Modeling photovoltaic systems for AC appliances

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Abstract ***– In this paper is described the development of a model which can simulate the performance of a photovoltaic (PV) system under specific meteorological conditions and transforming the DC current into AC current. In this model, the accent stands on the design of a series charge regulator. It is treated also the benefit of creating a circuit, with different methods, that can test the maximum power point trackers (MPPT) for different photovoltaic applications.***

Keywords: ***Renewable energy, Photovoltaic cells, Power converter.***

I. INTRODUCTION

It is known that the usage of photovoltaic cells generates electricity. The energy supplied by the PV modules to the system is subject to variations depending on the operating conditions, especially the irradiance and temperature values, as well as the load demand profile.

Most PV systems are used for direct current (DC) electrical appliances because the current produced by a PV cell is basically of the DC type. However, DC electrical appliances are rarely found in everyday usage. An inverter is added to the PV system in order to convert the DC generated by the PV modules into AC type suitable for AC appliances. An inverter system consists of the d.c. input, the power circuit and the control circuit. The d.c. input voltage into an inverter can be obtained from a storage battery.

II. TECHNICAL BACKGROUND INFORMATION

Generally, a PV system for AC electrical appliances consists of a photovoltaic array, battery storage, a controller, an inverter and loads as shown in Figure 1[1].

The PV array, normally consisting of several PV modules, converts solar radiation falling on the surface into DC electricity. This generated electricity is then transmitted to the controller (regulator), which is used to protect against overcharging as well as against excessive discharging of the battery. The function of the batteries is to store the energy produced during the daytime and to supply the load when the generated power is not sufficient for load demand during the night time. The function of the inverter is also very important in this process.

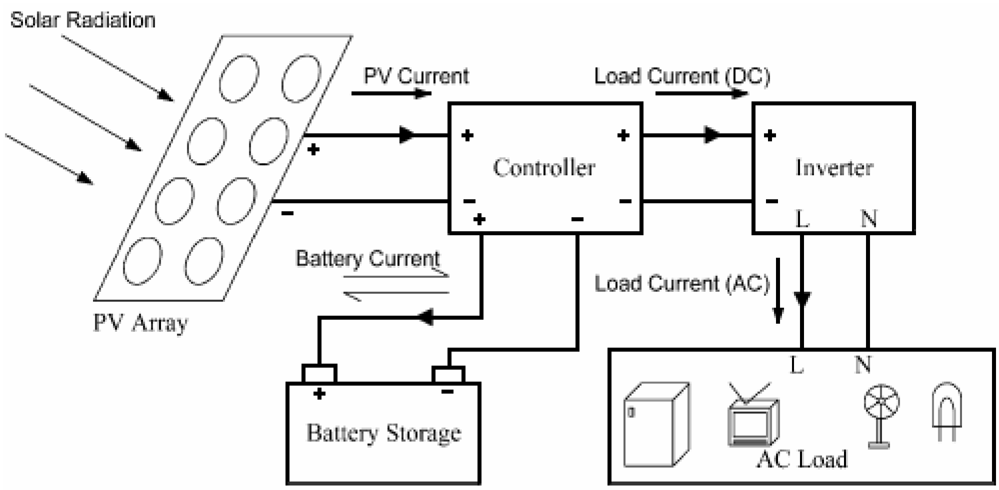

Fig.1. Basic configuration of PV system with AC appliance

III. THE MAIN PARTS OF THE PHOTOVOLTAIC PV SYSTEM

A. The PV array model

For a PV system that operates in the clamped voltage mode, the output voltage of the PV array is fixed at the system's operating voltage, which is usually equal to the battery voltage. The output current of the PV array consisting of several PV modules can be expressed as:

$$I_p = MI_1 - MI_0\left[\mathbf{exp}\left(\frac{e\left(NV + \frac{I_pR_sN}{M}\right)}{NAkT_p}\right) - 1\right] - \left[\frac{NV + \frac{I_pR_sN}{M}}{\frac{NR_{sh}}{M}}\right] \quad (1)$$

Where:

-I_p = output current of panel (A), I_p depends on the incident irradiance on the module and the cell operating temperature.

-I_l = light generated current per module (A),

-I_0= reverse saturation current per module (A), I_0 is basically a function of cell temperature only.

$$I_0 = BT_p^3 I_0\left[\mathbf{exp}\left(-\frac{E_{go}}{kT_p}\right)\right] \quad (2)$$

-M = number of module strings in paralle,

-N = number of modules in each series string,

-V = terminal voltage for PV module (V),

-R_s= diode series resistance per module (ohms),

-R_{sh} = diode shunt resistance per module (ohms),

-e = electron charge (1.6 x10–19 C),

-k = the Boltzmann constant (1.38 x10–23 J/K),

-A = diode ideality factor for the module,

-T_p = cell temperature (K).

Under the short-circuit condition, the panel output voltage is zero, and the panel output current is a maximum and is called the short-circuit current, I_{sc}. In this condition, the light-generated current becomes equal to the short-circuit current ($I_1 = I_{sc}$) since R_s is very small unless the light is concentrated. This model expresses I_{sc} as a function of solar irradiance and temperature.

$$I_1 = I_{sc} = P_1G\left[1 - P_2\left(G - G_r\right) + P_3\left(T_p - T_r\right)\right] \quad (3)$$

Where:

-P_1, P_2, P_3 = constant coefficients for I_{sc},

-G_r = reference solar irradiance (W/m^2),

-G = solar irradiance (W/m^2),

-T_r = reference temperature (298K).

The absorbed solar energy is converted into electrical energy output, thermal radiative and convective energy losses, and thermal energy stored in the PV module, causing the change in T_p. The rate of change of T_p is suggested by:

$$\left(mc_{p_{module}}\right)\frac{dT_p}{dt} = \dot{Q}_{in} - \dot{Q}_{rad} - \dot{Q}_{conv} - \dot{Q}_{elect} \quad (4)$$

Where:

- $mc_{p_{module}}$ = effective thermal capacity of the PV module (J/K) at temperature T_p,

- $\dot{Q}_{in}$ = solar energy absorbed by the module (W),

- $\dot{Q}_{rad}$ = radiative heat loss (W),

- $\dot{Q}_{conv}$ = convective heat loss (W)

- $\dot{Q}_{elect}$ = electrical power produced (W).

The solar energy absorbed by the photovoltaic module is expressed as:

$$Q_{in} = \alpha_{abs} G S_p \quad (5)$$

where :

- α_{abs} = overall absorption coefficient,

-S_p= total area of PV module (m^2)

-G = global solar radiation on the PV module surface (W/m^2).

B. The regulator model

In absence of irradiance the PV module short-circuit current, I_{sc}, is zero and the module *I(V)* characteristic becomes similar to that of a diode.

The presence of a diode in series implies a diode voltage drop, which can be of the order of 1V depending on the diode model and power rating.

The magnitude of the current loss, I_{mod}, depends strongly on the PV equivalent shunt resistance. Despite this dependence, considering typical equivalent shunt resistance values of real PV modules, the observed values of I_{mod} can be very small.

In this case, the protection function of the blocking diode will be covered by the regulation elements. Today, most of the charge regulators in photovoltaic applications use series regulation. The battery has a recommended voltage window between the low (V_{min}) and high (V_{max}) where it operates at rated capacity and efficiency. If the battery is forced to work outside of this window, it may be irreversibly damaged or operate incorrectly.

The series charge regulators prevent the battery from working out of this voltage window. Figure 2 shows a block diagram of a standalone PV system including a series charge regulator element.

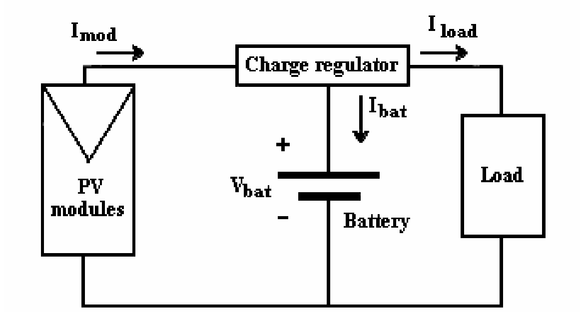

Fig.2. PV system including series charge regulator

Basically, the way the series charge controller works, is by opening the load when the battery reaches V_{min} and connecting the load circuit when the battery has been reached enough so that its output voltage recovers. On the other hand, the charge regulator disconnects the battery from the PV array when full charge is achieved, this means when the battery voltage reaches V_{max} and resets the connection as soon as the battery has been discharged enough.

C. The battery storage model

The most commonly used connection of a PV system to a battery and a load is the one depicted in Figure 3 where the three components are connected in parallel. Of course, a battery is necessary to extend the load supply when there is no power generated by the PV modules in absence of irradiance, or when the power generated is smaller than required. The battery will also store energy when the load demand is smaller than the power generated by the PV modules. A battery is an energy storage element and can be interpreted as a capacitive load connected to the PV generator output [2]. As can be seen in Figure 3 the voltage V_{bat} is common to all the components and by applying Kirchhoff's current law (KCL), the current flowing through the three elements is related by:

$$I_{mod} = I_{bat} + I_{load} \quad (6)$$

As can be seen in Figure 3, I_{bat} has positive sign at the positive terminal and charges the battery, whereas when the I_{bat} sign is negative, the battery discharges. The sign of I_{bat} is determined at every time *t,* by the instantaneous PV system *I(V)* characteristics, according to the irradiance and temperature values, and by the instantaneous value of the current demanded by the load.

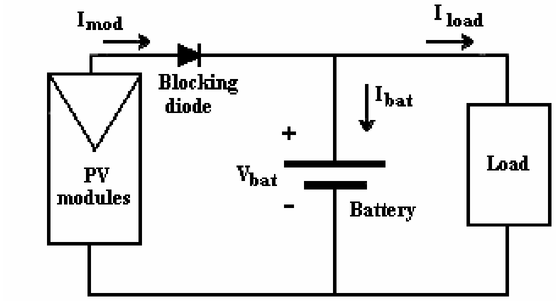

Fig. 3 Standalone PV system with battery connected

The terminal voltage of a battery can be expressed in terms of its open circuit voltage and the voltage drop across the internal resistance of the battery:

$$V_B = E_{oc} + I_{bat} R_B \quad (7)$$

Where:
-V_B= battery terminal voltage (V),
-E_{OC} = battery open circuit voltage (V),
-I_{bat}= battery current (A) (positive when charging and negative when discharging),
-R_B= internal resistance of the battery (ohms).

The battery state of charge (*SOC*) is the instantaneous ratio of the actual amount of charge stored in the battery and the total charge capacity of the battery at a certain battery current. In the model, it is estimated as:

$$SOC = SOC_0 + \left(\frac{Q}{BC} \right) \quad (8)$$

Where:
-SOC_o = previous *SOC*,
-*BC* = battery capacity (C),
-*Q* = amount of exchanged charge from the previous time to the time of interest (C), it can be determined by summing up the charge flowing over the period of interest:

$$Q = \int_0^1 I_{bat} dt \quad (9)$$

Where: I_{bat} = battery current (A).

D. The inverter model

The function of an inverter (Figure 4) is to convert the electricity from a DC input into an AC output [3]. The power circuit configuration of an inverter consists of semiconductor power devices that function as static switches.

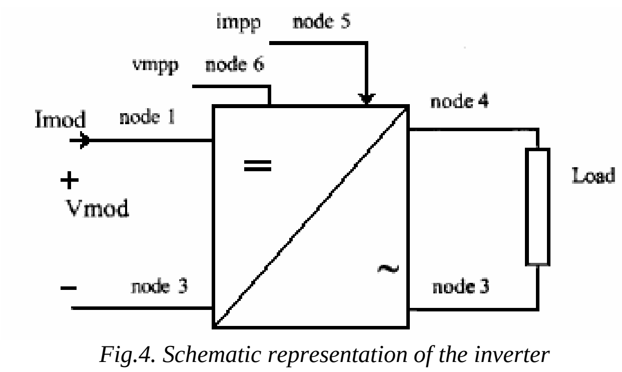

Fig.4. Schematic representation of the inverter

The input parameters of the inverter behavioral model are:

-Inverter efficiency: η. The model considers a constant value for this parameter. The efficiency of most inverters is non-constant but the value of this parameter remains reasonably constant for a wide range of inverter output power.

- Maximum output power: P_m. – the maximum power that the inverter can supply to the load.

- P_{load} - Load power demand.

The relation between the inverter input, P_I, and its output power, P_m, is as follows:

$$P_i = P_m - P_{loss} \quad (10)$$

The power loss, P_{loss}, of the inverter results from the switching circuit and the step-up transformer as mentioned above. The power loss in the switching circuit, P_s, is constant while the power loss in the transformer can be divided into two losses: the fixed core loss, P_c, and the variable copper loss, P_υ. Thus:

$$P_{loss} = P_s + P_c + P_\upsilon \quad (11)$$

E. The load model

Because of the high cost of PV modules, PV generation systems are attractive only for remote isolated areas and for small scale applications such as PV refrigerators and water-pumping systems.

The output power of PV cell is changed by environmental factors, such as illumination and temperature. Since the characteristic curve of a solar cell exhibits a non-linear voltage–current characteristic, a controller named maximum power point tracker (MPPT) is required to match the solar cell power to the environmental changes.

The load model determines the total power demand, P_{load}, requested by the loads of the system for each time step in the simulation. They can be divided into two groups based on the type of power consumption: these are, continuous, and intermittent power consumption loads.

The power consumption of the refrigerator comes from two main components: the compressor and the accessories which include a thermostat, a control unit and an internal circulating fan. The accessories consume constant power of about 12 W once the refrigerator is plugged in. The operation of the compressor is different. For the normal operation, it can be divided into two states, i.e., the initial cooling-down period and the stabilized-running period. During the initial cooling-down period, it consumes continuous power in order to reduce the temperature inside the refrigerator compartment from the ambient conditions to the desired operating temperature (low setting point in the thermostat). After reaching that temperature, the compressor stops running and the refrigerator compartment starts to warm up due to the heat gained from the surroundings. When it warms up to the setting temperature (high setting point), then the compressor starts running again.

The compressor is the only intermittent load in this study. In order to determine its power demand, a simple mathematical model is developed by considering the refrigerator as a black box as shown in Figure 5. The extraction of heat from the inside of the refrigerator is done by the electrical energy input supplied to the compressor. The rate of heat extraction can be expressed as:

$$\frac{\delta Q_{ext}}{\delta t} = (COP)(\eta_{oc})(P_{compressor}) \quad (12)$$

Where:

-δQ_{ext} = the amount of heat to be extracted or the cooling load (J),

-COP = coefficient of performance of the refrigerator,

- η_{oc} = overall efficiency of the

-$P_{compressor}$ = the rate of electrical energy input to the compressor (W)

-δt = the time interval of interest (s)

The cooling load of the refrigerator is comprised of two parts: (i) the heat contained in the refrigerator itself and the product load kept inside its compartment, Q_{store}, and (ii) the heat gain from the high-temperature surroundings, Q_{gain}. Therefore, the equation can be rewritten as:

$$\frac{\delta Q_{store}}{\delta t} + \frac{\delta Q_{gain}}{\delta t} = (COP)(\eta_{oc})(P_{compressor}) \quad (13)$$

The *COP* can vary depending on the room ambient temperature, the evaporator temperature and the condenser temperature. Thus, for the sake of simplicity, the *COP* is assumed to be a constant parameter in this study.

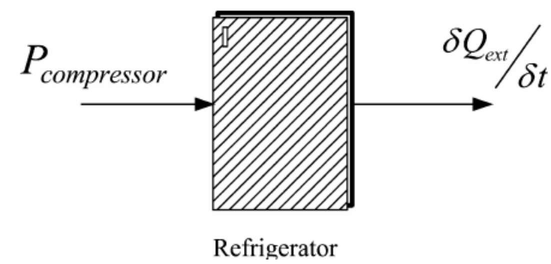

Fig.5. Black box diagram of the refrigerator

F. Maximum Power Point Tracker (MPPT)

The MPPT maximizes the energy that can be transferred from the array to an electrical system. Its main function is to adjust the panel output voltage to a value at which the panel supplies the maximum energy to the load. Most current designs consist of three basic components: a switch-mode dc–dc converter, a control, and tracking section.

In order to achieve an optimal power transfer, from generator to load, it is imperative to maintain both the PV generator and the load at their respective optimum operating conditions. Of course, the maximum power point is the target for the operating point of the PV generator and this is the main task of the MPPT circuits.

These circuits are especially useful in applications where loads are DC motors for daytime operation, and also in applications where the life of the load can be strongly reduced when forced to work in anomalous or extreme conditions, as can be the case of pumps in pumping applications.

The input power at the DC/DC converter is:

$$P_i = V_i I_i \tag{14}$$

And the power supplied by the converter at the output is:

$$P_o = V_o I_o \tag{15}$$

The relationship between input and output power defines the DC/DC converter efficiency, η:

$$\eta = \frac{P_o}{P_i} \tag{16}$$

Maximum power point trackers are basically DC/DC converters and can be represented as shown in Figure 6.

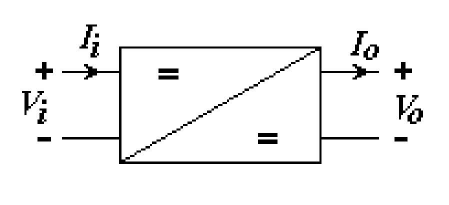

Fig.6. DC/DC converter schematic diagram

G. MPPT Controller Algorithm

1). Perturb and Observe (PAO)

The Perturb and Observe method has a simple feedback structure and few measured parameters. It operates by periodically perturbing (i.e. incrementing or decrementing) the duty cycle controlling the array current and comparing the PV output power with that of the previous perturbation cycle. If the perturbation leads to an increase (or decrease) in array power, the subsequent perturbation is made in the same (or opposite) direction. In this manner, the peak power tracker continuously seeks the peak power condition [5]. The PAO technique is easy to implement and costs the least among the other available techniques. It is considered to be a very efficient scheme in terms of power being extracted from the PV array. However the PAO technique will be confused in catching the MPP under rapid varying solar radiation.

2). Incremental Conductance Technique (ICT)

The ICT algorithm checks for MPP by comparing dI/dV against $-I/V$ till it reaches the voltage operating point at which the incremental conductance is equal to the source conductance. The flow chart for the ICT algorithm is described in Figure 7. The algorithm starts by obtaining the present values of I and V, then using the corresponding values stored at the end of the preceding cycle, I_b and V_b, the incremental changes are approximated as: $dI = I_i - I_b$, and $dV = V_i - V_b$ and according to the result of this check, the control reference signal V_{ref} will be adjusted in order to move the array voltage toward the MPP voltage. At the MPP, $dI/dV = -I/V$, no control action is needed, therefore the adjustment stage will be bypassed and the algorithm will update the stored parameters at the end of the cycle as usual. Another check is included in the algorithm to detect whether a control action is required when the array was operating at the previous cycle MPP ($dV = 0$); in this case the change in weather condition will be detected using ($dI \neq 0$).

This technique offers good performance under varying atmospheric conditions contrary to the PAO technique.

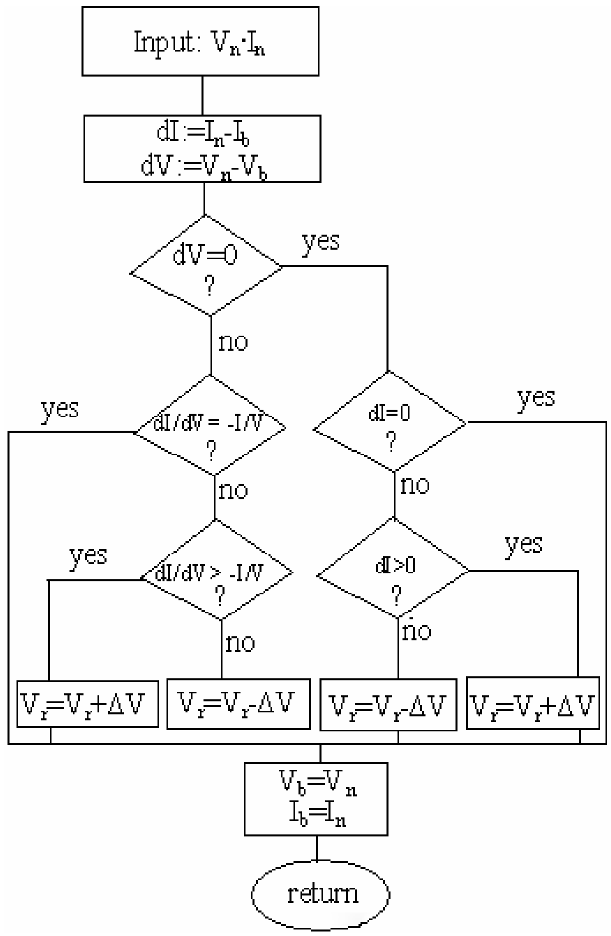

Fig.7. Flow chart of the ICT algorithm

3). Constant Reference Voltage

One very common MPPT technique is to compare the PV array voltage (or current) with a constant reference voltage (or current), which corresponds to the PV voltage (or current) at the maximum power point, under specific atmospheric conditions as shown in Figure 8. The resulting difference signal (error signal) is used to drive a power conditioner, which interfaces the PV array to the load. Although the implementation of this method is simple, the method itself is not very accurate, since it does not take into account the effects of temperature and irradiation variations.

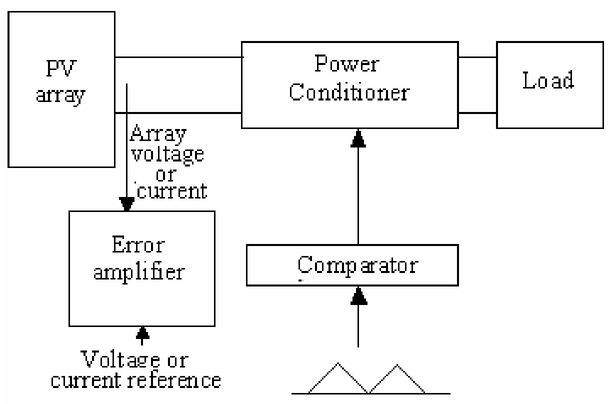

Fig.8. MPPT control system with constant voltage reference.

V. CONCLUSION

After presenting the advantages and disadvantages of each algorithm, and after an experiment for the same PV array, we can say that the ICT method has the highest efficiency (98%) in terms of power extracted from the PV array, next is the PAO technique efficiency (96.5%), and finally the Constant Voltage method efficiency (88%).

The ICT method offers good performance under rapidly changing weather conditions and seems to provide the highest tracking efficiency; however four sensors are required to perform the measurements for computations and decision making. If the system requires more conversion time in tracking the MPP, a large amount of power loss will occur. On the contrary, if the sampling and execution speed of the perturbation and observation method is increased, then the system loss will be reduced. This technique requires only two sensors. This results in the reduction of hardware requirement and cost.

It can be concluded that the development of such a model is able to predict the performance of a standalone PV system for AC electrical appliances within acceptable limits of accuracy. The use of this type of converter is more expensive, but has also a lot of advantages, taking into account the fact that does not produce pollutants; it is a silent operation, long lifetime and low maintenance. The model also provides the total amount of energy shortfall in trying to meet the load requirements, and this is a useful parameter for system sizing purposes. Generally, for a given set of PV modules and batteries, the size of the system which can provide minimum shortfall in energy demand with least cost will be chosen as the best solution.

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