output. The fuzzy membership values are referred as NB-Negative Big, NS-Negative Small, ZE-Zero, PS-Positive Small and PB-Positive Big. The mathematical expression for Error (E) and Change in Error (CE) are as shown in equation (16) & equation (17). The Triangular membership functions are used here and are plotted in Fig.9 & Fig.10.

\[ E(j) = \frac{P_{pv}(j) - P_{pv}(j-1)}{V_{pv}(j) - V_{pv}(j-1)} \quad \ldots \ (16) \]

\[ CE(j) = E(j) - E(j-1) \quad \ldots \ (17) \]

Where \( P_{pv}(j) \) and \( V_{pv}(j) \) are the instant power and voltage of the photovoltaic module respectively.

Fig. 9. Membership function for error

Fig. 10. Membership function for change in error

The developed Rule base for this study has been listed in the Table – III. Matlab-Simulink model of a PV module interfaced with the proposed converter under 1000W/m² using FLC algorithm is shown in Fig.11 and the Input-Output simulation responses under solar irradiation 800W/m² using FLC algorithm is illustrated in Fig. 12.

TABLE-III FUZZY RULE BASE

<table>
<thead>
<tr>
<th>CE</th>
<th>NB</th>
<th>NS</th>
<th>ZE</th>
<th>PS</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>ZE</td>
<td>ZE</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
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<tr>
<td>NS</td>
<td>ZE</td>
<td>ZE</td>
<td>PS</td>
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<tr>
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<td>NS</td>
<td>ZE</td>
<td>ZE</td>
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<tr>
<td>PB</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>ZE</td>
<td>ZE</td>
</tr>
</tbody>
</table>

Comparative analysis of I&C and FLC algorithm under 1000W/m², 25°C, 800W/m² 30°C, 600W/m² 25°C conditions are tabulated in Table-IV and it is inferred that the output power gets improved in Fuzzy control in compared to I&C method.

TABLE-IV -COMPARATIVE ANALYSIS OF I&C AND FLC MPPT ALGORITHM

<table>
<thead>
<tr>
<th>Operating conditions</th>
<th>MPPT</th>
<th>V_{out} (V)</th>
<th>I_{out} (A)</th>
<th>P_{out} (W)</th>
<th>H (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000W/m², 25°C</td>
<td>I&amp;C</td>
<td>196</td>
<td>0.97</td>
<td>191</td>
<td>96</td>
</tr>
<tr>
<td>800W/m², 30°C</td>
<td>FLC</td>
<td>198</td>
<td>0.98</td>
<td>195</td>
<td>97</td>
</tr>
<tr>
<td>600W/m², 25°C</td>
<td>I&amp;C</td>
<td>193</td>
<td>0.96</td>
<td>186</td>
<td>94</td>
</tr>
<tr>
<td></td>
<td>FLC</td>
<td>196</td>
<td>0.97</td>
<td>192</td>
<td>96</td>
</tr>
</tbody>
</table>

The defuzzification uses the center of gravity to compute the output of this FLC, which can be expressed by equation (18).

\[ D = \frac{\sum_{j=1}^{n} \mu(D_{j}) \cdot D_{j}}{\sum_{j=1}^{n} \mu(D_{j})} \quad \ldots \ (18) \]
Fig. 1. Matlab-Simulink model of a PV-module interfaced with the proposed converter under 1000W/m² with FLC algorithm

Fig. 2. Input-Output simulation responses under solar irradiation 800W/m² using FLC algorithm

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4. CONCLUSION

This paper investigated the performance analysis of coupled inductor Active Network Converter (ANC) for a standalone photovoltaic energy harvesting system. The Voltage gain characteristic curve of this converter circuit with different turn’s ratio (n) has been studied for various duty cycles. The Input-Output responses of the proposed converter for different voltage levels have been analyzed. Further, this proposed converter is integrated with the PV array for the harvesting of solar energy. The modular characteristics of PV module under different irradiance level and temperature have been analyzed using Matlab-Simulink environment. Here, the Incremental Conductance (I&C) algorithm and Fuzzy Logic Control (FLC) method are incorporated for finding the MPP under different operating conditions. The Fuzzy Rule base is also illustrated & the effectiveness of the FLC technique adopted in this work for finding MPP has been evaluated and the simulation results are compared with IC method. The simulation results show that the FLC method gives a better improvement in the tracking of MPP than I&C method. Further, this converter-PV system can be connected with On-grid interactive with suitable power inverter circuits for meeting the power demands.

References


