An Efficient Grid Connected Photovoltaic System Based on H6 Transformer-less Inverter

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ABSTRACT

Grid-connected photovoltaic (PV) systems based on transformer-less inverters have been widely used. Various topologies of transformer-less inverters are presented. The requirements of minimizing leakage current through transformer-less inverters and maximizing the power generated from PV arrays are of great importance. This paper presents a complete system that can effectively minimize the leakage current to safe values. In addition, operation at maximum PV array power point is realized. The system is based on modified H6 transformer-less inverter to minimize the leakage current. Perturbation and Observation P&O maximum power point tracker in addition to a dc-dc boost converter are utilized to achieve the second target. Analysis of each part and system controllers in the proposed system are presented in detail. Losses and system efficiency are introduced. Effects of sun irradiance variations are included. Simulation results prove the effectiveness of the proposed system.

Keywords: H6 transformer-less inverter, leakage current, maximum power point tracker, PV array, sun irradiance.

I. INTRODUCTION

Renewable energy technologies have seen remarkable growth during recent years as they are becoming cheaper and more efficient than before. These benefits make renewable energy technologies more attractive and an efficient alternative to other energy sources [1], [2]. Among renewable energy sources, Photovoltaics represents the most important renewable as PV arrays can be established everywhere [3], [4]. PV systems are expected to represent up to 60% of generated energy after few decades [5]. Most of PV systems are connected to utility grid and very low percentage of PV systems are delivering energy to off-grid loads (standalone systems) [6].

PV arrays require DC-AC inverters to be connected to the utility grid. Based on the galvanic isolation between electric utility grid and PV arrays, the grid connected PV arrays are divided into isolated and non-isolated systems. Galvanic isolation can be achieved either by a line frequency transformer or by a high frequency transformer. Several disadvantages are related to line frequency transformer like weight, size and cost. As a result, line frequency transformers are usually avoided. On the other hand, in high frequency transformers many power stages are required and consequently there'll be an increase in system costs and a decrease in system efficiency. Unfortunately, when the galvanic isolation is missed by removing both types of transformers, large leakage current flows through the parasitic capacitance between the frames of PV arrays and ground potential due to voltage fluctuation caused by conventional dc-ac inverters [7]-[9].

To overcome the leakage current problems, the so-called transformer-less inverters are utilized. Many topologies of transformer-less inverters are presented in literature including three phase and single-phase transformer-less inverters [10]-[17]. The main feature of transformer-less inverters is to decouple the photovoltaic arrays from the grid either on the dc side (PV array side) as in H5, H6 and H7 transformer-less inverters or on the dc side (grid side) as in the highly efficient and reliable inverter concept converter (HERIC) transformer-less inverter. Additional power switches are employed to achieve the decoupling and hence reduce the leakage currents to safe values according to standards [18]. These additional switches play very important role during power flow from PV arrays to grid (conduction modes) and during disconnecting PV arrays from grid (freewheeling modes). Regarding single phase transformer-less inverters, the most popular topologies are H5, H6 and HERIC inverters. In H5 inverters only five switches are utilized. However, three power switches are always turned-on during conduction modes in positive and negative half cycles. Therefore, total conduction losses go up. With HERIC transformer-less inverter, six power switches are used. However, there are only two power switches on during conduction mode and as a result the total conduction losses decrease.

Conventional H6 inverter is introduced in [19] using six power switches and two diodes. However, three switches are conducting during each conduction periods and as a result the conduction losses increase. Two different modified H6 transformer-less inverters are presented in [20] and [21]. In both topologies, three switches are conducting in the first half cycle conduction mode while only two switches are
conducting in the second half cycle conduction mode hence the conduction losses decrease. Furthermore, the additional diodes are omitted. In most transformer-less inverters in the literature, the main target is to overcome the problem of leakage currents regardless of the maximization of power extracted from PV arrays. Therefore, studying both issues in a complete system is rarely observed.

This paper presents the achievement of minimizing leakage current and maximizing the power generated by the PV array in a complete system. The proposed system as presented in Fig. 1 consists of two main parts, (1) the DC side including PV array, step up boost chopper, P&O MPPT and voltage controller of boost converter output voltage and (2) AC side including the modified H6 transformer-less inverter, LCL filter, H6 control unit in addition to the utility grid. Analysis of each part is provided in detail. Conduction losses and switching losses of H6 inverter and boost converter are studied. System efficiency and utilization factor are calculated. Simulation of the complete system is carried out to emphasize the high performance of the system. The paper is organized as follows: section II presents the PV array side and controllers. Section III presents the operation principle of the considered H6 transformer-less inverter. Section IV gives the study of losses in the system elements then the proper selection of elements is introduced. Section V presents simulation results and discussion and finally, section VI is the conclusion.

II. SYSTEM DC SIDE AND CONTROLLERS

This section describes the photovoltaic arrays model, maximum power point tracking algorithm and dc-dc boost converter.

A. PV Array Model

The well-known one diode photovoltaic cell model is given in Fig. 2. The model is composed of current source with a shunt resistance and a shunt diode in addition to a series resistance. The current in the shunt resistance can be neglected if that resistance is large enough. The model’s equations are well-known as given in [22].

B. DC-DC Boost Converter

DC-DC boost converter is employed where the converter output voltage is related to its input voltage (PV array terminal voltage) by:

\[ V_{out} = \frac{V_{in}}{1-D} \]  

(1)

‘D’ is the control signal duty ratio delivered to the converter power switch. This duty cycle is adjusted using the maximum power point tracker to track the operation of PV arrays at maximum power point at every level of sun irradiation. A voltage controller on the output side of the boost chopper is employed to maintain the converter output voltage at the required level to realize successful connection between the H6 transformer-less inverter and utility grid.

C. Maximum Power Point Tracker (MPPT)

Perturbation and Observation P&O MPPT is utilized in the proposed system. In addition to its simplicity, P&O MPPT does not require any details about the characteristics of the PV array [22], [23]. The P&O algorithm operates by decreasing or increasing the reference voltage of the PV array at regular intervals. The change in the output power of the PV array \( dP_{PV} \) and the change in the PV array terminal voltage \( dV_{PV} \) during successive intervals are used to determine the slope \( \frac{dP_{PV}}{dV_{PV}} \). This slope is positive on the left area of maximum power point, and it is negative on the right area of maximum power point as given in Fig. 3. Once the
slope \frac{dP_{PV}}{dV_{PV}} is determined, the decision of the algorithm is to increase or decrease \( V_{ref} \) according to the flow chart shown in Fig. 4. As the updated value of \( V_{ref} \) is determined, the required control signal duty cycle ‘D’ delivered to the power switch of boost chopper is generated. Procedure of MPPT in MATLAB/SIMULINK is given in Fig. 5.

![Flow chart of P&O MPPT](image)

**Fig. 4.** Flow chart of P&O MPPT.

The purpose of this voltage controller is to keep the dc-dc boost converter output voltage at the required voltage level (450 V) which is suitable to meet the grid voltage level. Fig. 6 presents the voltage controller where it receives the reference value (450 V), the actual output voltage of the boost converter, and its derivative. The controller combines the fuzzy logic controller intelligent feature and the simplicity of conventional controllers at the same time [25]. The controller gains \( K_1 \) and \( K_2 \) are set to 0.001 and 30, respectively while the reference grid current \( I_{g-ref} \) is the output of the controller.

![Controller of boost converter output voltage](image)

**Fig. 6.** Controller of boost converter output voltage.

**III. H6 TRANSFORMER-LESS INVERTER OPERATION**

Conventional and modified H6 transformer-less inverter are presented in Fig. 7 [20], [21]. In the modified H6 transformer-less inverter (Fig. 7b), the number of converter switches is reduced. Only two switches carry current in the active mode during negative half cycle which is the best feature of the modified H6 inverter over conventional H6 inverter. Therefore, the conduction losses, system complexity, and overall cost are reduced. Fig. 8 summarizes the four operation modes of the considered modified H6 inverter as follows:

![Four operation modes of the modified H6 inverter](image)

**Fig. 7.** (a) conventional H6 transformer-less inverter and (b) modified H6 transformer-less inverter.
Mode 1: Positive half cycle active mode. In this period, the power switches $Q_1$, $Q_2$, and $Q_5$ are turned ‘ON’ together as given in Fig. 8a. As a result, the energy is delivered from the photovoltaic panels to the grid and the output voltage of the inverter is $V_{dc}$.

Mode 2: Positive half cycle freewheeling mode during which the power switch $Q_1$ and the antiparallel diode of switch $Q_3$ are in the conduction state (Fig. 8b). The output voltage of the inverter is zero during this mode. In addition, the leakage current will decrease since there is no connection between the PV arrays and the utility grid.

Mode 3: Negative half cycle active mode. In this period, the power switches $Q_3$, $Q_4$, and $Q_6$ are turned ‘ON’ together as given in Fig. 8c. As a result, the energy is delivered from the photovoltaic panels to the grid and the output voltage of the inverter is $-V_{dc}$. Although $Q_3$ is kept in the ‘ON’ state during the negative half cycle (to make it operate at a low frequency operation), this switch carries no current in the active mode, and actually $Q_3$ and $Q_6$ are the only two conducting switches. This is the best feature of the modified H6 as previously mentioned.

Mode 4: Negative half cycle freewheeling mode during which the switch $Q_3$ and the antiparallel diode of switch $Q_1$ are in the conduction state (Fig. 8d). The output voltage of the inverter is zero during this mode. In addition, the leakage current will decrease since there is no connection between the photovoltaic panels and the utility grid.

IV. LOSSES AND EFFICIENCY OF THE PROPOSED SYSTEM

The efficiency of the proposed system $\eta$ is defined as:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{pu} - \text{Total Losses}}{P_{pu}}$$

The total losses are divided into conduction losses and switching losses in the power switches of H6 inverter and boost converter power switch in addition to the conduction losses in the boost converter diode. The dominant losses are the conduction losses. The following equations give the conduction losses of each power switch $P_{SW-Cond.}$ or diode $P_{D-Cond.}$:

$$P_{SW-Cond.} = \frac{1}{T} \int_{0}^{T} i_{SW}^2 R_{on} \, dt$$  \hspace{1cm} (3)

$$P_{D-Cond.} = \frac{1}{T} \int_{0}^{T} i_{D} V_{D} \, dt$$  \hspace{1cm} (4)

where

- $i_{SW}$ = switch instantaneous conduction current.
- $i_{D}$ = diode instantaneous conduction current.
- $R_{on}$ = switch on-state resistance.
- $V_{D}$ = diode forward voltage.
- $T$ = fundamental period.

For a switching frequency of “$f_s$”, the switching power losses $P_s$ is approximated by the following equation [15]:

Fig. 8. Modes of operation of modified H6 transformer-less inverter.
\[ P_2 = \frac{k_2 V_{Sm} I_{Sm}}{6} (t_{on} + t_{off}) \]  

(5)

where

- \( V_{Sm} \) = Maximum switch voltage.
- \( I_{Sm} \) = Maximum switch current.
- \( t_{on} \) = Turn-on delay time of the switch.
- \( t_{off} \) = Turn-off delay time of the switch.

The values of the variables \( I_{Sm}, k_2, V_{Sm}, I_{Sm} \) depend on the performance of the H6 inverter and boost converter and these values are determined instantaneously during system operation. On the other hand, the values of the constants \( R_{on}, V_p, \) \( t_{on} \) and \( t_{off} \) are determined from the specifications of power switches and diodes. \( R_{on} \) and \( V_D \) affect the conduction losses of the power switch and diode respectively while \( t_{on} \) and \( t_{off} \) affect the switching power losses.

Therefore, suitable switches and diodes should be selected properly to reduce the total losses as possible. Here are two suitable designs for the power switches that meet the requirements of the proposed system:

- **Design A:** H6 transformer-less inverter switches:
  - IPA80R360P7 (\( R_{on} = 0.36\Omega \))
  - Boost converter switch: SPP15N60C3 (\( R_{on} = 0.28\Omega \))

- **Design B:** H6 transformer-less inverter switches:
  - IPP80R750P7 (\( R_{on} = 0.75\Omega \))
  - Boost converter switch: SPP11N80C3 (\( R_{on} = 0.45\Omega \))

Through simulation results, the effects of each design on the system efficiency will be presented and discussed.

V. SIMULATION RESULTS AND DISCUSSION

The complete system presented in Fig. 1 is simulated through MATLAB/SIMULINK package. The specification of the selected PV array is given in Table 1 where the maximum achievable power \( P_{pvmax} \) is 1200 W at sun irradiance of 1000 W/m\(^2\). The boost chopper inductor is 100 mH and the chopper capacitor is 2 mF. The switching frequency is set to 10 kHz. The PV array terminal voltage and its output current are delivered to the perturb and observe MPPT which is an m-file written based on the pre-described algorithm of MPPT in section II-C. The MPPT algorithm generates the control signal having the adjusted duty ratio to the dc-dc boost chopper power switch. The voltage controller of boost converter maintains the input voltage of H6 transformer-less inverter at a constant suitable level that meets the requirements of connection to the utility grid by generating the reference utility grid current \( I_{g,ref} \). The combination of grid voltage \( V_g \), reference utility grid current \( I_{g,ref} \), actual grid current \( I_g \) in addition to phase locked loop circuit and PI controller forms the control unit whose purpose is to generate the control signals of H6 inverter power switches. An LCL filter is utilized to achieve sinusoidal output voltage of the system. The inductances and capacitance of the filter are set to 1.8mH and 3nF respectively. To limit large currents to the grid, a series inductor (50\( \mu \)H) is employed between the proposed system and grid.

Fig. 9 presents the PV array terminal voltage, current and power as the sun irradiance changes from 1000 W/m\(^2\) to 800 W/m\(^2\) at 4s then from 800 W/m\(^2\) to 600 W/m\(^2\) at 8s. The MPPT continuously tracks the maximum power from the PV array to 1200 W, 960 W then 720 W by generating the suitable control signal in such a way that the PV array operates at voltage and current corresponding to the maximum power point. Fig. 10 presents grid voltage, inverter output voltage before and after LCL filter, grid current, leakage current, and output voltage of the boost converter. The grid current output voltage utilizing the filter has a sinusoidal shape. The boost converter output voltage is kept constant at the required level. The leakage current has a very low safe value (18 mA to 20 mA) which is much less than the recommended values (300 mA) [18].

Fig. 11 shows the control signals of the power switches. \( Q_1 \) and \( Q_2 \) are turned on and off at the fundamental frequency (50 Hz) while the other four switches are turned on and off at the switching frequency (10kHz). The currents in the switches are presented in Fig. 12.

![Fig. 9. Sun irradiance (W/m\(^2\)), PV array voltage (V), PV array current (A) and PV array power (W).](image)

Switches \( Q_1 \) and \( Q_2 \) carries positive currents during active conduction modes and negative currents in their antiparallel diodes during freewheeling modes while the other switches carry current only during conduction modes. The currents in switches \( Q_2 \) and \( Q_5 \) are identical. Also, the currents in switches \( Q_1 \) and \( Q_4 \) are identical and similar to current in \( Q_2 \) and \( Q_5 \) with a half-cycle shifted. Therefore, the total conduction losses of the four switches are simply calculated by multiplying the conduction losses of any of them by 4.

The conduction losses and switching losses are calculated as in section IV then the total losses and consequently system efficiency are determined at sun irradiance levels changing from 10% \( (P_{pvmax} = 120W) \) to 100% \( (P_{pvmax} = 1200W) \).

Fig. 13 presents the variations of proposed system efficiency as the sun irradiance level changes considering both designs, design A and design B. It can be noticed that design A gives better performance than design B because of the reduced values of \( R_{on} \) in design A.

To study the achievement possibility of maximum power extracted from the PV array, the utilization factor \( K_u \) is calculated along the variations of sun irradiance level. \( K_u \) is the ratio between the average actual generated photovoltaic arrays' power \( P_{pv} \) to the maximum expected arrays' power \( P_{pvmax} \) at sun irradiance of 1000 W/m\(^2\).

\[ K_u = \frac{P_{pv}}{P_{pvmax}} \]  

(6)
Fig. 10. Grid voltage (V), inverter output voltage after filter (V), grid current (A), inverter output voltage after filter (V), leakage current (A) and output voltage of the boost converter (V).

Fig. 11. Power switches control signals of H6 transformer-less inverter.

Fig. 12. Currents in the power switches of H6 transformer-less inverter.
VI. CONCLUSION

An effective complete PV-grid connected system is proposed. The proposed system includes dc-dc boost converter and MPPT in addition to the PV array on the system DC side to maximize the power generated from the PV array. At the same time, there is the modified H6 transformer-less inverter, LCL filter and inverter controller on the system AC side to minimize the leakage current to safe values. The dc link voltage between the DC side and the AC side is controlled by the voltage controller to maintain this dc link voltage at a constant suitable level to meet the connection requirements between the photovoltaic panels with the utility grid. Operation of the modified H6 transformer-less inverter and detailed description of various controllers in the proposed system are presented. Losses in the power switches and diode and system efficiency are introduced. Simulation of the proposed system involving variations in sun irradiance levels is presented. Simulation results prove that the proposed system performs very well achieving both targets of the system at different sun irradiance levels. Furthermore, important guides are presented for the proper selection of power switches.

REFERENCES

[19] Yu W, Lai J, Qian H, and Hutchens C. High-efficiency MOSFET inverter with H6-type configuration for photovoltaic non-isolated ac-

![Fig. 13. Proposed system efficiency against variations of sun irradiance level.](image1)

![Fig. 14. Utilization factor K_u versus the PV array generated power.](image2)

**TABLE 1. PARAMETERS OF THE PV ARRAY AT 100% SUN IRRADIANCE 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 PV array power (W)</td>
<td>1200</td>
</tr>
<tr>
<td>Voltage at maximum PV array power V_{pmax} (V)</td>
<td>346</td>
</tr>
<tr>
<td>Current at maximum PV array power I_{pmax} (A)</td>
<td>3.47</td>
</tr>
</tbody>
</table>

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