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

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Abstract- This paper presents an efficient PV array connected to utility grid through H5 transformer-less 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}

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

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]:

$$K_{uf} = 0.5\, m \quad (2)$$

Where m is the modulation index

For m $\le$1, the utilization factor is $\le$ 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 %

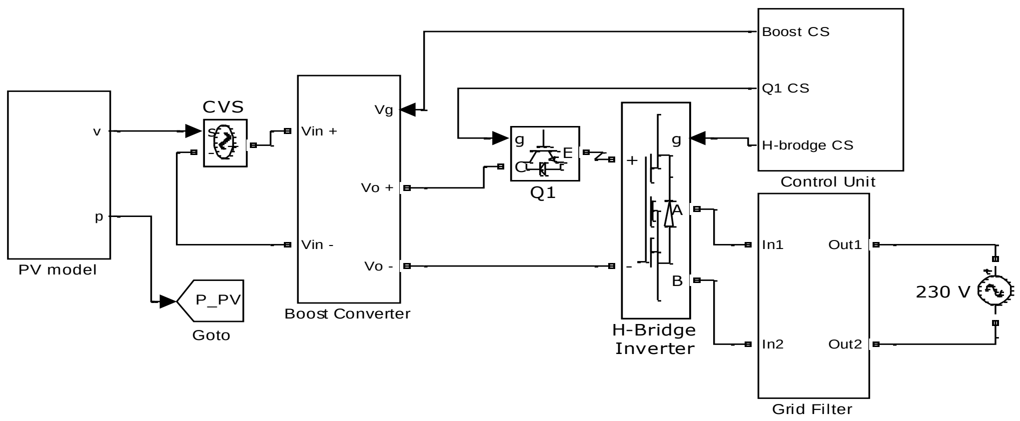

Fig. 1 Proposed PV grid connected system

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

Open circuit voltage (V)	422
Short circuit current (A)	15.2
Maximum power (W)	4839
Voltage for maximum power V_{pmax} (V)	343.9
Current for maximum power I_{pmax} (A)	14.07

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:

$$V_o = V_i / (1-D) \tag{3}$$

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 maintain 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].

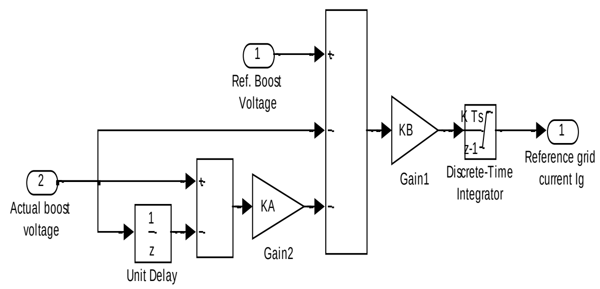

Fig. 2 Boost converter voltage controller

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.

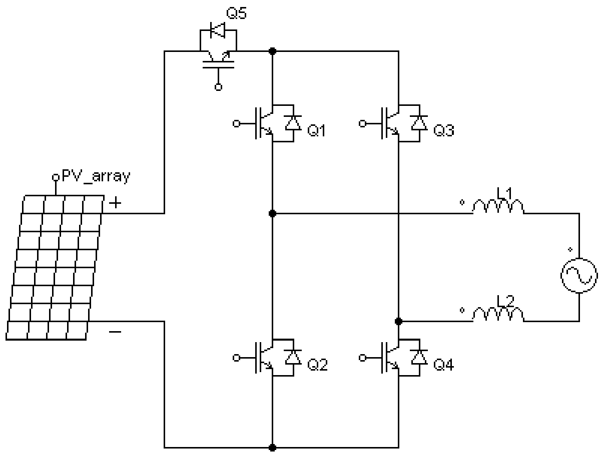

Fig. 3 H5 inverter fed by PV array

Modes of operation of the inverter are illustrated as follows:

- Positive level of inverter output voltage

This mode occurs during the positive half cycle where the switches Q5, Q1 and Q4 are turned on. This mode is known as the active mode and its current path is PV-Q5-Q1-L_1-grid-L_2-Q4-PV

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

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_{Q3}-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_{Q1}-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

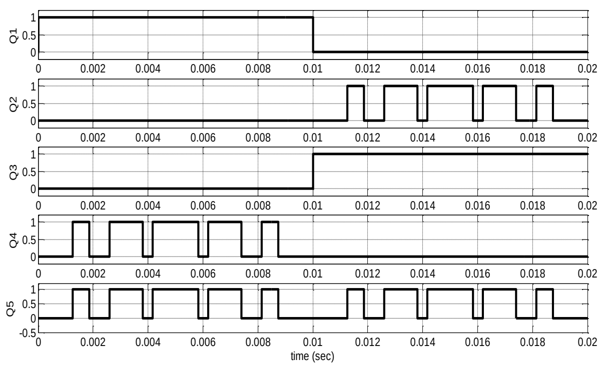

Fig. 4 Control signals of H5 inverter switches

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.

$$S2 = P \quad (4)$$

$$S3 = N \quad (5)$$

$S4 = \bar{Q} \ \&\& \ N$ (6)
$S5 = Q \ \&\& \ P$ (7)
$S1 = S4 \ || \ S5$ (8)

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].

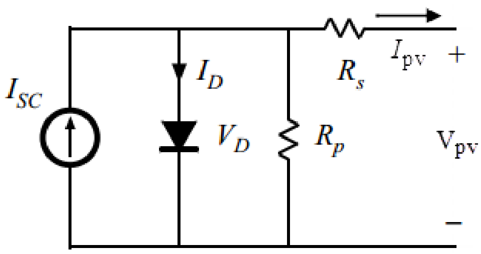

Fig. 5 Model of the PV cell.

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_{max} that can be achieved is known, the corresponding output current I_{pmax} can be determined and the controller is applied to maintain the PV array current at I_{pmax}. The proposed MPPT is a simple hysteresis current controller. A look-up-table is built to generate the reference current I_{pmax} corresponding to every P_{max}. The reference current (I_{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:

$e = I_{pmax} - I_{pv}$
if $e >= h/2$ $S = 1$
if $e <= - h/2$ $S = 0$ (9)
if $h/2 > e > -h/2$ no change in "S"

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

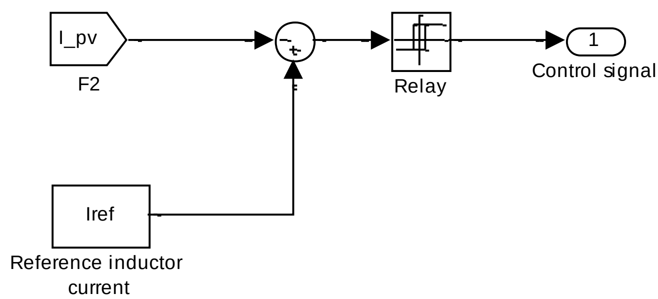

Fig. 6 Hysteresis current controller as a MPP tracker

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_{pmax} and I_{pmax} 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 Δi_L and Δv_o 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**

$$D = 1 - V_C / V_{pmax}$$

2- **The inductance "L" is calculated using the relation**

$$L = (D\ V_d) / (\Delta i_L\ f_s)$$

3- **The virtual load resistance seen by the converter "R" is calculated using the relation**

$$R = \frac{V_d}{(1-D)^2 * I_{pmax}}$$

4- **The capacitance "C" is calculated using the relation**

$$C = (D\ V_o) / (R\ f_s\ \Delta v_o)$$

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 rattings 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.

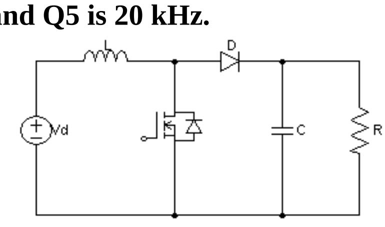

Fig. 7 Basic circuit of dc/dc boost converter

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

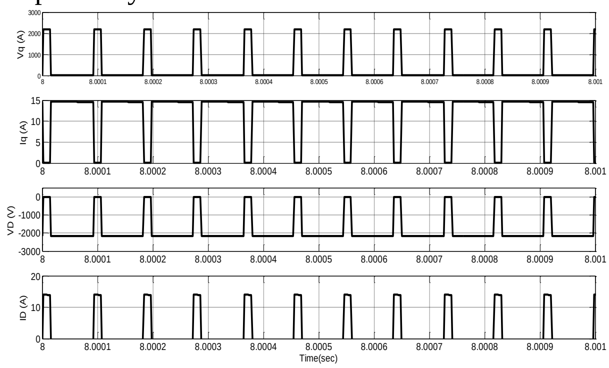

Fig. 8 Current and voltage of boost switch "q" and boost diode "D"

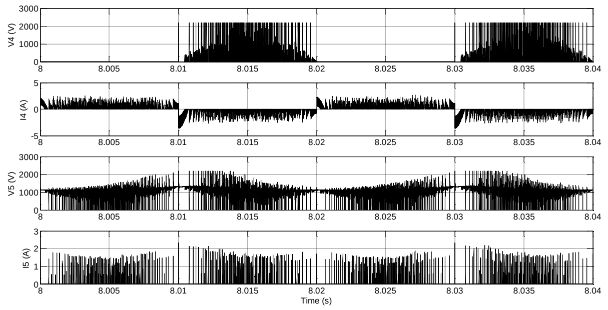

Fig. 9 Current and voltage of switches Q4 and Q5

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_{max}, its corresponding V_{pmax} and i_{pmax} 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_{max} and corresponding V_{pmax} then i_{pmax} can be easily determined from each curve. The hysteresis current controller for MPP receives i_{pmax} 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 repectively 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.

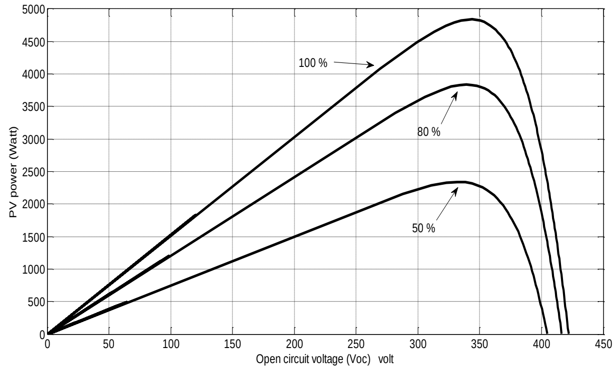

Fig. 10 P-V curves of the PV array at three different insolation levels

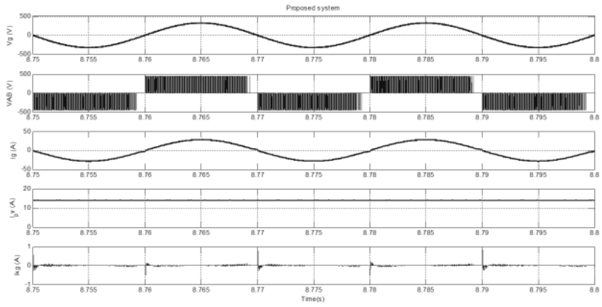

Fig. 11 inverter output voltage, grid current, PV array current and earth leakage current

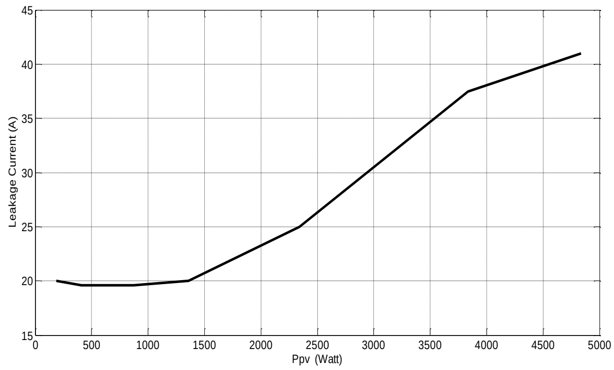

Fig. 12 Leakage current (rms) versus PV array power

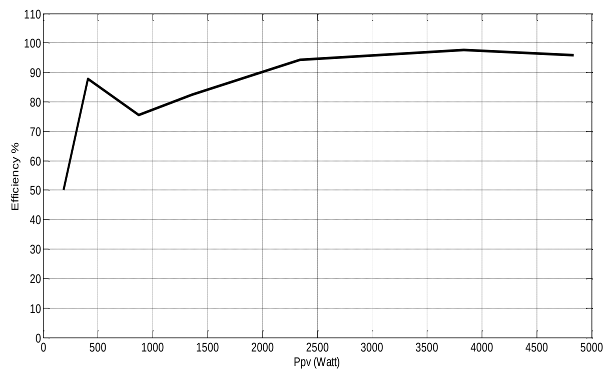

Fig. 13 Efficiency of the proposed system versus PV array power

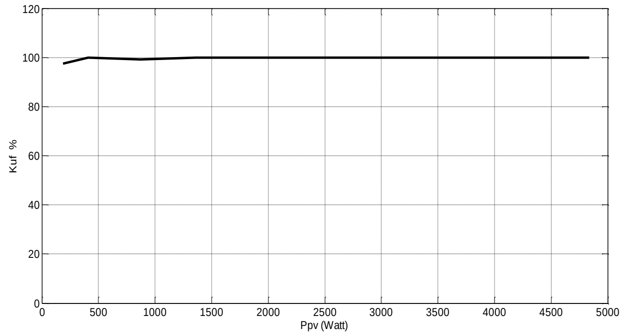

Fig. 14 Utilization factor of the PV array versus PV array power

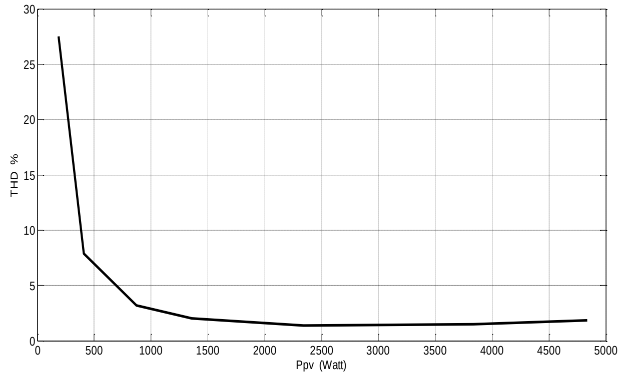

Fig. 15 THD of the proposed system versus PV array power

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

[1] M. Calais, J.Myrzik, T. Spooner, and V. G. Agelidis, “Inverters for single phase grid connected photovoltaic system—An overview,” in *Proc. IEEE, PESC*, 2000, pp. 1995–2000.

[2] F. T. K. Suan, N. A. Rahim, and H. W. Ping, “Modeling, analysis and control of various types of transformer-less grid connected PV inverters,” in *Proc. IEEE CET*, Jun. 2011, pp. 51–56.

[3] E. C. dos Santos, Jr., A. M. Farias, M. C. Cavalcanti, and F. Bradaschia, “Integrated three-phase transformer-less PV inverter,” in Proc. IEEE ISIE, May 2012, pp. 1780–1784.

[4] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, “Overview of control and grid synchronization for distributed power generation systems,” IEEE Trans. Ind. Electron., vol. 53, no. 5, pp. 1398–1409, Oct. 2006.

[5] H. Xiao and S. Xie, “Leakage current analytical model and application in single-phase transformerless photovoltaic grid-connected inverter,” IEEE Trans. Electromagn. Compat., vol. 52, no. 4, pp. 902–913, Nov. 2010.

[6] O. Lopez, F. D. Freijedo, A. G. Yepes, P. Fernandez-Comesana, J.Malvar, R. Teodorescu, and J. Doval-Gandoy, “Eliminating ground current in a transformerless photovoltaic application,” IEEE Trans. Energy Convers., vol. 25, no. 1, pp. 140–147, Mar. 2010.

[7] R. Gonzalez, J. Lopez, P. Sanchis, and L. Marroyo, “Transformerless inverter for single-phase photovoltaic systems,” IEEE Trans. Power Electron., vol. 22, no. 2, pp. 693–697, Mar. 2007.

[8] Gonzalez R, Lopez J, Sanchis P, Marroyo L. Transformer-less inverter for single phase photovoltaic systems. IEEE Trans Power Electron 2007;22(2):693–7, (Mar.)

[9] Xiao H, Xie S. Leakage current analytical model and application in single-phase transformer-less photovoltaic grid-connected inverter. IEEE Trans Electro 2010;52(4):902–13, (Nov.).

[10] VDE 0126-1-1-2006, “Automatic disconnection device between a generator and the public low-voltage grid,” DIN_VDE Normo, 2008.

[11] R. Gonzalez , E. Gubia, et al., “Transformer-less single-phase multilevel-based photovoltaic inverter,” IEEE Trans. Ind. Electron., vol. 55, no. 7, pp.2694-2702, July 2008.

[12] M. H. Rashid, “Power Electronics Handbook”, 2nd Edition, Academic Press, USA, 2007.

[13] L. Zhang, K. Sun, Y. Xing, and M. Xing, "H6 Transformer-less Full-Bridge PV Grid-Tied Inverters" IEEE Transactions on Power Electronics, Vol. 29, No. 3, March 2014

[14] G. Rizzoli, M. Mengoni, L. Zarri, A. Tani, G. Serra and D. Casadei, "Comparison of Single-Phase H4, H5, H6 Inverters for Transformer-less Photovoltaic Applications", Industrial Electronics Society , IECON 2016 - 42nd Annual Conference of the IEEE, pp. 3038-3045, Oct. 2016

[15] K. Rouzbehi, M. Davarifar , M. Martino, C. Citro, A. Luna, Z. Daneshifar and P. Rodriguez, "Comparative efficiency Study of Single Phase Photovoltaic Grid Connected Inverters using PLECS", Second International Congress on Technology, Communication and Knowledge (ICTCK 2015), pp. 536-541, Iran, Nov., 2015

[16] H. Li, Y. Zeng, T. Q. Zheng and B. Zhang, "A Novel H5-D Topology for Transformer-less Photovoltaic Grid-Connected Inverter Application", IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia), May, 2016
[17] Xiaoqiang Guo, Xiayu Jia, Zhigang Lu and Josep M. Guerrero," Single Phase Cascaded H5 Inverter with Leakage Current Elimination for Transformer-less Photovoltaic System", Applied Power Electronics Conference and Exposition (APEC), IEEE, MAR., 2016
[18] P.S.Gotekar, S.P.Muley, D.P.Kothari and B.S.Umre ,"Comparison of Full Bridge Bipolar, H5, H6 and HERIC Inverter for Single Phase Photovoltaic Systems – A Review", India Conference (INDICON), Annual IEEE, DEC. 2015
[19] T. K. S. Freddy, N. A. Rahim, W. P. Hew, and H. S. Che, "Modulation Techniques to Reduce Leakage Current in Three-Phase Transformer-less H7 Photovoltaic Inverter", IEEE Transactions on Industrial Electronics, Vol. 62, No. 1, pp. 322-331 JANUARY 2015
[20] Tekeshwar Prasad Sahu T. v. Dixit, "Modelling and Analysis of Perturb & Observe and Incremental Conductance MPPT Algorithm for PV Array Using Cuk Converter", IEEE Student's Conference on Electrical, Electronics and Computer Science, 2014.
[21] Azadeh Safari and Saad Mekhilef "Simulation and Hardware Implementation of Incremental Conductance MPPT with Direct Control Method Using Cuk Converter", IEEE Transaction on Industrial Electronics, Vol.5 , no.4., 2011.
[22] R. Faranda, S. Leva, and V. Maugeri, "MPPT techniques for PV Systems: energetic and cost comparison", IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008
[23] T.L. Kottas, Y.S.Boutalis and A. D. Karlis, "New Maximum Power Point Tracker for PV Arrays Using Fuzzy Controller in Close Cooperation with Fuzzy Cognitive Network," IEEE Trans. Energy Conv., vol. 21, No. 3, September, 2006.
[24] Anzalchi, A.; Sarwat, A., "Artificial neural network based Duty Cycle estimation for maximum Power Point tracking in Photovoltaic systems" Southeast Con 2015, Fort Lauderdale, FL, USA, 9-12 April 2015.
[25] S. A. Zaid and Ahmed M. Kassem, "Review, analysis and improving the utilization factor of a PV-grid connected system via HERIC transformerless approach", Renewable and Sustainable Energy Reviews, Vol. 73, pp. 1061–1069, Feb. 2017
[26] M. M. Salem, "Classical Controller with Intelligent Properties for Speed of Vector Controlled Induction motor", Vol. 8, No. 3, July 2008.
[27] Y. Atia, "Photovoltaic Maximum Power Point Tracking Using SEPIC Converter," Engineering Research Journal (ERJ), Shebin El-Kom Journal Vol. 36, No. 4, October, 2009