PV cell modeling on single-diode equivalent circuit

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***Abstract*— PV cell model is necessary both for software and hardware simulators in analyzing and testing the performance of PV generation systems. To get the characteristic non-linear I-V Curve of a PV cell, 5 characteristic parameters R_s, R_{sh}, I_0 and v_t should be extracted from the three remarkable operation points of the manufacture's datasheets, I_{sc}, V_{oc}, I_{MPP} and V_{MPP}. This paper analyzes conventional three representative PV modeling algorithms by comparison, and proposes a novel PV modeling algorithm which is fast, accurate and applicable to all kinds of PV cells such as Cr-Si type and thin-film type PV cells. Proposed theory is verified by simulations for various PV cell types such as Cr-Si type and thin-film type PV cells.**

Keywords— PV cell Modeling; Root of equation; Cr-Si type PV cell; Thin-film type PV cell; IEC EN50530

I. Introduction

Photovoltaic power generation is a technology that directly transforms unlimited, unpolluted and free solar energy into electric energy. Approximately 2m^2 of totally open space is typically required per kW in order to install PV array for PV power generation. Thus, much capital and labors are needed for performance testing of PCSs (Power conditioning systems) that uses PV arrays. Moreover, the performance of PCSs for PV power generation cannot be freely tested for desired weather conditions since the output of PV array is affected by climate environment.

IEC regulation draft for PV efficiency standard EN50530 [1] states that PV simulator is to be used for conducting general efficiency evaluation testing for PCSs. According to this regulation, both I-V curve and P-V curve must be simulated by PV simulators in Cr-Si type and thin-film type PV arrays [1]. As such, PV cell model is essential for constructing PV simulator. In addition, PV cell model is also needed for analyzing PV power generating system through simulation software.

Accordingly, there have been many researches on PV cell modeling [2-13]. In case of Villalva algorithm [4], voltage is made the domain in the selected pair of R_s-R_{sh}, where values of I(V) and P(V)=I(V)*V are sequentially obtained for operating area of V from which P_{MAX} is found. If the obtained P_{MAX} and P_{MPP} of manufacturer's datasheet do not match, the above process is iterated for next selected pair of R_s-R_{sh}, and the algorithm is finished when the values are found to match.

Villalva algorithm has a disadvantage of needing trial and error process in which the user needs to intervene and manipulate the diode quality factor from the outside, to match with the I-V curve provided by the manufacturer's datasheet. Fig. 1 shows difference of I-V curves according to diode quality factor value a. Value a is randomly assigned since it is unknown to the user. Thus, the searching process cannot be done automatically.

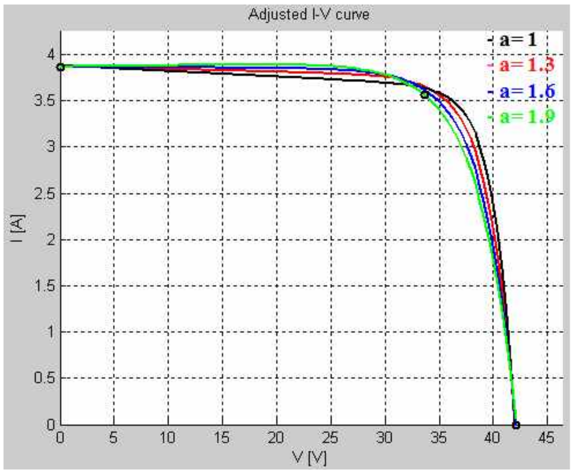


Fig. 1. Comparison on I-V Curves according to a (ideality factor).

Although Pedro algorithm [5] has an advantage of solving the problem without the need to external interruption of assigning a value for diode quality factor, its disadvantage is that R_s and R_{sh} need to be individually found in a repetitive manner while the convergence into a solution is difficult since relationship between the two values is not defined. Thus, Pedro algorithm is no more considered in this paper.

In case of Wagner algorithm [6], its advantage is that parameter extraction can be finished in one try, but because numerical analysis was adapted for Cr-Si type, much error is encountered when material composition of PV cell changes such as to thin-film type.

For precise operation of a PV simulator, PV cell modeling that has very small error even in various types of material such as thin-film type, Cr-Si type and Tandem(Cr-Si+thin-film) type is necessary. This paper proposes a novel PV cell modeling algorithm that has small error for any kind of PV cell types of material with little time required for computation. Superiority in the proposed method is verified through comparative analysis between conventional modeling methods and proposed modeling method through simulation.

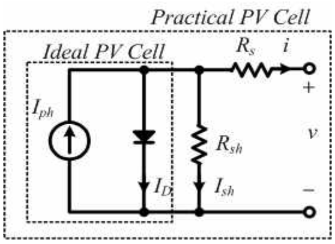


Fig. 2. Single-diode model of the PV cell.

II. EQUIVALENT CIRCUIT

Fig. 2 shows PV cell equivalent circuit for PV cell modeling [4]. Equation (1) shows I-V characteristic equation of PV cell based on this equivalent circuit.

In the datasheets provided by PV panel manufacturers, 3 remarkable points, which are V_{oc}, I_{sc} and P_{MPP}, are given for the characteristic I-V curve. Using these values PV cell modeling has to derive parameters of R_s, R_{sh}, I_{ph}, I_0 and v_t which are elements of the equivalent circuit of Fig.2.

$$i = I_{ph} - I_0(\exp^{\frac{v+iR_s}{n_s v_t}} - 1) - \frac{v + iR_s}{R_{sh}} \tag{1}$$

I_{ph}: Current generated by the incident light[A]

I_0: Diode saturation current[A]

R_{sh}: Cell parallel(shunt) resistance[ohm]

R_s: Cell series resistance[ohm]

n_s: Number of PV Cells connected in series

v_t: Diode thermal voltage(=akT/q)[V]

a: Diode quality(ideality) factor

k: Boltzmann's constant(1.381×10^{-23}) [J/K]

q: Charge of the electron(1.602×10^{-19}) [C]

T: Kelvin Temperature at standard test condition[K]

To get the characteristic non-linear I-V Curve of a PV cell, 5 characteristic parameters R_s, R_{sh}, I_0 and v_t, should be extracted from the three remarkable operation points of the manufacture's datasheets, I_{sc}, V_{oc}, I_{MPP} and V_{MPP}.

III. PROPOSED PV CELL MODELING

This paper proposes a novel PV cell modeling algorithm that reduces severe error according to the material composition of PV cells with less iterative computations. Fig.3 shows flow chart of proposed modeling algorithm. In the proposed algorithm, R_s value is increased from zero in the interval of R_{s_step} until reaching of R_{s_max} to find the solution for values of R_{sh} and v_t. Here, R_{s_step} and R_{s_max} are determined according to equations below.

$$R_{s\_max} = \frac{V_{oc} - V_{MPP}}{I_{MPP}} \tag{2}$$

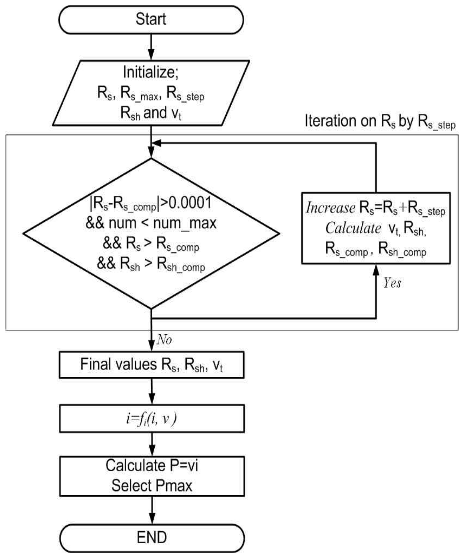


Fig. 3. Flow chart of proposed K-algorithm.

$$R_{s\_step} = \frac{R_{s\_max}}{1000} \tag{3}$$

Initial value of v_t is obtained through (4).

$$v_t = \frac{1.25kT}{q} \tag{4}$$

In the iterative routine, the values of R_{sh} and v_t is updated as follows;

$$R_{sh} = \frac{N_2 R_s^{\,2} + N_1 R_s + N_0}{D_1 R_s + D_0} \tag{5}$$

Here,

$N_0 = R_{MPP}(V_{MPP} - n_s v_t)$

$N_1 = n_s v_t - I_{sc} R_{MPP}$ $\quad N_2 = I_{sc} - I_{MPP}$

$D_0 = I_{sc} I_{MPP} - V_{MPP} - n_s v_t$ $\quad D_1 = I_{MPP} - I_{sc}$

$$v_t = \frac{I_{sc}R_s - V_{oc}}{n_s \ln[\frac{n_s v_t R_s}{(I_{sc}R_{sh} + I_{sc}R_s - V_{oc})(R_{sh} - R_s)}]} \tag{6–1}$$

$$v_t = \frac{I_{sc}R_s - V_{oc}}{n_s \ln[\frac{n_s v_t R_s}{(I_{sc}R_{sh} + I_{sc}R_s - V_{oc})(R_{sh} - R_s)}]} + R_s \tag{6–2}$$

$$v_t = \frac{V_{MPP} + I_{MPP}R_s - V_{oc}}{n_s \ln[\frac{n_s v_t (R_{sh} + R_s - R_{MPP})}{(I_{sc}R_{sh} + I_{sc}R_s - V_{oc})(R_{sh} - R_s)}]} \tag{6–3}$$

Depending on the method of updating value of v_t in equation (6), proposed algorithm will be referred to as K1-algorithm (6-1), K2-algorithm (6-2) and K3-algorithm (6-3).

As conditions for judging convergence of R_s and R_{sh}, R_{s_comp} and R_{sh_comp} are used as follows;

$$R_{s\_comp} = \frac{-(BD_0 - DN_0)}{CD_0 + BD_1 - DN_1} \tag{7}$$

$$R_{sh\_comp} = \frac{B + CR_s}{D} \tag{8}$$

Here,

$$B = -V_{MPP} + \frac{n_s v_t I_{MPP} V_{oc}}{I_{sc} V_{MPP}}$$

$$C = I_{sc} - I_{MPP} - \frac{n_s v_t I_{MPP}}{V_{MPP}}$$

$$D = I_{MPP} - I_{sc} - I_{sc} e^{\frac{V_{MPP} + I_{MPP} R_s - V_{oc}}{n_s v_t}}.$$

In the iterative routine, value of R_{sh} must be greater than R_{sh_comp}. Moreover, value of R_s also must be greater than R_{s_comp} and when the difference with R_{s_comp} is below a tolerance error, it is assumed that the value of R_s is found. Because the value of R_s influences as well due to its subordination in R_{sh} and v_t, the values of R_{sh} and v_t are determined when value of R_s is determined. Advantage of proposed modeling algorithm is that desired resulting value can be derived with relatively less iterative computation without the need for external intervention to manually assigning diode quality factor value a.

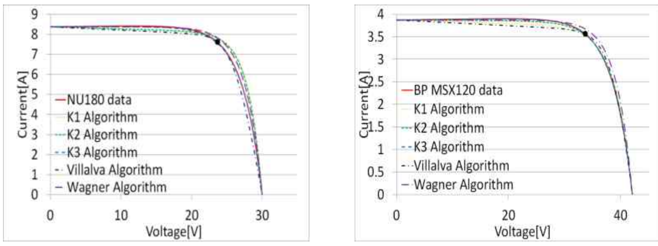
IV. Review of Validity for Proposed Algorithm

Fig.4 ~ Fig.6 show simulation results of characteristic I-V curves according to each modeling algorithm for three different types of PV cell, which are Cr-Si, thin-film and tandem type, by using proposed K-algorithm.

Fig.4 compares simulation results of characteristic I-V curves according to each modeling algorithm for two kinds of Cr-Si type PV cells; NU180 and BP MSX120. The solid line in the graphs describes the characteristic I-V curve provided by the manufacturer's datasheet. Although there are some differences of error, all the characteristic I-V curves by each algorithm converge to the solid line.

Fig.5 compares simulation results by each modeling algorithm for thin-film type PV cells; ASI-F 10/12 and SI-S22-170. The solid line in the graphs describes the characteristic I-V curve provided by the manufacturer's datasheet. The characteristic I-V curves extracted by Villalva algorithm and Wagner algorithm are far from the solid line while all the characteristic I-V curves by proposed K-algorithm converge to the solid line.

Fig.6 compares simulation results by each modeling algorithm for tandem type PV cells; NAF128GK and BS120-MA10.



a) b)

Fig. 4. Comparison of I-V Curve for Cr-Si algorithm a) NU180, b) BP MSX120.

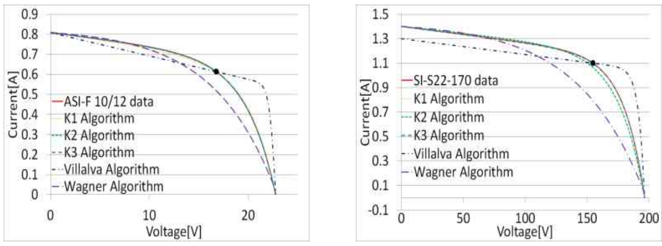


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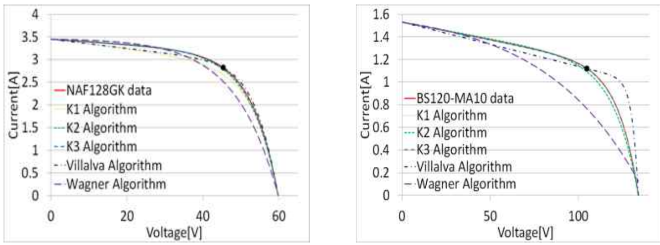
Fig. 5. Comparison of I-V Curve for thin-film algorithm a) ASI-F 10/12, b) SI-S22-170.



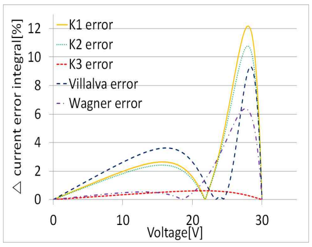
a) b)

Fig. 6. Comparison of I-V Curve for Tandem algorithm a) NAF128GK, b) BS120-MA10.

The solid line in the graphs describes the characteristic I-V curve provided by the manufacturer's datasheet. In case of Villalva algorithm, the simulation results of characteristic I-V curve of NAF128GK PV cell shows comparably small error, while that of BS120-MA10 PV cell shows large amount of error. In case of Wagner algorithm, the characteristic I-V curves of both tandem type PV cells show big error. While the characteristic I-V curves of both tandem type PV cells extracted by proposed K-algorithm show very small error.

Fig.7 shows comparison results of each modeling algorithm for several representative PV cells. The curves shown in Fig.7 means error of the characteristic I-V curve extracted by each algorithm, compared to the characteristic I-V curve provided by the manufacturer's datasheet.

Table I shows error integration of the I-V curves in the range of V_{MPP}±10%, which is MPPT (Maximum Power Point Tracking) range as stated in EN50530 regulation. It can be observed that integrated error value in proposed K-algorithm is smaller in characteristic I-V curve regardless of material of PV cells when compared to conventional modeling algorithms.



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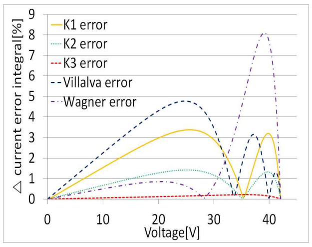

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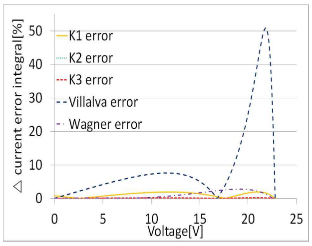
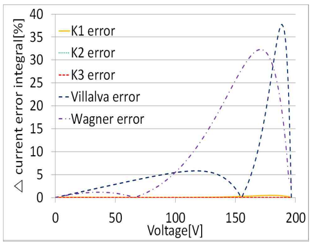
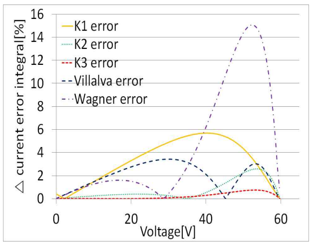


c)



d)



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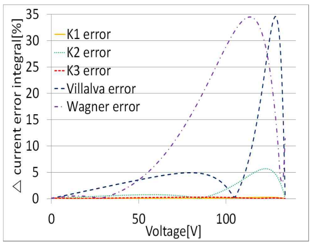

f)

Fig. 7. Comparison of error integration a) NU180, b) BP MSX120, c) ASI-F 10/12, d) SI-S22-170, e) NAF128GK, f) BS120-MA10.

TABLE I. COMPARISON RESULT OF EACH MODELING ALGORITHM FOR SEVERAL PV ARRAYS (ERR INTGRATION)

PV array / Algorithm	NU180	BP MSX120	ASI-F 10/12	SI-S22-170	NAF128GK	BS120-MA10	Avg. Error
K1-algorithm	3.42	1.47	0.69	0.17	4.99	0.12	1.81
K2-algorithm	3.14	0.58	0.02	3.05	1.2	2.66	1.78
K3-algorithm	0.59	0.21	0.06	0.12	0.44	0.17	0.27
Villalva algorithm	0.81	1.88	3.58	3.79	0.93	3.38	2.40
Wagner algorithm	3.08	3.32	2.33	25.94	9.5	31.67	12.64

*Integral range: $V=0.9*V_{MPP} \sim 1.1*V_{MPP}$.

The average integration error of K3-algorithm through 6 representative PV cells is only 0.27, while that of Villalva algorithm is 2.40 and that of Wagner algorithm is 12.64.

Table II shows number of iteration to accomplish each modeling algorithm.

TABLE II. COMPARISON RESULT OF EACH MODELING ALGORITHM FOR SEVERAL PV ARRAYS (ITERATION NUMBER)

PV array / Algorithm	NU180	BP MSX120	ASI-F 10/12	SI-S22-170	NAF128GK	BS120-MA10	Avg. Iter.$^{+}$
K1-algorithm	198	160	97	8	108	2	96
K2-algorithm	41	11	13	1	5	1	12
K3-algorithm	2	1	10	8	7	8	6
Villalva algorithm	3223	5000	5000	5000	5000	5000	4704
Wagner algorithm	1	1	1	1	1	1	1

Avg Iter^{+}: Average Iteration number of each algorithm.

Wagner algorithm is the fastest among the compared algorithms since it extracts the modeling parameters in single try. Villalva algorithm is the slowest among all the algorithms.

Villalva algorithm does not even converge the modeling parameters within iteration limit(5,000) in most PV cell materials sampled in this paper. Proposed K-algorithms is comparably fast. K3-algorithm is faster than the other two K-algorithms. The average iteration number of K3-algorithm through 6 representative PV cells is only 6. Thus, it can be confirmed that K3-algorithm among the proposed algorithms showed the best modeling performance for PV cells of any material type.

V. CONCLUSIONS

This paper proposed a novel PV cell modeling algorithm for establishing PV array simulators. Proposed modeling algorithm extracts the parameters of the PV cell equivalent circuit automatically without external intervention by user. Proposed modeling algorithm is applicable to any kind of PV cell material type such as Cr-Si type, Thin-film type, and tandem type, with very small error in characteristic I-V curve, by a few iterative calculations. Upon comparison with datasheet of PV panel manufacturer, it was verified that characteristic I-V curve from proposed modeling algorithm approached closely to P_{MPP} point. Superiority of proposed algorithm was proven by comparing error from $V_{MPP}\pm10\%$ region with the ones of other PV cell modeling algorithms.

ACKNOWLEDGEMENT

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (No. 2012R1A1A2039747). This research was also supported by Kaco-newenergy Co. Ltd.

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