Application of Incremental Conductance MPPT Method for a Photovoltaic Generator in LabVIEW

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Abstract. *In recent years, due to the rapid depletion of conventional energy resources and the ever-increasing energy demand, alternative energy sources and their optimal utilization have become a focal point in the field of power engineering. Photovoltaic (PV) power generation technology has seen major advances in the last decade, enabling its widespread use in both industrial and domestic applications.*

This paper presents a simplified method for calculation of the output current of a photovoltaic system, based on the Taylor series instead of the widely used Newton-Raphson's numerical method. This mathematical approximation ensures easier and faster calculations with satisfactory precision. To maximize the output power of a PV system, a maximum power point tracking (MPPT) technique is utilized. In this paper, the incremental conductance algorithm for MPPT of a PV system is implemented in the graphical programming language LabVIEW. The virtual instrument developed is used to control and visualize the output power of the simulated PV panel model and the simulation results are presented in comparison to the experimental data.

Keywords

Maximum Power Point Tracking, PV generator, Incremental conductance, LabVIEW

1. Introduction

The solar energy is one of the most important renewable energy types due to its availability, cleanness and cheap energy resources. Nowadays, there are a lot of different approaches for improving the solar energy utilization. The solar cell is a device that directly converts the energy from the solar radiation into electrical energy in a process based on the photovoltaic effect [1]. PV cells are commercially available in a wide range of different semiconductor materials, mainly mono- or polycrystalline silicon. The main advantage of mono-crystalline (mc-Si) cells is their high efficiency, typically about 14-17% [2]. Additionally, they have low maintenance cost, high reliability, low noise and are completely eco-friendly [1].

The overall performance of a mc-Si solar cell strongly depends on the environmental parameters such as light intensity, cell temperature, and tracking angle if the module is not fixed [1]. The PV cell I-U characteristic is non-linear due to the complex relationship between the output voltage and current, and it varies with temperature or with the irradiance. There is a single point on the I-U curve known as Maximum Power Point (MPP), in which the PV system operates with its highest efficiency possible and generates the highest output power. The main source of energy losses is the system's failure to track the MPP [3]. In order to maintain system's operating point at its maximum output power, many different MPP tracking algorithms have been developed, with a practical implementation in the DC-DC converter used for adjusting the output voltage to a particular active load [6].

In this paper, a model of a solar module is developed in LabVIEW (Laboratory Virtual Instrument Engineering Workbench) software environment, in order to simulate and analyze PV module operation characteristics. The PV cell output current is calculated with an explicit equation derived by an approximation using Taylor series. The weather conditions influence on the PV module operation is analyzed, through variations in the cell temperature and solar irradiation. The incremental conductance method is used for MPP tracking and for calculation of the most suitable load at the MPP.

2. PV mathematical model

2.1 PV cell model

A photovoltaic cell consists of p-n junction that releases electrons when exposed to light, which is known as photovoltaic effect. The solar cell can be modeled as a current source which represents the solar irradiation, in parallel with a single forward biased diode, as shown in Fig. 1 [4-6].

In practice, PV cells are not ideal p-n junctions, so the power losses are taken into account by the presence of series resistance R_S and parallel resistance R_P. The series resistance R_S is very small, which arises from the ohmic contact between metal and semiconductor internal resistance. In contrast, R_P is very large and represents the surface quality along the module's periphery. Leakage of current through the periphery is represented by I_P. Both the diode current I_d and shunt current I_P are provided by the photocurrent I_{ph}. In ideal case, R_S=0 and R_P=∞ [6].

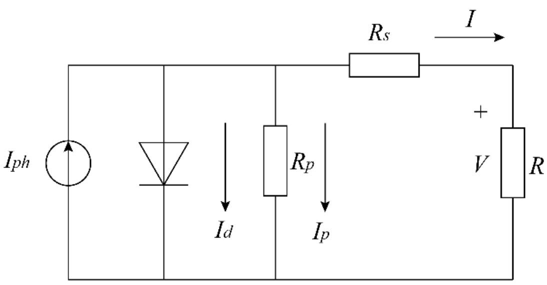

Fig. 1.The equivalent circuit of a silicon solar cell.

From Fig. 1, the output current of a solar cell can be calculated using Eq. (1):

$$I = I_{ph} - I_0\left(e^{\frac{q(V+R_S I)}{nkT_C}} - 1\right) - \frac{V + R_S I}{R_{Sh}} \qquad (1)$$

where I_0 is the cell saturation of dark current [A], V is the cell output voltage [V], $q=1.6\cdot 10^{-19}$ C is the electron charge, $k=1.38\cdot 10^{-23}$ J/K is the Boltzmann constant, n is the ideal factor of the p-n junction, T_c is the cell operating temperature [K], which can be calculated as shown in Eq. (2) [6]:

$$T_c = \frac{T_{noct} - 20}{0,8} G + T_a \qquad (2)$$

where T_{noct} is the nominal operating cell temperature [K] given by the PV module manufacturer, G is the solar irradiance [W/m^2], and T_a is the ambient temperature [K].

The photocurrent can be calculated using Eq. (3) [8]:

$$I_{ph} = I_{sn}\left[1 + \mu_{Isc}\left(T_c - T_{noct}\right)\right]. \qquad (3)$$

where I_{sn} is the nominal short-circuit current [A] which can be determined by Eq. (4). μ_{Isc} is the cell short-current temperature coefficient [A/K].

$$I_{sn} = \frac{G}{G_{nom}} I_{SC} \qquad (4)$$

where G_{nom} is the solar irradiation [W/m^2] at standard test conditions (STC: G=1000 W/m^2, T_c=25 ºC, AM 1.5 reference spectrum, wind velocity 1 m/s [4]), and I_{SC} is the short-circuit current [A].

The reverse bias saturation current can be determined using Eq. (5) [8]:

$$I_o = \frac{I_{SC}}{e^{\frac{qV_{OC}}{nkT_c N_s}\left[1+\mu_{Voc}\left(T_c - T_{noct}\right)\right]} - 1} \qquad (5)$$

where V_{oc} is the open circuit voltage [V], N_s is the number of series cells in the PV module, μ_{Voc} is the cell open circuit voltage temperature coefficient [V/K].

2.2 PV module model

Photovoltaic modules consist of a number of silicon based photovoltaic cells electrically connected in series and in parallel circuits, depending on the voltage or current requirements [3]. The equivalent circuit for the solar module arranged in N_p parallel and N_s series identical cells is shown in Fig. 2. Since the current of a single sell can be more than 3 A, and the voltage is less than 0.7 V, the parallel connection is rarely applied [6], and the series connection is made for increasing the output voltage.

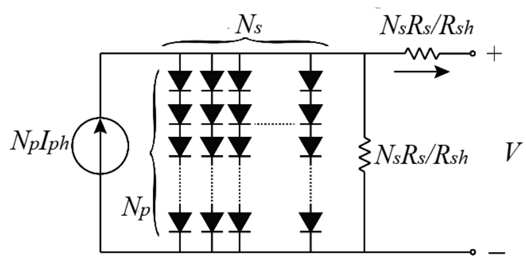

Fig. 2. PV module equivalent circuit.

The output current of the PV module is implicitly given in Eq. (6) [5]. The module's I-U curve has the same form as the cell's I-U curve, but the equivalent model parameters have changed, depending on the number of the cells: the photocurrent and the dark saturation current increase N_P times, the series and shunt resistances change according to Eq. (7), and the ideal diode factor increases N_S times.

$$I = N_p I_{ph} - N_p I_0\left(e^{\frac{q\left(\frac{V}{N_S}+\frac{R_S I}{N_P}\right)}{kT_c n}} - 1\right) - \frac{\frac{N_p V}{N_S} + R_S I}{R_p} . \qquad (6)$$

$$R_{S,T} = \frac{N_S}{N_P} R_S\,, \quad R_{P,T} = \frac{N_P}{N_S} R_P\,. \qquad (7)$$

2.3 Method for PV output current explicit calculation

The main difficulty when calculating the PV output current is that Eq. (6) does not have analytical solution. Numerical methods have been widely applied to solve this equation, such as the Newton-Rapson's method. In this paper, a different approach is made in order to establish an explicit form of the Eq. (6). If the Taylor series is utilized to represent the function $f(x)=e^x$ as a power series, the resulting approximation will be as shown in Eq. (8) [9]:

$$f(x)=e^x=\sum_{n=0}^{\infty}\frac{x^n}{n!}=1+x+\frac{x^2}{2!}+\frac{x^3}{3!}+\ldots \qquad (8)$$

If the same Taylor series representation is used for Eq. (6), taking into consideration only the first two parts of the series (first order approximation - FOA) the PV module output current can be determined by solving the linear Eq. (9). It is assumed that R_S is given by the PV module manufacturer or otherwise previously determined, and $R_P=\infty$.

$$I=\frac{N_P I_{ph}-N_P I_o\left(e^{\lambda V}-1\right)}{1+R_S I_o e^{\lambda V}} \qquad (9)$$

where $\lambda = q/nkT_c N_s$.

3. Maximum power point tracking

The voltage that produces maximum output power (P_{max}) in PV system depends on the sunlight intensity level and on the cells temperature. Several techniques have been proposed for implementation of MPPT. The basic idea consists of setting P_{max} when $dP/dV=0$. The control is achieved by adjusting the output current through changes in the equivalent load impedance.

Incremental conductance (IC) method utilizes the fundamental concept of hill climbing, in which the slope of the P-U curve is zero at the MPP, positive at the left side and negative at the right side of the curve, as shown in Fig. 3 [9-10]. In this algorithm, present and previous values of PV module voltage and current are sensed and are used to calculate the values of *dI* and *dV* [4].

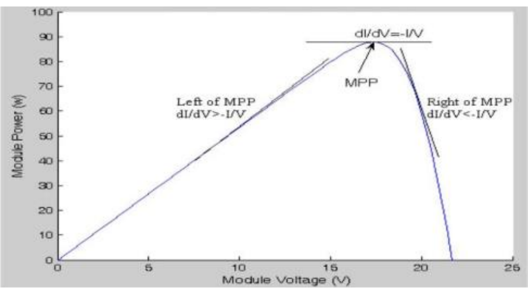

Fig. 3. Basic idea of the incremental conductance method on a P-U curve of a solar module.

The mathematical description of the IC method is shown in Eq. (10), and the flow chart software design is shown in Fig. 4 [2].

$$\text{At MPP: } dP/dV=0 \Rightarrow \frac{dI}{dV}=-\frac{I}{V} \qquad (10.a)$$

$$\text{Left of MPP: } dP/dV>0 \Rightarrow \frac{dI}{dV}>-\frac{I}{V} \qquad (10.b)$$

$$\text{Right of MPP: } dP/dV<0 \Rightarrow \frac{dI}{dV}<-\frac{I}{V} \qquad (10.c)$$

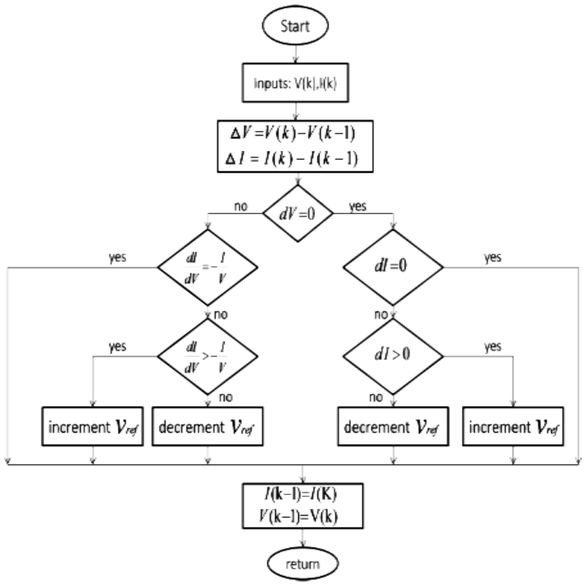

Fig. 4. Incremental conductance algorithm for PV module maximum power point tracking

The main advantage of IC method, which is superior to the other MPPT algorithms, is that it can calculate and find the exact perturbation direction for the operating voltage of PV modules. Also it is easy to implement, has high tracking speed and is highly efficient. [4].

4. PV module simulation and MPPT in LabVIEW

A LabVIEW model of the PV panel is developed to determine the output current by using Eq. (9). The panel specifications are given in Table 1 [11], and number of cells connected is N_S=18 and N_P=1.

The block diagram of the solar panel model in LabVIEW is shown in Fig. 5. The model implementation is shown in Fig. 6, where I-U and P-U curves are plotted for different solar irradiations at a constant cell temperature T_c=47°C. In Fig. 7 the influence of T_c is shown, at a constant irradiation of 1000 W/m^2.

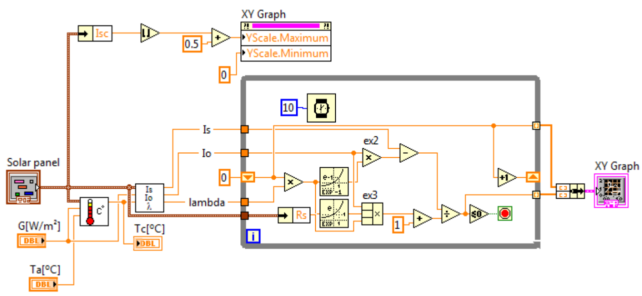

Fig. 5. Block diagram of the LabVIEW virtual instrument containing the solar panel model.

The main purpose is to compare the I-U curve obtained by the model and the curve provided by the PV module manufacturer, in order to verify the simulation model developed in LabVIEW.

Parameter	Symbol	Value	
Nominal power	P_m	50	W
Maximum power voltage	V_{mp}	18	V
Maximum power current	I_{mp}	2.78	A
Open circuit voltage	V_{OC}	22.2	V
Short-circuit current	I_{SC}	3.16	A
Efficiency	η	15.03	%
Nominal operating cell temperature	T_{noct}	45±2	°C
Temperature coefficient of maximum power	μ_{Pm}	-0.24	W/°C
Temperature coefficient of open circuit voltage	μ_{Voc}	-0.07548	V/°C
Temperature coefficient of short-circuit current	μ_{Isc}	0.001169	A/°C
Series resistance	R_S	0.83	Ω
Shunt resistance	R_P	8817.92	Ω

Tab. 1. Technical specifications of SPM030501200 PV module.

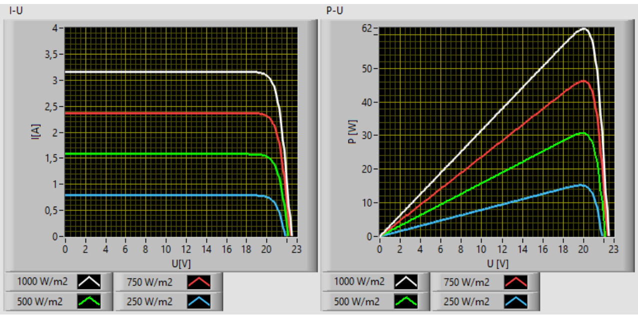

Fig. 6. I-U and P-U curves obtained by the LabVIEW model at a constant cell temperature and variable solar irradiance.

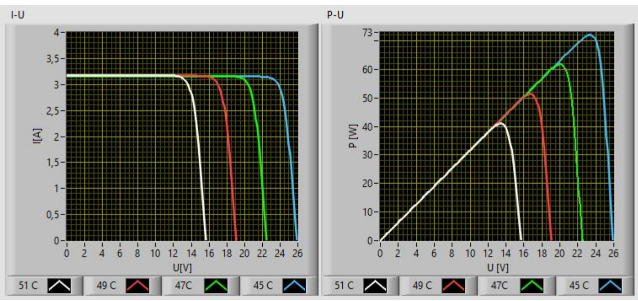

Fig. 7. I-U and P-U curves obtained by the LabVIEW model at a constant solar irradiance and variable cell temperature.

The front panel and block diagram of the final implementation of the model with MPP tracking are shown in Fig.8 and Fig.9 respectively.

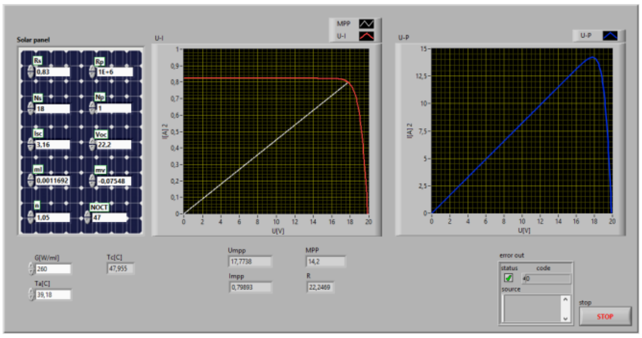

Fig. 8. Front panel of the virtual instrument used for MPPT of the solar panel model

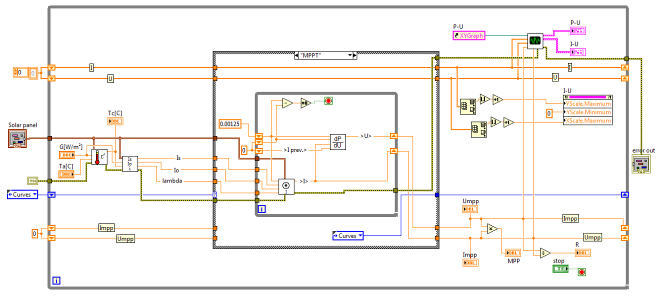

Fig. 9. Block diagram of the virtual instrument used for MPPT of the solar panel model

5. Verification and validation of the LabVIEW model

5.1 Measurement procedure

In order to verify the exactness of the PV panel model designed in LabVIEW, three series of measurements were conducted. The solar panel was irradiated with 3x500W halogen lamps. The I-U curve was then obtained for three different lighting conditions, realized by regulating the voltage of the lamps with an autotransformer. For each measurement series, the lighting conditions were determined by using a lux meter to measure the illuminance on 30 points of the surface of the panel, and then an average value was calculated.

A load consisting of a variable resistor with a maximal resistance of 780 Ω was connected to the panel output. By regulating the resistance, the I-U curves were acquired with a voltmeter and an ammeter. The obtained I-U curves were then compared to the I-U curves generated by the LabVIEW model of the PV panel in order to verify the model accuracy.

It is important to note that the standard test conditions (STC) of an irradiation of 1000W/m^2, a temperature of 25ºC and an air mass of 1,5 could not be achieved. The ambient temperature during the measurements was 20 ºC and the maximum irradiation achieved was 260 W/m^2.

5.2 Results analysis

To quantify the matching between the exact I-U curve and the approximated curve calculated with Eq. (9), a coefficient of determination (R^2) is used. It is a number that indicates how well certain data fit a statistical model: R^2=1 indicates that the regression line perfectly fits the data [14]. Basically, the method of least squares is utilized for two curves comparison.

The coefficient of determination R^2 was calculated for the I-U curve at STC provided by the manufacturer, as well as for the three series of measurements of the solar panel I-U curve. The test conditions for all four curves were applied to the LabVIEW model and R^2 was calculated for each of them. The results are as follows: R^2=0.979 for the I-U curve at STC, and R^2=0,908, R^2=0,946 and R^2=0,952 for the I-U curves show in Fig. 10 respectively.

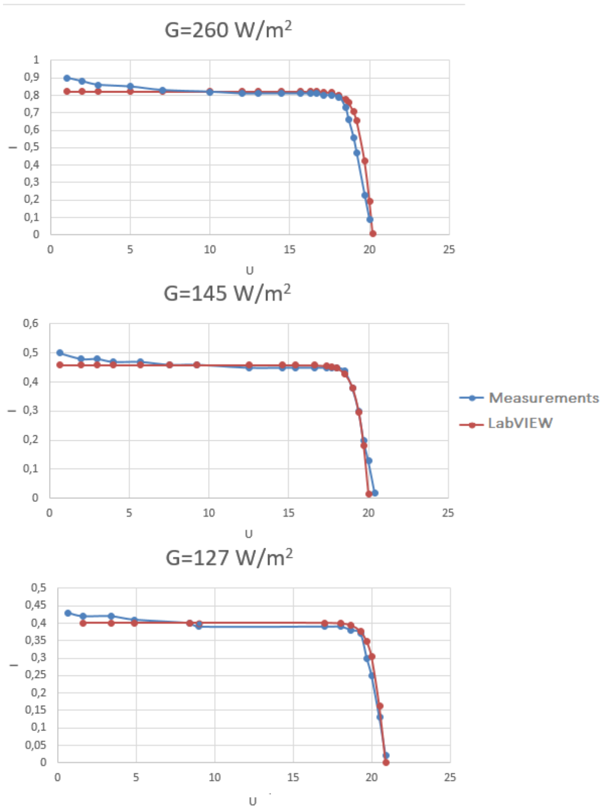

Fig. 10. Comparison between the measured and simulated I-U curves for three different irradiations.

The results deviations for the three measured curves are due to the non-standard test conditions in which the measurements were performed. The wind velocity of 1 m/s was not reproduced in laboratory conditions, and this was modeled by increasing the ambient temperature. The connection wires introduce additional resistance in the electrical circuit, and the instrument's imprecision should be taken into account. Furthermore, the halogen lamps were not entirely equivalent to the sun's irradiation: the majority of the lamp's emitted energy is in the infrared region, with a colour temperature of 3000 K, and the solar panel was not uniformly illuminated.

However, the measurement results verify that the LabVIEW model gives an acceptably accurate mathematical representation of the panel characteristics.

Using IC method, the LabVIEW model calculates the resistive load that should be applied to the solar panel, in order to utilize the maximum available output power. For irradiation of 260 W/m^2, the best matching load is R_L=22.674 Ω, for 145 W/m^2 the load is R_L=40.446 Ω, and for 127 W/m^2 the load value should be R_L=48.169 Ω.

6. Conclusion

In this paper, a mathematical model of a solar panel was presented, as well as the incremental conductance algorithm for maximum power point tracking. The model was designed in LabVIEW to simulate a real solar panel with and implementation of the MPPT algorithm. The verification and validation of the simulated results for the I-U curves included comparison to the data from the technical specification and I-U curve at STC of the panel provided by the manufacturer, as well as to results obtained through measurements of the I-U curves of the panel for three different irradiations. Using the method of least squares, the accuracy of the model was calculated and it can be concluded that the model gives an accurate representation of the characteristics of the real solar panel.

Further considerations include designing a data acquisition system to monitor the panel and to track the MPP in real-time. This approach ensures greater solar power utilization, due to the possibility of load regulation in order to maintain the operation point at its maximum output power.

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