A PROPOSAL FOR MAXIMIZING THE EXPLORATION OF PHOTOVOLTAIC SYSTEMS CONNECTED TO THE UTILITY POWER GRID

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Abstract – **The photovoltaic solar conversion is one of the alternative energy forms most cited to substitute the conventional methods for electricity generation. However, there is the need of optimizing such system in order to be more competitive in the energy market, making it technically and economically viable. Within this context, this work aims to develop the modeling of a control equipment to search for the maximum operating power of a photovoltaic system connected to the main power grid. To achieve this objective, pulse width modulation techniques are used to adjust the voltage on the dc side to the point of maximum power, allowing the system to be able to absorb all the available energy of the photovoltaic generator at any condition. Therefore, the control equipment developed should act as fast as possible when the available solar power varies. Some results are also presented to confirm the efficacy of this 'maximum power tracer'.**

KEYWORDS

Photovoltaic Solar Energy, Distributed Generation, PWM Inverter, Active Power, Reactive Power.

I. INTRODUCTION

Nowadays, the Brazilian power system is composed by large and centralized power plants, distributing electricity through a extense transmission and distribution network. To attend the load demand increase, the normal solution has been to construct more power plants as well as transmission lines. However, the adoption of such alternative as the unique way to solve this problem increase the power losses as well as results in high investment costs and others drawbacks. These facts have motivated the use of local power supply as the new option, the so-called "Distributed Generation" that provides electricity at a site closer to the customer, eliminating the unnecessary high transmission and distribution costs. In addition, it can provide other advantages such as: less maintenance, low losses, improvement in the distribution feeder voltage regulation and power factor increase. Some investment in the large power grid can also be avoided or postponed.

Another remarkable benefit is the production of small amount of energy by renewable sources such as: small hydroelectric power plants, wind power plants, fuel cells, photovoltaic modules, etc.

The exploration of these renewable sources of energy, extracted from the direct transformation of natural resources, has been an important decision for the present world conjuncture. It is foreseen that, in about 15 years, around a quarter of the total European consumption of energy will be attended by solar energy. In Brazil, this type of generation is still uncommon due mainly to the high initial installation cost [1]. However, with the growing global need of energy and the impact of new energy polices to protect the society and the environment, there has been the need to look for more efficient, cheaper and harmless sources of energy to supply the demand and, thereafter, creating the basis for a sustainable development.

The electric power produced by photovoltaic systems is still more expensive than other sources of renewable energy, as the wind power, small hydropower and biomass. Even so, the former alternative has the advantages of lower losses, higher efficiency and longer useful lifetime. Moreover, there is a favorable ratio between the initial installation cost and the quantity of energy produced. Recently, planning to spread the photovoltaic systems, as the program to install 1,000 photovoltaic roofs in Germany [2], and the progress in the manufacturing of the photovoltaic modules and components, will make a significant cost reduction. The search for solar photovoltaic conversion systems has gradually been appointed as the desirable option to replace the conventional electricity generation methods. This is because that, everyday, the environmental problems are getting worse and the amount of prime matters for the continuous exploration of the fossil fuels are steadily decreasing.

II. THE PHOTOVOLTAIC CELL

The energy conversion from solar radiations to electricity is a phenomenon known as photovoltaic effect, in which the solar cell is the most important device [3].

The conventional photovoltaic solar cells are obtained through the junction of two semiconductor crystal regions, named p and n, with different conductivities (figure I). When the cell is illuminated, electron-hole pairs are produced by the interaction of the incident photons with the atoms of the cell. The electric field created by the cell junction causes the photon-generated electron-hole pairs to separate, with the electrons drifting into the n-region of the cell and the holes drifting into the p-region. Consequently, an electric current is generated in the semiconductor, which is capable to circulate in the external circuit, liberating the energy supplied by the photons when electrons-hole pairs are created.

Thus, when this cell connected to an external load is illuminated, as indicated in figure I, a potential difference in the load will be produced. This will cause a current circulation that leaves the positive cell terminal to the external circuit and comes back to the negative terminal.

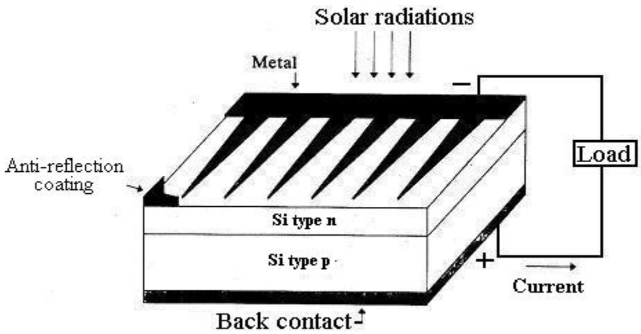

FIGURE I
Conventional silicon cell structures

II.1. I-V Characteristic and Performance

Figure II shows some I-V characteristics of a typical photovoltaic cell [4]. Notice that the amount of current and voltage available from the cell depends upon the cell illumination level and that the photovoltaic cell has both voltage and current limitations.

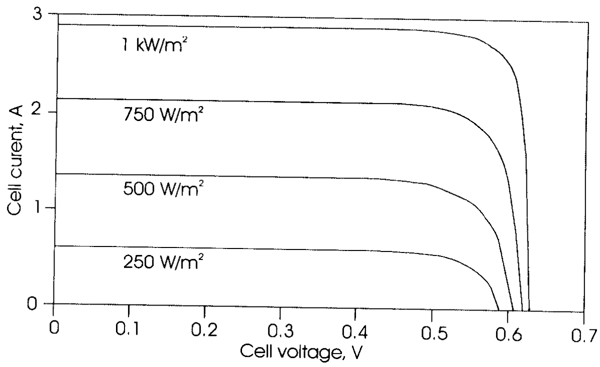

FIGURE II
I-V characteristics of a ideal photovoltaic cells under different illumination levels

In the ideal case, the I-V characteristic is given by equation (1).

$$I = I_L - I_0\left[\exp\frac{eV}{mkT} - 1\right] \tag{1}$$

Where, I_L is the cell current due to photons, I_0 is the saturation inverse current, e = electron charge = $1.6\text{x}10^{-19}$ Coulomb, $k=1.38\text{x}10^{-23}$ J/K and T is the cell temperature in Kelvin (K) .

Within a good approximation, the cell current is directly proportional to the cell irradiance. Thus, if the current is known under standard test conditions (G_0 = 1 kW/m^2 at AM 1.5), then the cell current at any other irradiance G, is given by equation (2) [4].

$$I_L(G) = \left(\frac{G}{G_0}\right) I_L(G_0) \tag{2}$$

II.2. Equivalent Circuits

The circuit of the figure III(a), constituted by an ideal p-n diode, with a saturation current I_D and a current source I_L, has the same electric behavior of that solar cell described in equation (1). Though, there are some effects in real solar cells which are not considered in equation (1), and that can affect its external behavior. At least two of than can be considered the series resistance effect and the shunt resistance effect, as shown in figure III(b).

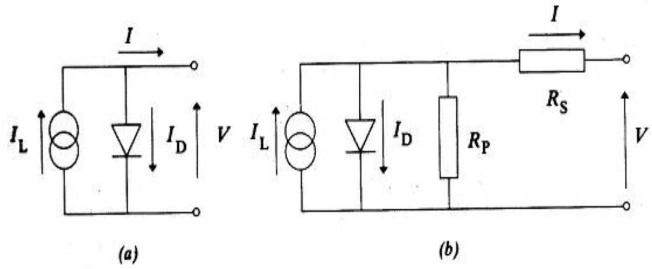

FIGURE III
Equivalent solar cell circuits

To obtain an operation voltage at maximum power, the cells should be connected in series to form a module, until the desired voltage is reached. This means that for any sunstroke condition, the module should supply the same voltage.

II.3. Maximum Power Operation

Taking into account the photovoltaic system connected to the grid, it is always desirable to have the maximum power operation condition. As can be observed in figure IV, there is a point in the I-V cell characteristic where such situation is reached. It can also be seen in the same figure that the cell voltage is dependent on the illumination level. However, this voltage at the maximum power point for the highest sunstroke level is approximately the same as the other three lower levels.

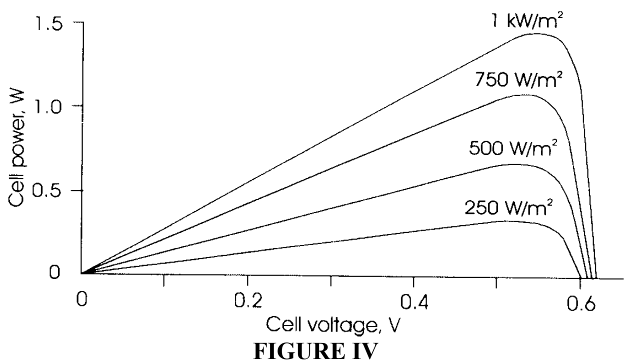

FIGURE IV
Photovoltaic cell power vs. voltage for 4 illumination levels

The maximum operation power has been a challenge, considering it requires that the electric system connected to the module be capable of using all available power of the photovoltaic system during all time. Not just this means that the system needs to absorb all the energy when the sunstroke index is maximum, but that the system should adjust as fast as possible in case the index decreases. In any condition, the I-V characteristic of an ideal load will intercept the point of maximum power of the photovoltaic system I-V characteristic for several illumination levels. The I-V characteristic for this ideal load is shown in figure V, together with the characteristics of other common loads.

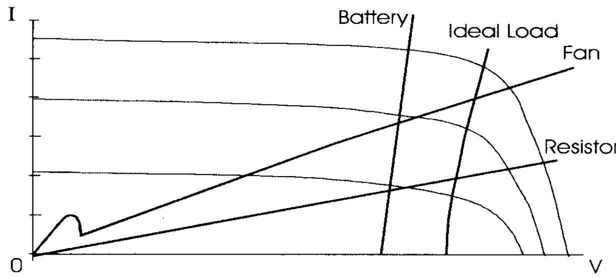

FIGURE V
I-V characteristics for several common loads along with ideal load I-V characteristic for maximum power operation of a photovoltaic system

If the intersection of the I-V characteristic with the load one drives significantly away from the point of maximum power of the photovoltaic system, it is advisable to apply the electronic tracer mentioned so as to return the voltage to such point. This tracer usually applies techniques of pulse width modulation (PWM) to maintain the dc input voltage of the module near to a fixed value established for different sunstroke levels (figure IV). The tracer employs a feedback loop to adjust the voltage appropriately until the output power is maximized.

III. OPERATIONAL PRINCIPLES

To promote the photovoltaic system interface with the ac system, the use of a PWM inverter (VSI type) is proposed. The idea is to make this system to operate as a controllable voltage source connected in parallel with the power grid. By controlling the inverter output voltage phase angle in relation to the grid voltage, it is possible to have the photovoltaic system operating in its maximum power, independently of the sunstroke level.

The simplest steady state model of an inverter connected to an electric power system is shown in figure VI.

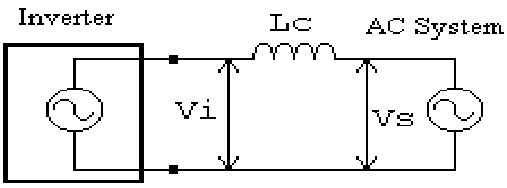

FIGURE VI
Inverter connected to the power grid

The active and reactive power flows in the system of figure VI are not uncoupled. In fact, the active power depends predominantly on the phase angle (δ, also called load angle) between the inverter (V_i) and system (V_s) voltages, and the reactive power is a function of V_i and V_s voltage magnitudes, as shown in figure VII and equations (3) and (4).

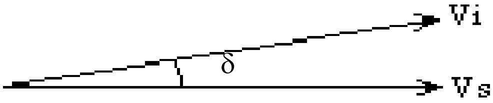

FIGURE VII
Voltage phasor diagram

$$P = \frac{V_i V_s}{2\pi f L_c} sen\delta = P_{MAX} sen\delta \qquad (3)$$

$$Q = \frac{V_i^2}{2\pi f L_c} - \frac{V_i V_s}{2\pi f L_c}\cos\delta \qquad (4)$$

Where:
V_i = Inverter terminal voltage,
Vs = System bus voltage,
L_c = Coupling inductance,
F = System frequency,
δ = Load angle.

According to figure VII and equations (3) and (4), the power flow adjustment of the inverter unit, connected in parallel with the system grid, can be performed through the control of the voltage magnitude (V_I) and angle (δ) of the inverter.

IV. POWER CIRCUIT AND CONTROL SCHEMATICS

Figure VIII presents the power circuit and the control block diagram proposed for this application. The power circuit is composed by a full-bridge inverter, a dc-side capacitor, a low-pass filter and two ac-side coupling inductors [5] -[8].

The control technique used was developed with the objective of adjusting the inverter active power supplied to the electric grid, according to that produced by the photovoltaic system, in order to maintain the dc side inverter voltage regulated in 250 V (voltage for maximum power production). Therefore, with the variation of the solar incidence, the photovoltaic system power will change and the control should act on the inverter active power supply to keep the dc voltage unchanged. In this sense, a closed loop voltage control is used to act on the load angle variation, or on the dc/ac power adjustment.

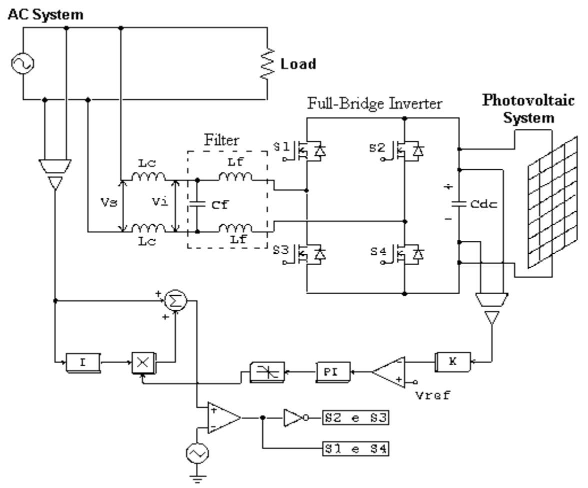

FIGURE VIII
Power circuit and control block diagram

V. SIMULATION RESULTS

For the development of this work, the modeling of a photovoltaic system was used, which consisted of 15 modules in series. The rated specification of each module is 60 W, 16.8 V and 3.57 A, for maximum power condition, having 1000 W/m^2 sunstroke index and 25ºC temperature. For full load system operation, the dc side voltage was fixed on 250V, independently of the sunstroke level. Therefore, for such conditions, the maximum system power is 900 W. This system is connected to the secondary of a 127 V single-phase distribution grid, which is feeding a 1600 W resistive load.

The power circuit parameters are as follow:
f_S =10.02 kHz; V_{dc} = 250 V; C_{dc} = 1600 μF; L_f = 1 mH; C_f = 20 μF and L_C = 2 mH.

All the simulations were accomplished using the PSpice software. Voltage and current waveforms are shown, on the dc side, which is connected to the photovoltaic system, as well as on the ac side, which is connected to the main grid.

The results obtained for steady-state operation are shown in figures 9 to 19, which are arranged in three groups: case 1, for a sunstroke index of 700 W/m^2, case 2, for a sunstroke index of 1000 W/m^2 and case 3 which represents the transient response of the analyzed system, taking into account a variation step on the sunstroke index or the current associated to the photovoltaic system.

Case 1: Steady state with 700 W/m^2 sunstroke index

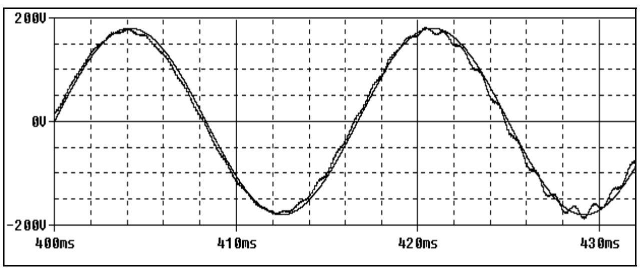

FIGURE IX
Voltages on grid bus and inverter output

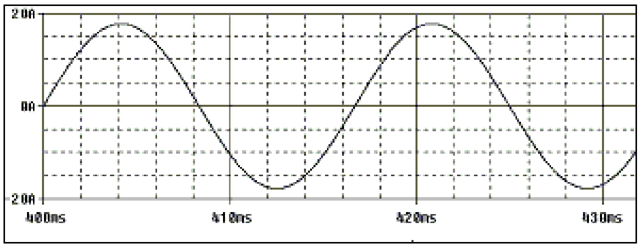

FIGURE X
Load current

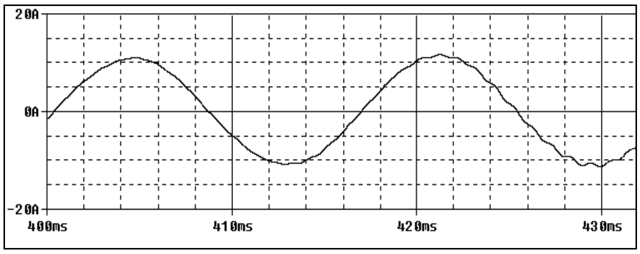

Figure XI
Grid current

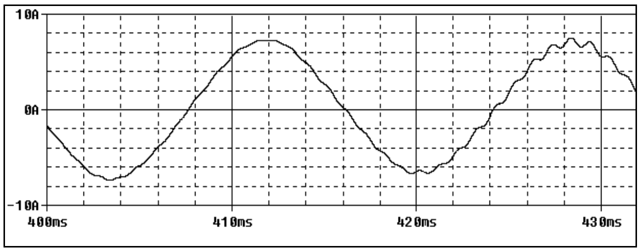

FIGURE XII
Inverter output current

In case 1, the photovoltaic system is supplying an rms current of 4,95 A (or a power of 620 W) to the electric load, through the inverter, for an rms voltage of 127 V, as shown in the figure XII. Is also observed that the power grid is delivering a current of 7,7 A (or a power of 980 W) to the load, as shown in figure XI. Thus, these parallel-connected sources feed a load of 1600 W.

As can be seen in figure IX, the inverter voltage angle is slightly leading the grid voltage angle, having a phase displacement proportional to the active power transfer.

Case 2: Steady state with 1000 W/m^2 sunstroke index

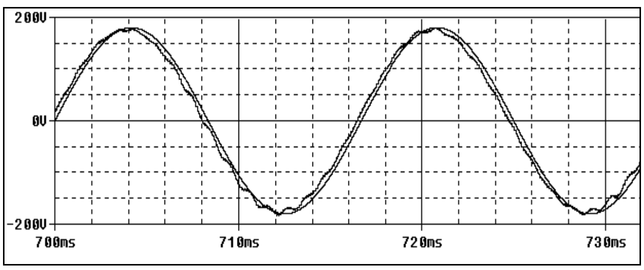

FIGURE XIII
Voltages on grid bus and inverter output

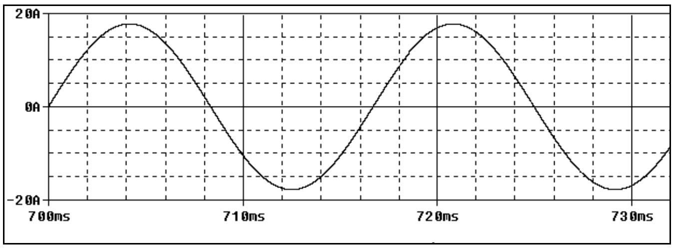

FIGURE XIV
Load current

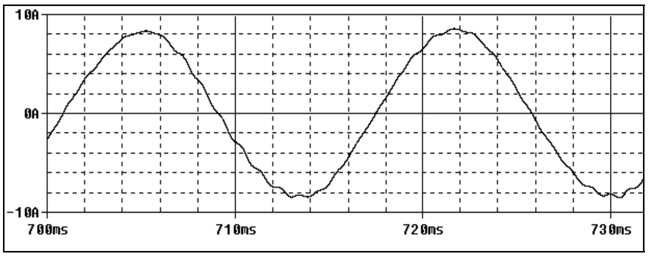

FIGURE XI
Grid current

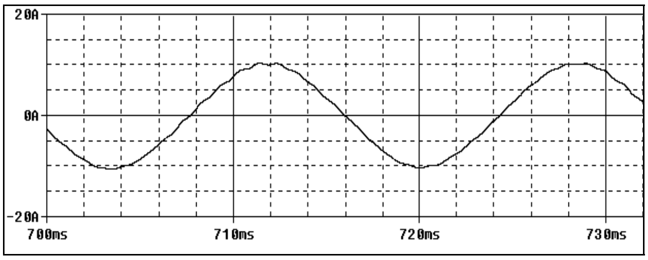

FIGURE XVI
Inverter output current

In case 2, the photovoltaic system is working with the maximum sunstroke index. The photovoltaic system is supplying an rms current of 7,1 A (or a power of 890 W) to the electric load, through the inverter, for an rms voltage of 127 V, as shown in the figure XVI. Is also observed that the power grid is delivering a current of 5,6 A (or a power of 710W) to the load, as shown in figure XV. Again, these parallel-connected sources feed a load of 1600 W.

Comparing cases 1 and 2, it is observed that, with the sunstroke increase, the photovoltaic system started to supply more energy to the load, reducing the power from the utility bus.

Case 3: Transient state due to sunstroke index change

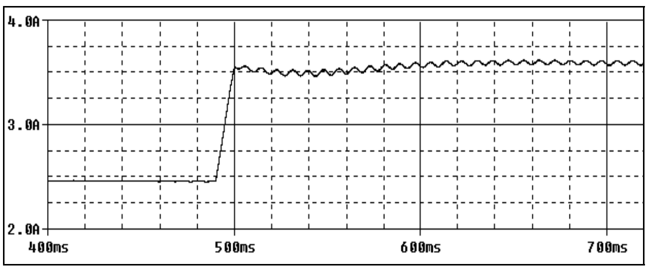

FIGURE XVII
dc side inverter current

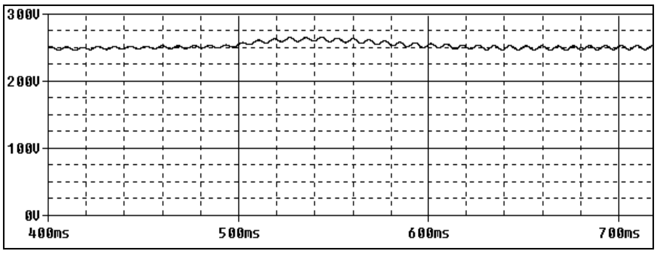

FIGURE XVIII
dc side inverter voltage

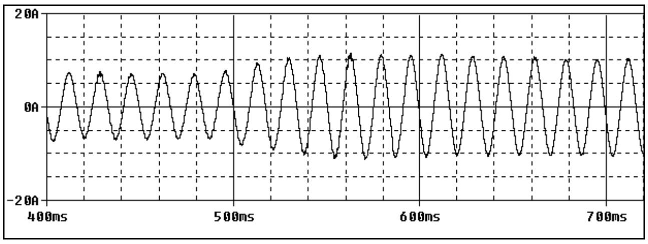

FIGURE XIX
ac side inverter output current

As shown in figure XVII, the current supplied by the photovoltaic system to the inverter suffered a considerable alteration, from 2,5 A to 3,53 A, due to the heatstroke index change from 700 W/m^2 to 1000 W/m^2.

It is observed in figure XVIII that the dc voltage suffered a slight oscillation when the heatstroke index varied and it went back to 250 V, which is the optimal voltage for maximum power supply.

As shown in figure XIX, during the transient state, the ac side inverter current changes from 4,95 A to 7,1 A, without suffering any noticeable disturbances.

Therefore, according to figures XVIII and XIX, the performance of the control system proposed can be also considered good, during the transient state.

VI. CONCLUSION

The simulation results revealed that the control equipment, developed to adjust the phase angle and, consequently, the active power flow for the grid, presented a satisfactory performance for the analyzed photovoltaic system. In fact, it responded fast to variations in the sunstroke index, maintaining the voltage on the dc side adjusted for the desired maximum power value. It can also be observed that there was no disturbance in the current and voltage on the ac side when a change in the amount of energy supplied by the photovoltaic systems occurred.

Another advantage is that, besides supplying active power for the electric grid, this combined system (control equipment plus phtovoltaic modules) can also supply reactive power through the adjustment of the voltage magnitude on the ac side of the inverter, which resulted in the improvement of local voltage level. Moreover, when there is no enough solar energy, this equipment can still act as a reactive compensator, like a capacitor.

In conclusion, the use of the proposed system to work with photovoltaic systems connected to the main electric power grid can result in a better cost/benefit ratio. This is possible because photovoltaic system can be operated in the condition of maximum energy use, independently of sunstroke level, and it can also act as reactive supplier, avoiding the need of capacitors.

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