International Journal of Electrical and Power Engineering 1 (2): 177-183, 2007

Performance Optimization of Grid Connected PV Systems: An Effective Aided Design Technique

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Abstract: Since 1985, many Photovoltaic (PV) systems have been sited in Batna Region (Algeria). They are used to supply energy to isolated schools, nurseries and for water pumping. In addition to this; the grid connected photovoltaic system study was investigated for domestic applications. The progressive tendency, in the Photovoltaic (PV) system connected to the electrical grid, is establishing new applications, in such a way that, the grid connected PV system has to be optimally used. Nowadays many optimised configurations starting to bring benefits into the electrical network, such as: Export/import of real and reactive power, quick fix to shortages in power when used with storage equipment, active power mains harmonics filtering and reduction of greenhouse emission and environment friendly power generation source. Thus, within this context, this study deals with the optimisation model for the grid connected PV systems, targeting their optimum performing. Maximising the daily inverter path efficiency model is used to make a continuous matching operation between the PV array generator and the utility grid-load, leading to an adequate control law which can transfer the maximum available power. This technique provides the designer with a useful tool that optimises different functional control parameters as well as sizes the system components efficacy. Simulation results show the system performance prediction and the corresponding optimised parameters.

Key words: Real and reactive power, grid connected Photovoltaic (PV) systems, inverter path efficiency

INTRODUCTION

Nowadays, the photovoltaic systems are used to be connected with the conventional grid, in residential and commercial systems (Meinhardt and Cramer, 2000; Fetten *et al*., 2006; Wu *et al*., 2000). This due of many optimised configurations beginning to bring benefits into the electrical network, such as: export/import of real and reactive power, quick fix to shortages in power when used with storage equipment and active power mains harmonics filtering (Wu *et al*., 2000).

This study deals with the optimisation of the inverter path efficiency model, which consists of several sub-models, of the interactive, bidirectional, photovoltaic system connected to the grid. This optimisation method offers the designer a tool that through it, the sizing, the performance evaluation and consequently the comparison between different solutions can be made.

Maximising of the inverter path efficiency is used to make a continuous matching operation between the PV generator and the load (grid), leading to an adequate control law which can transfer the available maximum PV power. This technique provides the designer with a useful tool that optimises different functional control parameters as well as sizes the system components efficacy. Simulation results show the system performance prediction and the corresponding optimised parameters.

EXPERIMENTAL SITE

Algeria is a large area country (2382000 km^2) with variety in sites leading to diversity in climate. The average global insolation at the received horizontal plane varies between 4.5 and 7.5 kWh m•^{2}. Algeria can be divided into 8 climatic zones (Capderou, 1986) which have approximately a homogenous insolation (Fig. 1). Solar energy for an average insolation day, at surface oriented to south with an inclination angle equals to latitude (• = 35.33°) is shown in Fig. 2.

Batna site (zone 3) in Algeria is one of the sites, where a number of solar projects such as pumping, lighting systems, are already implemented (Hamouda *et al*., 1997, 1998). These projects have been implemented by Batna University in collaboration with national organisations like the Renewable Energies development centre, Algiers, Algeria and the Technical

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Fig. 1: Algeria climatic zones (Hamouda, 1997, 1998)

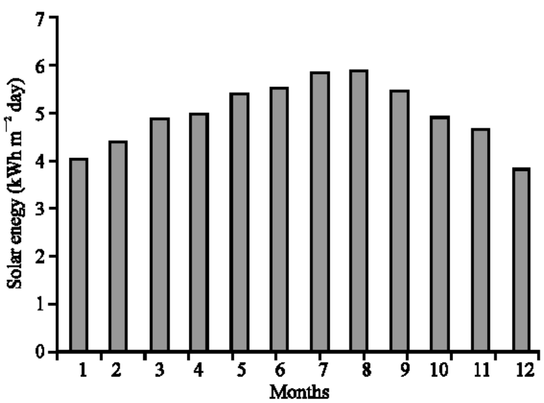

Fig. 2: Daily solar energy

University of Berlin (Germany). Since 1993 research projects relating to the development of solar energy have been strengthened by the substantial support of the GTZ (Deutsche Gesellschaft für Technische Zusammenarbeit GTZ GmbH, Eschborn, Germany). From these projects, we found the development and the installation of the small solar pumping systems for irrigation of remote areas of about 0.5-2 ha.

Actually a novel axis is under investigation, concerning the study and the implementation of grid-connected photovoltaic systems. As it is known, the most obstacle for dissemination of such applications, is the initial PV array cost, which is relatively high. So the grid connected PV systems must be operated near to (or coincide with) the Maximum Power Points (MPP) curve as it is shown in Fig. 3.

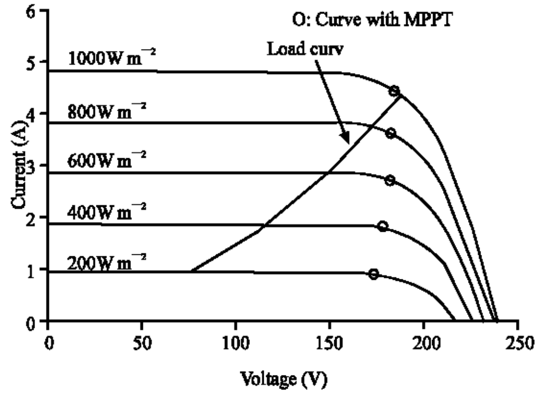

Fig. 3: Non optimal load characteristics

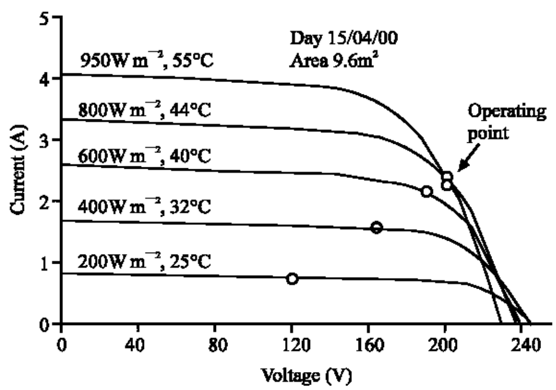

Fig. 4: Experimental results on the non optimal pumping system

Regarding Batna site, where the application results on an optimal pumping system was depicted in Fig.4, the suggested grid connected PV system should be operated in an optimal comportment; consequently an efficient and simple design technique is required.

SYSTEM CONFIGURATION

A typical grid connected transformer less photovoltaic system is shown in Fig. 5. Its corresponding equivalent circuit is depicted in Fig. 6, which is deduced under the following assumptions: the PV array is represented by one-diode model (Xiao *et al*., 2004) in which the shunt resistance is neglected, ripple current and voltage are neglected (high switching frequencies), R and L are the overall resistance (parasitic and inverter resistance) and filter inductance accounting for any other flux leakage respectively and system is considered to be in the steady state.

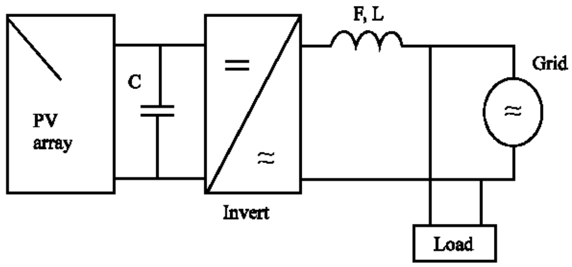

Fig. 5: Typical grid connected photovoltaic system

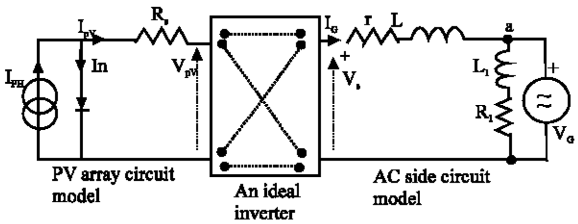

Fig. 6: Grid connected PV system corresponding equivalent circuit

SYSTEM MODELLING

A model has been developed for each part of the grid connected PV system chain using the equivalent circuit developed in Fig. 6. The PV array is described by its daily energy array characteristics, the ideal inverter by its output input ratio and the AC side circuit by its mathematical formulas deduced from the corresponding phasor diagram.

Photovoltaic array energy model: The photovoltaic array is an arrangement of several modules connected in series/parallel to get a suitable power and voltage. The basic element of the photovoltaic array is the solar cell which usually uses a p-n junction diode in a physical configuration to produce photovoltaic electricity. The DC side model (Fig. 6), one-diode model, contains a current source IPH, one diode and a series resistance RS which represents the total resistance of the array accounting that of wiring. The PV array net output voltage at a given time is expressed as (Machado *et al*., 2003):

$$V_{PV} = AN_S kT/q \ln\left(\frac{I_{PH} - I_{PV} + I_0}{I_0}\right) - I_{PV}.R_S \qquad (1)$$

where A is the ideality factor, k Boltzmann's gas constant, N_S the total number of series cells (modules), T the absolute temperature of the array, q electron charge, I_0 the array reverse saturation current and I_{PV} the net delivered array output current.

The array output power, which depends on the AC loop parameters, can be formulated as:

$$P_{PV} = AN_S kT/q \ln\left(\frac{I_{PH} - I_{PV} + I_0}{I_0}\right).I_{PV} - I_{PV}^2.R_S \qquad (2)$$

The Maximum Power Point (MPP) of the array at a given time can be obtained by differentiating Eq. 2 w.r.t. the current and equating to zero. The current at that point I_{mpp} can found by solving,

$$I_{mpp} = I_{PH} - I_0\left[\exp\left(\frac{2I_{mpp}.R_S}{AN_S V_{th}} - \frac{I_{mpp}}{I_{PH} - I_{mpp} + I_0}\right) - 1\right] \qquad (3)$$

where $V_{th} = kT/q$; is the thermal voltage.

Having obtained I_{mpp}, then the V_{mpp} can be deduced from Eq. 1 and P_{mpp} from Eq. 2, which allows the calculation of the array maximum energy throughout one sunny day period,

$$E_{mpp} = \int_{T_L}^{T_C} P(t)dt \qquad (4)$$

where T_L and T_C are the sunrise and sunset times, respectively.

Manipulation of the previous equations throughout a one sunny day period requires another two models: insolation model, C(t) and the photocurrent model $I_{PH}(t)$, all as a function of solar time; here are these models (Khouzam *et al*., 1986):

$$C(t) = C_{noon} \sin[15.(t - T_L)] \qquad (5)$$

$$I_{PH}(t) = I_{PHnoon} \sin[15 * (t - T_L)] \qquad (6)$$

where

C_{noon} and I_{PHnoon} are the insolation and the array photogenerated current at solar noon, respectively; while t, in hour, is the corresponding solar time of the sunny day.

Inverter: The inverter, with its associated functions to get the optimum interface between the PV generator and the grid, is the pivot for successful operation of the grid connected PV system. An H-bridge Selective Harmonic Eliminated PWM (SHE PWM) inverter with a three- level switching technique is used in this study (Fig. 7). This choice is done for the purpose of studying behaviours of the switching parameters with respect to irradiations (Alonso *et al*., 2003).

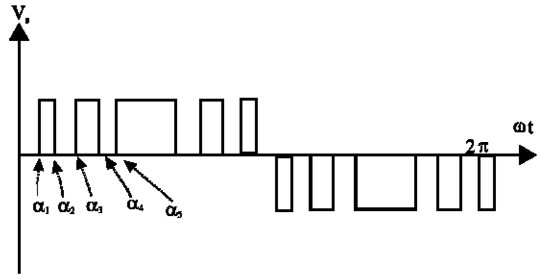

Fig. 7: Three level of SHE PWM waveform with 10 chops per half-cycle

The inverter output voltage can be obtained by using the Fourier series of the SHE PWM waveform by the following equations:

$$v_s = \sum_{n=1,3,5,...}^{\infty} a_n.\sin(n.w.t) \quad (7)$$

where

$$a_n = \frac{4.V_{dc}}{\pi.n}\sum_{k=1}^{N}(-1)^{k+1}\cos(n.\alpha_k) \text{, for odd n}$$

in which:

- N is the number of switching angles per quarter,
- α_k are the switching angles, which must satisfy the following condition:

$$\alpha_1 < \alpha_2 < \alpha_3 < \alpha_4 < \alpha_5 < \pi/2$$

- V_{dc} is the inverter input voltage, which can be assumed equal to V_{pv}.

In order to get a good quality of the inverter output voltage, the lowest four odd harmonics are eliminated by using the following non linear set of Eq. 8:

$$\cos(\alpha_1) - \cos(\alpha_2) + \cos(\alpha_3) - \cos(\alpha_4) + \cos(\alpha_5) = \frac{\pi}{4}.m$$

$$\cos(3\alpha_1) - \cos(3\alpha_2) + \cos(3\alpha_3) - \cos(3\alpha_4) + \cos(3\alpha_5) = 0$$

$$\cos(5\alpha_1) - \cos(5\alpha_2) + \cos(5\alpha_3) - \cos(5\alpha_4) + \cos(5\alpha_5) = 0$$

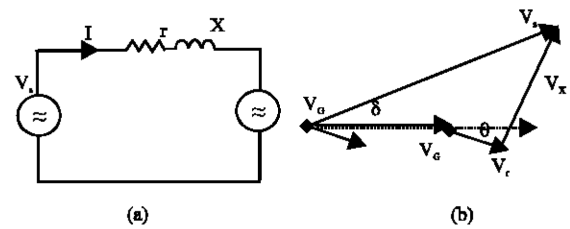

Fig. 8: a) AC side equivalent circuit; b) the corresponding phasor diagram.

$$\cos(7\alpha_1) - \cos(7\alpha_2) + \cos(7\alpha_3) - \cos(7\alpha_4) + \cos(7\alpha_5) = 0$$

$$\cos(9\alpha_1) - \cos(9\alpha_2) + \cos(9\alpha_3) - \cos(9\alpha_4) + \cos(9\alpha_5) = 0$$

where

m is the amplitude modulation ratio, which is defined as the inverter fundamental peak output voltage to the inverter dc input voltage:

$$m = \frac{\sqrt{2}.V_S}{V_{pv}} \quad (9)$$

Inverter-grid interface model: The equivalent circuit and the related phasor diagram of this interface are shown in Fig. 8a and b, respectively.

By taking in consideration the parasitic elements (resistance r and reactance X) of the conditioning system and with several mathematical manipulations, the complex power flow into the grid can be expressed as in (10), with the active and the reactive powers/currents (P, Q, I_a) and (I_r) as in (11) and (12) (Djarallah *et al*., 2006),

$$S = V_G.I^* = P + jQ \quad (10)$$

$$I_a = \frac{P}{V_G} = \frac{V_s\cos\delta - V_G r + V_s X\sin\delta}{Z^2} \quad (11)$$

$$I_r = \frac{Q}{V_G} = \frac{V_s X\cos\delta - XV_G - V_s r\sin\delta}{Z^2} \quad (12)$$

where

$$Z = \sqrt{r^2 + X^2}$$

From Fig. 4b and in the case of unity power factor, the δ angle can be deduced as:

$$\cos(\delta) = \frac{V_G + I_a r}{V_s} \quad (13)$$

In addition to the previous set of equations, the expression of the injected Energy (E_I) into the grid is deduced for unity power factor, using Eq. (10), (11), with the help of Fig. 4b, as:

$$E_I = 2\int_{T_{TH}}^{T_{noon}} (V_s I \ \cos\delta - I_a^2.r)dt \qquad (14)$$

where

$$I = \sqrt{I_a^2 + I_r^2}$$

T_{TH} is the time at which the load just starts extracting the useful power, which can be taken nearly equal T_C (equal 6am) and T_{noon} corresponds to 12 o'clock.

Finally, the inverter efficiency path (•), which can be defined as the ratio of the injected Energy (E_I) to the PV maximum power point Energy (E_{mpp}), is used as a criteria to evaluate the performance of the system for different values of the inverter switching parameters and under different climatic conditions. The • mathematical formula can be written as:

$$\eta = \frac{E_I}{E_{mpp}} \qquad (15)$$

where all losses are neglected except that of the resistance r.

EFFICIENCY MODEL OPTIMISATION

Before caring out the efficiency model optimisation, let see, by simulation, the effect of some shortening made on parameters affecting the selected index of performance given by (15) (neglecting of Q or unity power factor).

Since the E_{mpp} is fixed for a given PV array and climatic conditions, then the optimised objective function is the injected energy to the grid, which includes enough parameters suitable to describe the behaviour of the system. To perform this optimisation, all AC equations necessitate to be transferred to the DC side, from which the optimisation vector parameters are: the PV current, PV voltage, inverter output voltage and its phase angle with respect to the grid voltage.

After performing the optimisation/solving of the integrals (4 and 14) using MATLAB programming tool functions (fmincon, fsolve and quad8), the following results, in per unit, are obtained for a sunny day period time:

- The amplitude modulation ratio and the phase angle delta.
- The switching angles, where the lowest four odd harmonics are eliminated.
- MPP and injected optimal powers/energies and the optimal efficiency (n_{opt}).

SIMULATION RESULTS

For power expotation (p>0), the power factor can be controlled to stay in the order of unite (Fig. 9) and since practically, the maximum power angle is usually chosen around 20 degree (Machado *et al*., 2003); then the Fig. 10 and 11 justify (Q is very small compared to P) the selection of the active energy as the principal parameters for the optimisation index.

After optimisation, results show that the obtained dailyaverage efficiency is more than 96%. Figure 10 shows

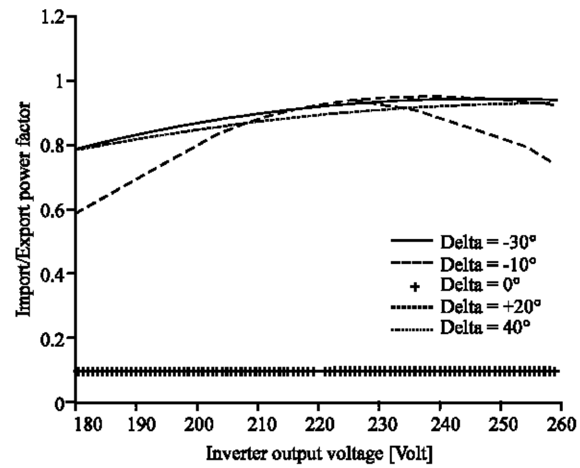

Fig. 9: Power factor in term of VS with r = 0 and V = 200V

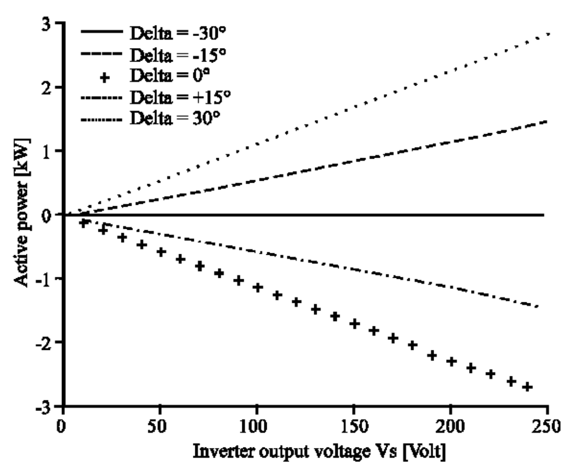

Fig. 10: Active power P in term of VS with r = 0 and V = 200V

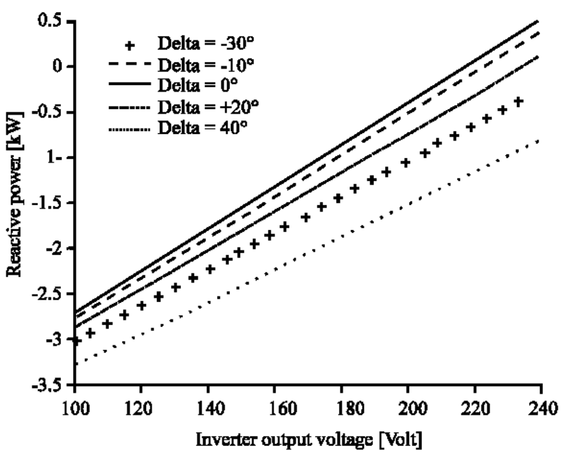

Fig. 11: Reactive power Q in term of VS with r = 0 and V = 200V

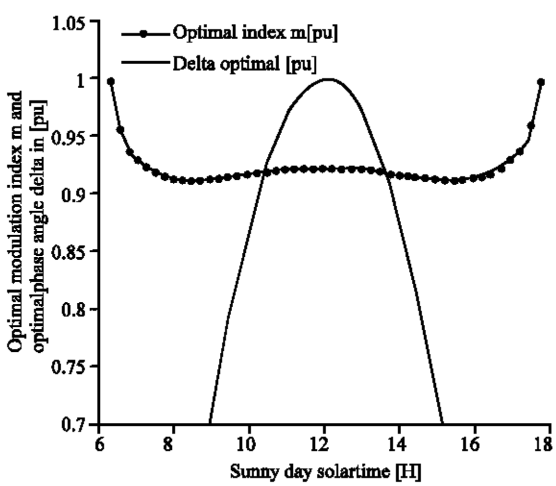

Fig. 12: Paths (swings) of m_{opt} and $\bullet_{opt}$

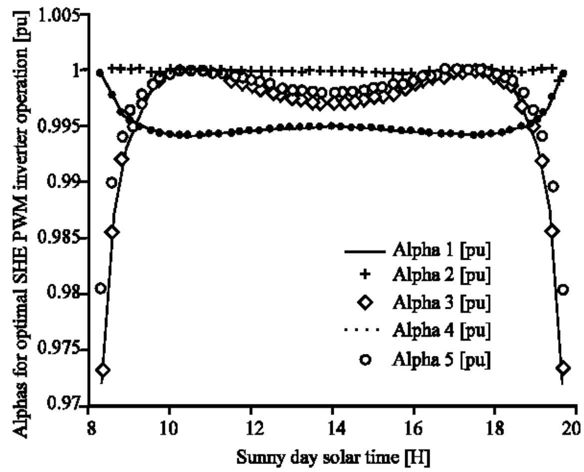

Fig. 13: Optimal SHE PWM inverter commutation angles

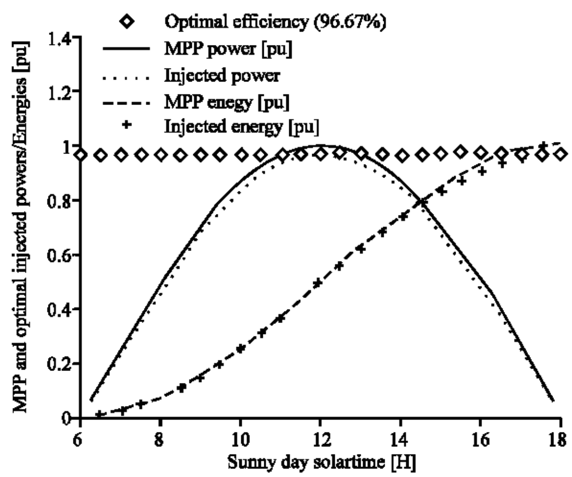

Fig. 14: MPP and injected optimal powers/Energies and the optimal efficiency ($\bullet_{opt}$)

that the paths of P_g and E_I are following that of P_{mpp} and E_{mpp} with a gap indicating the losses in the impedance Z. In addition to that, the following clarifications are made:

- Figure 12 shows swings of the optimal modulation index m_{opt} and the optimal power angle $\bullet_{opt}$ during the day. These parameters represent the factors to be controlled in order to get the desirable magnitude and direction of the power flow. The great swing of m, where a lower sensitivity of the operating points to this parameter is satisfied and for äas well; so the maximum power points can be obtained without using a separately device as a tracker.
- As the coupling coil reduces ripples in the injected current and the SHE PWM inverter control scheme used for reducing the ripples in the inverter output voltage; Fig. 13 shows the paths of the calculated commutation angles, resulting in the eliminating of the lowest four odd harmonics.
- Figure 14 shows the decrease in the injected power/energy caused by the losses in the AC side, accompanying the self (coupling coil), wiring and welding spots; so it is very important to take this in consideration during the design and the implementation phases.

CONCLUSION

The concept of the grid connected PV energetic efficiency model optimisation has been introduced; which can be used as an aided design tool for the system Sizing and performance optimisation. It gives a great simplicity in the grid connected photovoltaic system design.

The deduced control law can be easily implemented with microcontroller-based single phase inverter using New Switching Strategies (Fujii *et al*., 2006). A single-phase grid connected PV system is under development using this aided design technique; in our research Laboratory (LEB).

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