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Solar Energy Materials & Solar Cells 67 (2001) 389–395
Solar Energy Materials & Solar Cells
www.elsevier.com/locate/solmat

Estimation of equivalent circuit parameters of PV module and its application to optimal operation of PV system

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Abstract

A method to estimate the equivalent circuit parameters of a PV (photovoltaic) module is presented. The parameters are calculated using a least-squares fitting of the equivalent model current–voltage characteristic with the measured one. For applications of the equivalent circuit model parameters, a quantitative diagnostic method of the PV modules by evaluating the parameters is introduced and examined by simulation. A new maximum peak power tracking (MPPT) method using the model parameters, a solar insolation, and a cell temperature is also shown. Its performance is compared with other MPPT control algorithms by simulations. The performance of the proposed method was better than other MPPT methods. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: PV module; Equivalent circuit parameter; Diagnostics; MPPT

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1. Introduction

A precise current–voltage (I–V) characteristic of PV modules and arrays is necessary to estimate their performance and improve the efficiency of the PV power generation system. A PV array consists of many PV modules and a PV module consists of many

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PII: S0927-0248(00)00307-X

PV cells connected in series or in parallel. Therefore, an equivalent circuit of the PV cell, which can be expressed as a photodiode with a large p–n junction, can express PV arrays and modules. Although an equivalent circuit of PV modules can express well the *I–V* characteristic, practical *I–V* characteristics of PV module are usually obtained by using polynomial approximate equations with coefficients obtained experimentally [1]. This may result from the difficulty in estimating the correct model parameters. Recent progress in microprocessor performance has enabled us to calculate the parameters in real time. In this paper, a calculation method of PV model parameters using measured *I–V* data and its application to a MPPT method are presented.

2. Estimation method of model parameters

An equivalent circuit shown in Fig. 1 is used together with the following set of circuit equations to express a typical current–voltage (*I–V*) characteristic of PV modules and arrays.

$$I = I_{\mathrm{ph}} - I_{\mathrm{d}} - I_{\mathrm{r}}, \tag{1}$$

$$I_{\mathrm{ph}} = I_{\mathrm{sho}}\left(\frac{S}{1000}\right) + J_0(T - T_{\mathrm{ref}}), \tag{2}$$

$$I_{\mathrm{d}} = I_0\left[\exp\left\{\frac{q(V + R_{\mathrm{s}}I)}{nkT}\right\} - 1\right], \tag{3}$$

$$I_0 = I_{\mathrm{d0}}\left(\frac{T}{T_{\mathrm{ref}}}\right)^3 \exp\left\{\frac{qE_{\mathrm{g}}}{nk}\left(\frac{1}{T_{\mathrm{ref}}} - \frac{1}{T}\right)\right\}, \tag{4}$$

$$I_{\mathrm{r}} = \frac{V + R_{\mathrm{s}}I}{R_{\mathrm{sh}}}, \tag{5}$$

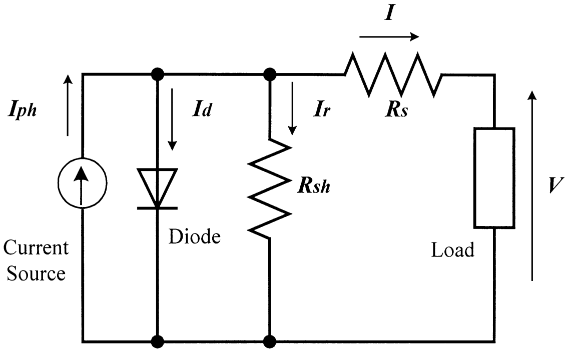

Fig. 1. Equivalent circuit for PV modules and PV arrays.

where S is the solar insolation in $\mathrm{W/m^2}$, T_{ref} is the reference temperature (298 K), T is the cell temperature, E_g is the band gap energy of the cell semiconductor, k is Boltzmann constant, R_s is the series resistance, R_{sh} is the shunt resistance, n is the diode emission factor, I_{d0} is the diode reversal current, I_{sho} is the short-circuit current at reference state and J_0 is its temperature coefficient. As can be seen from Eq. (4), E_g and I_{do} are not independent of each other, therefore E_g was calculated using Eq. (6) for a silicon semiconductor [2] and m which is the number of cells connected in series.

$$E_g = m\left(1.16 - 7.02\times 10^{-4}\frac{T^2}{T-1108}\right). \tag{6}$$

In order to estimate the optimal PV model parameters that fit best to the measured I–V curve, the following merit function χ^2 was minimized using the Levenberg–Marquardt method [3]:

$$\chi^2(\mathbf{x}) = \sum_{i=1}^{N}\left[\frac{I_i(V_i) - I(V_i,\mathbf{x})}{\sigma_i}\right]^2. \tag{7}$$

Here, a vector $\mathbf{x}$ stands for five model parameters (R_s, R_{sh}, n, I_{do}, I_{sho}), N is the number of data points used, I_i and V_i are i-th measured current and voltage values, respectively, σ_i is a standard deviation at that data point, and $I(V_i, \mathbf{x})$ is the calculated current at V_i which is obtained by solving Eqs. (1)–(6) with the estimated $\mathbf{x}$, and the measured S and T. In this paper, J_o value is provided by the PV manufacturers because adequate I–V data at different T are not available at this time. An initial value of $\mathbf{x}$ was estimated from the measured I–V curves and from the specifications data of the PV module. Calculations searching for non-linear model parameters were iterated until χ^2 converged.

3. MPPT control using model parameters

In order to extract the maximum available power from the PV modules, it is necessary to operate the PV modules at their maximum power point (MPP). Several MPPT methods, such as perturbation, fuzzy control [4], power–voltage differentiation [5] and on-line method [6] have been reported. These control methods have drawbacks in stability and response time in the case when solar insolation changes abruptly. Here, a direct MPPT method using PV model parameters is introduced.

A derivative of the output power P with respect to the output voltage V is equal to zero at MPP. If equivalent circuit model parameters, S and T are given, MPP is obtained by solving Eq. (8) together with Eqs. (1)–(6) using the Newton–Raphson method:

$$\frac{dP}{dV} = I - V\left[\frac{q/nkT\{I_{ph} + I_0 - I - (V + R_sI)/R_{sh}\} + 1/R_{sh}}{1 + qR_s/nkT\{I_{ph} + I_0 - I - (V + R_sI)/R_{sh}\} + R_s/R_{sh}}\right] = 0. \tag{8}$$

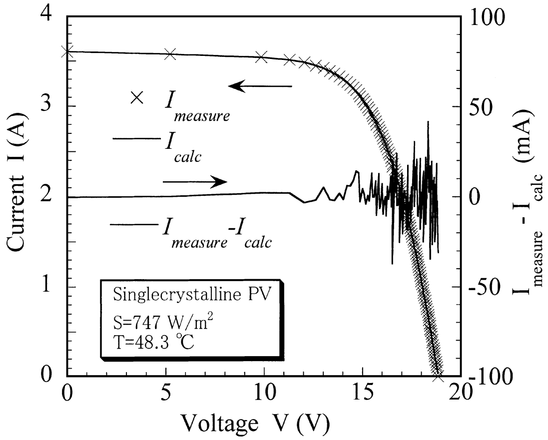

Fig. 2. Measured (×) and calculated using model parameters (solid line) I–V characteristics of single-crystalline PV module.

When the model parameters and S are obtained in a real time, a correct MPP can be calculated without knowing the cell temperature or the dependence of the cell parameters on temperature.

4. Results and discussions

Fig. 2 shows the measured I–V data (×) of the single-crystalline PV module (Showa Shell GT136, $P_{max} = 54.5$W) and the fitted curve (solid line) calculated using optimized parameters, and the difference between the measured and the calculated currents is also shown. The calculated model parameters give a good approximation to the measured characteristic and the current difference is less than 50 mA.

The parameters of three type (single-, polycrystalline and amorphous) PV modules are shown in Table 1. There is a large difference in R_{sh} and I_{do} among these modules. Since a large R_{sh} is difficult to estimate because it is affected by the data in a constant current region, R_{sh} of the polycrystalline module might be overestimated. In amorphous module, both the diode reversal current I_{do} and the diode emission factor n are larger than those of the crystalline modules. In this table, electrical properties of the modules both measured from I–V data and calculated using the parameters are shown. These show that the I–V curve is fitted correctly.

Equivalent circuit parameters of a PV array which consists of two PV modules, a normal module and a degraded one connected in series, are obtained numerically in order to investigate the effect of the degraded module on the array. Table 2 shows the electrical properties and the parameters of the array for three different cases; only one of the parameters out of R_s, R_{sh}, and I_{sho} of one side module is modified to express the degraded module. For comparison, the parameters of the normal module and the array which consists of two normal modules are also shown in Table 2. In the case

Table 1
Estimated equivalent circuit parameters of different type of PV modules

PV type	Single-crystalline		Polycrystalline		Amorphous	
S (W/m^2)	747.1		715.8		770.9	
T_{cell} (°C)	48.3		50.1		36.5	
	Measured	Calculated	Measured	Calculated	Measured	Calculated
P_{max} (W)	46.6	46.4	42.6	42.5	23.2	23.2
V_{opt} (V)	14.7	14.4	14.8	14.6	15.1	15.2
I_{opt} (A)	3.18	3.22	2.88	2.91	1.53	1.52
V_{open} (V)	18.8	19.0	18.7	18.8	21.0	21.2
I_{short} (A)	3.60	3.59	3.22	3.22	1.90	1.89
FF (%)	68.6	68.1	70.6	70.3	57.9	57.9
R_s (Ω)	0.3464		0.3597		0.4204	
R_{sh} (Ω)	193.7		972.6		138.4	
n	49.53		46.6		104.95	
I_{sho} (A)	4.784		4.443		2.459	
I_{do} (μA)	0.2287		0.0711		467.36	
J_o (mA/K)	1.6		1.6		1.8	
E_g (V)	45.08		45.12		44.79	
χ^2	1.28×10^{-2}		2.46×10^{-2}		3.53×10^{-3}	

Table 2
Estimated equivalent parameters of PV array which consists of two modules connected in series

	One normal module	Array (normal + normal)	Array (normal + degraded)		
			$R_s = 0.6$ (Ω)	$R_{sh} = 300$ (Ω)	$I_{\text{sho}} = 2.8$ (A)
P_{max} (W)	44.9	89.8	88.3	89.4	86.0
V_{opt} (V)	16.4	32.8	32.4	32.8	33.1
I_{opt} (A)	2.73	2.73	2.73	2.72	2.60
V_{open} (V)	20.9	41.8	41.8	41.7	41.7
I_{short} (A)	3.00	3.00	3.00	3.00	2.83
FF (%)	71.7	71.7	70.5	71.4	73.0
R_s (Ω)	0.3924	0.843	1.0404	0.8528	1.0881
R_{sh} (Ω)	511.3	935.9	942.4	665.7	591.8
n	47.69	93.04	93.14	92.48	74.78
I_{sho} (A)	2.96	2.961	2.96	2.963	2.792
I_{d0} (μA)	0.0201	0.0536	0.0547	0.0481	0.0007
J_0 (mA/K)	1.6	1.6	1.6	1.6	1.6
E_g (V)	45.12	90.24	90.24	90.24	90.24
χ^2	1.61×10^{-4}	1.22×10^{-3}	1.01×10^{-3}	1.68×10^{-3}	6.02×10^{-3}

when R_s or R_{sh} is modified, a change in the same parameter of the array is found. Whilst a modification of I_{sho} affects all other parameters. The result shows that the change of R_s, R_{sh} of the module can be detected by the estimated parameters.

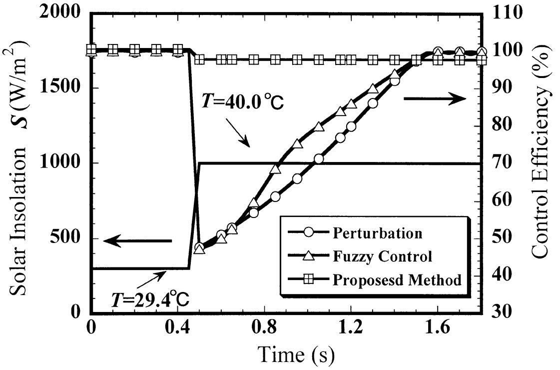

Fig. 3. Control efficiency of three MPPT algorithms.

A simulation model which consists of a PV module expressed by the equivalent circuit and a DC chopper which changes operation points were used to evaluate three MPPT control methods, perturbation method, fuzzy control method and the proposed method using PV model parameters. Fig. 3 shows the control efficiencies of these methods, which is defined as the ratio of the PV output power controlled by the algorithm to the maximum available PV power, under the condition that S increased suddenly from 300 to 1000 W/m^2. The efficiency of the proposed method is almost constant even for a quick increase of S, while those of other methods decreased to about 50%. In the proposed method, the efficiency remains at 98% after S changed because the simulation assumes that the cell temperature increases from 29.4°C to 40°C with S and the model parameters calculated at 29.4°C are used. In the practical application, if the model parameters are expressed as a function of T or the parameters are renewed in real time using a fast I–V tracer as T changes, this method can always track the MPP.

5. Conclusions

The equivalent circuit parameters of the PV module were successfully obtained by a least-squares fitting of the I–V curves. The parameters of different kind of PV modules were estimated by this method and they were found to be useful to characterize the module. PV diagnostics can be possible by monitoring the PV parameters and comparing them with those at their initial states. A PV module simulator using equivalent circuit model parameters evaluates some MPPT control methods under the same condition. The proposed MPPT method using equivalent parameters was verified to show better performance than other methods in the simulation.

Acknowledgements

This research is commissioned and financially supported by Kyushu Electric Power Co., Inc, Japan.

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