Grid Connected PV System with Maximum Power Point Achievement Based on H5 Transformerless Inverter

Essam Hendawi¹, Sherif Zaid²

¹Electronics Research Institute, Cairo, Egypt
²Department of Electrical Power, Faculty of Engineering, Cairo University, Egypt
sherifzaid3@yahoo.com, esam_hendawi@hotmail.com

Abstract- This paper presents an efficient PV array connected to utility grid through H5 transformerless inverter. A boost converter is employed between the PV array and the inverter. Hysteresis current controller is presented as a maximum power tracker which maintains the PV array current at a constant value corresponding to the maximum power that can be drawn from the PV array. Leakage current in the parasitic capacitances is reduced to reasonable values according to standards. Voltage controller is utilized to maintain the output voltage of the boost converters nearly constant to meet the utility grid voltage and generate the required reference grid current as well. Phase locked loop with the reference grid current are used to generate the control signals of H5 inverter switches. The utilization factor and overall efficiency are improved. Design procedure of the elements of boost converter and H5 inverter is proposed. Simulation results validate the high performance of the proposed system.

Keywords: PV array, H5 inverter, Boos converter MPPT, Utility grid

1. Introduction
Among the renewable energy sources, the photovoltaic energy is considered as the most attractive and sustainable resource because of the availability all over the year and sustainability of solar energy. In the future, it is expected that more than 45% of necessary energy in the world will be generated by photovoltaic array. The cost of photovoltaic systems is dependent on the PV array area. To minimize the cost of PV array powered systems, the electric power generated by the PV array should be efficiently utilized. For that, different system configurations can be used to enhance the overall system efficiency [1-3].

PV arrays can provide energy to stand-alone applications or utility grid. The second case is increasing continuously and becomes very popular. To connect PV arrays to utility grid, a dc/ac inverter followed by a line transformer are employed [4]. The line transformer realizes the following goals: (1) galvanic isolation between the PV-array and the utility grid and consequently makes personal safety (2) raise the output voltage of the inverter to a suitable value to meet the utility grid voltage. However, these transformers have many drawbacks. The system cost will mightily increase and the efficiency will decrease as well. Such transformers have also a big size and a heavy weight. When dispensing with line transformer, a path of leakage current is formed through the parasitic capacitances between the PV array and the ground [5-8]. This leakage current results in radiated interference issues and serious safety problems and as a result it must be reduced to limited values [9]. The German DIN VDE 0126-1-1 standard [10] restricts the values of the leakage current which occurs in photovoltaic grid-connected system. The leakage current is caused by the variation in the common mode voltage (CM) of the inverter. As a result the variation of the common mode voltage must be minimized to reduce the leakage current.

To solve the problem of leakage currents, several solutions are introduced. Conventional half bridge inverters are utilized but its main problem is that the dc voltage utilization is 50% and consequently large numbers of PV arrays are needed [11]. Conventional full-bridge inverters with bipolar or unipolar SPWM overcome the
problems of half bridge inverters [12]. However, with bipolar SPWM, the current ripples in the filter inductors and switching losses are high while with unipolar SPWM, the common mode voltage changes at switching frequency resulting to high leakage current. Another approach of minimizing the leakage current is the employment of transformer-less inverters [13-19]. The basic idea of transformer-less inverters is to disconnect the dc side (PV-array) from the ac side (inverter and grid) during freewheeling modes thus the common mode voltage is nearly kept constant. Transformer-less PV systems exhibit the advantages of lower cost, lower system size and higher efficiency compared with line transformer systems. Several topologies are developed in the literature including highly efficient and reliable inverter concept (HERIC) topology, H5 topology, and H6 topology. Various versions with modifications to those transformer-less inverters are introduced. Each topology has its own advantages and disadvantages regarding to the following points of view: (1) ability of reducing the leakage current, (2) no. of switches and their total losses and cost, (3) system efficiency and cost. Among these transformer-less inverters, H5 inverter is chosen as a case of study. H5 inverters have the least number of switches (five switches) and therefore the cost is reduced and the inverter is simpler compared to its counterparts. The only considered problem is the high conduction losses where three switches conduct together during active modes. With transformer-less systems, researches which take into account the maximum power drawn from the PV array are very rare though the high importance of maximum power tracking and the need of improving the utilization factor of PV systems. In this paper, reduction of leakage current to reasonable values according to standards is achieved by applying H5 transformer-less inverter. In addition, a maximum power point tracker is utilized to continuously draw maximum power from the PV array. Many MPPT techniques are developed and used in literatures. Examples of MPPT techniques are: Perturb and Observe (P&O) method, Incremental Conductance (IC) method, Artificial Neural Network method, Fuzzy Logic method, etc. [20-24]. In this paper, the boost converter is used as an impedance matching device between PV array on one side and H5 inverter and grid on the other side. A boost converter is connected between the PV array and the H5 inverter. The maximum power point tracker is a simple hysteresis current controller that controls the PV array current (boost inductor current) to maintain this current at a constant value corresponding to the value of the maximum power. The hysteresis current controller provides the control signal with the suitable duty cycle to the boost converter switch. A voltage controller is introduced to maintain the output voltage of the boost converter at a suitable value to meet the utility grid voltage. The voltage controller produces the reference grid current. A phase locked loop is employed with the reference grid current to generate the required control signals of the inverter five switches.

2. Utilization factor of PV array
The Utilization factor ($K_{uf}$) of PV array is defined as the ratio between the average power generated during normal operation $P_{pv-n}$ to the maximum power that can be drawn from the PV array $P_{pv-max}$

$$K_{uf} = \frac{P_{pv-n}}{P_{pv-max}}$$  (1)

For conventional transformer-less inverters like HERIC inverters and H5 inverters, the PV array current is discontinuous and has nearly constant discrete values during each period of active state mode. Therefore, the utilization factor can be calculated as [25]:

$$K_{uf} = 0.5 m$$  (2)

Where $m$ is the modulation index.

For $m<=1$, the utilization factor is $<=50\%$ which means that the maximum power that is provided from the PV array cannot be achieved. Adding a dc/dc boost converter between the PV array and H5 inverter as proposed in Fig. 1 and adjusting the MPP algorithm maintain the PV array current constant and maximize the power provided from the PV array. In addition, the utilization factor is significantly improved and becomes very close to $100\%$. 

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3. System description

Fig. 1 presents the MATLAB/SIMULINK model of the proposed system. The proposed system includes the following parts:

3.1 PV array

The PV array consists of 720 series modules and 4 parallel modules to give the suitable voltage for the boost converter and in turn achieve the required dc link voltage. The parameters of the PV array are given in Table 1 for sun insolation level equals “1”.

Table 1 PV array parameters at 100% insolation level

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open circuit voltage (V)</td>
<td>422</td>
</tr>
<tr>
<td>Short circuit current (A)</td>
<td>15.2</td>
</tr>
<tr>
<td>Maximum power (W)</td>
<td>4839</td>
</tr>
<tr>
<td>Voltage for maximum power V_{pmax} (V)</td>
<td>343.9</td>
</tr>
<tr>
<td>Current for maximum power I_{pmax} (A)</td>
<td>14.07</td>
</tr>
</tbody>
</table>

3.2 Boost converter

The conventional boost circuit is utilized. The well-known relation between the converter input voltage V_i (PV array voltage) and the converter output voltage V_o is:

\[ V_o = V_i / (1-D) \]  

(3)

Where D is the duty cycle of the control signal.

The converter is supplied from the PV array. Therefore the inductor current is exactly the PV array output current. This inductor current is controlled by the maximum power tracker (described later) to achieve a maximum power drawn from the PV array at a certain sun insolation level. On the other hand, a PI controller is proposed to control the output voltage of the boost converter and gives the required reference grid current I_g.

3.2.1 Output voltage controller of boost converter

This controller maintains the output voltage of the boost converter at a constant value that is suitable to meet the voltage level of the utility grid. The controller as proposed in Fig. 2 has a reference set point of boost voltage which is about 450 V. The feedback signal is the actual boost voltage value and its derivative. An integrator is applied to the error between the reference voltage and the sum of the actual value and its derivative. The loop of boost converter voltage control is an outer loop where its inner loop is the grid current control loop. The gains KA and KB are chosen so that the outer loop is much slower than the inner one to achieve stability of the system. The voltage controller generates the required reference grid current I_g. The controller combines the adaptive nature of artificial intelligent controllers like fuzzy logic controller and the simplicity of classical PI controller [26].

![Fig. 1 Proposed PV grid connected system](image1)

![Fig. 2 Boost converter voltage controller](image2)
### 3.3 H5 inverter operation principle

H5 transformer-less inverter consists of the conventional H-bridge inverter in addition to an extra fifth switch. As a result, this topology utilizes less power switches compared with other common transformer-less inverter like HERIC and H6 inverters. This fifth switch disconnects the PV array from the grid when the output voltage of the inverter is zero and consequently the path of the leakage current is cut off. As a result, the common mode leakage current is suppressed to very small values. Configuration of H5 inverter fed by the PV array is shown in Fig. 3. LCL type filter is coupled to the grid to ensure that the inverter output voltage is close to the sine-wave shape.

The operation principle of H5 inverter can be summarized as follows:

- The upper switches (Q1 and Q3) operate at the grid frequency during the positive and negative half cycles respectively.
- The switch (Q5) operates at a high frequency and it is turned on simultaneously with either switch (Q4) in the positive half cycle or switch (Q2) in the negative half cycle
- The lower switches (Q4 and Q2) operate at a high frequency during the positive and negative half cycles respectively.

$$
\begin{align*}
S1 &= P \\
S2 &= P \\
S3 &= N \\
S4 &= N
\end{align*}
$$

During this mode, the PV array is disconnected from the grid. The switch Q1 and the antiparallel diode of switch Q3 conducts together. This mode is known as freewheeling mode. The current path is $Q1-L_1$-grid-$L_2$-$D_3$-$Q1$

- Negative level of inverter output voltage

This mode occurs during the negative half cycle where the switches Q5, Q3 and Q2 are turned on. This mode is known as the active mode

- Zero level of inverter output voltage in the negative half cycle

During this mode, the PV array is disconnected from the grid. The switch Q3 and the antiparallel diode of switch Q1 conducts together. This mode is known as freewheeling mode. The current path is $Q3-L_2$-grid-$L_1$-$D_0$-$Q3$

According to the previous descriptions of the modes of operation, the control signals of the five switches can be like that in Fig. 4 over one cycle.

$$
\begin{align*}
S2 &= P \\
S3 &= N
\end{align*}
$$

#### 3.4 H5 inverter controller

The output of the boost converter feeds the H5 inverter. Grid voltage $V_g$, grid current $I_g$ and reference grid current $I_G$ are utilized to generate the control signals of the five switches. Phase locked loop (PLL) is applied to $V_g$ and PI controller is utilized to generate the modulating voltage which is used to generate the high frequency control signal $Q$ and its complement $\bar{Q}$ during positive and negative half cycles. The phase locked loop (PLL) achieves synchronization between the PV array and the grid. Comparing $V_g$ with zero voltage gives the signals of “P” and “N” in the positive and negative half cycles respectively. The following relations give the control signals of the five switches.

$$
S2 = P \quad (4) \\
S3 = N \quad (5)
$$

---

**Fig. 4 Control signals of H5 inverter switches**
Where the operator && and || represents the logic "AND" and logic "OR" respectively.

4. Photovoltaic System Modeling

The one diode PV cell model as shown in Fig. 5 is composed of current source with parallel diode, series and parallel resistances. If the parallel resistance is large enough, its current can be neglected in the cell model. The equations of the model is well known in the literature [27].

4.1 Hysteresis MPP tracker

The output characteristics of PV array depends on the sun insolation, cell temperature and output voltage of PV array. Since PV has nonlinear characteristics, it needs Maximum Power Point Tracking (MPPT) algorithm to maximize the output power for PV powered applications. So it is continuously tune the system so that it draws maximum power from the PV array regardless of weather or load conditions.

To improve the utilization factor of the PV array MPPT is used. According to maximum power point theorem, output power of any circuit can be maximized by adjusting source impedance so that it equals to the load impedance, so the MPPT algorithm is equivalent to the problem of impedance matching. The described boost converter is employed as an impedance matching device between PV array and electrical load by changing the duty cycle of the converter circuit. Output voltage of the converter depends on the duty cycle, so MPPT is applied to calculate the duty cycle to achieve the maximum output power of the PV array.

Unlike aforementioned MPPT techniques, a hysteresis current controller is presented for MPPT. The hysteresis controller maintains the PV current (boost inductor current) at a value corresponding to the maximum power that can be drawn from the PV-array.

For different sun insolation level, there is a maximum power that can be drawn from the PV array. This maximum power occurs at corresponding values of PV array voltage and current. Therefore, if the maximum power \( P_{\text{max}} \) that can be achieved is known, the corresponding output current \( I_{\text{pmax}} \) can be determined and the controller is applied to maintain the PV array current at \( I_{\text{pmax}} \). The proposed MPPT is a simple hysteresis current controller. A look-up-table is built to generate the reference current \( I_{\text{pmax}} \) corresponding to every \( P_{\text{max}} \). The reference current \( (I_{\text{pmax}}) \) is compared with actual PV array current generating the error signal. A hysteresis controller, whose hysteresis band is “h”, process the error signal. The output of the controller gives the control signal “S” of the boost converter switch. The algorithm of the hysteresis current controller is:

\[
\begin{align*}
\text{e} &= I_{\text{pmax}} - I_{\text{pv}} \\
\text{if} & \quad e \geq h/2 \quad S = 1 \\
\text{if} & \quad e \leq -h/2 \quad S = 0 \\
\text{if} & \quad h/2 > e > -h/2 \quad \text{no change in "S"}
\end{align*}
\]

The reference current for different values of sun insulation level (i.e. different values of \( P_{\text{max}} \)) is acquired through off line calculation using the PV array characteristics. Fig. 6 presents the proposed MPPT

5. Design procedure for elements of boost converter and H5 inverter

The elements of the boost converter shown in Fig. 7 have to be designed properly. The converter is supplied directly from the PV array. The boost inductor current and input voltage are the same as the PV array voltage. To design the elements of dc/dc boost converter, the following data are given:
• The maximum input voltage and current occurs at insolation level of 100%. Also these maximum values are assumed to be $V_{p_{\text{max}}}$ and $I_{p_{\text{max}}}$ corresponding to maximum power drawn from the PV array.
• The boost capacitor voltage is set to $V_C$ to meet the utility grid voltage
• The inductor current ripple and capacitor voltage ripple are $\Delta i_L$ and $\Delta v_C$, respectively
• The average switching frequency is $f_s$
• The converter efficiency is assumed to be 100%

Design procedure is as follows:
1- The average duty cycle during steady state “D” is calculated using the relation
$$D = 1 - \frac{V_C}{V_{p_{\text{max}}}}$$
2- The inductance “L” is calculated using the relation
$$L = \frac{(D V_d)}{(\Delta i_L f_s)}$$
3- The virtual load resistance seen by the converter “R” is calculated using the relation
$$R = \frac{V_d}{(1 - D)^2 + I_{p_{\text{max}}}}$$
4- The capacitance “C” is calculated using the relation
$$C = \frac{(D V_o)}{(R f_s \Delta v_o)}$$

The current and voltage ratings of the boost converter switch "q" and diode "D" are 15A and 2200V respectively as it can be investigated from Fig. 8. The current and voltage ratings of the H5 inverter switches can be determined directly from the waveforms of currents flowing in the switches and voltages across them as shown in Fig. 9. The current and voltage ratings of the inverter switches are 2.5A and 2200V respectively. The switching frequency of Q1 and Q2 is the grid frequency while the average switching frequency of switches Q2, Q4 and Q5 is 20 kHz.

![Fig. 7 Basic circuit of dc/dc boost converter](image)

For switch Q5 which operates at the sinusoidal PWM frequency (high switching switch), the current and voltage ratings are 2.5A and 2200V respectively.

**Simulation results**

The PV array connected to the utility grid through dc/dc boost converter, H5 inverter and grid filter as presented in Fig. 1 is simulated using Matlab/Simulink software. The PV array is tested separately from the system for different insolation levels. The maximum power point $P_{\text{max}}$, its corresponding $V_{p_{\text{max}}}$ and $I_{p_{\text{max}}}$ are calculated. Therefore, the proposed hysteresis current controller as a maximum power point tracker can operate properly at any insolation level. P-V curves for insolation levels 100%, 80% and 50% are shown in Fig. 10. $P_{\text{max}}$ and corresponding $V_{p_{\text{max}}}$ then $I_{p_{\text{max}}}$ can be easily determined from each curve. The hysteresis current controller for MPP receives $I_{p_{\text{max}}}$ as a reference value and the actual PV array current and the mentioned rules in (9) is applied to generate the control signal with a suitable duty cycle to boost converter switch. The hysteresis band is set at about 1.5%, which makes the PV array current almost constant and the switching frequency is nearly 10 kHz. The output voltage controller of boost converter compares the reference dc link voltage with the sum of the actual boost voltage and its derivative. The gains KA and KB are set at 100 and 30 respectively. These
values maintain the dc link voltage at a nearly constant value which in turn reduces the leakage current to reasonable values according to standards. This controller behaves like fuzzy logic controller although it is categorized under conventional controllers. The output of this controller is the reference grid current controller. The boost converter inductor and capacitor are chosen as 100 mH and 10 mF respectively based on the design procedure mentioned in section 5. The reference grid current and the phase locked loop circuit are utilized to generate the control signals of H5 inverter switches in such a way that the output voltage connected to the grid after filtering is very close to sinusoidal shape. Power MOSFET switches are selected having current and voltage ratings as mentioned in section 5. The grid filter is a simple LCL filter where inductance of 1.8 mH and capacitance of 2 nF are chosen. Fig. 11 presents the output inverter voltage (after and before filtering), grid current, PV array current and earth leakage current. The results in Fig. 11 is based on insolation level of 100%. It can be noticed that the inverter output voltage has a sinusoidal shape synchronized with the grid voltage. The power factor is unity as investigated from the inverter output voltage and grid current shapes. The PV array current is constant which achieves maximum power tracking. Simulation is carried out with insolation levels of 100%, 80%, 50%, 30%, 20%, 10% and 5% according to European standards. As the insolation level changes, the PV array power changes. Fig. 12 shows the root mean square values of the leakage current as the PV array power changes. The maximum value of the leakage current is 41 mA which occurs at 100% insolation level. This maximum value is still smaller than the permissible values mentioned in [10]. The efficiency of the proposed system as the PV array power changes is presented in Fig. 13. The efficiency increases as the PV array power increases and reaches 95.9% at 100% insolation level. Fig. 14 presents the utilization factor $K_{uf}$ of the PV array as its power changes. $K_{uf}$ is almost 100%. This high value of $K_{uf}$ is expected after inserting the dc/dc boost converter and the application of MPP tracker. The total harmonic distortion of the proposed system is given in Fig. 15. The THD is lower than 4% for insolation levels > 10% and this gives an indication of the high quality waveforms very closed to sinusoidal shape.
Conclusion

PV grid connected system supplied through H5 transformer-less inverter and dc/dc boost converter is proposed. Maximum power point operation is achieved through a hysteresis current controller which maintains the PV array current at a constant value related to the maximum power. Conventional PI controller behaving like fuzzy logic controller is proposed to maintain the dc link voltage at a constant value. Current control loop with PLL circuit generate the required control signals of the H5 inverter. Simulation results prove the high performance of the system with regard to the excellent values of system efficiency, utilization factor of PV array, leakage current and THD. Design procedure for the elements of the boost converter and H5 inverter switches is introduced.

References


