論 文
53B-4-8

태양전지 온도 센싱만을 통한 태양광 발전시스템의 최적 운전전압에 관한 연구

A Study on the Optimal Voltage for MPPT Obtained by only Surface's Temperature of Solar Cell

朴 敏 遠* · 劉 仁 根**
(Minwon Park·In-Keun Yu)

Abstract - Photovoltaic(PV) system has been studied and watched with keen interest due to a clean and renewable power source. But, the output power of PV system is not only unstable but uncontrollable, because the maximum power point tracking (MPPT) of PV system is still hard with the tracking failure under the sudden fluctuation of irradiance. Authors suggest that the optimal voltage for MPPT be obtained by only solar cell temperature. Having an eye on that the optimal voltage point of solar cell is in proportion to its panel temperature, with operating the power converter whose operating point keeps its input voltage to the optimal voltage imagined by the surface's temperature of PV panel, the maximum power point becomes tenderly possible to be tracked. In order to confirm the availability of the proposed control scheme. And both control methods are simulated not only on the various angle of sampling time of switching control, but also with the real field weather condition. As the results of that, the conversion efficiency between PV panel and converter of the proposed control scheme was much better than that of the power comparison MPPT control, and what is better, the output voltage of PV panel was extremely in stable when the optimal voltage for MPPT is obtained by only solar cell temperature.

Key Words : MPPT, Photovoltaic power generation system, Solar cell, Optimal voltage

1. Introduction

With the distinguishing mark of photovoltaic(PV) energy, due to the crisis of fuel energy and the gravity of the environmental issue, the PV energy system has been researched with a lot of concern. However, the output power of PV generating system is not systematically tracked and influenced by various factors; solar irradiance, solar cell temperature and the connected load condition. According to its characteristics, various control methods were made public and are still being released.

So far, the basic theory of MPPT control is the power comparison method[1]; "mountain climbing method". Theoretically, how to decide the width of the changing voltage(□V) on changing the operating voltage point has been bringing a lot of researchers to the field of MPPT research. However, the more □V is big, the more the speed of response is fast, but the stability of PV system becomes worse [2].

$$\Delta V \propto \frac{1}{Stability(PVsystem)}\ \textit{under irradiance fluctuation}$$

How to decide □V is dependant on various factors of PV system. Due to the above, various methods were approached and made public attention [3-10]. But, the risk of control failure according to the sudden fluctuation of irradiance, which is related to the stability of PV system, is doubtlessly the significant demerit of the power comparison MPPT method. In order to satisfy both the stability and efficiency of PV system, the indirect MPPT method, which the imaginary maximum power point is assumed from the measured data of solar irradiance, panel's temperature, and load condition, has been researching [11]. But, because there are many sensors, it costs. And, the recorded data could be different from real value according to the aged deterioration. These kinds of control methods have their own demerit, and the constant voltage control method was also proposed, but this method is inefficient, especially under summer season [12].

In this paper, authors suggest that the optimal voltage for MPPT can be obtained by only solar cell temperature. The optimal voltage of a solar cell is not remarkably changed by the amount of irradiance, but in proportion to the surface's temperature of solar cell. Therefore, if the input voltage of converter side holds to an optimal voltage of solar cell, the maximum power of solar cell will be optimally tracked. The voltage-type converter can allow the input voltage to maintain the desired voltage. Therefore, deciding its optimal voltage from the surface's temperature of solar cell and immediately controlling the input voltage of converter to maintain its optimal voltage, the maximum power point will be trapped without the risk of tracking failure. This proposed method remarkably makes the stable operation possible and reduces the tracking time to the maximum power point

---

* 正 會 員 : 次世代超傳導應用技術開發事業團 技術팀장
** 正 會 員 : 國立昌原大學校 電氣工學科 敎授
接受日字 : 2003年 12月 03日
最終完了 : 2004年 2月 09日

2. Module surface temperature and optimal voltage

2.1 V-I characteristics equation of solar cell

Figure 1 illustrates typical voltage-current (V-I) curves of a multi-crystalline silicon solar cell according to the variations of irradiance level and cell temperature. Mainly, the open-circuit voltage of solar cell varies with cell temperature, and the short-circuit current is directly proportional to irradiance and is relatively steady in changing cell temperature.

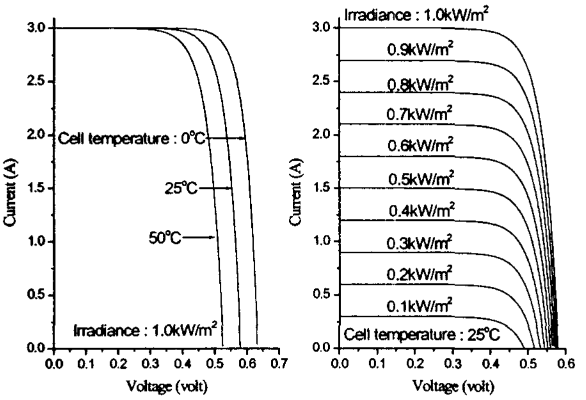

Fig. 1 V-I characteristics curves of a solar cell (a) Influence of cell temperature, (b) Influence of irradianc

The characteristics of a solar cell can be expressed by the following equations(Eq. 1 and 2). [13]

$$I = I_{sc} - I_{os}\left[\exp\left(\frac{q}{n\cdot k\cdot T}\cdot V\right)-1\right] \tag{1}$$

$$I_{os} = AT^{\gamma}\exp\left(\frac{-E_g}{n\cdot k\cdot T}\right) \tag{2}$$

With Equation 1 above, we can conclude that the output current and voltage of a solar cell are directly effected by irradiance and cell temperature. Its equivalent circuit described in Fig. 2 explains the internal condition of a solar cell.

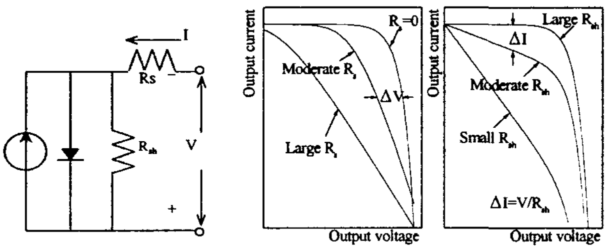

Fig. 2 Equivalent circuit of a solar cell and effect of parasitic resistances on the output of it

Both types of parasitic resistances act to reduce the fill factor as shown in Fig. 2. Considering this assumption, Equation 1 can be rewritten as Eq.3

$$I = I_{sc} - I_{os}\left\{\exp\left[\frac{q\cdot(V+I\cdot R_s)}{n\cdot k\cdot T}\right]-1\right\} - \frac{V+I\cdot R_s}{R_{sh}} \tag{3}$$

2.2 Effect of temperature to open-circuit voltage of solar cell

In order to confirm whether the optimal voltage of solar cell is obtained by only cell temperature, there needs the numerical analysis between the cell temperature and the optimal voltage. The short-circuit current of solar cells is not strongly temperature-dependent. It tends to increase slightly with increasing temperature. This can be attributed to increased light absorption, since semiconductor band gaps generally decrease with temperature. The other cell parameters, the open-circuit voltage and the fill factor, both decrease. The relation between short-circuit current and open-circuit voltage is explained with Eq. 4 as the output current is zero and *n* is 1.

$$I_{sc} = I_o\left(e^{qV_{oc}/kT}-1\right) \tag{4}$$

Neglecting the small negative term, this can be written as Eq. 5.

$$I_{sc} = AT^{\gamma}e^{-E_{go}/kT}e^{qV_{oc}/kT} \tag{5}$$

where *A* is independent of temperature, *Eg* is the linearly extrapolated zero temperature band gap of the semiconductor making up the cell, and □ includes the temperature dependencies of the remaining parameters determining *Io*. Differentiating gives, with *Vgo=Eg/q*,

$$\frac{dI_{sc}}{dT} = A\gamma T^{\gamma-1}e^{q(V_{oc}-V_{go})/kT} + AT^{\gamma}\left(\frac{q}{kT}\right)\left[\frac{dV_{oc}}{dT}-\left(\frac{V_{oc}-V_{go}}{T}\right)\right]e^{q(V_{oc}-V_{go})/kT} \tag{6}$$

Neglecting *dIsc/dT* in comparison with more significant terms results in the expression

$$\frac{dV_{oc}}{dT} = -\frac{V_{oc}-V_{go}+\gamma(kT/q)}{T} \tag{7}$$

This predicts an approximately linear decrease in *Voc* with increasing temperature. Substituting values for silicon(*Vgo*~1.2V, *Voc*~0.6V, □~3,*T*=300K) gives

$$\frac{dV_{oc}}{dT} = -\frac{1.2-0.6+0.078}{300}\ V/^{\circ}C \tag{8}$$

$$= -2.3mV/^{\circ}C \tag{9}$$

This agrees well with the experimental results. Figure 3 obtained for 160 minutes is the experimental curves, which shows the relationship between the open-circuit voltage and cell temperature. With this figure, it can be confirmed that the open-circuit voltage is in proportion to cell temperature and few relation with irradiance.

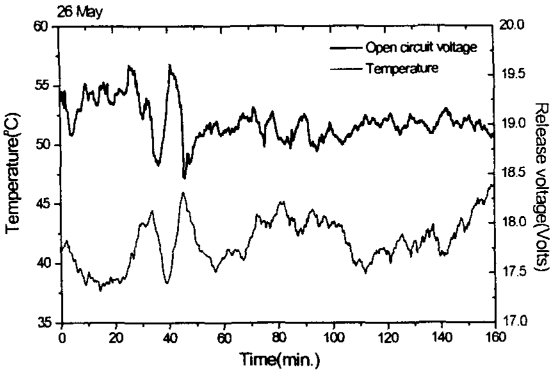

Fig. 3 Waveform of the relation between open-circuit voltage and cell temperature

2.3 Optimal voltage equation of solar cell

In *2.2 Effect of temperature to open-circuit voltage of solar cell* it is mainly explained that the open-circuit voltage of a solar cell is inversely proportional to cell temperature. Here, how to obtain the optimal voltage, which is the voltage point that the output power of solar cell is maximum, with only solar cell temperature will be described.

Assuming that the parasitic shunt resistance, *Rsh*, is unlimited high, the open-circuit voltage can be obtained when the current flowing into load, I, is zero as Eq. 10.

$$V_{oc}=\frac{1}{KK}\cdot\ln\left(\frac{I_{sc}}{I_{os}}+1\right) \tag{10}$$

Consequently, the open-circuit voltage is defined as follows.

$$V_{oc}=\frac{1}{KK}\cdot\ln\left(\frac{I_{sc}}{I_{os}}+1\right) \tag{11}$$

$$KK=\frac{q}{n\cdot k\cdot T} \tag{12}$$

Here, when *dP/dV*, Eq. 13, is zero, the voltage across of solar cell becomes optimal, and accordingly we can obtain Eq. 14.

$$\frac{dP}{dV}=I_{sc}+I_{os} - I_{os}\cdot e^{KK\cdot IR_s}\cdot e^{KK\cdot V}(1+KK\cdot IR_s\cdot V) \tag{13}$$

$$\frac{I_{sc}}{I_{os}}+1 = e^{KK\cdot IR_s}\cdot e^{KK\cdot V_{op}}\cdot(1+KK\cdot IR_s\cdot V_{op}) \tag{14}$$

Finally, because Eq. 14 can be inserted into Eq.11, the optimal voltage of solar cell is described as following.

$$e^{KK\cdot V_{oc}} = e^{KK\cdot IR_s}\cdot e^{KK\cdot V_{op}}\cdot(1+KK\cdot IR_s\cdot V_{op}) \tag{15}$$

With Eq. 15 it is confirmed that the optimal voltage, *Vop*, is strongly influenced by the open-circuit voltage, *Voc*.

Using Table 1 as parameters, Figure 4 shows the alteration of the optimal voltage and open-circuit voltage at 25℃of temperature by changing of irradiance. The open-circuit voltage *Voc* of solar cell is distorted even at the same cell temperature of PV array, because *Isc* and *Ios* varied with different rate of irradiance. And, *Vop* is also distorted by the irradiance level because *Voc* is the significant factor to decide *Vop* as described in Eq. 15. Figure 4 was using Eq. 11 and Eq. 15 at 25℃of cell temperature not considering *Rs* and *Rsh*.

Table 1 Parameters of a solar cell obtained from experiment

n	1.5	γ	3
A	9e-2	Eg	1.103eV
Rs	0.028Ω	Rsh	1kΩ
Voc at 25℃	0.58 Volt	Isc at 1.0kW/m²	3.0 A

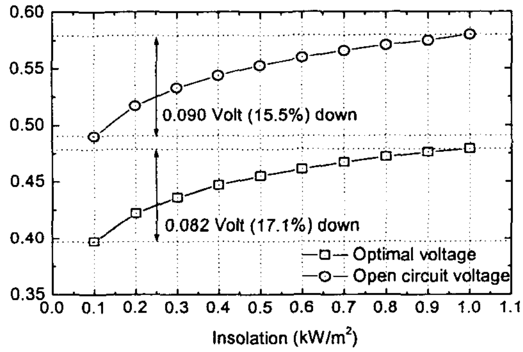

Fig. 4 Alteration of the optimal voltage and the open-circuit voltage at 25℃ of cell temperature by changing of the irradiance level not considering *Rs* and *Rsh*

However, according as there exist the parasitic resistances; *Rs* and *Rsh*, in solar cell, the alteration curve of optimal voltage in Fig. 4 must, therefore, be modified as shown in Fig. 2, which expresses the alteration of VI curve according to the parasitic resistances. The series resistance *Rs* affects the terminal voltage, and the shunt resistance *Rsh* slightly reduces the output current of solar cell. Figure 5 depicted by Eq. 15 shows the optimal voltage points under various weather conditions considering *Rs* and *Rsh*.

Also, as shown in Fig. 5 there is no doubt about that the optimal voltage equation by cell temperature is different in constant level by the different irradiance level. Table 2 shows each parameters of the optimal voltage equation as described in Eq. 16 briefly in regard to the irradiance level.

$$V_{op}\cong(u+s\cdot v)-T\cdot(w+s\cdot y) \tag{16}$$

Table 2 Parameters of the optimal voltage equation in accordance with irradiance level

Irradiance level	*u*	*v*	*w*	*y*
0.1～0.2kW/m²	0.43404	0.1621	0.00235	-6 e-4
0.2～0.3kW/m²	0.45404	0.0621	0.00237	-7 e-4
0.3～0.4kW/m²	0.46604	0.0221	0.00228	-4 e-4
0.4～0.5kW/m²	0.46964	0.0131	0.00224	-3 e-4
0.5～0.6kW/m²	0.47969	-0.0070	0.00224	-3 e-4
0.6～0.7kW/m²	0.48563	-0.0169	0.00218	-2 e-4
0.7～0.8kW/m²	0.49270	-0.0270	0.00239	-5 e-4
0.8～0.9kW/m²	0.49190	-0.0260	0.00223	-3 e-4
0.9～1.0kW/m²	0.49073	-0.0247	0.00205	-1 e-4

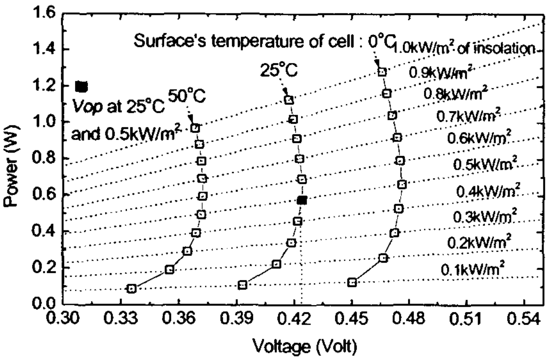

Fig. 5 Alteration of the optimal voltage and the open-circuit voltage at various cell temperature conditions by changing of the irradiance level considering *Rs and Rsh*

3. Total conversion efficiency when the optimal voltage is obtained by only cell temperature

In accordance with the mentioned above, the cell temperature must be a satisfactory control source to obtain the optimal voltage of a solar cell. However, even at the same temperature condition, the optimal voltage is slightly altered by the irradiance level. Furthermore, it is for the most part impossible that the feedbacked temperature for controller is same with the real average temperature of PV array. Considering these factors; temperature distribution, irradiance dependency, parasitic resistances, and the error of the measured temperature, it is analyzed how much we can expect the total conversion efficiency when the measured cell temperature is used as the control source of the optimal voltage for MPPT.

In order to actualize the numerical expression much closer to reality, three kinds of the real weather data are used in this paper. As shown in Fig. 6 (a), (b), and (c), the real field data of weather condition are composed of sunny, cloudy, and rainy day, respectively. The sampling time of data is here 1.0 sec and the total data point is 28,800 points for 8 hours. The real field data of wind velocity and air humidity are omitted. Briefly speaking about the sampling weather condition:

i) Sunny day, irradiance smoothly went up and down and cell temperature also drew same curve

ii) Cloudy day, because of the dotted cloudy weather, irradiance suddenly went down and up

iii) Rainy day, it was darkly cloudy and rainy and the average irradiance level was not over 0.2kW/m^2

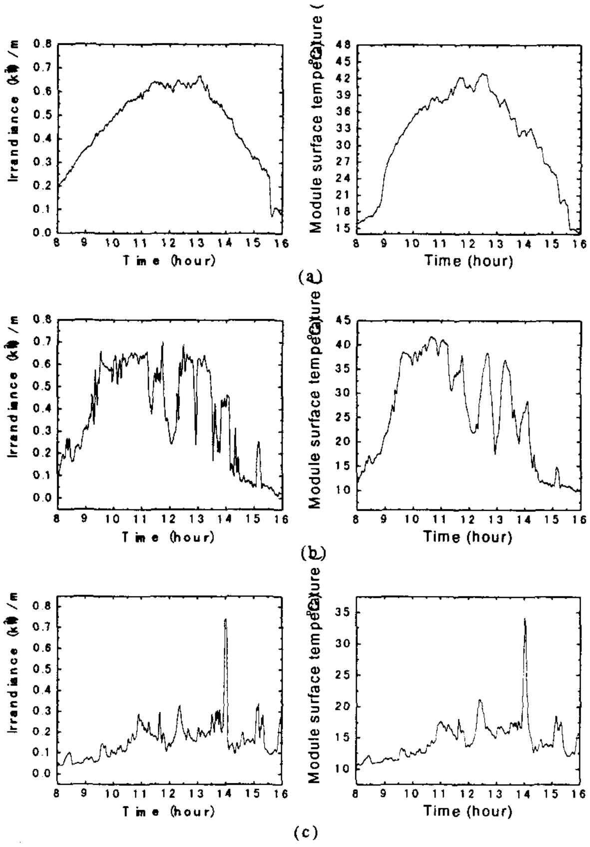

Fig. 6 Three kinds of real weather data, (a) Sunny day, (b) Cloudy day, (c) Rainy day

The analyzed PV power generation system is depicted in Fig. 7. Figure 8 shows the conceptual diagram of the analysis process. Irradiance and cell temperature data is classified to three patterns shown in Fig. 6 (a), (b), (c). In each weather pattern the measuring error of cell temperature is considered from +10℃ to 10℃ and it is separated to 21 patterns. And, the optimal voltage equation is reformed variously among Table 2. For example, if the optimal voltage equation is decided at 0.7kW/m^2 of irradiance, during the weather condition of Fig. 6 (a) the output power of PV array must be maximized at only 0.7kW/m^2 of irradiance. The most output power points would however be slightly estranged from the maximum points according to the irradiance dependency and the parasitic resistances; *Rs* and *Rsh*.

Figure 9 expresses the total conversion efficiency when the optimal voltage is obtained by only cell temperature. In Fig. 9 the horizontal axis is used in two senses; the temperature gaps *1)*between the measured temperature and the average *2)* between the feedbacked temperature and the practical temperature of measured spot. In case of the vertical axis, it stands for which irradiance level is used in the optimal voltage equation of Table 2. It means that the vertical axis symbolizes the affect of the irradiance dependency and the parasitic resistance. As results, the average power using the reference voltage MPPT control are described in Table. 3.

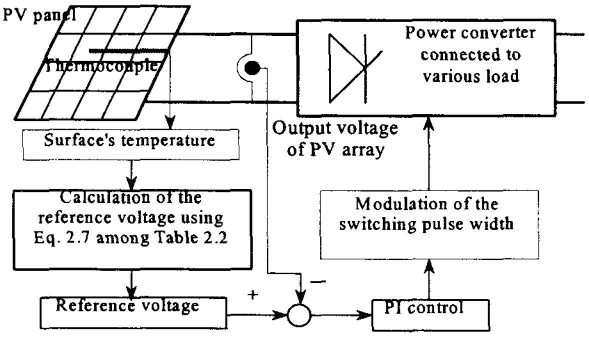

Fig. 7 MPPT control whose optimal voltage obtained by only solar cell temperature

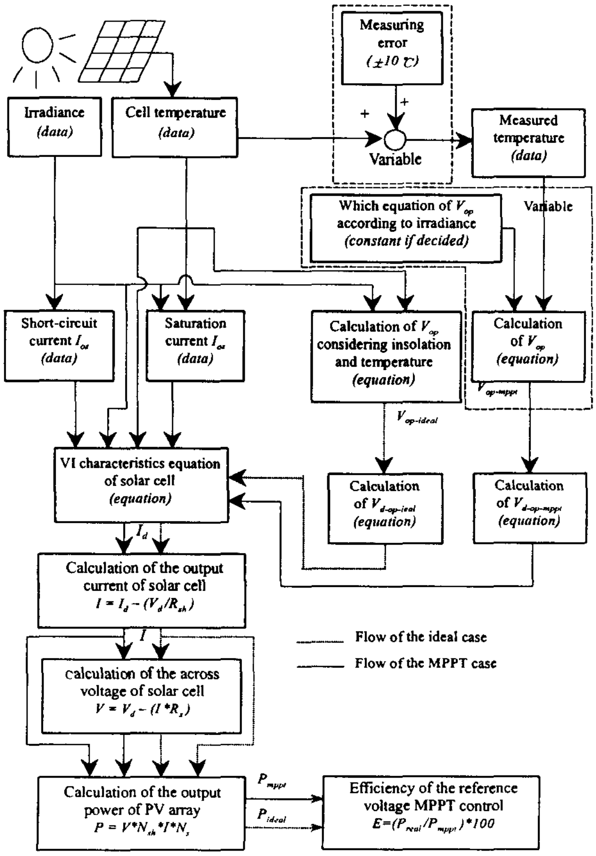

Fig. 8 Conceptual diagram of the analysis process

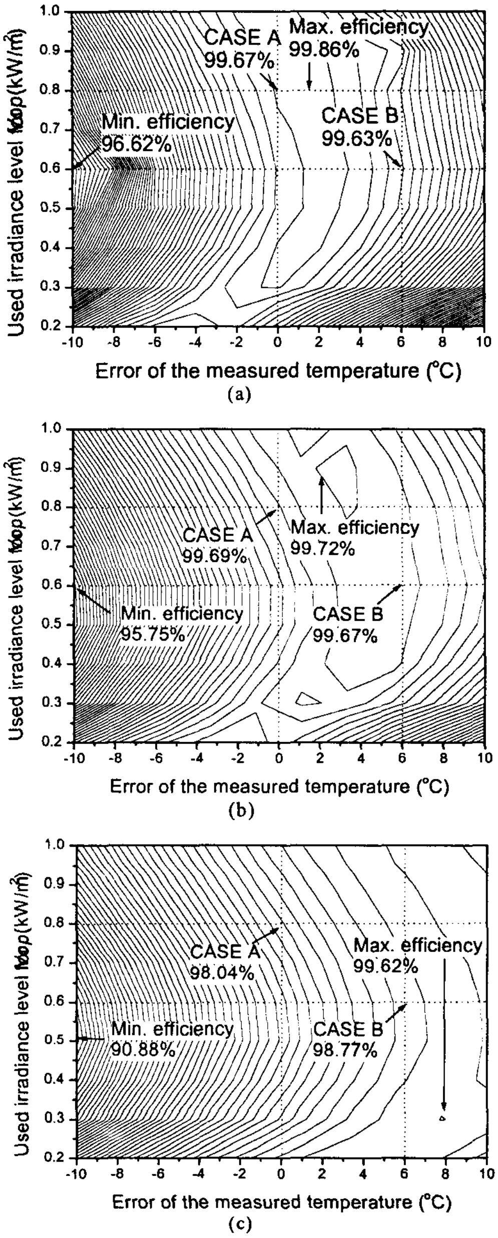

Fig. 9 Distribution charts of the conversion efficiency, (a) Sunny day, (b) Cloudy day, (c) Rainy day

Table 3 Average conversion efficiency

Factors / Examples	Temperature gap between the measured and the average	Error of the measured temperature	Used irradiance level for V_{op} equation
CASE A	0℃	0℃	0.8kW/m²
CASE B	+4℃	+2℃	0.6kW/m²
Weather	The obtainable max. ave. power	CASE A	CASE B
Sunny day	100%	99.67%	99.63%
Cloudy day	100%	99.69%	99.67%
Rainy day	100%	98.04%	98.77%

4. Conclusion

Considering the circumstances of PV power generation system apparatus, CASE B, whose temperature error is +6℃, is more reasonable case than CASE A; there is no temperature error, and must be a realistic case. Figure 9 and Table 3 indicate that the total conversion efficiency of the reference voltage control can be said to be over 98% at any cases which are among ±5℃ of temperature error and from 0.6 to 0.8 kW/m^2 of irradiance level of Table 2.

The sort of the solar cell experimented and analyzed is a multi-crystalline silicon PN junction cell that research cells approach 18-percent efficiency, and commercial modules approach 14-percent, which is the most generalized type in field. But, there are not only used crystalline silicon type but also Gallium-Arsenide type and so on, so the conversion efficiency of Fig. 9 and Table 3 must be reformed according to the sort of solar cell. The decisive factors, which effect the structure of Fig. 9, are the series parasitic resistance *Rs* and the saturation current *Ios*. Also, *Ios* is significantly influenced by *Eg*, *A*, and □. Among them, the larger series parasitic resistance *Rs* has worse effect upon the conversion efficiency when the optimal voltage obtained by only cell temperature. Generally, the *Loss Factor* of *Si* is worse than any others, and the *Rs* of *Si* is also much larger than others except *AlSb*. Because the *Si* cell was used here, the conversion efficiency must be over 98% regardless of which kind of cell is used.

The horizontally cut-section structure of Fig. 9 expresses the affect of temperature. It depends on the temperature coefficient of *Vop*, and it is -2.03mV/℃ in case of this experimented solar cell. And, the larger the temperature coefficient is, the worse the conversion efficiency is as much as the measuring error and temperature gap is wide. However, considering the sort of solar cell, the temperature coefficient is between -2.00mV/℃ and -2.50mV/℃. Therefore, it is not expected that the entire configuration form of Fig. 9 is changed.

Acknowledgements

This work has been supported in part by EESRI (02340-17), which is funded by MOCIE (Ministry of commerce, industry and energy), and in part by KEMCO (Korea Energy Management Cooperation)

References

[1] J.H.R. Enslin, "Maximum Power Point Tracking: A Cost Saving Necessity in Solar Energy Systems", Journal, Renewable Energy Vol.2, No. 6, pp.543-549, 1992

[2] T. Kawamura et al. "Analysis of MPPT Characteristics in Photovoltaic Power System", Journal, Solar Energy Materials and Solar Cells Vol.47 pp.155-165, 199

[3] I.H.Altas, A.M.Sharaf, "A novel on-line MPP search algorithm for PV arrays", IEEE Transactions on Energy Conversion, Vol.11, No.4, pp748-754, 1996

[4] C.Hua, J.Lin, C.Shen, "Implementation of a DSP-Controlled Photovoltaic System with Peak Power Tracking", IEEE Transactions on Industrial Electronics, Vol.45, No.1, pp99-107, 1998

[5] A.F.Boehringer, "Self-Adapting dc Converter for Solar Spacecraft Power Supply", IEEE Transactions on Aero-space & Electron. System, AES-4, 102, 1968

[6] T.Senjyu, K.Unezato, S.Okuma, "Maximum Power Point Tracking Control of Photovoltaic Array Using Fuzzy Control", T.IEE Japan, Vol. 114-D, No.9 pp.843-848, 1994

[7] Johan H.R. Enslin, MarioS. Wolf, Daniel B. Snyman, Wernher Swiegers, "Intergrated Photovoltaic Maximum Power Point Tracking Converter", IEEE Transactions on Industrial Electronics, Vol.44, No.6, pp769-773, 1997

[8] I.D.Van Wyk & J.J.Schoeman, "A Study of a Class of Low Loss Power Conditioners with Self-Adaptive, Maximising Power Controllers for Low Voltage Photo-voltaic Panel Arrays", Ipec-Tokyo 1983, p.1061, 1983

[9] H.Dong, H.Sugimoto, N.Nishio, "A Maximum Power Tracking Control Method for Photovoltaic Power Generation System Based on Derivation of Output Power with Respect to Output Voltage", T. IEE Japan, Vol.118-D, No.12, pp1435-1442, 1998

[10] Tsai-Fu Wu, Chien-Hsuan Chang, and Yu-Kai Chen, "A Fuzzy-Logic-Controlled Single-Stage Converter for PV-Powered Lighting System Applications", IEEE Transactions on Industrial Electronics, Vol.47, No.2, April 2000

[11] T.Hiyama, S.Kouzuma, T.Imakubo, T.H.Ortmeyer, "Evaluation of Neural Network Based Real Time Maximum power Tracking Controller for PV System", IEEE Transactions on Energy Conversion, Vol.10, No.3, pp543-548, 1995

[12] J.Chou, Y.Makino, Y.Hukuda, A.Danaka, E.Taniguchi, "A Stduy on the Constant Voltage Control of Photo-voltaic Generation", 1993 National Convention Record IEEJ, 588, pp5(161-162)

[13] Martin A. Green, "Solar Cells Operating Principles, Technology, and System Applications", 1982 by Prentice-Hall, Inc., Englewood Cliffs, N.J. 0763

저 자 소 개

Minwon Park was born in Masan, Korea in 1970 and received a bachelor degree in Electrical Engineering from Changwon National University in 1997 and a master degree and Ph. D in Electrical Engineering, Osaka University in 2000 and 2002 respectively. He is presently works at the Center for Applied Superconductivity Technology. He is currently works at Center for Applied Superconductivity Technology. His research mainly deals with the dispersed generation system and the control theory of it. And, he is also interested in the high-frequency AC link DC-AC converter and the development of the simulation model of power conversion equipment and renewable energy source using EMTP type simulators.

Tel : 055-280-1043

E-mail : paku@keri.re.kr

In-Keun Yu was born in Seoul, Korea in 1954. He received the B.S. degree in electrical engineering from Dongguk University in 1981 and the M.S. and Ph.D. degrees in electrical engineering from Hanyang University in 1983 and 1986, respectively. Currently, he is a Full Professor at Changwon National University, where he has been since 1988. From 1985 to 1988, he was with the Korea Electrotechnology Research Institute. From 1996 to 1998, he was a visiting scholar at Brunel University, Middlesex, UK. Also he was a Postdoctoral fellow at the Energy Systems Research Center (ESRC) at the University of Texas at Arlington from 1990 to 1992. His interests include wavelet transform applications, electric energy storage and control systems, peak load management & energy saving systems, PSCAD/ EMTDC and RTDS simulation studies, and renewable energy sources.

Tel : 055-279-7512

E-mail : yuik@sarim.changwon.ac.kr