EXPERIMENTAL IDENTIFICATION OF THE EQUIVALENT CIRCUIT USED FOR THE PHOTOVOLTAIC POWER SYSTEM SIMULATION

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Abstract In order to analyse a photo-voltaic power system we can use the following methods: analytical, circuit simulation or experimental. In this paper we propose to measure the current-voltage characteristics of a photo-voltaic cell influenced by temperature and radiation intensity using a low-frequency signal injection method. This one permits to obtain the parameters of an equivalent cell circuit used in the circuit simulation software EMTP. Comparison of measured and simulated data at quasi steady-state and dynamic conditions has been carried out. We present briefly an application case concerning the determination of a photo-voltaic module characteristics under partial shading. This proposed method can be useful for further studies of photo-voltaic power systems such as array modelling, array fault analysis, isolated network operation, etc…

Keywords Renewable energy, PV system; equivalent circuit, parameter identification, experimental method, circuit simulation.

1. INTRODUCTION

Methods for analysing a photo-voltaic (PV) power system include analytical, circuit simulation and experimental methods. An analytical method is often used for a system of relatively small size owing to difficulties encountered in solving a large set of non-linear equations.
The experimental method is limited to a reduced scale for diminishing the cost.
On the other hand, the circuit simulation method involves a circuit simulation software such as P-Spice [1], SABER or EMTP (Electro-Magnetic Transients Program [2]) which can simulate a PV system efficiently.
While the P-Spice model for PV system has been well developed, it is not yet the case for the EMTP model of a PV cell (or module, array). Because the EMTP is a software widely used in power engineering, a dedicated PV cell model will be of interest for many EMTP users.
This paper begins with the experimental parameter identification of the equivalent circuit of a solar cell taking into account the temperature and solar radiation influences.

The measurement procedure can be applied to PV module or array. An equivalent circuit model suitable for the EMTP is then proposed and compared with experimental results.
Other applications of the proposed EMTP model are briefly pointed out.

2. EXPERIMENTAL IDENTIFICATION METHOD

A low-frequency current injection method is used to obtain the current-voltage curve of the PV cell. Fig. 1 shows the measurement block diagram and the corresponding experimental set up.

A function generator is used for generating a sine or a triangle wave. The signal is amplified then it is injected into the cell terminal. In addition to the cell current and voltage waveforms, temperature and radiation intensity are also recorded [3].
Solar radiation intensity is simulated by using several halogen lamps and measured by a calibrated pyranometer. The intensity is controlled by on/off switching the lamps and adjusting the distance between the lamps and the cell.

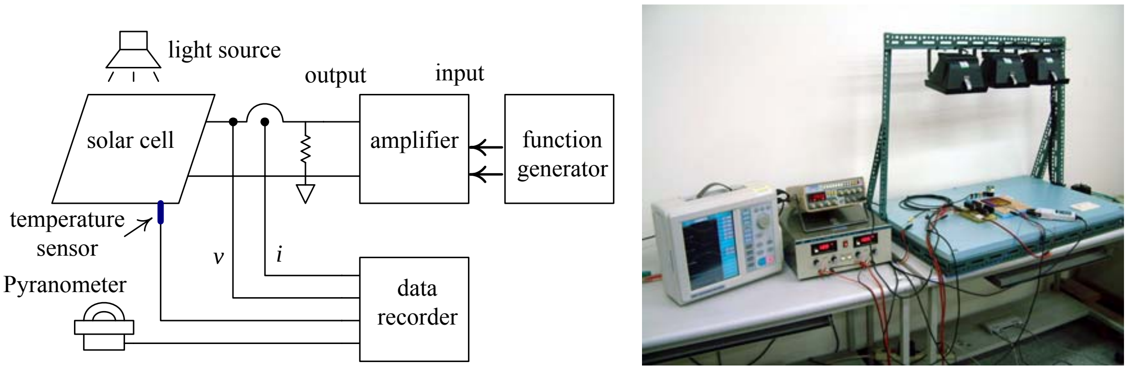


Fig.1 Measurement block diagram and Experimental set up

3. EQUIVALENT CIRCUIT

Several suitable models have been developed for characterising PV devices, such cells or arrays [4,5]. Fig. 2 shows the equivalent circuit of a PV cell used in the EMTP for simulation of the cell circuit [2].

The current source I_{ph} refers to the light-generated current which is proportional to the solar radiation intensity and the other current source I_{tp} refers to the temperature-induced current.

The voltage source V_{tp} refers to the temperature-induced voltage. R_p and R_s are the parallel and series [6] cell resistances. D_j is an ideal diode.

The non-linear diode current-voltage characteristic is represented by R_d, that is a pseudo non-linear resistance provided by the EMTP (type-99).

The circuit parameters are identified from the measured current-voltage characteristics. The resistance R_d can be deduced from the two following equations:

$$I_d = I_{ph} - I_{pv} - \frac{V_{pv} + I_{pv} \times R_s}{R_p} \tag{1}$$

$$V_d = I_{pv} \times R_s + V_{pv} \tag{2}$$

The resistances (R_p, R_s) can be approximately calculated by using the local derivatives of the characteristics such as:

$$R_s = -\left.\frac{dV}{dI}\right|_{V=V_{oc}} \qquad R_p = -\left.\frac{dV}{dI}\right|_{I=I_{sc}} \tag{3}$$

where V_{oc} and I_{sc} are the open-circuit voltage and the short-circuit current, respectively.
The light-generated current is given by:

$$I_{ph} = I_{ref}\left(\frac{L}{L_{ref}}\right) \qquad (4)$$

where L_{ref} is the reference radiation intensity (1000 W/m^2) and I_{ref} the corresponding light-generated current at L_{ref}.
The temperature-induced current and voltage are given by:

$$I_{tp} = I_{sc} \times \alpha \times \left(T_p - T_{ref}\right) \qquad (5)$$

$$V_{tp} = \beta \times \left(T_p - T_{ref}\right) \qquad (6)$$

with α and β the temperature correction coefficients for current and voltage.

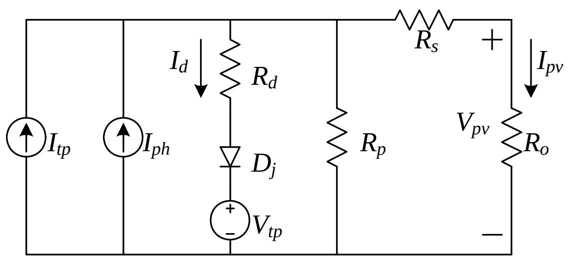


Fig. 2 Equivalent circuit of an EMTP PV cell

4. PARAMETER IDENTIFICATION

The data recorded in experiments are processed using linear and non-linear regression techniques to find the best parameter values. When all the parameters are determined, they are injected into the EMTP to simulate the current-voltage characteristics of the cell or modules.

Fig. 3 (a) shows the measured relationships (scattered points) of I_d of a PV module at different radiation intensity levels. The curve (continuous) in Fig. 3(a) has the following expression:

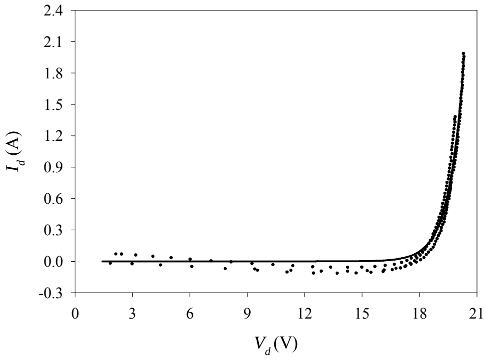
$$I_d = \exp\left(k\left(V_d - V_f\right)\right). \qquad (7)$$

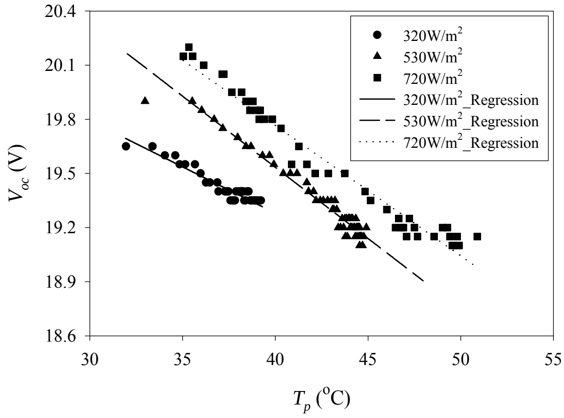
where k=1.299 and V_f=19.812 V have been obtained by non-linear regression. Eq. (7) is to be used for modelling the type-99 pseudo-non-linear resistance R_d of the EMTP.

The variations of I_{sc} and V_{oc} of the PV module function of the temperature are plotted in Fig. 3 (b) and (c) and they show a linear dependence of the two variables on temperature. After finding the slopes of the regression lines for three different radiation intensity levels (320, 530 and 720W/m^2) we take their average as the temperature coefficients α and β. The results thus obtained are: α = 4.651 $mA/^\circ C$ and β = -67.500 $mV/^\circ C$.

The series and parallel resistances R_s and R_p of the module at various levels of radiation intensity and temperature calculated using Eq. (3), are listed in Tables I and II. It can be observed that both R_s and R_p decrease function of the temperature as well as of the radiation intensity.

When all the parameters of the equivalent circuit shown in Fig. 2 have been determined, the current-voltage curves at different radiation intensity and temperature can be calculated by the EMTP.





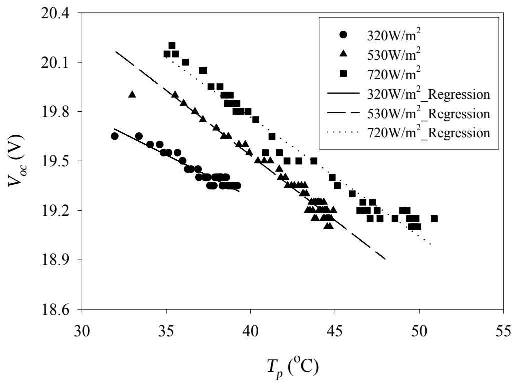


Fig. 3 Measured and curve-fitting results of (a)I_d, (b)I_{sc}, (c)V_{oc}

Fig. 4 shows the so calculated curves at a module temperature of 30 $^\circ C$ and radiation intensity levels of 320, 530 and 720W/m^2. The measured data (scattered points) are also plotted in Fig.4, showing good agreement with the identified equivalent model.

Table 1 Calculated value of $R_s(\Omega)$ of the module

Temper. (°C) Radiation	30	35	40	45	50
320 W/m^2	1.4286	1.1111	0.9091	0.8333	--
530 W/m^2	1.1111	0.8333	0.7692	0.6667	--
720 W/m^2	--	0.8333	0.7143	0.6667	0.625

Table 2 Calculated value of $R_p(\Omega)$ of the module

Temper. (°C) Radiation	30	35	40	45	50
320 W/m^2	70	67.5	60	60	--
530 W/m^2	63.33	56.25	54.3	51.286	--
720 W/m^2	--	52.1	50.5	48.65	48

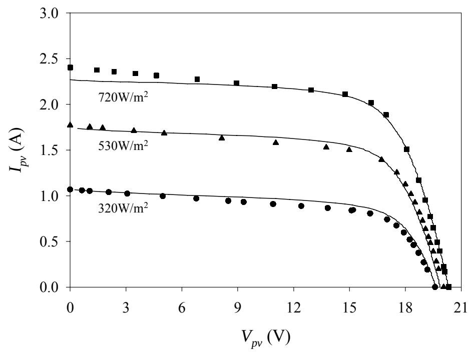


Fig. 4 Measured and simulated current-voltage curves at 3 different radiation intensity levels

5. APPLICATION TO PARTIAL SHADING

The constructed EMTP model can be used to study a commonly encountered partial shading problem in a PV system [7]. Fig. 5 shows two PV modules connected in series. A by-pass diode is connected in parallel with each module in order to prevent inverse-voltage.

The experiment is designed to study partial shading effect, that is when the two modules receive different levels of radiation intensity. Lower level means that the module is partially shaded or oriented to a less favourable direction.

Fig. 6(a) is a comparison of measured (dashed line) and EMTP simulated (solid line) current-voltage curves without partial shading at a level of 800 W/m^2.

When one module receives only 410 W/m^2 and the other one receives 800 W/m^2, the experimental (dashed line) and EMTP simulated (solid line) current-voltage curves are shown in Fig. 6(b).

It is noted that we deliberately increase the voltage V_{pv} to 45 V in order to show the effect of inverse-current (i.e. the region of negative current.). The inverse-voltage has been prevented by the by-pass diodes. In general, good agreement between experimental and simulated results has been obtained.

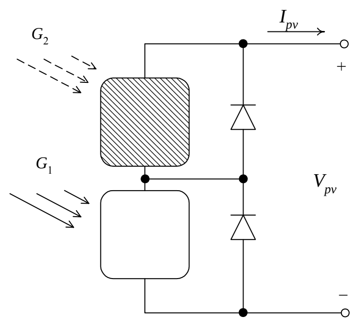
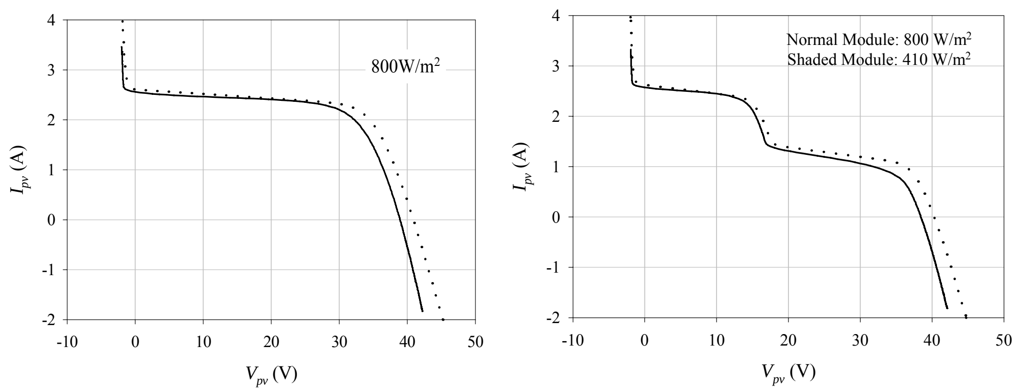


Fig. 5 Two PV modules in series for measurement under partial shading



(a) (b)

Fig. 6 Curves obtained from experiment (dashed lines) and EMTP simulation (solid lines); (a) without partial shading, (b) with partial shading.

6. CONCLUSIONS

A method of low-frequency current injection for measuring current-voltage characteristics of PV cells and modules has been developed. Also proposed is an equivalent circuit model that can be used in the simulation software EMTP. Comparison of results of experiments and EMTP simulation shows good agreement. As an illustration, the proposed EMTP model has been used to study the partial shading problem and satisfactory results have been obtained. This model is useful for further studies in PV engineering [8] such as array modelling, array fault analysis, isolated network operation , etc…

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