Indonesian Journal of Electrical Engineering and Computer Science
Vol. 13, No. 3, March 2019, pp. 1022~1030
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v13.i3.pp1022-1030

Internet of things (IoT) based i-v curve tracer for photovoltaic monitoring systems

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Article Info

Article history:

Received Sep 21, 2018
Revised Dec 10, 2018
Accepted Dec 22, 2018

Keywords:

DC-DC converter
Internet of things
I-V curve tracer
Photovoltaic systems

ABSTRACT

This paper presents a low-cost PV current-voltage or I-V curve tracer that has the Internet of Things (IoT) capability. Single ended primary inductance converter (SEPIC) is used to develop the I-V tracer, which is able to cope with rapidly changing irradiation conditions. The I-V tracer control software also has the ability to automatically adapt to the varying irradiation conditions. The performance of the I-V curve tracer is evaluated and verified using simulation and experimental tests.

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1. INTRODUCTION

The widespread and rapid development and integration of photovoltaic (PV) systems have created the dire need for precise and accurate methods to calculate and measure the health, degradation, and performance of PV modules. While the current monitoring methods provide a good indication of these attributes, they are incapable of presenting the necessary information to accurately determine these attributes. The current-voltage (I-V) curve of a PV module can provide this information, making it a far superior approach to the currently employed monitoring methods. However, the tools and methodology required to extract the I-V curve are highly invasive and undesirable. In order to derive the I-V curve, the PV module has to be disconnected from its load and connected to a tool. The I-V tracers monitor several characteristics of a PV module including short circuit current (Isc), open circuit voltage (Voc), maximum power (W), voltage at maximum power (Vmp), current at maximum power (Imp) and the conversion efficiency(%) [1]. The current form of I-V tracing is not feasible or financially viable and therefore there are no known PV operation and maintenance (O&M) companies that employ it as a monitoring approach. Furthermore, since the I-V curves are traced manually, the process cannot be repeated regularly. Frequent and periodic measurement and record of I-V curves can be extremely helpful and informative for tracking the performance and degradation of PV modules.

There are multiple I-V tracers available commercially, varying in price, accuracy, and portability. However, all such products are operated in a similar manner. The PV module(s) or string(s) are disconnected from the generation circuit and then attached to the positive and negative terminals of the I-V tracer. The next step is to trace and capture the I-V curve for the attached module/string, store the captured curve to a device, and the modules are re-connected to their generation circuit. This series of steps must be repeated for each module or string to extract their I-V curves. This disconnection and re-connection of PV modules are highly undesirable for a PV plant owner since it adds to the cost and requires extra labor. Moreover, most PV plants are located in areas with very low population densities, therefore any available O&M technicians are located far from the plant and would require significant time to dispatch a solution. The owners of PV plants are therefore interested in a more automated monitoring system that requires little or no manual labor.

The developed I-V tracer offers a low-cost solution to the issue. It is integrated with IoT technology and can be placed between a string of modules and the inverter. A power electronics interface is also required which traces the string. The I-V curve can be traced once a day or multiple times during the day. The automated approach of the I-V tracer eliminates any human element and extra labor costs associated with conventional I-V tracers. The presented approach can also be implemented at the string level, where it can provide an exhaustive measure of the PV system's health. Moreover, the regular data storage can be used to compute degradation rates. Any issues with the PV system including failures and unexpected degradation can be detected earlier and appropriate measures can be taken.

2. LITERATURE REVIEW

2.1. *I-V* and *P-V* Characteristics of PV Modules

The important PV characteristics like the optimum voltage, optimum current, and optimum power can be extracted from its curves. The I-V curve shows the relationship between the PV current and voltage, while the relationship between PV output voltage and power is shown by the P-V curve. However, there are several external factors that govern the performance of a PV module including irradiance and temperature. Figures 1 and 2 show how these factors can affect the output power of PV modules.

2.2. Importance of *I-V* Curve Tracer and Different Methods Used

The I-V tracer plays a crucial role in determining the performance of a PV module or system by acting as a monitoring system. The traced current and voltage rating gives a measure of the performance of the PV module. It is the fastest method for performance evaluation in commercial PV arrays and is the standard tool used by electrical contractors and PV system installers for both commercial and utility PV. I-V tracers can evaluate the performance of a PV system regardless of whether it is arranged in modules or arrays, and provides a graphical representation of the operating characteristics of the PV system. This graphical representation can be used to detect any unforeseen changes or signs of degradation.

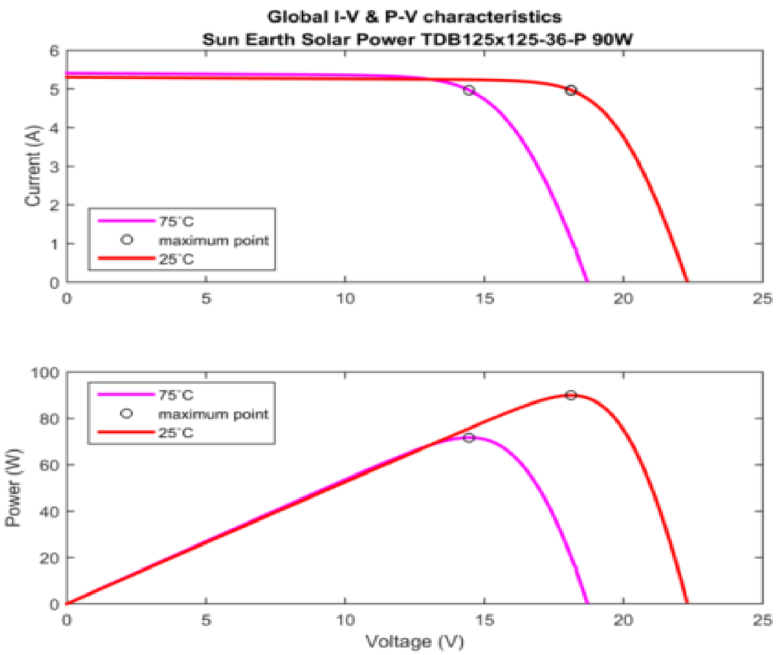

Figure 1. *I-V* and *P-V* curves under different temperature

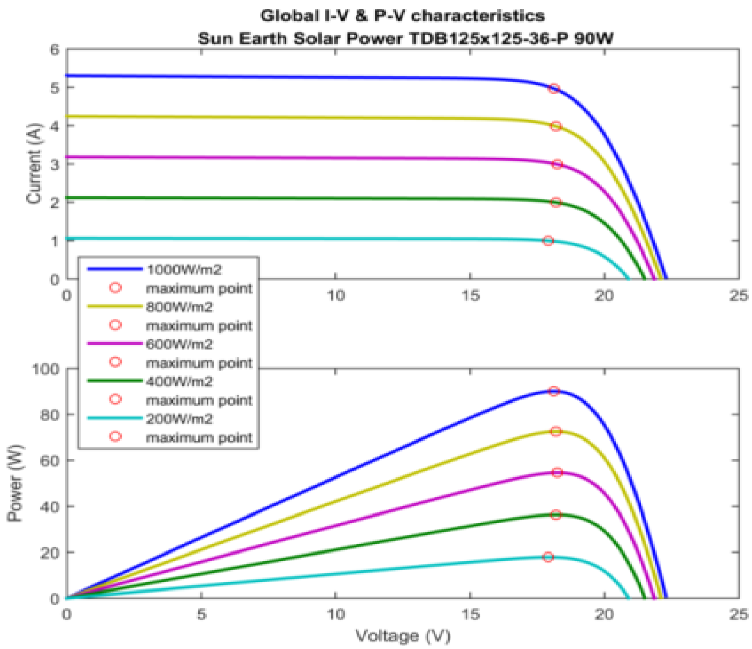

Figure 2. *I-V* and *P-V* curves under different irradiance

There are several methods used to obtain the I-V curve such as capacitive charging, variable resistors, and DC-DC converter. In order to trace the characteristics curves, the current and voltage must be varied. By using a capacitive load, the capacitor will discharge and charge as controlled by the switches shown in Figure 3. Moreover, the charging time is determined by open circuit voltage, short circuit current, and capacitor rating. However, the capacitance must be high enough to enable slow charging, which avoids fast transients that will damage the capacitor and switches.

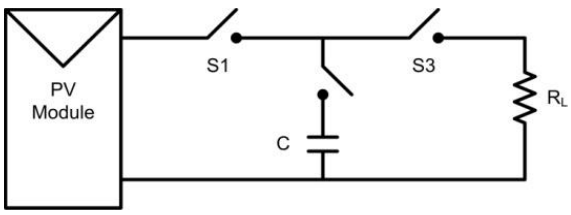

Figure 3. The method of capacitive load [2]

On the other hand, the conventional I-V curve tracer uses variable resistors to vary the voltage and current rating in order to plot the curve as shown in Figure 4. The value of resistance is varied from zero to infinity in order to capture the points from short circuit to open circuit. However, this method is not recommended for high power applications as short circuit current cannot reach and the reverse bias characteristics cannot be determined.

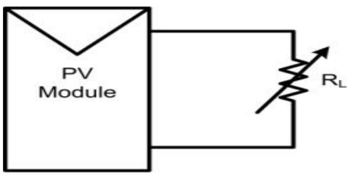

Figure 4. The method of variable resistor [2]

The DC-DC converter method, as shown in Figure 5, varies the voltage and current ratings by adjusting the duty cycle. Generally, the output voltage of the load is varied by the duty cycle and the input voltage. In this way, the characteristic curve of current and voltage can be plotted according to the duty cycle. Thus, with zero duty cycles, voltage rating becomes the open circuit voltage and current becomes zero. On the other hand, with completely one duty cycle, the voltage rating becomes zero and current becomes short circuit current. The open circuit voltage and short circuit current can be taken from the PV modules datasheet [2].

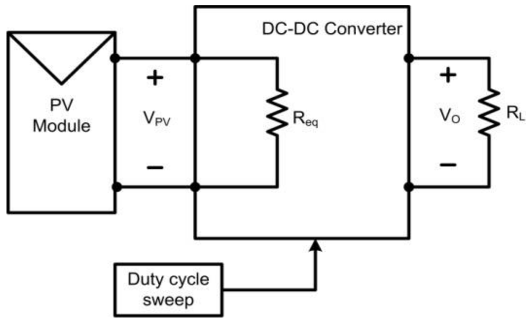

Figure 5. The method of DC-DC converter [2]

2.3. *I-V* Curve Tracer Based on the DC-DC Converter

Literature Buck and boost converters are not suitable for PV applications due to their partial operational region as shown in Figures 6-8. Generally, a buck converter is able to only step down the input voltage and not able to step up the input voltage. Therefore, the buck converter is not sufficient to be used in tracing I-V curve for PV modules. On the other hand, the boost converter is only able to step up the input voltage but is not able to step down the input voltage. In this way, a boost converter is also not applicable in tracing I-V curve for PV modules. However, a buck-boost converter, Cuk converter, and SEPIC converter can perform well in tracing I-V curve as shown in Figure 8. SEPIC is chosen in this work because it has no inverting output values compared to the buck-boost converter and has higher efficiency than the Cuk converter.

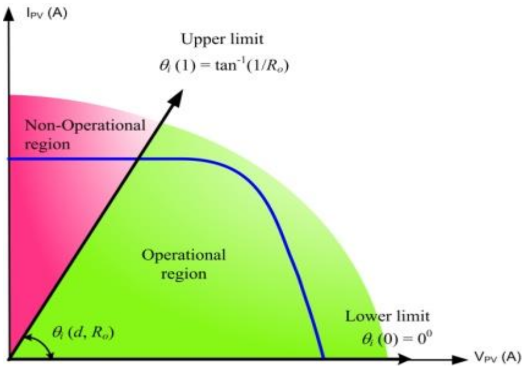

Figure 6. Operational region of buck converter [3]

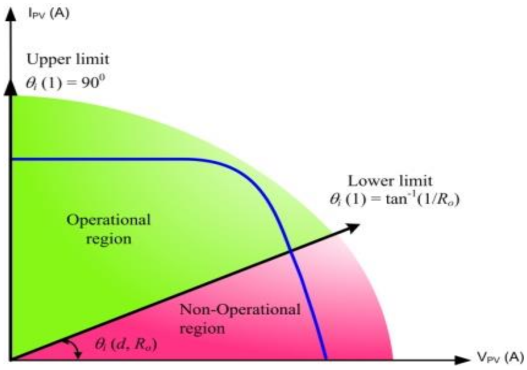

Figure 7. Operational region of boost converter [3]

3. SEPIC BASED *I*-V CURVE TRACER

The single-ended primary-inductance converter (SEPIC) converter is a non-inverting DC-DC converter capable of producing an output voltage less than, greater than, or equal to its output voltage. It is advantageous for I-V tracing due to its ability to buck and boost, its non-inverting input, and its continuous input current [4-7]. A suitable load resistor is chosen with a value that ensures the SEPIC converter remains in continuous conduction mode (CCM) for the entirety of the trace. It is helpful to keep the converter in CCM for analysis and control purposes, as the dynamics of the converter change as it enters the discontinuous conduction mode (DCM). In CCM, the converter can be assumed to have two states, ON or OFF. In the first state, ON, the switch is turned on and the input voltage source charges the first inductor. The second inductor takes energy from coupling capacitor CP. In this state, the diode is not turned on. In the second state, OFF, the switch is turned off and the first inductor charges the coupling capacitor and provides current to the load. The second inductor also provides current to the load. Figure 9 shows the overall setup of the developed I-V tracer and Figure 10 shows the hardware test setup.

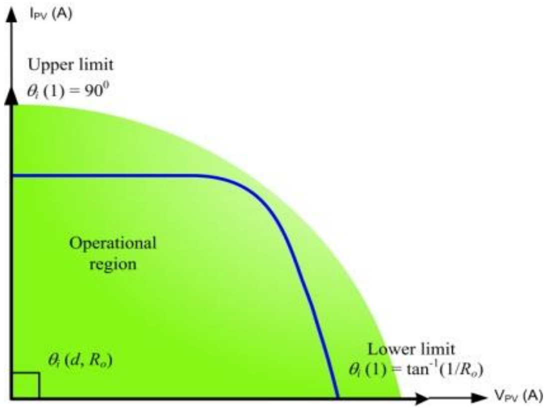

Figure 8. Operational region of buck-boost converter, SEPIC and Cuk [3]

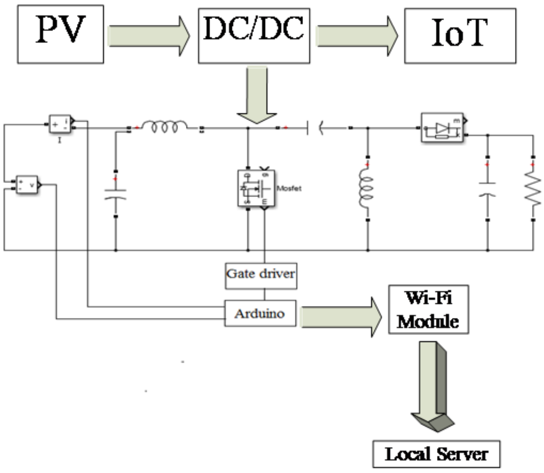

Figure 9. Overall block diagram of the developed *I-V* tracer

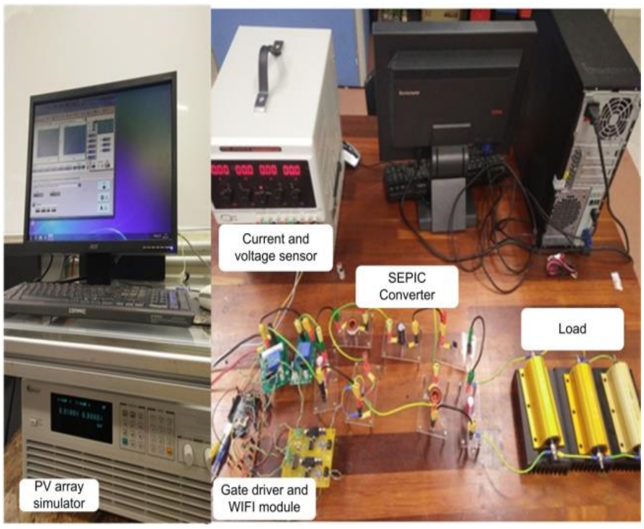

Figure 10. Snapshot of the hardware setup in the laboratory

4. RESULTS AND DISCUSSION

4.1. Optimize The *I-V* Curve Tracer Performance

The sampling time and the step size must be wisely chosen to optimize the performance level of I-V curve tracer [9-12]. Since the duty cycle provided by SEPIC will be generated in automatic mode, sampling time and step size play very important roles in determining the I-V curve tracer performance. The sampling time indicates the time taken for each duty cycle change, e.g. the time taken for duty cycle changing from 0.1 to 0.2 is the sampling time. Furthermore, the step size indicates the interval of duty cycle when it changes. For example, the step size will be 0.01 if the duty cycle is changed from 0.1 to 0.11. Several analyses of I-V curve tracer performance are carried out with the aim to have the fastest and smoothest curve tracing system as shown in Table 1-2.

Table 1. Optimal Step Size Settings

Sampling time	Step size
100 ms	0.1
	0.01
	0.05

Table 2. Optimal Sampling Time Settings

Step size	Sampling time
0.01	50 ms
	10 ms

Throughout all the analyses, 50 ms sampling time with 0.01 step size setting gives the best *I-V* curve tracer performance as shown in Figure 11. The total tracing time depends on the number of samplings and the step size. For a step size of 0.01, the total samplings are 83. Thus, each tracing time is around 4s.

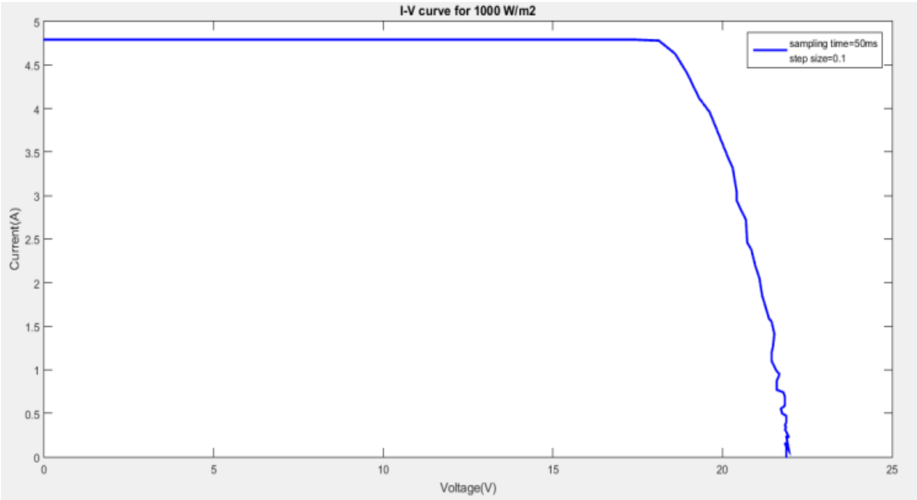

Figure 11. Tested with 50ms sampling time and 0.01 step size

4.2. Hardware testing under a uniform condition with different irradiance

It can be concluded that a higher irradiance has higher current, voltage and power ratings. If compared to current and power ratings, voltage ratings under different irradiance are consistent. However, the short circuit current and open circuit voltage under different irradiance are not the same. The higher irradiance has higher short circuit current and open circuit voltage. The irradiance of 1000 W/m2 has the highest maximum power point as shown in Figure 12.

4.3. IoT Based *I-V Curve Tracer*

In the final stage, both I-V and P-V curves are displayed in the web-based curves through a local server. In this way, the performance of PV modules can be evaluated and examined anytime by the users. Furthermore, all the data is based on real-time and thus the users can evaluate the real-time condition of PV modules. Figure 13 shows both I-V and P-V curves in real-time. The previous and current maximum power executed from PV modules is also tracked in the last chart as shown in Figure 13. This IoT based I-V curve tracer has higher commercial potential if compared to the existing commercial tracers [13-18]. The developed tracer is able to track all the voltage, current, and power executed from the PV modules in real time and the characteristics performances of PV modules are stored in web-based curves. Through integration with IoT technology, the tracer becomes more powerful and effective. It also presents the opportunity for users around the world to share the same information and analyze the data at the same time with the same results.

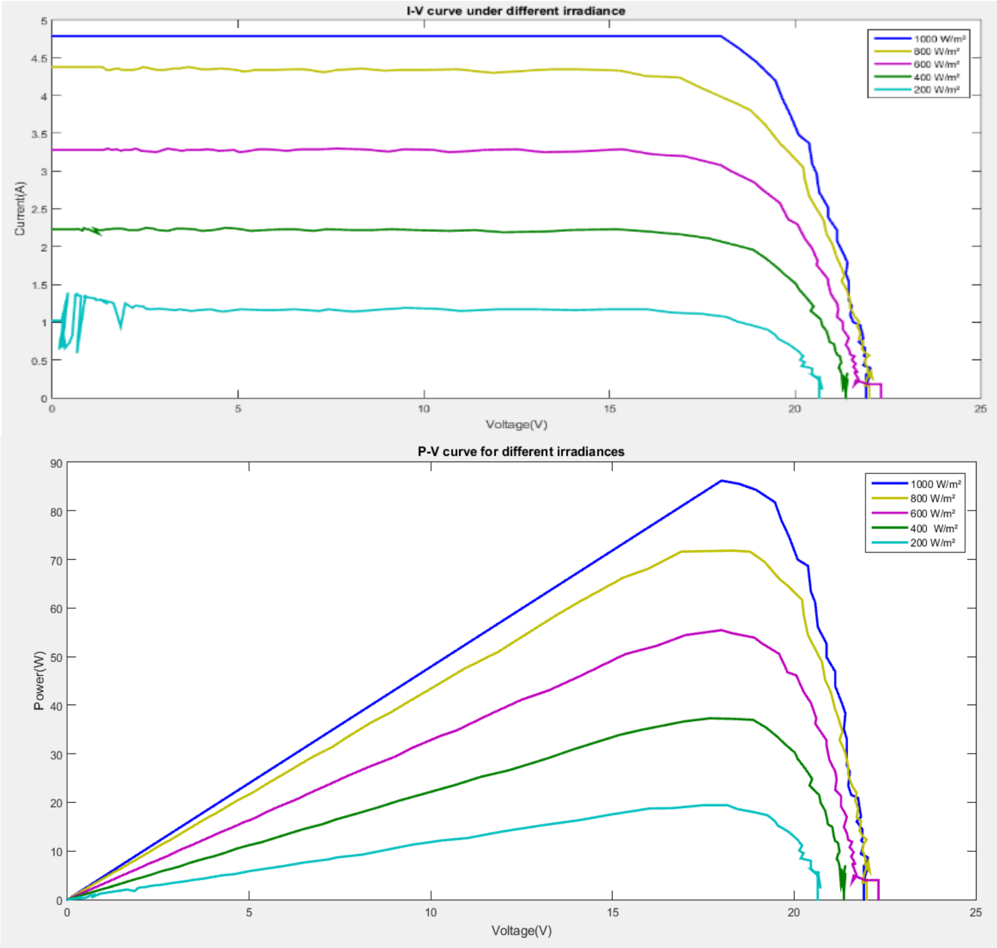

Figure 12. *I-V* curve and P-V curve under different irradiance

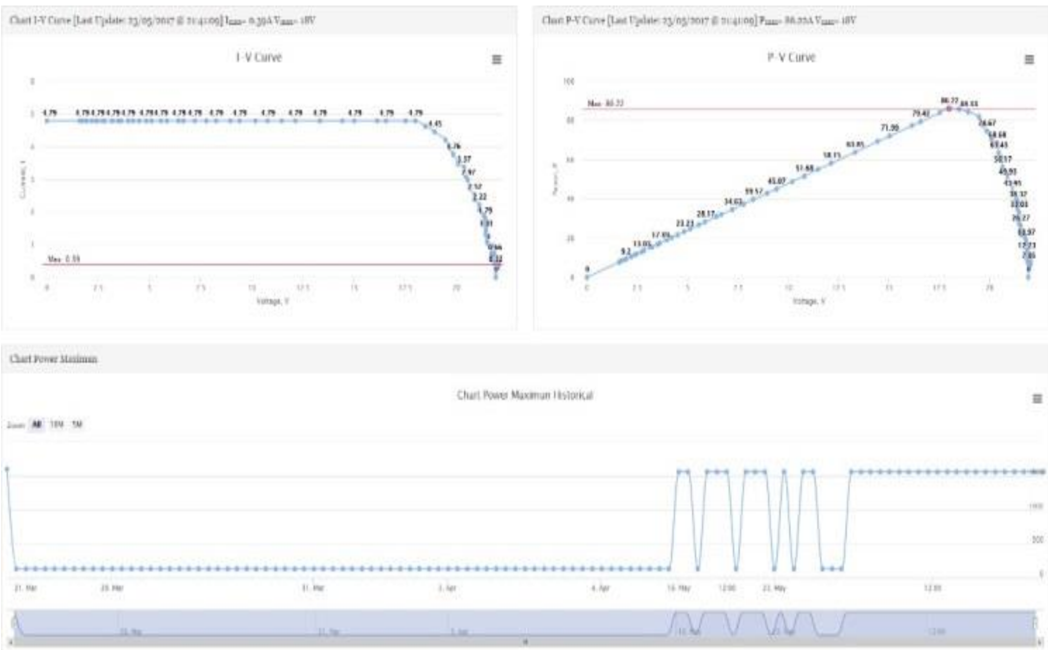

Figure 13. Web-based data

On the other hand, since the tracer is able to examine and monitor PV modules performances all the times, it becomes very useful particularly when the PV modules are installed at the rooftop or in a rural area. For example, if PV module is installed at the rooftop, the users face difficulties in monitoring the PV modules through conventional tracers. With the developed tracer with IoT technology, users can monitor the PV modules performances conveniently. Generally, PV power plants are built in rural areas, and for such cases, the power plant operators can execute the performance analysis anytime The IoT based tracer has a better efficiency compared to conventional and commercially available traces because it enables PV modules to be monitored conveniently and allows for early fault detection of PV modules.

5. CONCLUSION

In this paper, the concept of a low-cost I-V tracer using a SEPIC converter with IoT capability has been presented. The designed I-V curve tracer offers a high degree of flexibility considering the various current and voltage scale levels and adaptation to irradiance condition. The presented flexible I-V curve tracer is suitable for testing photovoltaic panels of different voltage and current levels, in various irradiance conditions.

ACKNOWLEDGEMENT

The authors would like to thank Universiti Malaysia Perlis and Ministry of Higher Education (MOHE) Malaysia for providing the facilities and financial support (Fundamental Research Grant Scheme (FRGS) under a grant number of FRGS/1/2015/TK10/UNIMAP/03/2) and (Short Term Grant No. 9001-00567).

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