International Journal of Modern Engineering Research (IJMER)
www.ijmer.com Vol. 3, Issue. 5, Sep - Oct. 2013 pp-2932-2938 ISSN: 2249-6645

Analysis and Modeling of Transformerless Photovoltaic Inverter Systems

J.Nagarjuna Reddy*, K Jyothi
*Assistant Professor, Dept. of EEE, RGMCET, Nandyal, India,
PG Student, Power Electronics/EEE, RGMCET, Nandyal, India,

ABSTRACT: *The need for a cleaner environment and the continuous increase in power demands makes decentralized renewable energy production, like solar and wind more and more interesting. Decentralized energy production using solar energy could be a solution for balancing the continuously-increasing power demands. This continuously increasing consumption overloads the distribution grids as well as the power stations. Therefore having negative impact on power availability, security and quality. The efficiency and reliability of single-phase PV inverter systems suffers from new problems related to leakage current and safety. This problem can be reduced by using transformerless inverter topologies. The work presented in this paper deals with analyzing and modeling of transformerless PV inverter systems regarding the leakage current phenomenon that can damage solar panels and pose safety problems.*

Index Terms: *DC–AC power conversion, photovoltaic(PV) systems, transformer less inverter.*

I. INTRODUCTION

Grid-connected photovoltaic (PV) systems, particularly low-power single-phase systems, are becoming more important worldwide. They are usually private systems where the owner tries to get the maximum system profitability. Issues such as reliability, high efficiency, small size and weight, and
low price are of great importance to the conversion stage of the PV system . Quite often, these grid-connected PV systems include a line transformer in the power-conversion stage, which guarantees galvanic isolation between the grid and the PV system, thus providing personal protection. Furthermore, it strongly reduces the leakage currents between the PV system and the ground, ensures that no continuous current is injected into the grid, and can be used to increase the inverter output voltage level. The line transformer makes possible the use of a full-bridge inverter with unipolar pulse width modulation (PWM). The inverter is simple. It requires only four insulated gate bipolar transistors (IGBTs) and has a good trade-off between efficiency, complexity and price. Due to its low frequency, the line transformer is large, heavy and expensive.

This paper proposes a new topology that generates no varying common-mode voltage, requires the same low-input voltage as the bipolar PWM full-bridge topology, and achieves a higher efficiency and a lower current ripple in the inductor. The topology consists of six switches and can be an advantageous power conversion stage for transformer less grid-connected PV systems.

II. COMMON-MODE CURRENTS INTRANSFORMERLESS PV SYSTEMS

When no transformer is used, a galvanic connection between the ground of the grid and the PV array exists. As a consequence a common-mode resonant circuit appears, consisting of the stray capacity between the PV modules and the ground, the dc and ac filter elements, and the grid impedance (Fig. 1). A varying common-mode voltage can excite this resonant circuit and generate a common-mode current. Due to the large surface of the PV generator, its stray capacity with respect to the ground reaches values that can be even higher than 200 nF/kWp in damp environments or on rainy days. These high values can generate ground currents with amplitudes well above the permissible levels, such as those concerning the standards. The currents can cause severe (conducted and radiated) electromagnetic interferences, distortion in the grid current and additional losses in the system. These leakage currents can be avoided, or at least limited, by including damping passive components in the resonant circuit. Obviously, additional losses will appear in the damping elements, thus decreasing the conversion stage efficiency.

The use of conversion topologies with a constant common mode voltage is another option. The instantaneous common mode voltage V_{cm} in the full-bridge inverter of Fig. 1can be calculated from the voltage of the two mid-points of both legs,

V_{AO} and V_{BO} as

$$V_{cm} = \frac{V_{AO} + V_{BO}}{2} \qquad (1)$$

To avoid leakage currents, the common-mode voltage must be kept constant during all commutation states, that is

$$V_{cm} = V_{AO} + V_{BO}$$

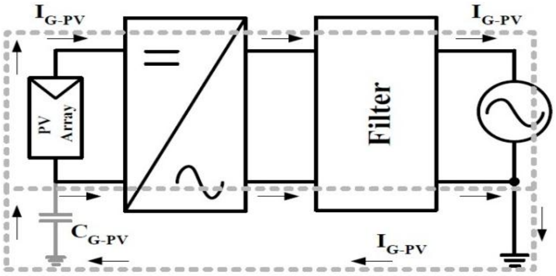

Fig.1 Common-mode currents in a transformer less conversion stage

III. MODELLING OF PV MODULE

The most commonly used model for PV-cell is one – diode equivalent circuit as shown in figure (2). Since the shunt resistance R_{sh} is large, it is normally neglected. This simplified circuit is used in this paper for modeling of a PV-cell.

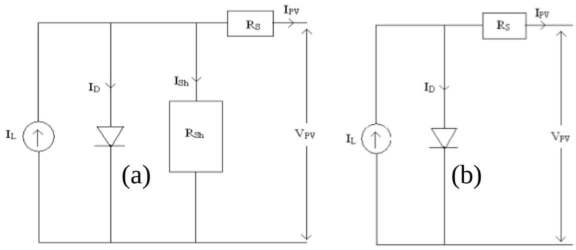

Fig.2. One-diode equivalent circuit model for a PV cell.
(a) Five parameters model;
(b) Simplified four parameters model

The non-linear of V_{pv}-I_{pv} and P-V curves are correspondingly drawn as shown below:
From figure (2.b) the relation between the output V_{pv} and the output current I_{pv} can be expressed as:

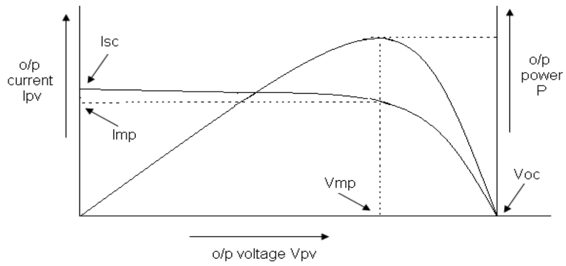

Fig.3. V_{pv}-I_{pv}& P-V_{pv} characteristics of a PV cell

From figure (2.b) the relation between the output V_{pv} and the output current I_{pv} can be expressed as:

$$I_{PV} = I_L - I_D$$

$$I_{PV} = I_L - I_0\left(\exp\left(\frac{V_{PV} + I_{PV} R_S}{\propto}\right) - 1\right) \qquad (2)$$

Where I_L= Light current; I_o= Saturation current; R_s= Series Resistance; α = Thermal voltage timing completion factor.

The above four parameters are need to be determined to obtain the I-V characteristics of PV-module. Thus, this model can be termed as Four-parameter model. The equations for determining the four parameters are given below:

A. ***Light Current (I_L)***

$$I_L = \frac{G}{G_{ref}}\left(I_{Lref} + \mu_{Isc}(T_C - T_{Cref})\right) \qquad (3)$$

Where G= irradiance (W/m^2);
Gref = Reference iradiance (1000W/m^2 issued in this study);
I_{Lref} = light current at the reference condition (1000W/m^2 and 25˚C); Tc = PV cell temperature (˚C);
T_{cref} = Reference temperature (25˚C issued in this study);
μ_{Isc} = temperature coefficient of the short-circuit current (A/˚C).

From the above equation for light current it can be observed that I_L is a function of both temperature and irradiance. Both I_{Lref} and μ_{Isc} can be obtained from manufacturer data sheet.

B. Saturation Current (I_O)

$$I_O = I_{Oref}\left(\frac{T_C+273}{T_{Cref}+273}\right)^3 \exp\left(\frac{e_{gap}\,q}{N_S \propto_{ref}}\left(1-\frac{T_{Cref}+273}{T_C+273}\right)\right) \quad (4)$$

Where I_{oref} = saturation current at the reference condition (A);
e_{gap} = band gap of the material1. 17eV for Simaterials);
N_S = number of cell sin series of a PV module;
q = charge of an electron (1.60217733×10^{-19} C);
α_{ref} = the value of α at reference condition.
I_{oref} can be calculated as:

$$I_{Oref} = I_{Lref}\exp\left(-\frac{V_{OCref}}{\propto_{ref}}\right) \quad (5)$$

Where V_{ocref} = the open circuit voltage of the PV module at reference condition (V).

C. Calculation of α

$$\propto = \frac{T_C + 273}{T_{Cref} + 273}\propto_{ref} \quad (6)$$

The value of α_{ref} can be calculated as:

$$\propto_{ref} \frac{2V_{mpref} - V_{ocref}}{\frac{I_{scref}}{I_{scref} - I_{mpref}} + ln\left(1-\frac{I_{mpref}}{I_{scref}}\right)} \quad (7)$$

Where
V_{mpref}= maximum power point voltage at the reference condition (V);
I_{mpref} = maximum power point current at the reference condition (A);
I_{scref} = short circuit current at the reference condition (A).

D. Series Resistance (R_S)

Some manufacturers provide the value of R_S.If not provided, the following equation can be used to estimate its value:

$$R_S = \frac{\propto_{ref}\ ln\left(1-\frac{I_{mpref}}{I_{scref}}\right) + V_{ocref} - V_{mpref}}{I_{mpref}} \quad (8)$$

R_S is taken as a constant in the model of this study.

E. *Thermal Model of PV*

From equations (1) to (7), it can be noted that the temperature plays an important role in the PV performance. Therefore, it is necessary to have a thermal model for a PV cell / module. In this study, a lumped thermal model is developed for the PV module. The temperature of the PV module varies with surrounding temperature, irradiance, and its output current and voltage, and can be written as:

$$C_{pv}\frac{dT_C}{dt} = K_{inpv}\,G - \frac{V_{pv}I_{pv}}{A} - K_{loss}(T_C - T_a) \quad (9)$$

C_{PV} = the overall heat capacity per unit area of the PV cell / module [J/ (˚C-m^2)];
K_{inpv} = Transmittance – absorption product of PV cells;
K_{loss} = overall heat loss coefficient [W/ (˚C-m^2)];
T_a = ambient temperature (˚C);
A = effective area of the PV cell / module (m^2).

IV. REVIEW OFTRANSFORMERLESS INVERTER TOPOLOGIES

Ideal transformerless inverter generates constant common mode voltage. However, if the voltage varies with time, then a leakage current is produced. For the sake of minimizing this leakage current, different topologies were studied. Among these are the full bridge with bipolar PWM, the half bridge, HERIC, H5, H6 and NPC all of which experience certain drawbacks which are discussed next.

2.1. Full Bridge Inverter

The full-bridge inverter with bipolar PWM causes high switching losses and large current ripples and does not eliminate the DC current injected into the grid that has the tendency of saturating the transformer cores. Even though, this topology is being used in some commercial transformerless inverters, it still presents quite low efficiency according to the European standards due to the losses caused by the double switching frequency.

2.2. Half Bridge Inverter

The half bridge inverter, on the other hand, requires a high input voltage and a boost converter in the DC side that would increase the inverter size and cost and reduce its efficiency down to 92% [6,8]. For this reason the half bridge is not recommended.

2.3. HERIC Inverter

Meanwhile the HERIC topology, shown in Fig. 1, combines the advantages of the unipolar and bipolar modulations. It has a three level output voltage, a high efficiency and a low leakage current. However, the HERIC topology presents low frequency harmonics and does not allow for reactive power flow. This is due to the control strategy.

2.4. H5 Inverter

This topology is based on the full bridge with an extra switch on the DC side. In this topology, the upper switches operate at grid frequency while the lower switches operate at high frequency. The extra switch operates at high frequency and guarantees the disconnection of the DC source from the grid. This topology has two main disadvantages. The first one is the high conduction losses due to the fact that three switches operate simultaneously. The second one is that the reactive power flow is not possible due to the control strategy.

2.5. NPC Inverter

The NPC inverter topology is being considered as an attractive solution in case of transformerless systems. This inverter has the advantages of no internal reactive power flow, a three level inverter output voltage and a low leakage current. However, it requires an input voltage as high as twice the input voltage required by other topologies and a boost stage which increases inverter losses and size.

V. FULL-BRIDGE INVERTER

The full-bridge inverter (Fig. 3) is a single stage dc–ac conversion topology that is used quite often in PV inverters. Different PWM techniques can be applied to this topology. Depending on the shape of the output voltage waveform, they can be classified in two groups, namely unipolar and bipolar PWM. When the full bridge is part of a conversion stage with a line transformer, unipolar PWM techniques can be applied. This is in proposed topology. Here, $S_4$is on duringthe positive half cycle, while switches S_1andS_2commutateat the switching frequency. During the negative cycle, $S_2$is on andS_3, S_4 commutate at the switching frequency. In this converter

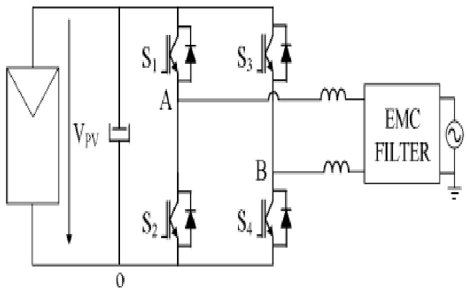

Fig 4. Full-bridge inverter

Only two switches are on at the same time, and only one IGBT and one diode commutate at the switching frequency with the whole input voltage. The main drawback, that it generates a varying common-mode voltage of amplitude V_{pv} /2 at the switching frequency.

In the bipolar PWM, the diagonal pairs of switches S_1- S_4 and $S_2 - S_3$are switched alternatively at the switching frequency. As a consequence

$$V_{BO} = V_{PV} - V_{Ao} \Rightarrow V_{cm} = V_{PV}/2 \ = \text{cte}$$

If the switching actions are carried out at the same time, no changes appear in the common-mode voltage and no leakage currents are generated. However, the bipolar PWM also has draw backs. Two IGBTs and two diodes are switching at the switching frequency with the whole input voltage, therefore doubling the switching losses. Additionally, the output voltage changes between $V_{PV}$and - V_{PV}, creating a current rippletwice that obtained in the unipolar modulation.

VI. SIMULATION RESULTS

Based on the mathematical equations discussed before, a dynamic model for a PV module consisting of 153 cells in series has been developed using MATLAB/Simulink. The input quantities (solar irradiance G and the ambient temperature Ta) together with manufacturer data are used to calculate the four parameters. Then, based on equation (1), the output voltage is obtained numerically. The thermal model is used to estimate the PV cell temperature. The two output quantities

(PV output voltage V_{pv} and the PV cell temperature T_c), and the load current I_{pv}, are fed back to participate in the calculations. The model parameters used in the simulation are given in Table I

Table 1. THE PV MODEL PARAMETERS

$I_{SCref}(I_{Lref})$	2.664A
α_{ref}	5.472
R_S	1.324Ω
V_{OCref}	87.72V
V_{MPref}	70.731V
I_{MPref}	2.448A
G_{ref}	1000w/m^2
T_{cref}	25°c
C_{pv}	$5*10^4$J/(^{0}c-m^2)
A	1.5m^2
K_{inpv}	0.9
K_{loss}	30W/(^{0}c-m^2)

A. Model Performance

The model I_{pv}-V_{pv} characteristic curves under different irradiances are given in Figure (6) at 25˚C. It is noted from the figure that the higher is the irradiance, the larger are the short-circuit current (I_{SC}) and the open- circuit voltage (V_{oc}). And, obviously, the larger will be the maximum power (P), shown in Figure (7).

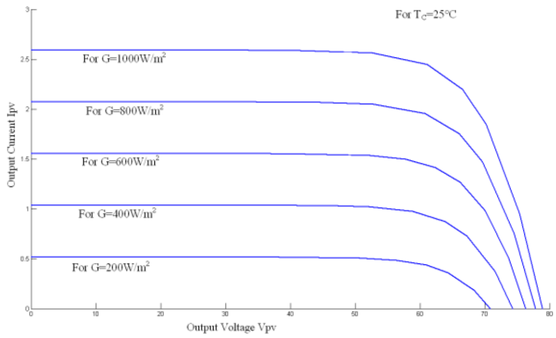

Fig6. V_{pv}-I_{pv} characteristics for constant T_c and Varying G

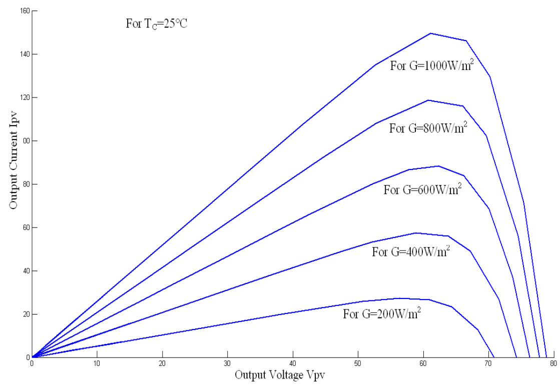

Fig.7. P-V_{pv} characteristics for constant Tc and Varying G

The simulation results of full bridge inverter with unipolar PWM and bipolar PWM te are shown in fig 8 and fig 9

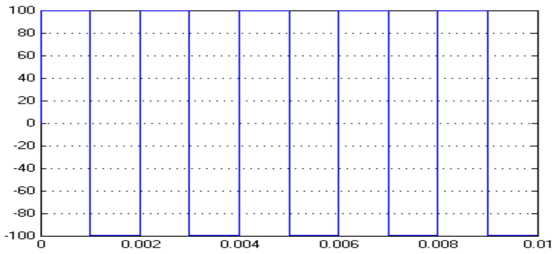

Fig 8. Output voltage in a full bridge inverter topology with bipolar PWM.

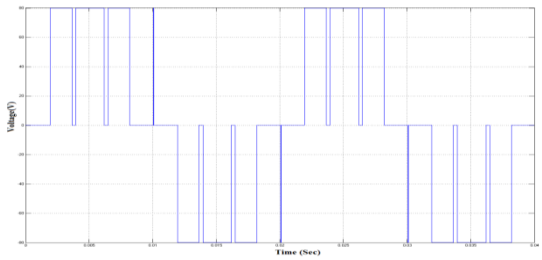

Fig 9. Output voltage in a full bridge inverter topology with unipolar PWM.

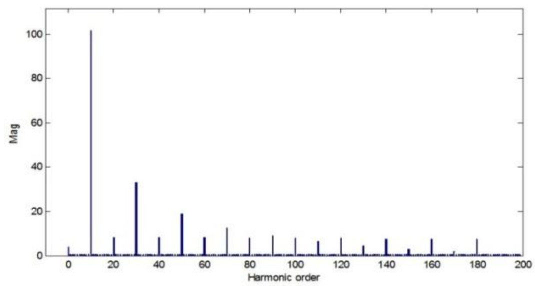

Fig 10. FFT analysis of bipolar PWM switching

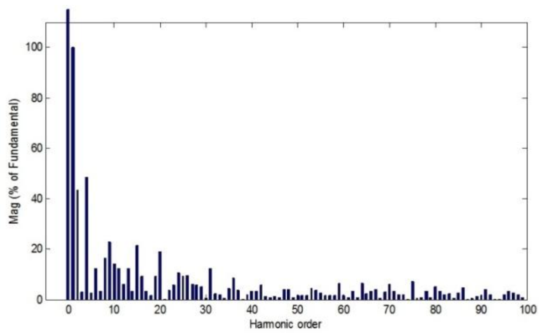

Fig 11. FFT analysis of unipolar PWM switching

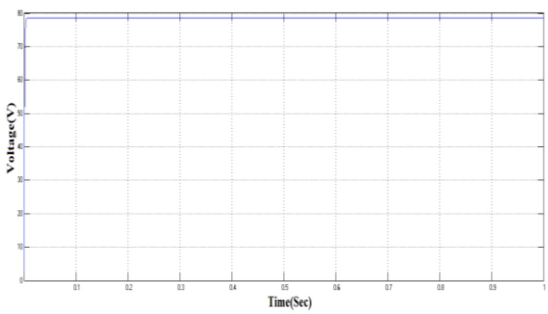

Fig 12. Output Of Pv Cell

Table 3. Lekage Currents Of Unipolar And Bipolar Switching

S.No	Leakage Current
PV cell With Unipolar PWM Switching	10mA
PV cell With bipolar PWM Switching	5mA

VII. CONCLUSION

This paper proposes a new transformerless, single-phase PV inverter with six switches and two diodes. The proposed topology generates no common-mode voltage, exhibits a high efficiency, and can operate with any power factor. It has been compared to other topologies and validated satisfactory results. The maximum efficiency achieved by the topology is 97.4%, As a conclusion, the proposed topology can be an advantageous power-conversion stage for transformer less, grid-connected PV systems.

REFERENCES

[1] M. Calais and V. G. Agelidis, "Multilevel converters for single-phase grid connected photovoltaic systems— An overview," in *Proc. IEEEInt.Symp. Ind. Electron.*, 1998, vol. 1, pp. 224–229.

[2] M. Calais, J. M. A. Myrzik, and V. G. Agelidis, "Inverters for single phase grid connected photovoltaic systems—Overview and prospects,"in*Proc. 17th Eur.Photovoltaic Solar Energy Conf.*, Munich, Germany, Oct. 22–26, 2001, pp. 437–440.

[3] B. Epp, "Big crowds," *Sun & Wind Energy: Photovoltaics*, pp. 69–77,Feb. 2005.

[4] J. M. A. Myrzik and M. Calais, "String and module integrated inverter for single-phase grid connected photovoltaic systems—A review," in *Proc. IEEE Power Tech. Conf.*, Bologna, Italy, Jun. 23–26, 2003, vol.2, pp. 1–8.

[5] W. N. Mohan, T. Undeland, and W. P. Robbins, *Power Electronics: Converters, Applications, and Design*. New York: Wiley, 2003.

[6] *VVerband der Elektrotechnik, Elektronik und Informations technik(VDE)*, Std. V 0126-1-1, Deutsches Institute fürNormung, Feb. 2006.

[7] *IEEE Standard for Interconnecting Distributed Resources with ElectricPower Systems*, IEEE Std. 1547, 2003.

[8] S. B. Kjaer, J. K. Pedersen, and F. Blaabjerg, "A review of single-phase grid-connected inverters for photovoltaic modules," *IEEE Trans. Ind.Appl.*, vol. 41, no. 5, pp. 1292–1306, Sep./Oct. 2005.

[9] M. F. Arman and L. Zhong, "A new, transformerless, photovoltaic array to utility grid interconnection," in *Proc. Int. Conf. Power Electron Drive Syst.*, May 26–29, 1997, vol. 1, pp. 139–143.

[10] Y. Nishida, S. Nakamura, N. Aikawa, S. Sumiyoshi, H. Yamashita, and H. Omori, "A novel type of utility-interactive inverter for photovoltaic system," in *Proc. 29th Annu. IEEE Ind. Electron. Soc. Conf.*, Nov. 2–6, 2003, vol. 3, pp. 2338–2343.

[11] Y. Chen and K. M. Smedley, "A cost-effective single-stage inverter with maximum power point tracking," *IEEE Trans. Power Electron.*,vol. 19, no. 5, pp. 1289– 1294, Sep. 2004.

J.Nagarjuna Reddy was born in 1985 in India. He received the B.Tech from Dr.Paul Raj Engg. College in 2005 and Post graduated from Jawaharlal Nehru Technological University (JNTU), Hyderabad, In 2006-2008. He is currently working as a assistant professor in the department of electrical and electronics engineering in RGM college of engineering and technology, Nandyal, Andhra Pradesh, India. He has Two years of teaching experience. His main areas of research include Electrical Drives & Renewable energy source.

K Jyothi was born in Kurnool India. He received the B.Tech (Electrical and Electronics Engineering) degree from the Jawaharla Nehru Technological University, Hyderabad in 2011 and persuing the M.Tech (Power Electronics) from Jawaharlal Nehru Technological University, Anantapur. His area of interest in the field of power electronic converters and Electric Drives. (E-mail: jyothi.kancham@gmail.com).