Development of a New Maximum Power Point Tracking Method for Power Conversion Efficiency Measurement of Metastable Perovskite Solar Cells

Hidenori SAIITO,* Daisuke AOKI, Tomoyuki TOBE, and Shinichi MAGAINO

Kanagawa Institute of Industrial Science and Technology (KISTEC), 3-2-1 Sakado, Takatsu, Kawasaki, Kanagawa 213-0012, Japan

* Corresponding author: saito@newkast.or.jp

ABSTRACT

A new algorithm for the maximum power point tracking (MPPT) method has been developed in order to determine the maximum power \( P_{\text{max}} \) for slow-responding metastable PV devices such as perovskite solar cells (PSCs). It is well known that such devices often cause significant \( P_{\text{max}} \) oscillation during a standard MPPT measurement. This oscillation was found to occur caused by difference in the current acquired after increasing the voltage and that acquired after decreasing the voltage. The new algorithm developed in this paper has eliminated such oscillation with comparison between the powers at different voltages after changing the voltage in the same direction. \( P_{\text{max}} \) data determined by using this algorithm were found to be reliable by comparing with those determined by the dynamic \( I-V \) measurements.

© The Author(s) 2020. Published by ECSJ. This is an open access article distributed under the terms of the Creative Commons Attribution 4.0 License (CC BY, http://creativecommons.org/licenses/by/4.0/), which permits unrestricted reuse of the work in any medium provided the original work is properly cited. [DOI: 10.5796/electrochemistry.20-00022]. Uploading “PDF file created by publishers” to institutional repositories or public websites is not permitted by the copyright license agreement.

Keywords: Perovskite Solar Cell, Maximum Power, MPPT, Oscillation

1. Introduction

Over the past ten years, perovskite solar cells (PSCs) have shown a rapid advance in the power conversion efficiency (PCE). PCE which was 3.8% for the first cell reported in 2009\(^1\) has improved rapidly to the highest reported values of over 21%.\(^2\) However, there are considerable difficulties in reliable measurements of PCE for PSCs that is a serious concern for fair and accurate tracking of advancement in PSC technologies. These considerable difficulties are thought to result from slow current response to the applied voltage and change in electrical properties with light irradiation.\(^3\)-\(^12\) The slow current response generally appears as the hysteresis in the current–voltage curves \((I-V)\) curves. When the hysteresis comes from simple capacitance effect and electrical properties do not change during the \( I-V \) measurements, as is the case for most crystalline silicon PV devices, the hysteresis disappears with decreasing the voltage sweep rate. However, in the case of most PSCs, the hysteresis does not disappear even when the voltage sweep rate is extremely decreased. This phenomenon may be related to change in electrical properties caused by light irradiation during the \( I-V \) curve measurements. Change in electrical properties is not so large for state-of-the-art PSCs, for example, it has been reported that 10–15% decrease was observed after five hours of the operation at the maximum power point, and the initial efficiency was fully recovered when leaving the device in the dark.\(^11\) We call such characteristic of PSCs as “metastable” in this paper.

Although 10–15% decrease in the conversion efficiency in the daytime may not prevent commercialization of the photovoltaic devices if this decrease is fully recovered in the nighttime, this change may prevent fair and accurate measurements of PCE by the use of the standard measurement procedures defined in IEC 60904-1.\(^13\) In this paper applications of the maximum power point tracking (MPPT) method has been investigated for metastable PSCs to measure steady-state maximum power \( P_{\text{max}} \) while change in electrical properties are negligible. The MPPT method is originally the method for outdoor operation of PV systems, and a number of tracking algorithms are available.\(^14\) However, it has been reported that a direct application of those tracking algorithm to the hysteric PSC often causes significant \( P_{\text{max}} \) oscillations.\(^15\) In this paper we have developed a new tracking algorithm that can prevent \( P_{\text{max}} \) oscillation, and \( P_{\text{max}} \) determined by using this algorithm was compared to that determined by the dynamic \( I-V \) method\(^16\) in order to examine reliability.

2. Standard MPPT Method

Figure 1 shows a flow chart for a typical standard MPPT method called ‘perturb and observe’ algorithm. In this figure, \( V(k), V(k+1), I(k), I(k+1), P(k), \) and \( \Delta V \) represent the data number, the voltage, the current, the power, and the amount of step-like voltage change, respectively. First, \( V(1) \) is set to an initial value, which can be set arbitrarily, but \( P_{\text{max}} \) can be determined quickly when the value is set around the voltage at the maximum power point \( V_{\text{mpp}} \), then \( P(1) \) is calculated by multiplying \( V(1) \) and \( I(1) \) measured. At the first measurement, \( V(k+1) \) is set to \( V(k)+\Delta V \) directly, then \( k \) is incremented by 1 and the voltage and current are measured. If \( P(k) \) calculated from these values is greater than the previously recorded one, direction of volt change is set same to the previous setting. If \( P(k) \) is not greater than the previously recorded one, direction of volt change is set opposite to the previous direction. Then, \( k \) is incremented by 1, the voltage was set, and the measurement was repeated in a similar manner as above.

Two different types of PSCs were supplied by SEKISUI CHEMICAL CO., LTD. Cell structures are: Glass/FTO/TiO₂/MAPbI₃/Spiro-OMeTAD/MoO₃/Metal electrode (PSC 1) and Aluminax substrate/Insulating layer/Metal electrode/TiO₂/MAPbI₃/Spiro-OMeTAD/ITO (PSC 2). Edges of the cells were sealed with an adhesive to prevent degradation due to moisture and oxygen in the atmosphere, and masked with a low-reflective metal aperture which was used to define the active area as 0.1 cm². 4-wire electrical connections were used to eliminate voltage drop originating from resistances of lead wires.

First, \( I-V \) curves were measured according to the conventional procedure defined in IEC 60904-1. The \( I-V \) curves measurements
were performed at STC (AM 1.5 G, 1 kW m⁻², 25°C) by using a source meter (ADC Corp. type 6246), a solar simulator (Yamashita Denso YSS-T150A), a thermostatic chamber and a Peltier cooling unit. The bias voltage was swept from −0.1 V to −1.1 V, then from 1.1 V to −0.1 V, importing 201 points data for one direction sweep. The start delay time, the acquisition delay time and the integration time were set to 5 s, 480 ms and 20 ms, respectively, in order to stabilize the current after voltage setting. I-V curves determined for PSC 1 and PSC 2 are shown in Fig. 2. The I-V curves showed hysteresis, and the hysteresis of PSC 2 was larger than that of PSC 1.

Figure 1. Flow chart for a typical standard MPPT method called ‘perturb and observe’ algorithm.

were performed at STC (AM 1.5 G, 1 kW m⁻², 25°C) by using a source meter (ADC Corp. type 6246), a solar simulator (Yamashita Denso YSS-T150A), a thermostatic chamber and a Peltier cooling unit. The bias voltage was swept from −0.1 V to −1.1 V, then from 1.1 V to −0.1 V, importing 201 points data for one direction sweep. The start delay time, the acquisition delay time and the integration time were set to 5 s, 480 ms and 20 ms, respectively, in order to stabilize the current after voltage setting. I-V curves determined for PSC 1 and PSC 2 are shown in Fig. 2. The I-V curves showed hysteresis, and the hysteresis of PSC 2 was larger than that of PSC 1.

Figure 1. Flow chart for a typical standard MPPT method called ‘perturb and observe’ algorithm.

Forward sweep (1st) Reverse sweep (2nd)
Start delay time 5000 ms Delay time 480 ms Integration time 20 ms Data points 201

Figure 2. Examples of hysteresis observed in I-V curves of (a) PSC 1 and (b) PSC 2.

Forward sweep (1st) Reverse sweep (2nd)
Start delay time 5000 ms Delay time 480 ms Integration time 20 ms Data points 201

3. Cause of Oscillation

Figure 4 shows transient currents after applying the step-like voltage changes determined for (a) the c-Si cell and (b) PSC 2. The currents of the c-Si cell attained steady-state values immediately after applying the step-like voltage changes and difference in the current with the direction of the voltage change was not observed as shown in Fig. 4(a). In the case of PSC 2, sharp current decrease followed by slow increase toward steady-state was observed in response to the step-like voltage increase, and on the contrary, sharp current increase followed by slow decrease toward steady-state was observed in response to the step-like voltage decrease. The results show the power determined after decreasing the voltage is greater than that determined after increasing the voltage at the same voltage before steady-state. Figure 5 shows schematic diagram of current change during the MPPT measurement. In Fig. 5 a solid line, a dotted line, and a chain line represent I-V curves corresponding to forward, reverse, and steady-state, respectively. When the voltage is increased from the value at point S to the value at point A, the current first decreases to the value at A, then increases toward the value at point A'. When the voltage is decreased from the value at point S to the value at point B, the current first increases to the value at B, then decreases toward the value at point B'. When these current changes are very slow and the current data are acquired before steady-state, the tracking program may misjudge that the power increases with decreasing voltage, whereas the steady-state power decreases. Thus, the voltage may continue moving in the negative direction until the program finds that the power decreases with decreasing the voltage, then the hill climbing starts. The voltage starts decreasing again after reaching the summit of the hill. Thus, oscillation of the voltage and the power may occur.

4. New Tracking Algorithm to Prevent Oscillation

Figure 6 shows a flow chart of a tracking algorithm developed in this paper to prevent the oscillation of the voltage and the power. Routine A surrounded by a dotted line represents a procedure for getting the quasi steady-state power as the first step to prevent the oscillation. However, introducing this procedure may not be enough to prevent the oscillation for cells having large hysteresis because complete steady-state is difficult to attain. As described above, the oscillation is caused by difference between the currents determined after increase and decrease of the voltage. So, the oscillation may not occur when comparison between the powers at different voltages after changing the voltage in the same direction. Routine B surrounded by a chain line represents this procedure. When the
voltage needs to be decreased $\Delta V$ to compare the power, the voltage is decreased $2 \cdot \Delta V$ first, then is increased $\Delta V$ after stabilization, and the power is compared with the previous value determined after increasing the voltage. Figure 7 represents changes in the voltage and the power obtained for PSC 1 by using this algorithm. Only the power data shown surrounded by circles were sampled and used for MPPT. A similar algorithm but using the power data only after decreasing the voltage was also developed.

Changes in $P_{\text{max}}$ with the irradiation time determined for (a) a c-Si cell, (b) PSC 1, and (c) PSC 2 determined by the standard MPPT method.

Figure 3. Changes in $P_{\text{max}}$ with the irradiation time determined for (a) a c-Si cell, (b) PSC 1, and (c) PSC 2 determined by the standard MPPT method.

5. Reliability of Results

Reliability of the MPPT method developed in this paper was examined by comparing the $P_{\text{max}}$ data with that obtained by the dynamic $I$-$V$ method. The dynamic $I$-$V$ method is a kind of steady-state method for the $I$-$V$ curve measurement, which can be used when the standard method for the $I$-$V$ curve measurement defined in IEC 60904-1 is difficult to be applied. In the case of the dynamic $I$-$V$ method, the wait time at each step in the applied voltage is not fixed, but is allowed to vary in order to achieve a pre-determined degree of stability in the measured current, whereas the wait time is fixed for the standard $I$-$V$ curve measurement. The dynamic $I$-$V$ method is thought to be one of the best methods for the steady-state $I$-$V$ curve measurement.
measurement if change in electrical performance of a PV device is negligible during a measurement.

Figure 9 shows $I-V$ curves determined for PSC 1 and PSC 2 by the dynamic $I-V$ method at STC. In Fig. 9 a solid line curve and a dotted line curve represent forward and reverse sweeps, respectively. The experimental apparatus was same to that used for MPPT measurements, and a measurement software was made by ourselves. The voltage was changed to the next value after the rate of current change became less than 0.01% per 10 seconds, which is same to the value employed by the MPPT method described before. Hysteresis of the $I-V$ curves determined by using this method were much less than that determined by using the conventional method shown in Fig. 2. $P_{\text{max}}$ determined by the MPPT method and by the dynamic $I-V$ method are shown in Table 1 for comparison. In Table 1 $P_{\text{max}}$ determined by the MPPT method is average of $P_{\text{max}}$s obtained by using two algorithms, and $P_{\text{max}}$ determined by the dynamic $I-V$ method is average of $P_{\text{max}}$s obtained by forward and reverse sweeps. As shown in Table 1, discrepancy between $P_{\text{max}}$ results determined by the MPPT method and the dynamic $I-V$ method was 0.7% for PSC 1 and 1.4% for PSC 2, and both the results may approve the reliability of the MPPT algorithm developed in this paper.

Figure 10 shows change in $P_{\text{max}}$ with the irradiation time at STC determined by using the power data only after increasing the voltage for a standard mesoporous PSC whose active area was 1 cm$^2$ supplied by a company different from the supplier of PSC 1 and PSC 2. In this case, discrepancy between $P_{\text{max}}$ results determined by the MPPT method and the dynamic $I-V$ method was 2.4%.

6. Discussion

Can we measure PCE of metastable PV devices such as PSCs? It may be a common sense that a parameter to be measured should be unchanged during the measurement, in other words, the measurement should be performed at the steady-state. In this sense, PCE of a metastable PV device can be measured when the steady-state is kept at least during the measurement period. It may be clear that a full $I-V$
The method is an average of the method developed in this paper and by the dynamic method. By using two algorithms, and when the rate of current change with time became less than a certain value, the procedure is repeated with changing the input voltage. The voltage is measured continuously until stabilization occurs. This method is called the dynamic I-V (Stabilized) method, also called as the Steady-state (or Stabilized) power output (SPO), also called as the maximum power voltage (SCFV), and (3) Dynamic (or Stabilized) I-V methods. These methods may be classified into following three methods: (1) Maximum power point tracking (MPPT), (2) Steady-state (or Stabilized) power output (SPO), also called as Stabilized current at fixed voltage (SCFV), and (3) Dynamic (or Stabilized) I-V methods. In the SPO method, current at a fixed voltage until the maximum power is found. In this paper we have decided that stabilization occurred when the rate of current change with time became less than the defined value for the MPPT and the dynamic I-V measurements. Three methods described above may be same in principle if decision of stabilization in the SPO method is performed in the same manner. Difference in three methods is only the manner for setting a voltage. In general, the voltage change is performed manually for SPO, but automatically by using a computer program for MPPT and dynamic I-V. If SPO is automated, remaining difference may be just an order of voltage change.

Although three methods for \( P_{\text{max}} \) determination is same in principle and may offer almost same results, we recommend the MPPT method free from oscillation for slow-responding metastable devices because a continuous MPPT measurement provides not only \( P_{\text{max}} \) but also important information for steady-state. Further, total measurement period for the MPPT method may be less than that for the SPO and the dynamic I-V methods because experiments to estimate the maximum power voltage is not necessary.

### 7. Conclusion

A new MPPT method to determine \( P_{\text{max}} \) for slow-responding metastable PV devices such as PSCs has been developed. Such devices often show large hysteresis in I-V curve measurements, and cause significant \( P_{\text{max}} \) oscillation during a standard MPPT measurement. This oscillation was found to occur caused by difference in the current acquired after increasing the voltage and that acquired after decreasing the voltage. The new algorithm developed in this paper has eliminated such oscillation with comparison between the powers at different voltages after changing the voltage in the same direction. \( P_{\text{max}} \) data determined by this algorithm were found to be reliable by comparing with those determined by the dynamic I-V measurements.

### Acknowledgments

This work was supported by Industrial Technology Development Organization (NEDO) and Ministry of Economy, Trade and Industry (METI) of Japan. Authors wish to thank SEKISUI CHEMICAL CO., LTD for supplying PSC cells.

### References

1. A. Kojima, K. Teshima, Y. Shirai, and T. Miyasaka, *J. Am. Chem. Soc.*, **131**, 6050 (2009).
2. M. A. Green, E. D. Dunlop, J. Hohl-Ebinger, M. Yoshita, N. Kopidakis, and A. W. Y. Ho-Baillie, *Prog. Photovolt. Res. Appl.*, **28**, 3 (2020).
3. E. L. Unger, E. T. Hoke, C. D. Bailie, W. H. Nguyen, A. R. Bowring, T.
Heumüller, M. G. Christoforo, and M. D. McGehee, *Energy Environ. Sci.*, 7, 3690 (2014).

4. H. J. Snaith, A. Abate, J. M. Ball, G. E. Eperon, T. Leijtens, N. K. Noel, S. D. Stranks, J. T.-W. Wang, K. Wojciechowski, and W. Zhang, *J. Phys. Chem. Lett.*, 5, 1511 (2014).

5. J. A. Christians, J. S. Manser, and P. V. Kamat, *J. Phys. Chem. Lett.*, 6, 852 (2015).

6. E. Zimmermann, K. K. Wong, M. Müller, H. Hu, P. Ehrenreich, M. Kohlstäd, U. Würfle, S. Mastroianni, G. Mathiazhagan, A. Hinsch, T. P. Gujar, M. Thelakkat, T. Pfadler, and L. Schmidt-Mende, *APL Mater.*, 4, 091901 (2016).

7. W. Nie, J.-C. Blancou, A. J. Neukirch, K. Appavoo, H. Tsai, M. Chhowalla, M. A. Alam, M. Y. Srir, C. Katan, J. Even, S. Tretiak, J. J. Crochet, G. Gupta, and A. D. Mohite, *Nat. Commun.*, 7, 11574 (2016).

8. Y. Hishikawa, H. Shimura, T. Ueda, A. Sasaki, and Y. Ishii, *Curr. Appl. Phys.*, 16, 898 (2016).

9. L. Contreras, J. Idigoras, A. Todinova, M. Salado, S. Kazim, S. Ahmad, and J. A. Anta, *Phys. Chem. Chem. Phys.*, 18, 31033 (2016).

10. R. B. Dunbar, B. C. Dack, T. Moriarty, K. F. Anderson, N. W. Duffy, C. J. Fell, J. Kim, A. Ho-Baillie, D. Vak, T. Duong, Y. Wu, K. Weber, A. Pascoe, Y.-B. Cheng, Q. Lin, P. L. Burn, R. Bhattacharjee, H. Wang, and G. J. Wilson, *J. Mater. Chem. A*, 5, 22542 (2017).

11. K. Domanski, B. Roose, T. Matsu, M. Saliba, S.-H. Turren-Cruz, J.-P. Correa-Baena, C. R. Carmona, G. Richardson, J. M. Foster, F. De Angelis, J. M. Ball, A. Petrozza, N. Mine, M. K. Nazeeruddin, W. Tress, M. Grätzel, U. Steiner, A. Hagfeldt, and A. Abate, *Energy Environ. Sci.*, 10, 604 (2017).

12. G. A. Nemnes, C. Besleaga, A. G. Tomulescu, A. Palici, L. Pintilie, A. Manolesce, and I. Pintilie, *Sol. Energy*, 173, 976 (2018).

13. IEC 60904-1, Measurement of photovoltaic current-voltage characteristics, 2nd edition: 2006-09.

14. T. Esram and P. L. Chapman, *IEEE Trans. Energ. Convers.*, 22, 439 (2007).

15. N. Pellet, F. Giordano, M. I. Dar, G. Gregori, S. M. Zakeeruddin, J. Maier, and M. Grätzel, *Prog. Photovolt. Res. Appl.*, 25, 942 (2017).

16. C. Monokrousos, D. Etienne, K. Morita, C. Dreier, U. Therhaag, and W. Herrmann, *Proceedings of the 27th EUPVSEC*, 3687–3692 (2012).