I-V Performance Characterisation of Perovskite Solar Cells

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Abstract

Interlaboratory comparisons of I-V performance measurements of perovskite solar cells have highlighted a clear need for development in application of measurement routines to deliver repeatable and comparable results. This work investigates the impact of applied measurement methodologies and conditions on I-V performance. Dependencies on light soaking, temperature effects and I-V curve trace speed are investigated. Furthermore, the problems faced with tracking the maximum power point are detailed. Measurement results on slow responding perovskite solar cells highlight the problems when tracing the I-V curve and show that maximum power point trackers can easily fail to track the real maximum output. Best practice advice is given with the aim to achieve realistic and reproducible characterisation results that are comparable among laboratories.

1 Introduction

For perovskite solar cells, accurate I-V performance characterisation can be a major challenge. Un-accredited R&D laboratories in an inter-laboratory measurement comparison showed a ~35% standard deviation in reported efficiency of slow responding perovskite samples compared to ~3.7% of silicon solar cells [1]. Although comparability was much better on fast responding devices, generally the device performance between laboratories is difficult to compare. This ultimately can result in following the wrong path in device development. The main cause of measurement problems with perovskite solar cells is the metastability in device performance dependent on voltage load and incident irradiance. This causes a hysteresis between Current-Voltage (I-V) curves measured in forwards and reverse direction, which can result substantial over- or under-estimation of device performance when ignored or not appropriately dealt with. Thus, it leads to misleading results when comparing samples and shows that there is a strong need for development to deliver repeatable and comparable results for all perovskite solar cell architectures.

Vital methodologies for I-V measurement of perovskite devices have been developed [1-4]. This work investigates the impact of the I-V performance on the applied method and conditions. Effects of light soaking, temperature and I-V curve trace speed on performance are investigated. Furthermore, the problems faced with tracking the maximum power point (P_{MPP}) are detailed. Factors that need close attention when measuring samples are described and a guide to best practice is given with the aim to achieve realistic and reproducible characterisation results that are comparable among laboratories.

Measurements are carried out on a slow responding perovskite device type. This type of device highlights best the measurement problems exhibited. The test samples are of a triple mesoscopic structure [5] and exhibit strong metastable effects with hysteresis in I-V curve measurements.

2 Light soaking and soaking load

Because perovskite solar cells show metastable effects dependent on voltage and irradiance history devices are preconditioned before I-V measurements, during which the performance of devices in general improves significantly. Figure 1 shows the effect of preconditioning at various loads on I-V curve measurements. The top graph details the recorded current/voltage during preconditioning. In both cases a peak value is recoded. The I-V curves have been measured at peak value and after 20 min preconditioning (bottom graph of Figure 1). The device type tested here shows the highest performance after 20 min of preconditioning at V_{OC} load and not at the peak V_{OC} measured after ~3 min of preconditioning. This suggests that preconditioning should be carried out at V_{OC} until the device has stabilized rather than at peak.

Preconditioning is usually carried out under light at V_{OC} load. In some cases, higher voltages are used to speed up the preconditioning process and to achieve the best possible I-V curve with highest efficiency. While this makes the device look at its best, this can lead to an over/underestimation of the performance in steady state at maximum power point. Hence, the investigation remains as to if conditioning at V_{OC} is optimal, because at outdoor conditions devices are at or near maximum power point (P_{MPP}) operation.

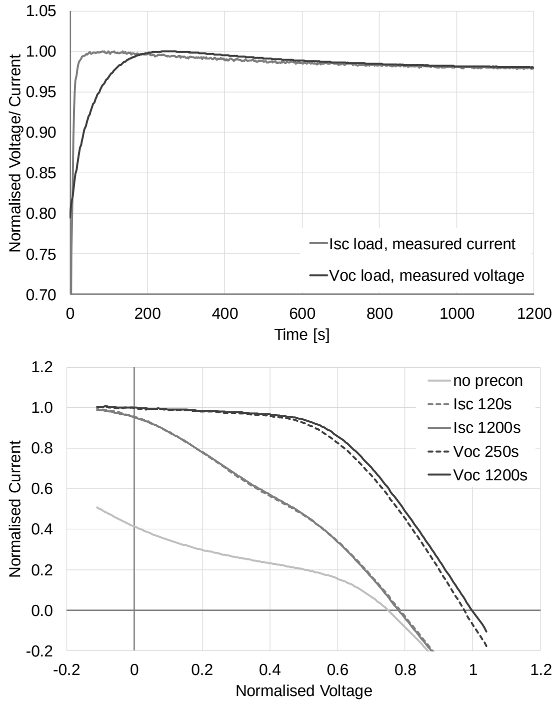

Figure 1: (Top) Measured current/voltage during preconditioning at I_{SC}/V_{OC}; (Bot) I-V curves measured directly after preconditioning

3 IV measurement speed

The trace speed of the I-V curve has a large effect on performance measurements. The response can vary significantly between different perovskite device architectures, different production batches, with aging and preconditioning state. Perovskite devices with slow responding metastable effects are most difficult to measure accurately due to the long-time response constants and the resulting increased measurement time that can also cause degradation.

To get a true representation of the performance at steady state, the I-V curve should be traced slow enough to not detect hysteresis between forward (from I_{SC} to V_{OC}) and reverse direction I-V measurements. This statement can be somewhat misleading, as shown for the tested device type (top of Figure 2), which shows very little hysteresis during fast measurements and an increase in hysteresis with reduced I-V trace speed. This is due to the devices' "delayed" metastable response (i.e. the I-V is traced faster than the device responds to the change in operating conditions). At very low trace speeds (bottom of Figure 2) the hysteresis reduces again because the sample is given more time to stabilise. Nevertheless, due to the slow response of the DUT even at more than 1 h trace time per I-V direction a hysteresis is remaining.

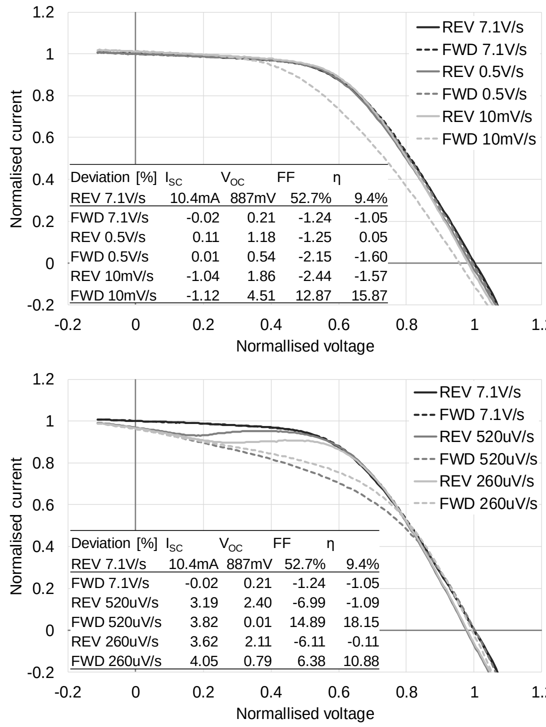

Figure 2: I-V curves at varying trace speed; FWD is in direction from I_{SC} to V_{OC}; different tracing speeds are achieved by adjusting the delay, 200 points per I-V curve are used.

In the presented I-V curves of Figure 2 the I-V curve was measured first in reverse and then in forward direction to reduce the step size from preconditioning at V_{OC}. However, with the aim of measuring a steady state I-V at slow trace speeds this should not affect results immensely.

4 IV-point tracing

Because slow I-V measurements are undesirable and can cause degradation in unstable samples, I-V point tracking is used to get faster to a better understanding of the steady state performance of the most critical I-V parameters: I_{SC}, V_{OC} and P_{MPP}.

When tracking the I_{SC}, the source unit is kept in voltage mode at 0 V. During V_{OC} tracking the source unit is controlled in current more at 0 A or kept at open circuit with only voltage probes connected. Tracing the I_{SC} and V_{OC} is by no means problematic and leads to the same results as presented in Figure 1.

To verify the maximum power output at STC most commonly the P_{MPP} point is actively tracked using maximum power point tracker (MPPT). Static voltage tracking at the V_{MPP} point of I-V curve measurement has also been applied but is not recommended because V_{MPP} can vary significantly between I-V curves at different sweep times (see Figure 2) and thus may not accurately represent steady state which results in underestimating P_{MPP}.

A commonly used MPPT algorithm is the perturb-and-observe (P&O) method due to its simplicity. The MPPT timing and step size needs to be appropriate for the response of the DUT for accurate tracking of P_{MPP}. Incorrect settings can cause the MPPT to fail tracking P_{MPP} as shown in Figure 3. Static or manual tracking at for example V_{MPP} obtained from I-V measurements can be used to verify the MPPT accuracy, which is clearly not the for the cases shown in Figure 3.

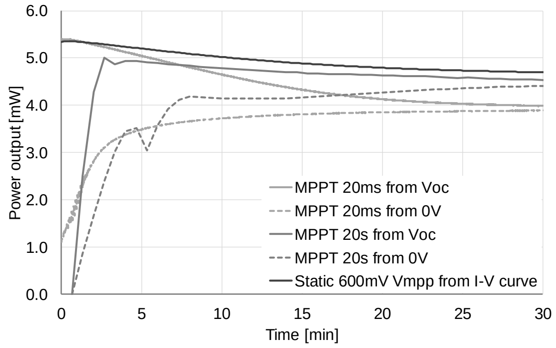

Figure 3: MPPT tracking results different setting times compared to static voltage tracking; even at 20 s setting time of the P&O MPPT fails to keep tracking true P_{MPP}.

The failure in tracking P_{MPP} is caused by the slow time constants of the metastable processes. This time constant is voltage dependent as becomes apparent from the I-V curve measurements shown in Figure 2, where in the region of the actual P_{MPP} the hysteresis remains even at extremely slow measurement rates. During MPPT the initial response of the DUT stepping the voltage towards V_{MPP} can be a reduction in power output, however the slope in power output increases, leading eventually to an increased power output. Vice-versa, when stepping away from V_{MPP} the immediate response from the device can be an increase in power output, but the slope reduces leading to a reduced power output over time.

To improve the tracking accuracy and reliability a modified P&O can be used that adjusts the timing dependent on the slope of the recorded output. In other words, the voltage level is not changed until the slope has reached a small maximum rate of change at which it is assumed the device has reached steady state. A downside of this approach is that it can take a long time until the MPPT has found the true P_{MPP}. To overcome this issue one can employ a predictive MPPT algorithm such as that detailed in [6], in which the algorithm fits an exponential decay function to the recorded response of the DUT and predicts the static power output. A predictive algorithm can therefore reach the actual P_{MPP} much faster. However, as with conventional MPPT methods unoptimised settings can again lead to inaccurate P_{MPP} tracking as shown in Figure 4.

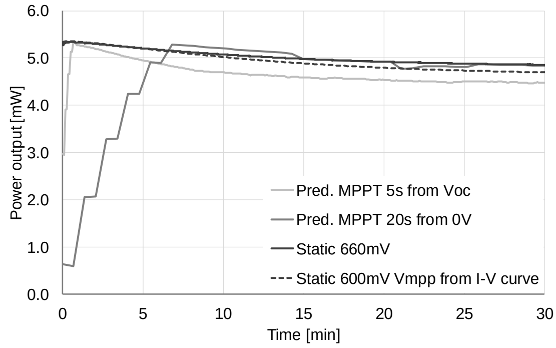

Figure 4: MPPT tracking results using a predictive P&O method with threshold in predicted value.

The predictive MPPT method used for the graphs in Figure 4 is based on descriptions in [6]. It uses a single order decay function for better fitting stability and a threshold value for the tolerance of the predicted value. In other words, the voltage is only adjusted if the old and new predicted values are within tolerance. Thus, the stepping time is variable. Results show an improvement in MPPT tracking (see also Table 1) but also show room for optimisation, which could not be done as part of this work.

Table 1: Power output after 30min tracking using different methods and timings

Method	P [mW]	Difference
MPPT 20ms from V_{OC}	3.99	-17.7%
MPPT 20ms from 0V	3.91	-19.2%
MPPT 20s from V_{OC}	4.35	-10.3%
MPPT 20s from 0V	4.53	-6.6%
Pred. MPPT 5s from V_{OC}	4.47	-7.7%
Pred. MPPT 20s from 0V	4.84	0.0%
Static 660mV	4.81	-0.7%
Static 600mV V_{MPP} of I-V	4.63	-4.3%

Because failed P_{MPP} tracking is not immediately obvious it is recommended to verify the results with manual tracking using V_{MPP} of the I-V curve as a start point. This should be done with every new sample type or better yet with every processed batch. The best start condition for P_{MPP} tracking is after precondition under light at V_{MPP} of an initial I-V trace. In tests carried out as part of this work, this has led to faster P_{MPP} determination.

Apart from reaching P_{MPP} accurately, the question remains as to which value is finally reported. Often MPPT is carried out for a minute to a few minutes and the final or average value is reported without consideration if a static condition has been reached. In this work a 30 min tracking time was selected arbitrarily at which point the device had not reached its final steady state. It is also important to consider here that a device may degrade significantly during MPPT, which is clearly undesirable. The device type tested here did not show significant degradation during tests and losses in performance were completely reversible.

5 Temperature Control

Temperature control at 25 °C was used throughout this work. In general the temperature coefficient of perovskite devices is negative above 25 °C [7]. Long MPPT and I-V measurements can thus be negatively affected when no means of temperature control is applied. Although not ideal, if no control system is available, simple fan cooling can improve accuracy. On the device type tested throughout this work it was observed that power output was reduced by ~2% and the metastable effects stabilized over a shorter time. Using a fan only (ambient air ~21 °C) lead to a negligible change in stabilized power output.

6 Discussion

To achieve best accuracy and comparability performance measurements of perovskite devices need to be made at steady state conditions when the DUT has fully stabilized and metastable processes are complete. This is achieved by either measuring the I-V curve using a slow enough measurement speed in forward and reverse direction to not cause hysteresis, or by tracking the main I-V curve parameters I_{SC}, V_{OC} and P_{MPP}. Best practice is to carefully measure the I-V curve before and after tracking the I-V parameters. The I-V curves acquired can also be used to estimate or even correct for degradation of the sample although this option has not been investigated as part of this work.

One problem with measuring at steady state is that it takes a long time especially for slow responding devices and thus limits the throughput when measuring a batch of samples. If highest accuracy is not essential, measuring the I-V curves at reasonable trace speed is acceptable. To get a better indication of the performance at steady state at least some samples of a batch should also be measured using parameter tracking. The results at steady state of a small set of samples indicates the general trend. This can be related to the batch using the measured I-V curves as an indicator.

7 Conclusion and future work

The impact of method and configuration on I-V performance measurements of a slow responding perovskite solar cell type was investigated here. This has highlighted the range of measurement problems generally found with such perovskite solar cells. Measuring the steady-state I-V curve was impractical due to the very long time constant of the metastable effects, which also made tracking the maximum power point particularly difficult with a conventional tracking algorithm. Tests using a better suited predictive tracking algorithm showed improvements but are still in need of optimisation. This will be carried out as part of future work.

The remaining question to be answered relates to the definition of stabilized performance and how to report maximum power and efficiency.

The measurement problems and solutions highlighted here should lead to better reproducibility of measurements and to lower uncertainty. This has a positive impact on measurement comparability and gives better indicators of which development path to follow.

Acknowledgements

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