FINAL TECHNICAL REPORT

Project Title:	**Non-contact Current-Voltage (I-V) Tracer for Photovoltaics**
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EXECUTIVE SUMMARY

This report presents a non-contact approach to simultaneously obtain current-voltage (I-V) curves of photovoltaic (PV) substrings and modules in a string without the need of disconnecting the individual modules from the string.

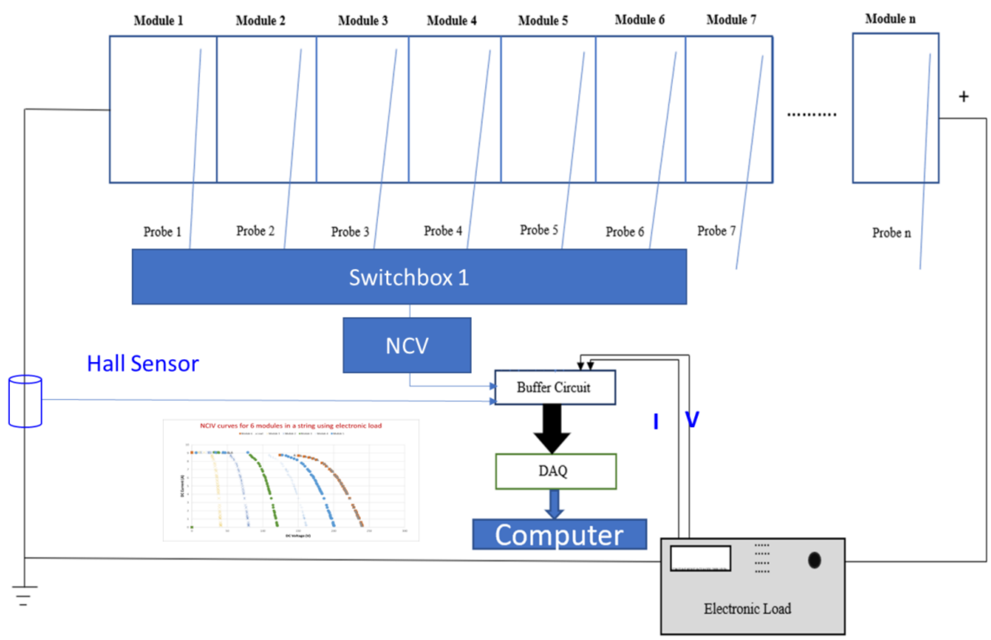
State-of-the-art

There are two types of I-V curve tracers currently available in the marketplace, capacitor-based and electronic load-based. The primary requirement of these conventional I-V tracers is the disconnection of individual modules in the string so the individual modules *contacted* through the connectors of the individual modules. These contact-tracers have three major limitations in the utility scale power plants:

First limitation – Weather and Accuracy: The mass-produced commercial contact-tracers cannot obtain the I-V curves of both string and its modules (as high as 30 modules), almost simultaneously (within about 5 minutes) at a single irradiance level, a single module temperature, a single spectrum and a single AOI (angle of incidence). This inability of the contact-tracers forces the testing personnel to wait for an extended or multiple sunny duration(s) of a cloudy day. This is a serious limitation as waiting for the sunny conditions or days is a huge practical challenge in almost all locations, except desert locations. Also, since the I-V curves are obtained at different prevailing weather conditions, it becomes critical to translate all the measured I-V curves of 30 modules in the string to a single test condition, for example STC (standard test conditions), so the underperforming modules can be identified. The accuracy of translation equations is heavily influenced by the irradiance level and temperature, spectral and AOI ranges; Second limitation - Safety: The second limitation is related to the high voltage electrical safety of the test personnel during disconnecting and reconnecting of individual modules or cable connectors from the string under daylight conditions and damaging of the original module connectors (especially the field aged connectors) during the disconnecting and reconnecting process; Third limitation – Labor: The third limitation is related to the enormous amount of time and hardship for the test personnel under prevailing (often harsh) protracted field conditions.

Project approach

This project was executed by Arizona State University in collaboration with its industry partner, PV Measurements Inc. (PVM). To mitigate all the three challenges of the state-of-the-art equipment indicated above, we utilized a non-contact I-V (NCIV) tracer approach. In this approach, we utilized an electrostatic voltmeter (ESV) and voltage sensor/probe combination to obtain I-V curves. The ESV units are extensively used in the high voltage industry but not in the PV industry. To obtain the simultaneous I-V curves of the substrings and modules within a string, we utilized multiple commercial ESV-Probe sets. In this approach, we utilized a non-contact voltage sensor (called, Probe) placed on the glass surface of the module (above the last cell of the module). This probe senses the module voltage (with respect to ground) through measured capacitance which is dictated by the surface charges (which in turn is dictated by the module voltage) and transmits the sensed voltage to the voltmeter (called, ESV or NCV, non-contact voltmeter). The current is sensed by a non-contact hall sensor. In a 30-module string, the 30^{th} probe obtains the entire string I-V along with the string I-V obtained by the electronic load. so that the I-V curves of the substrings and modules can be obtained by NCIV without the need of disconnecting the individual modules in the string. The string I-V curves obtained by the electronic load and NCIV can be compared for the accuracy determination. One can use 30 ESV units and 30 Probes to obtain 30 I-V curves of a 30-module string or use just 5 ESV units and 30 Probes in conjunction with 5 six-channel switchboxes (called, 6:1 switchboxes). To reduce the equipment cost, we utilized the 6:1 switchbox approach as shown in the figure below so the number of ESV units is reduced from 30 to 5. The approaches, achievements and challenges of this project are detailed in this report.



Objective and goals

The primary objective of the project is to develop and evaluate a non-contact I-V (NCIV) tracer to simultaneously and safely measure the I-V curves of a string and the individual modules within the string without disconnecting/reconnecting the high voltage connectors of the modules.

The two primary goals of the project are:

- Identify at least one non-contact ESV-Probe combination/set/pair from a commercial vendor for PV-specific application with an accuracy deviation target of less than 1.5% Pmax at the string level and individual module level in the 1000V and 1500V systems.
- Reduce the overall non-contact I-V curve tracer cost below the comparable contact tracers available in the market.

The project encountered and (mostly) mitigated two challenges and they are briefly described here: *i) Identification of ESV-Probe set:* Based on the lessons learned from the down-selected commercial ESV-probe set, it was originally planned to develop a PV-specific homemade ESV-probe set so the cost goal of the project can be met. During the initial period of this project, it was realized that the probe construction and its electrical communication to the ESV box were so complex that the homemade ESV-Probe set cannot be built within the current project period and budget. Since our eventual goal of the project was to reduce the cost of the test equipment, we took an alternate approach to meet the cost goal. In the alternate approach, we mitigated this challenge and achieved the cost goal by reducing the number of commercial ESV boxes from 30 to 5 using 5 inexpensive six-channel switchboxes (6:1 switchboxes). In this approach, we used only 5 ESV boxes instead of 30 ESV boxes (for a 1500V system having 30 modules) so the ESV box related cost was reduced from about $120,000 to $20,000 as each ESV costs about $4,000; *ii) Accuracy within 1.5% for string, substrings and individual modules:* Our goal was to obtain the I-V curves of the string, sub-strings and individual modules using NCIV tracer within an accuracy of 1.5% compared to the contact I-V tracers. We were able to achieve this accuracy goal at the string and sub-string levels. However, we met with a challenge in meeting the accuracy requirement at the module level because of "voltage offset drift" issue. Since the voltage at the module level is so low, any small voltage offset drift due to varying environmental conditions (especially, local wind speed and humidity on the glass surface of the module) can affect the surface charge and hence the accuracy of the measured performance parameters. We attempted to address this challenge using two methods: use a different probe which is less sensitive to the local environmental conditions; use a transparent miniature ionization-chamber on the module surface. The second method is still ongoing. For the first method, we experimented with a different probe and found that it was less sensitive, if any, compared to the previous probe. So, we placed order for three additional probes, but the delivery of these new probes was delayed over 10 months due to COVID-19 issue and the additional experiments using these new probes were prematurely terminated as the project ended before the new probes arrived.

Key achievements

- Identified a large number of commercial ESV models and probe models (from multiple manufacturers in the United States, Europe and Japan) that can potentially meet the intended PV-specific application requirements
- Down-selected appropriate ESV models and probe models which would meet three major requirements: ensure that the selected ESV and probe models will be commercially available now and in the future; ESV models and probe models that can withstand high testing voltages, as high as 1500V; Probe models that casts minimum shadow on the PV modules during the measurements.
- Installed a 3-row PV racking system at a fixed tilt angle of 33^{o} (local latitude)
- Installed and commissioned a 30-module string on the racking system
- Demonstrated the operation of 15 ESV-Probe sets in a 20-module string (1000V) using an electronic load to obtain simultaneous I-V curves of 15 modules of the 20-module string
- Demonstrated the operation of 24 ESV-Probe sets in a 30-module string (1500V) using an electronic load to obtain simultaneous I-V curves of 24 modules in a 30-module string.
- Designed and developed five switchboxes to reduce the number of ESVs from 30 to 5.
- Conducted the high and low temperature operational capability testing of ESV/Probe setup using an environmental chamber

- Through an extensive down-selection process and enormous amount of field testing, two ESV-Probe pairs were finally used to obtain simultaneous the I-V curves of string, substring and modules. Using the first ESV-Probe pair, it was demonstrated that the 1.5% accuracy requirement can be met for the strings and substrings having four or more modules. However, the 1.5% accuracy requirement could not be met for the individual modules using the first ESV-Probe pair due to the voltage offset drift issue. Using the second ESV-Probe pair, it was demonstrated that the 1.5% accuracy requirement can be met even at the individual module level. Unfortunately, we had only one probe for testing using the second pair. We placed order for additional probes for testing using the second pairs but did not, due to COVID-19 related delivery delay from the probe manufacturer, receive the probes on time to complete the project before the end date
- Our goal was to reduce the equipment price close to $60,000 (the commercial multi-curve tracer available from a commercial vendor for 16 modules costs about $60,000). Five battery powered 6:1 switchboxes were fabricated with double enclosures for safety. Each switchbox accommodates 6 probes (each probe costs about $700) and a 30-module string requires only 5 switchboxes so the cost of ESV units is reduced from $120,000 (for 30 units) to $20,000 (for 5 units). So, the total cost of ESVs and probes is reduced from $141,000 to $41,000 (more than 70% cost reduction). We believe that it is possible to maintain the price close to $60,000 which would include other components (slow sweeper, DAS and buffer circuit).
- This work demonstrates that a non-contact I-V tracer is clearly a workable approach to obtain simultaneous I-V curves of the string and substrings (having more than 3 modules) with commercially available ESV-Probe sets in combination with a 1500V string slow sweeper. It is highly likely to address the accuracy (<1.5%) challenges encountered in the I-V measurements at the module level using appropriate commercially available ESV-Probe set in combination with a slow sweeper and/or mini-environment box containing dual-polarity ionizer.

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INTRODUCTION

State-of-the-art

The performance characteristics of solar photovoltaic (PV) devices in PV plants can be measured by a string inverter, dc/ac microinverter, dc/dc optimizer or an I-V (current-voltage) curve tracer. The inverter provides only a single-point performance characteristic of Pmax (maximum power point) of the entire string, but not the individual modules. The microinverter and optimizer provide only a single-point performance characteristic of Pmax of the individual modules in a string, but not the entire string. The I-V curve tracer provides all the performance characteristics including Pmax, Isc (short-circuit current), Voc (open-circuit voltage), FF (fill factor), Rs (quasi series resistance) and Rsh (quasi shunt resistance).

Assuming the MPPT (maximum power point tracking) algorithm is accurate, the string inverter-based Pmax data can tell if the string is underperforming or not, but it cannot tell what caused the underperformance or which module in the string caused the underperformance and also it cannot be used for warranty claims from the module manufacturers as it does not tell which module(s) in the string is/are underperforming. Assuming the MPPT algorithm is accurate, the microinverter- and optimizer-based Pmax data can tell if the individual modules in the string are underperforming or not, but they cannot tell what caused the underperformance and cannot be used for warranty claims from the module manufacturers as the MPPT algorithm may be questionable. Since I-V tracers address all the demerits of the string inverters, microinverters and optimizers, they are extensively used by the O&M companies, PV plant owners and insurance companies. In the utility scale plants, there are huge number of strings and modules involved. For example, a 250MW plant would involve about 40,000 strings and 1,000,000 modules. Measuring I-V curves of all the strings in the utility scale plants is not practically and economically viable. Hence, a hybrid approach is currently used by the industry: identify the bad strings using inverters and identify the bad modules within the bad strings using I-V tracers.

This report presents a non-contact approach to simultaneously obtain current-voltage (I-V) curves of photovoltaic (PV) substrings and modules in a string without the need of disconnecting the individual modules from the string. There are two types of I-V curve tracers currently available in the marketplace, capacitor-based and electronic load-based. The primary requirement of these I-V tracers is the disconnection of individual modules in the string so the individual modules *contacted* through the connectors of the individual modules. These contact-tracers have <u>three major limitations</u> in the utility scale power plants:

<u>First limitation – Weather and Accuracy:</u> The existing mass-produced commercial contact-tracers cannot obtain the I-V curves of both string and its modules (as high as 30 modules), almost simultaneously (within about 5 minutes) at a single irradiance level, a single module temperature, a single spectrum and a single AOI (angle of incidence). This inability of the contact-tracers forces the testing personnel to wait for an extended or multiple sunny duration(s) of a cloudy day. This is a serious limitation as waiting for the sunny conditions or days is a huge practical challenge in almost all locations, except desert locations. Also, since the I-V curves are obtained at different prevailing weather conditions, it becomes critical to translate all the measured I-V curves of 30 modules in the string to a single test condition, for example STC (standard test conditions), so the underperforming modules can be identified. The accuracy of translation equations is heavily influenced by the irradiance level and temperature, spectral and AOI ranges.

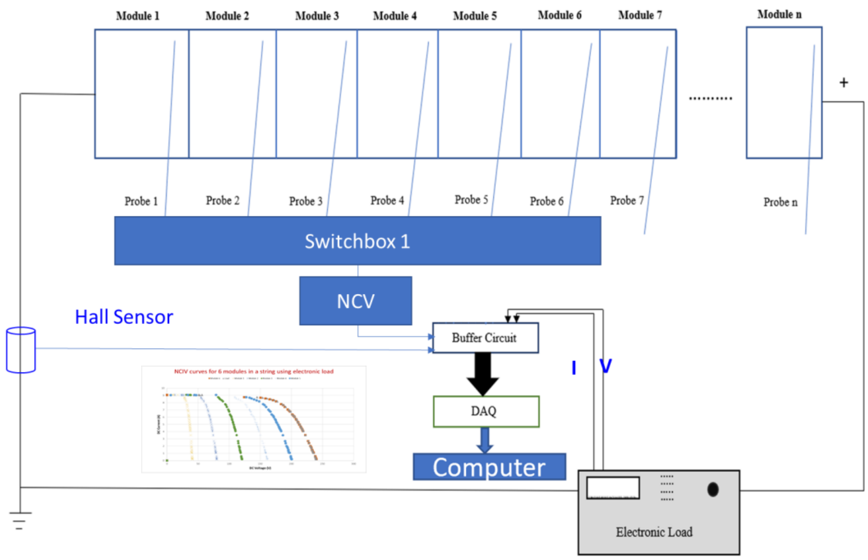
Second limitation - Safety: The second limitation is related to the high voltage electrical safety of the test personnel during disconnecting and reconnecting of individual modules or cable connectors from the string under daylight conditions and damaging of the original module connectors (especially the field aged connectors) during the disconnecting and reconnecting process.

Third limitation – Labor: The third limitation is related to the enormous amount of time and hardship for the test personnel under prevailing (often harsh) protracted field conditions.

Project approach – A quick summary

This report contains two major parts: Testing and Evaluation (tasks performed by Arizona State University); Instrumentation and Development (tasks performed by the industry partner, PV Measurements, Inc.). The testing and evaluation part involved various tasks including: down-selecting of a commercial ESV(electrostatic voltmeter)-Probe pair based on the photovoltaic (PV) technical requirements and commercial availability; building 1000V and 1500V PV arrays; testing various commercial ESV-Probe pairs at the string and module levels to narrow down the selection process; testing the operational capability of the down selected pair at low and high ambient temperatures in environmental chambers; reporting the accuracy deviation at the string, substring and module levels for the commercial ESV-Probe pair in conjunction with the PV-specific instruments built, by PVM, such as buffer circuit, switchbox and software. The instrumentation part involved various tasks including: Leading the testing (electrical configuration, tasks, procedures) to evaluate the performance of the equipment and techniques that PVM developed; Developing relevant data acquisition systems including signal conditioning circuitry; Developing techniques for comprehensive calibration of non-contact voltage measurement instruments; Developing techniques for non-contact voltage measurements in the dynamic voltage context; Evaluating effects of various ion-introduction techniques to mitigate offset voltage drift; Designing the switchboxes that PVM built and tested; Designing the RadioVoltmeters (much of the building was done by ASU-PRL); building and testing transparent miniature ionizing chamber; building radio-voltmeters; building buffer circuit; developing related software.

This section provides a quick summary on the project approach and the detailed results in the forthcoming sections. To mitigate all the three challenges of the state-of-the-art equipment, we utilized a non-contact I-V (NCIV) tracer approach. In this approach, we utilized an electrostatic voltmeter (ESV) and voltage sensor/probe combination to obtain I-V curves [1, 2]. To obtain the simultaneous I-V curves of the substrings and modules within a string, we utilized multiple commercial ESV-Probe sets in conjunction with homemade switchboxes as shown in the conceptual figure below. In this approach, we utilized a non-contact voltage sensor (called, probe) placed on the glass surface of the module (above the last cell of the module). This probe senses the module voltage (with respect to ground) through measured capacitance which is dictated by the surface charges (which in turn is dictated by the module voltage) and transmits the sensed voltage to the voltmeter (called, ESV or NCV, non-contact voltmeter). The current is sensed by a non-contact hall sensor. In a 30-module string, the 30th probe obtains the entire string I-V along with the string I-V obtained by the electronic load. The electronic load is connected to the string at the combiner box so that the I-V curves of the substrings and modules can be obtained by NCIV without the need of disconnecting the individual modules in the string. The string I-V curves obtained by the electronic load and NCIV can be compared for the accuracy determination. In this approach, one can use 30 ESV units and 30 Probes to obtain 30 I-V curves of a 30-module string or 5 ESV units and 30 Probes in conjunction with 5 six-channel switchboxes. To reduce the equipment cost, we chose the second approach and implemented in the project. The approaches, achievements and challenges of this project are detailed in this report.



Goals

The primary objective of the project is to develop and evaluate a non-contact I-V (NCIV) tracer to simultaneously and safely measure the I-V curves of a string and the individual modules within the string without disconnecting/reconnecting the high voltage connectors of the modules.

The two primary goals of the project are:

- Identify at least one non-contact ESV-Probe combination/set/pair from a commercial vendor for PV-specific application with an accuracy deviation target of less than 1.5% Pmax at the string level and individual module level in the 1000V and 1500V systems.
- Reduce the overall non-contact I-V curve tracer cost below the comparable contact tracers available in the market.

Milestones

Quarter 1 (Oct. 2017 – Dec. 2017)

Milestone
Report on the theoretical limits on the accuracy and geometry of ESV probes; Report on the survey and purchase of up to four commercial ESV probes

Progress Summary: In the first quarter, the required number of commercial electrostatic voltmeters (ESVs) were purchased based on a literature review and internet search. The accuracy and geometry of these ESV probes were reported in the Q1 report.

Quarter 2 (Jan. 2018 – Mar. 2018)

Milestone
Report on the practical limits on the accuracy and geometry of ESV probes; Evaluation of final selected ESV probe in 1000V strings using two different string tracers.

Progress Summary: A high voltage (1000V system) PV string was designed and installed in the field at ASU-PRL. Six candidate ESVs were down-selected and evaluated. Measurements obtained using the selected ESV were compared with digital multimeter (DMM) measurements and Solmetric IV-curve tracer measurements, and then the accuracy of the ESV was determined.

Quarter 3 (Apr. 2018 – Jun. 2018)

Milestone
Identification and validation of at least one commercial ESV probe for PV-specific application with an accuracy target of at least 1.5% for up to 1000V system voltage with fresh cable connectors.

Progress Summary: IV-curves were obtained using ESV-Probe, hall sensor, rheostat as a load and a Data Acquisition System (DAS). As the DAS used was too slow to capture accurate responses from ESV and hall sensor, PV Measurements built a faster DAS to communicate with ESVs and a current shunt. ASU-PRL built cables and connectors as required to take measurements on a 1000V system in the ASU-PRL field. Using the above mentioned ESV-Probe setup and a Solmetric IV-curve tracer (PVA-1000 PV analyzer), the string IV curves were taken and compared for the 1000V string. The accuracy target of 1.5% for the 1000V string was met with the fresh cable connectors.

Quarter 4 (Jul. 2018 – Sep. 2018)

Milestone (Go/No Go)
Identification and validation of at least one commercial ESV probe for PV-specific application with an accuracy target of at least 1.5% Pmax for up to 1000V system voltage with fresh, aged and incompatible cable connectors.

Progress Summary: Two new pieces of equipment for recording data were purchased, which combinedly provided six input ports for measuring five IV curves simultaneously. A new feature ‘buffer circuit’ was added in the connection scheme to protect the Data Acquisition System (DAS) from accidental high voltage input from ESV. Fifteen ESV-probe units, one Hall current sensor, Solmetric PVA-1000 IV-sweeper and a data acquisition system were used to measure fifteen IV curves simultaneously. The 1.5% Pmax accuracy requirement for a 1000V string with fresh and aged connectors was met.

Quarter 5, 6, 7 (Oct. 2018 – Jun. 2019)

Milestone
Accuracy validation of homemade ESV probe for PV-specific application with an accuracy target of 1.5% Pmax or better for up to 1500V system voltage with fresh cable connectors at ASU-PRL site using T-probes.

Progress Summary: Due to several reasons, ASU-PRL requested a no-cost time extension to meet the Q5 milestone. As reported in first two quarters of this project, an extensive investigation of large number of ESVs and probes from different manufacturers was conducted. Based on this investigation, we narrowed down our choice to Trek Inc. ESVs and probes. Trek model 368SS was selected for testing, however, this unit was discontinued by the manufacturer. Therefore, we had to explore more units. Trek models 565, 347 and 344 were purchased from e-commerce operation such as eBay and a few units were purchased from Trek Inc. Although the ESVs were available on eBay, the probes were not available in the required quantity. The deliverable of year 1 was to perform measurements on a PV array of 1000V. After year 1, in the milestone Q5, the deliverable was to perform measurements on a PV array of 1500 V. This array consists of 30 PV modules which require 30 probes. Required number of modules and ballasts to expand the array from 1000V to 1500V were procured. We placed orders for additional ESVs and probes, but the manufacturer had a significant lead time of more than 12 weeks.

Quarter 8 (Jul. 2019 – Sep. 2019)

Milestone
Homemade ESV probe for PV-specific application for up to 1500V system voltage with aged and incompatible cable connectors at ASU-PRL site using needle-probes will be validated by demonstrating that the voltage measured by ESV probe differs from the reference T-probe voltage measurement by ≤1.5%

Progress Summary: Starting this quarter and until the end of the project, the project encountered (and mostly mitigated at the end of the project) two challenges and they are briefly described here: i) <u>Homemade ESV-Probe set:</u> Based on the lessons learned from the down-selected commercial ESV-probe set, it was originally planned to develop a PV-specific homemade ESV-probe set so the cost goal of the project can be met. During the initial period of this project, it was realized that the probe construction and its electrical communication to the ESV box were so complex that the homemade ESV-Probe set cannot be built within the current project period and budget. Since our eventual goal of the project was to reduce the cost of the test equipment, we took another approach to meet the cost goal. We mitigated this challenge and achieved the cost goal by reducing the number of commercial ESV boxes from 30 to 5 using 5 inexpensive six-channel switchboxes. In this approach, we used only 5 ESV boxes instead of 30 ESV boxes (for a 1500V system having 30 modules) so the ESV box related cost was reduced from about $120,000 to $20,000 as each ESV costs about $4,000; <u>ii) Accuracy within 1.5% for individual</u>

modules: Our goal was to obtain the I-V curves of the string, sub-strings and individual modules using NCIV tracer within an accuracy of 1.5% compared to the contact I-V tracers. We were able to achieve this accuracy goal at the string and sub-string levels. However, we met with a challenge in meeting the accuracy requirement at the module level because of "voltage offset drift" issue. Since the voltage at the module level is so low, any small voltage offset drift due to varying environmental conditions (especially, local wind speed and humidity on the glass surface of the module) can affect the surface charge and hence the accuracy of the measured performance parameters. We attempted to address this challenge using two methods: use a different probe which is less sensitive to the local environmental conditions; use a transparent miniature ionization-chamber on the module surface. The second method is still ongoing. For the first method, we experimented with a different probe (called, P1 probe) and found that it was less sensitive, if any, compared to the previous probe (called, P4 probe). So, we placed order for three additional probes but the delivery of these new probes was delayed over 10 months due to COVID-19 issue and the additional experiments using these new probes were prematurely terminated as the project ended before the new probes arrived.

Quarter 9 (Oct. 2019 – Dec. 2019)

Milestone
Homemade ESV probe for PV-specific application for up to 1500V system voltage with fresh and aged cable connectors at actual commercial power plant sites of project supporting partners will be validated by demonstrating that the voltage measured by ESV probe differs from the reference T-probe voltage measurement by ≤1.5% and that the current measured by non-contact current sensor differs from the reference contact-based current measurement by ≤1.5%.

Progress Summary: See the Quarter 6 summary.

Quarter 10, 11, 12 (Jan. 2020 – Sep. 2020)

Milestone
Validation of non-contact module I-V tracer using a non-contact voltage probe, based on homemade ESV probe, and a non-contact current probe for 1500 V PV systems with fresh, aged and incompatible cable connectors at ASU-PRL and at least two power plant sites. The validation will be done by demonstrating that Pmax and the full I-V curve parameters, including Voc, Isc, Imax and Vmax, measured with the I-V tracer getting the voltage signal from the ESV-based non-contact voltage probe and current signal from the contactless current sensor, deviate from the Pmax, and the full I-V curve parameters, including Voc, Isc, Imax and Vmax, measured with the I-V tracer that uses T-connectors is ≤1.5% for each parameter respectively

Progress Summary: See the Quarter 6 summary.

PART 1: TESTING AND EVALUATION

Selection requirements of commercial ESVs

In the first and second project quarters, a list of requirements for ESVs suitable for this project was developed and refined by PVM and ASU:

Accuracy and Resolution: Our milestone goal of ESV is accuracy at 1.5%. When a typical 72-cell module showing the voltage at peak power is 38V is considered, 1.5% is 0.57V. However, there will be other contributors to overall accuracy as well. To leave room for them, we require accuracy at the 0.2V level. Thus, resolution should be, at worst, 0.2V. The reading information must be available with the required accuracy in a way that a computer can access it.

Geometry: ESV probe should be able to measure voltage for insulated PV module cables. Because we were unable to find any ESV that claims compliance with this requirement, we found alternative paths to success that do not rely on it. Thus, this requirement is updated to be a "nice-to-have".

Measurement Response Time: A typical module I-V sweep rate is about 50V in 10ms. But to make this requirement easier to meet, we'll anticipate we will have 100ms and plan to use slower-sweep testers if needed. For approximation purposes, consider linear voltage sweep, which means 0.5V per ms. Since we are trying to reach 0.1V resolution, this means the time constant should be shorter than 200us. This is probably a challenge for ESVs, so anticipate that we might have to make a special module and/or string sweeper that sweeps more slowly. Since we can probably do this, make 200us be a "nice-to-have" and 10ms to be a requirement (sweep in 5 seconds).

Analog Output: We're going to feed this data into a data acquisition system and synchronize it with current measurements. We envision that this will require real-time analog output to feed into our ADC, but we will accept output in digital form as long as there is a way to synchronize them with other readings.

Human-readable Display: We need this for development purposes, but we can put a voltmeter on the analog output if needed. This is a "nice-to-have".

Ranges 50V and above or ability to change the scaling: If there is not a 50V range, then we need to be able to adjust the scaling with a modification to get the best accuracy possible out of the meter. We found that this is not a common feature of ESVs and have therefore determined that we will probably have to perform circuitry modifications on the most-promising ESVs to adjust the reading scaling.

Verification Method: Very low voltage drift with temperature, or the ability to verify it in the field is required. Commercial ESV manufacturers do not specify temperature coefficient of accuracy. Thus, we plan to study how to calibrate our ESVs and strive to incorporate such calibrations into our application if necessary.

Weight: ESVs should be portable. Any unnecessary heavy components will not be included in the final product, but ESVs containing heavy, non-essential components are acceptable for the initial purchase and survey.

Power consumption: AC power will be supplied from the measurement sites to the ESVs, so high-power consumption is acceptable.

Power source voltage requirement: Voltages from power sources are easily changed, so any power source should be fine.

Probe cable length: For convenience, we want it to be more than a meter. If a particular ESV is otherwise suitable, look for whether it can still work with a homemade cable extension.

Drift in calibration: We want it to hold its calibration for at least an hour. It is even better if it can hold calibration for 4-8 hours. Users can run a calibration at the beginning of each measurement session if needed.

Size: Less than a few liters volume for the essential components. This is to ensure it's luggable if it isn't portable.

Special environmental requirements: Requirements must not preclude use outdoors on a sunny day.

Compressed gas requirement: It would be nice to not require this, but it ought not to rule out a particular ESV. Small compressed gas canisters can be included in the field setup. Flow rate requirement should be extremely low such as 1 liter per hour.

Sensor capacitance: Since there is no current flowing, any capacitance would cause a very long time constant of response. Thus, we will shun high-capacitance sensors. This issue can be categorized with Measurement Response Time.

IV curve testing for single module and string

IV curve testing – Single Module

ASU-PRL used two oscilloscopes, a Fluke 190 and a Hantek 5000, for recording data. The Fluke 690 has 4 input channels with universal probes whereas the Hantek 5000 series comes with 2 input channels with universal probes. Both oscilloscopes are handy to use and easy to carry. Both oscilloscopes allow the user to retrieve and export data in CSV format. The use of both oscilloscopes enabled the team to work with six input channels in total. Out of those six, five were used for voltage recording and the sixth was used for current recording. Five ESV units were connected to the oscilloscopes to feed transient voltages to them. The hall sensor was connected to the remaining channel of the oscilloscopes to feed transient current to it. A commercial IV-curve tracer was used as dynamic load and the testing was done with one PV module.

Connections:

Connect the IV-curve tracer as shown in Figure 1-1.
Attach ESV probes on the last cells of all modules.
Sweep IV-curve with the help of tracer (case 1: Solmetric, case 2: Daystar)
Record data in the oscilloscope from ESVs and hall sensor.

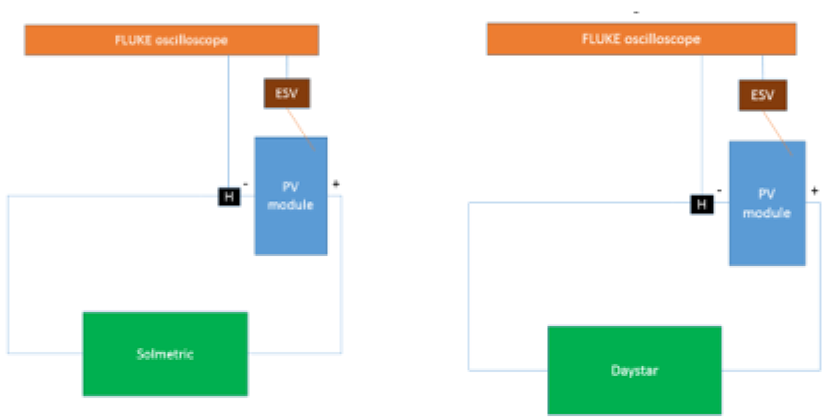


Figure 1-1: Selection of IV-curve tracer to work along with oscilloscopes

Observations:

Data retrieved with Solmetric tracer as load: The transient voltage response recorded is shown in Figure1-2.

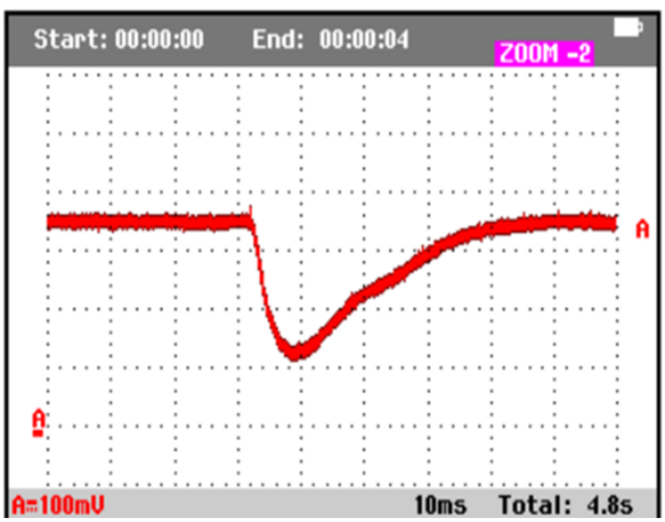


Figure 1-2: Transient Voltage Response - Fluke Oscilloscope with Solmetric Tracer as the load

In Figure 1-2, y-axis represents the voltage and x-axis represents the time. On the y-axis, one unit represents 10V. Thus, we see that the maximum voltage (V_{OC}) is around 36V but the minimum voltage (V_{SC}) is around 10V. However, in reality, the minimum voltage (V_{SC}) reaches zero. Therefore, this data would not be useful for tracing an IV-curve.

Data retrieved when Daystar tracer was the load: The transient voltage response recorded is shown in Figure 1-3.

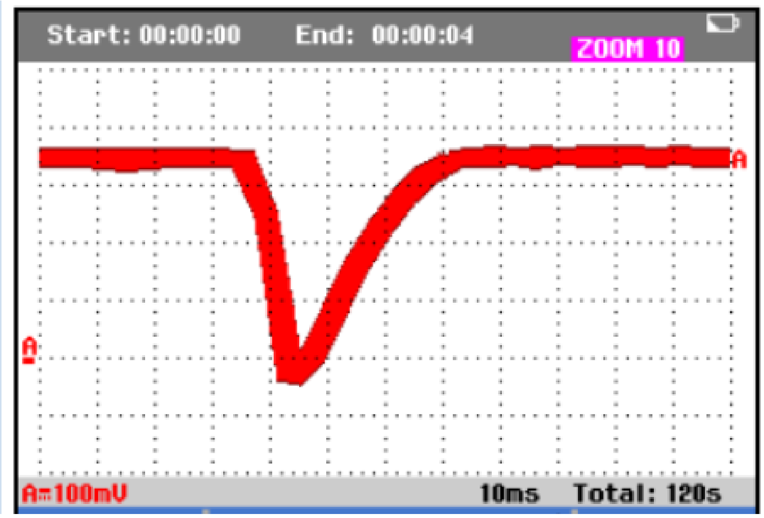


Figure 1-3: Transient Voltage Response - Fluke Oscilloscope with Daystar Tracer as the Load

In Figure 1-3, the same experiment was conducted with the Daystar curve tracer. We see that the maximum voltage (V_{OC}) is around 36V and the minimum voltage (V_{SC}) is around -3V. However, the oscilloscope tells us two values, maximum and minimum. The average taken comes to zero. Hence, the conclusion was that the Daystar curve tracer is better suited to work with the Fluke oscilloscope. The team repeated the entire procedure with Hantek oscilloscope, and same results were observed.

IV Curve tracing – Multiple Modules in String

On the day of experiment, the team started testing the workability of ESVs TREK 565 units around 7:30 AM. The ambient temperature was noted as 27°C. The testing was done within two and half hours. Then the team made connections to obtain IV-curves. At 10:30 AM, the ambient temperature rose to 35°C. All the TREK 565 ESVs failed at 35°C. They were showing incorrect values. The team had to use coolers to keep all the equipment cool and functioning. When cold air was blown on the equipment, they started reading correct values. As explained earlier, total six input channels are available on the oscilloscopes. Out of those, five were used for voltage inputs and one for current input. The entire connection scheme is shown in Figure 1-4.

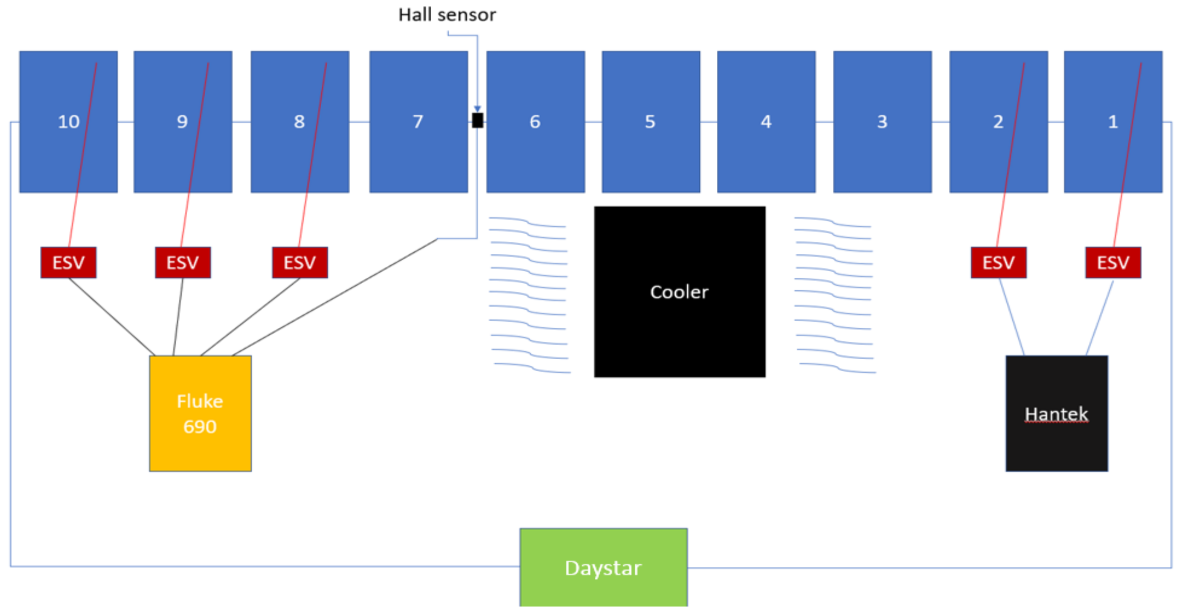


Figure 1-4: Schematic of Test Setup - 5 curves

Connection: Ten PV modules were connected in series. (The Daystar 100C has a voltage range of up to 600V).
Three TREK 565 ESVs and probes were attached to the 8th, 9th and 10th PV module. The outputs of those ESVs were fed into the input channels of the Fluke oscilloscope. A hall sensor was connected in the circuit and its output was fed into the input channel of the Fluke oscilloscope.
One Monroe Electronics ESV and probe was attached to the 2nd PV module and one TREK 565 ESV and probe was attached to the 1st PV module. Outputs of both ESVs were fed into the input channels of the Hantek 5000 oscilloscope.
The Daystar IV-curve tracer was connected between 1st PV module and 10th PV module. Coolers were directed to blow air on ESVs.

Procedure: When the IV-curve was swept using Daystar curve tracer, transient voltage and transient current data were recorded in Fluke and Hantek oscilloscopes. Subsequently, the data was saved and exported to a computer in CSV format. As the recording speeds of the Fluke scope meter and the Hantek scope meter are different, the values of the Hantek unit were adjusted to sync with the values from the Fluke. The processing took some effort since two different data recorders were used (Hantek and Fluke). Time between two data points is 8 ms in Fluke. Time between two data points in Hantek is 1ms.

We noted minimum voltage value in Fluke. We noted minimum voltage value in Hantek. We made those two points coincident as "point 1". Current was only monitored by Fluke. So, we had to find corresponding voltages on Hantek with currents on Fluke. For t=0 on both Fluke and Hantek, we noted the values. For t = 0.008 on Fluke we noted current value and for t = 0.008

on Hantek we noted voltage value. To make this simpler we used vlookup tool on Excel. An example is shown in Figure 1-5.

Column1	Column2	Column3	Column4	Column5	Column6
	Fluke				Hantek
t	V	I		t	V
0	V1	I1		0	V1'
0.008	V2	I2		0.001	V2'
0.016	V3	I3		0.002	V3'
0.024	V4	I4		0.003	V4'
0.032	V5	I5		0.004	V5'
				0.005	V6'
				0.006	V7'
				0.007	V8'
				0.008	V9'
				0.009	V10'

Figure 1-5: Snapshot of Values from Hantek and Fluke Oscilloscopes

In Figure 1-5, V9' corresponds to I2. Similarly, V17' would correspond to I3 and so on.
Data of voltages and current were retrieved from ESVs and a hall sensor by the oscilloscopes in the form of CSV. Then the curves were plotted manually in Excel. Figure 1-6 shows five curves obtained at the same time. Four curves obtained using TREK 565 ESVs and one curve obtained using the Monroe Electronics ESV.

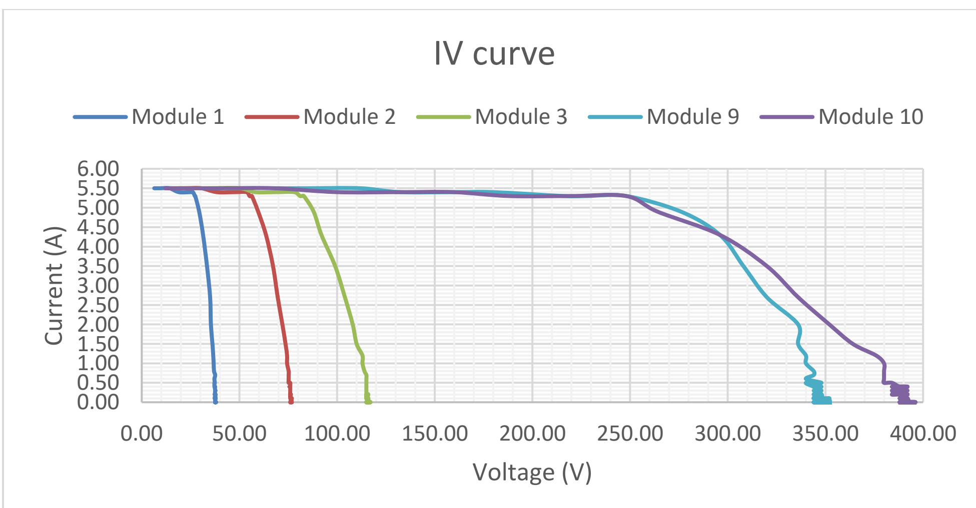


Figure 1-6: Five Simultaneous IV Curves using Oscilloscope

In Figure 1-6, the IV curve from Monroe begins at around V = 75V. The reason for this is that the response time of Monroe ESV is different from the response time of TREK ESV. Hence, data points are collected at different times and the number of data points collected with the Monroe unit and those with the TREK units is different. Therefore, the PV-curve obtained using Monroe, is different and shows incorrect values. It is shown in Figure 1-7. We just ignored the incorrect curve for this measurement and make sure to use ESVs with same response times.

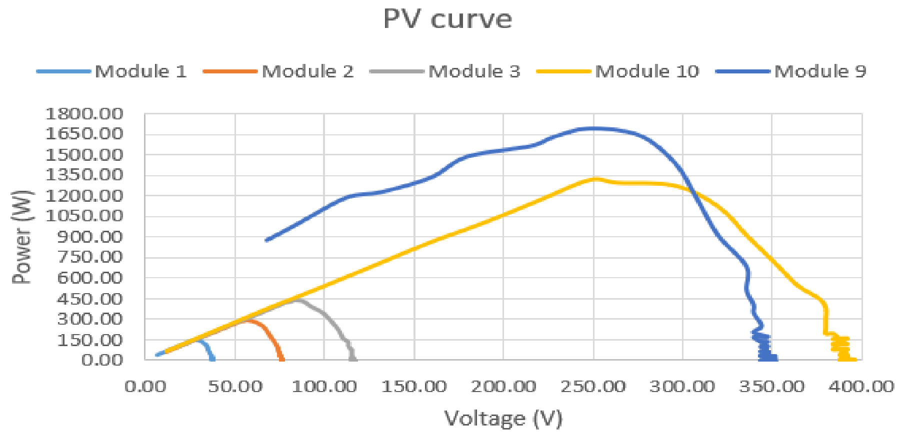
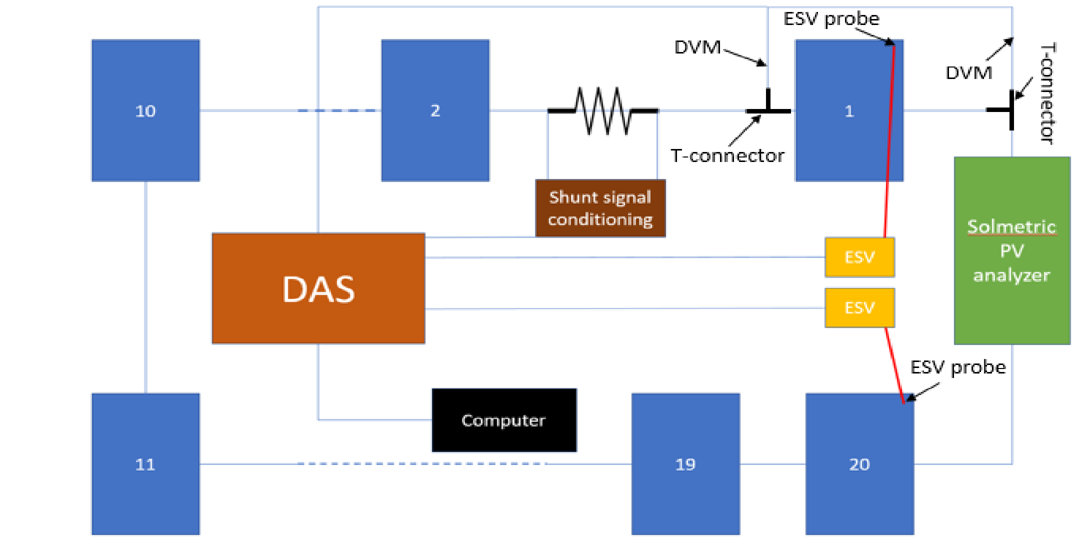


Figure 1-7: PV- Curve obtained using ESVs and Hall Sensor

Simultaneous IV-curve tracing in a 1000V string

<u>IV-curve tracing of one module in 1000V string</u>

To start the measurement process on the string level, all Trek ESVs were tested on a single module to confirm that all are in working condition. The open-circuit voltage of module 1 was measured with a DMM (model no. 83 V) as 39.11 V. The testing was started with the Trek ESV 368SS unit. Although the digital display of the ESV was showing 39 V, the output terminal of the ESV indicated 0.22 V. Expected voltage at output terminal of the ESV was 0.0039V. This might have been caused due to the high temperature at the day of the measurement. Due to the limited temperature operating range of the Trek 368SS (0-35 degrees Celsius) and the manufacturing discontinuation of this model by the manufacturer, it was decided to discard this model going forward. Instead, the team decided to go with the other ESVs Trek 565 and 344. Four units of Trek 565 were tested under open circuit condition and among those four units, only one unit was found functional. Trek 344 was also tested under open circuit condition and it was found functional. Since, only two units of ESVs were found functional on that day and hence, it was decided to trace the IV-curve of the string (1000 V system) and module 1 (of the same string) simultaneously. With two operational ESVs, simultaneous IV-curves of a string (1000V) and one module (of the same string) were taken. The respective circuit diagram is shown in Figure 1-8.



DVM: Direct voltage measurement

DAS: Data acquisition system

ESV: Electrostatic voltmeter

Figure 1-8: Simultaneous String and Module IV Curve Tracer - Circuit Diagram

Test Set-Up: Cables and connectors: For connections of different components in the circuit, several types and lengths of cables and connectors were required:

PV modules: MC-4 connectors (male & female)
Solmetric IV-curve tracer: MC-4 connectors (male & female)
ESV output: BNC female
ESV ground: banana connector
Ground wire on the PV array: alligator clip
DAS: ring connectors

Several combinations of the above-mentioned connectors were made for the test setup preparation.

Tools used for making cables and connectors: wire cutter, crimping tool, electrical tape.

Probe holders: To hold the ESV probes firmly on the PV modules, probe holders were designed made of plexiglass, due to its transparency and bending ability. For the simultaneous measurement of voltages, the probe of Trek 344 ESV was attached on the front glass surface of the twentieth module (as shown in Figure 1-9) to measure the string voltage and the probe of Trek 565 ESV was attached on the front glass surface of the first module (as shown in Figure 1-10) to measure the voltage of the first module in the string.

Figure 1-9: Probe (Trek 344) with Probe Holder

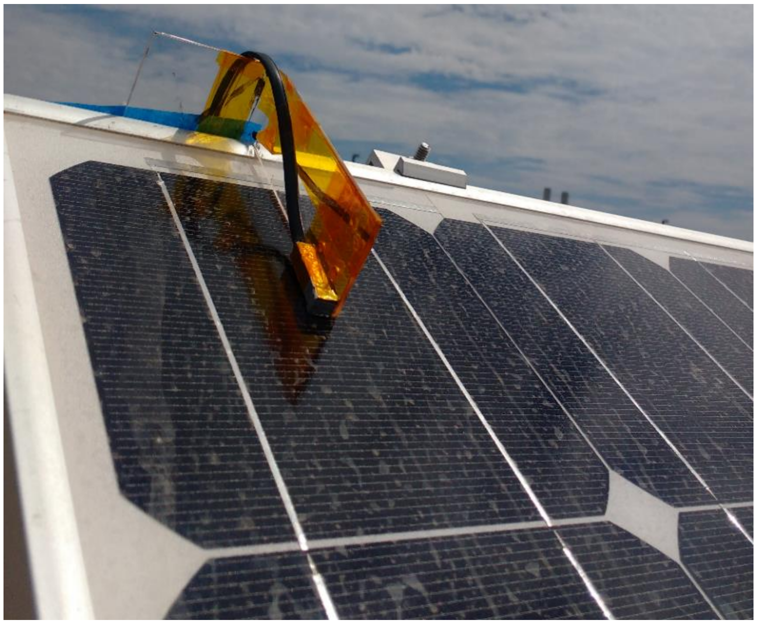


Figure 1-10: Probe (Trek 565) with Probe Holder

On the day of the test (Friday July 06, 2018), connections were made according to the circuit diagram as shown in Figure 1-8. The Solmetric IV-curve tracer was selected to act as load and to compare the IV-curved obtained using ESV-shunt combination.

Test Procedure: The circuit includes a PV array of 20 modules in ASU-PRL field, 2 ESVs- Trek 565 and Trek 344, Solmetric PV analyzer (IV-curve tracer), data acquisition system (provided by PV Measurements Inc. – additional details are provided in the later part of this report), a current shunt, a signal conditioning unit, cables and connectors made by ASU-PRL.

Connect all the devices in circuit as shown in circuit diagram (Figure 1-8).
Switch on the ESVs, Solmetric PV analyzer, DAS, and computer.
Start monitoring data in the DAS.
Within a second, sweep a curve with Solmetric PV analyzer.
Save all the data from Solmetric and DAS.

Results and Observations: With the test setup as shown in Figure 1-8, simultaneous string-module IV-curves were successfully obtained as shown in Figure 1-11. The module IV-curve is the curve for the first module in the string and the string IV-curve is for 1000V system.

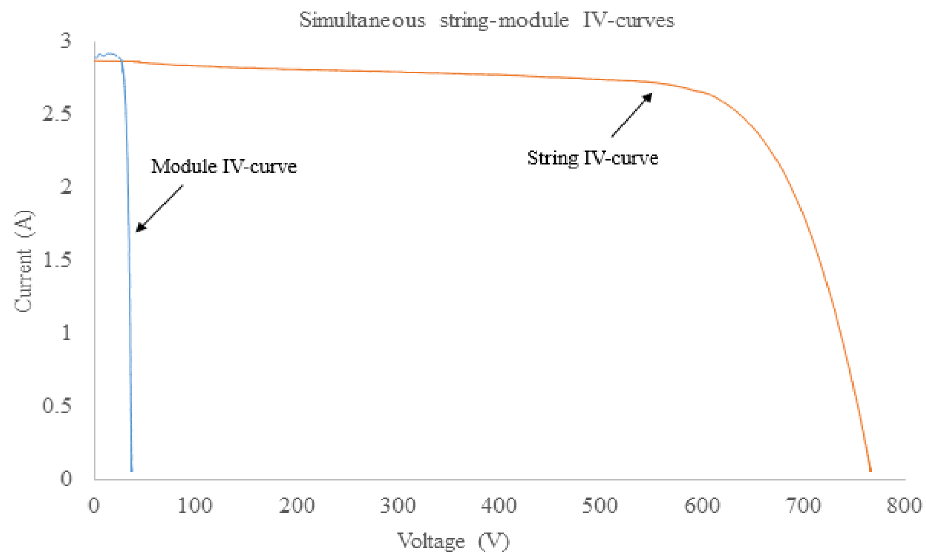


Figure 1-11: Simultaneous String-Module IV Curve

Voltage and current data in transient condition were collected in the DAS. It was found that the voltage input to the DAS had a delay of 2ms (200 data points) with respect to the current input to the DAS. The plot (Figure 1-12) shows the difference between the Solmetric, ESV-Shunt data and ESV-shunt data delayed by 200 data points (I_{shunt} delayed) from the string IV-curve measured. The shunt's nominal 0.05139 ohm value was used to compute the current from the measured voltage. IV-curve parameters including P_{max}, I_{sc}, V_{oc}, I_{mp}, V_{mp} and FF are presented in Table 1..

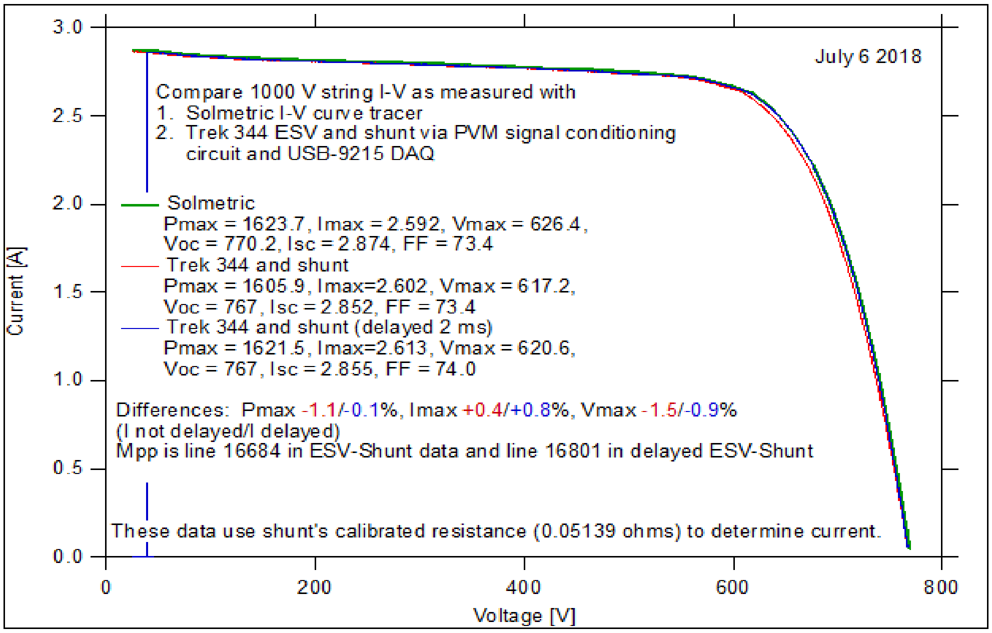


Figure 1-12: String IV Curve (Green: Solmetric, Red: ESV-Shunt and Blue: ESV-Shunt delayed)

Table 1: IV Curve parameters

IV-curve tracer	P_{max} (W)	I_{sc} (A)	I_{mp} (A)	V_{oc} (V)	V_{mp} (V)	Fill Factor (FF)
Solmetric	1623.7	2.874	2.592	770.2	626.4	0.734
ESV-shunt	1605.9	2.852	2.602	767	617.2	0.734
ESV-shunt delayed by 2 ms	1621.5	2.855	2.613	767	620.6	0.740

Table 2: IV Curve parameters - Percentage Deviation

	P_{max}	I_{sc}	I_{mp}	V_{oc}	V_{mp}	FF
Percentage deviation	1.1	0.76	-0.38	0.41	1.47	0.0
Percentage deviation (delayed by 2 ms)	0.13	0.66	-0.81	0.41	0.92	-0.81

In Table 2, it can be observed that the percentage deviation in the IV-curve parameters including P_{max}, I_{sc}, I_{mp}, V_{oc}, V_{mp} and FF are within ±1.5% of acceptable limit. After delaying the I_{shunt} data by 200 data points (2 ms) the deviation in all the IV-curve parameters came well within ±1.0% (target limit < ±1.5%). The IV-curve parameters obtained by Solmetric 1000 PV analyzer were compared with the IV-curve parameters obtained by calibrated Daystar 100C PV analyzer on

500V system. This was done to check the accuracy of Solmetric 1000 PV analyzer. The deviation in IV-curve parameters were found within ±1 % of accuracy range.

Simultaneous IV-curve tracing in 1000V string

In order to obtain 16 I-V curves, 16 pairs of ESVs and probes were needed. ASU-PRL's inventory included 9 units of TREK 565, 6 units of TREK 344, 2 units of TREK 347 and one hall effect sensor Magnelab JS10NH-10. To measure 16 IV-curves simultaneously, a Data Acquisition System was needed which can take in 16 input channels from voltage readers (ESVs) and one input channel from the current reader (Hall sensor). For this reason, the project partner, PV Measurements recommended purchasing two units of DAQ USB-1616FS from Measurement Computing. Both units have sixteen input channels each. It was planned that on the test day sixteen channels of the first DAQ will be used to take inputs from voltage readers (ESVs) and one channel of the second DAQ unit also with 16 channels, will be used as the input channel for the current reader (hall sensor).

A protection feature, called a buffer circuit, was built, and added in between the path from ESVs and hall sensor to the DAQ. In case of accidental application of high voltage to the apparatus, the buffer will blow up instead of the DAQ. Additionally, this buffer is inexpensive to replace. For ease of connections and time constraint, the team decided to use a breadboard to make the buffer circuit. All the connections were made using AWG 22 wires.

Testing of the buffer circuit: If an out-of-range signal is applied through the connections, the buffer circuit would fail and prevent this signal from reaching to the DAQ. This buffer circuit can then be replaced easily for use again.

The test procedure for the buffer circuit is as follows:

Attach an ESV probe to the last cell of a PV module. Monitor the display reading on the ESV.
Connect output of the ESV to Input 1 (pin 3); and measure output between Output 1 (pin 1) and ground. Measure using a DMM.
Check reading on the ESV display and check reading on the DMM.
Repeat the process for all the 16 input channels.

The ESV used for this test was TREK 565. At the output, the ESV gives a reading (1/100) of the actual voltage. At the output terminal of the ESV, a BNC male connector was connected. The positive terminal of the BNC connector was connected to input and the negative terminal was connected to the common ground. During the test time, the ESV display screen showed a voltage of 40 V. Moreover, the output of the buffer circuit was read on DMM Fluke 83 by measuring the voltage between output and the common ground which read 0. 4 V for all the 16 input and output channels ensuring the proper working of the buffer circuit.

Test Set-up: The team started with arranging the required equipment. They included ESVs, probes, probe holders, hall sensor, power supply cables, extension cables and boards, DMM, ground cable, T-connector, stressed connectors (from thermal cycling), buffer circuit, BNC connectors, AWG 22 wires for connecting ESV outputs to the buffer circuit, DAQ, a computer and IV curve tracer Solmetric PVA 1000 analyzer. The Solmetric curve tracer was selected over the daystar curve tracer for this experiment because of the 600 V voltage limitation of daystar curve tracer which does not allow it to be used in a system with a voltage rating of more than 600 V. As discussed earlier it was planned to take simultaneous 16 IV curves. However, on the test day, only 15 ESVs functioned properly. So, 15 voltage signal curves along with a current signal curve were recorded utilizing only one of the 16 channel DAQs. Figure 1-13 represents the test set-up for this experiment.

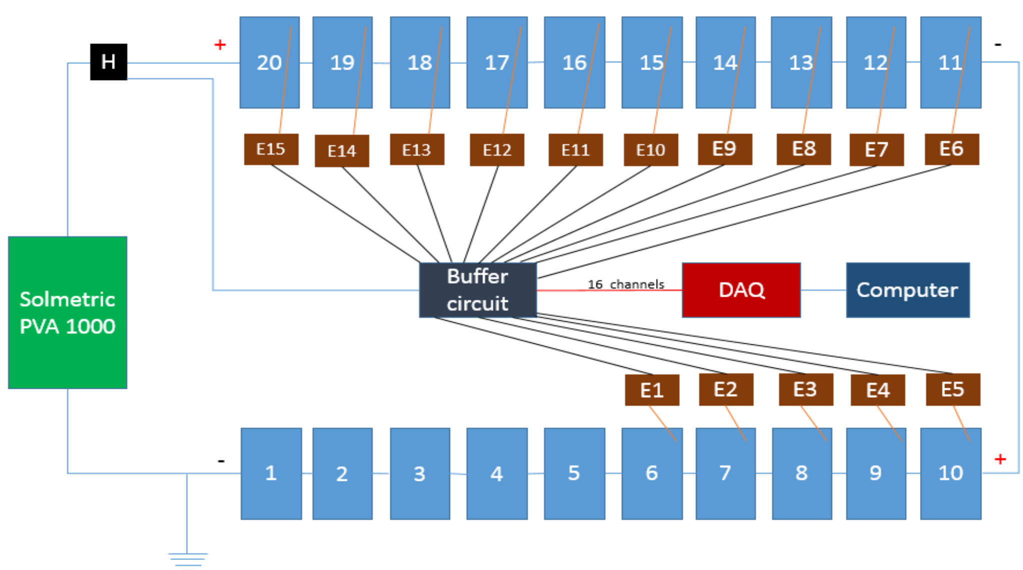


Figure 1-13: Test Setup -15 IV Curve Measurement

- Place ESVs close to the PV modules' glass surfaces.
- Place DAQ and buffer circuit in the center to allow easy connections with all ESVs
- Make all necessary wire connections including
- Power cords to all ESVs, hall sensor, buffer circuit and DAQ

- Probes to ESVs
- ESV outputs to buffer circuit inputs using BNC connectors and AWG 22 wire.
- Buffer circuit outputs to DAQ inputs.
- DAQ output to the computer.
- Connect the stressed connectors from thermal cycling to the terminals of all PV modules.
- Connect all 20 PV modules in series. Connect negative terminal of first module to ground.
- Connect Solmetric PVA-1000 analyzer between first and the last (20^{th}) module.
- Connect the hall sensor in the circuit.

Verify that all connections are correct.

Test Procedure: All ESVs were placed on their positions as planned. However, at times, some ESVs started showing incorrect values. They were then either replaced or we waited for them to show correct values. This undesired process is explained further in the report. Each pair of ESV and probe was tested for their accurate operation. This was done by carrying out the following steps:

1. Connect the positive probe and negative probe of a DMM to the positive terminal and negative terminal of a PV module, respectively.
2. Record the open-circuit voltage of the PV module using the DMM.
3. Remove the DMM.
4. Ground the negative terminal of the PV module.
5. Place the ESV probe above the last cell of the module using a probe holder.
6. Turn on the ESV and record the voltage reading of the module.
7. Compare the voltage readings coming from the ESV and the DMM.
8. Repeat steps 5 to 7 using 14 other different pairs of ESVs and probes.

As discussed before, after doing the test on the ESVs and probes, it was found that only 15 pairs of ESVs and probes were operating as expected. Among those 15 units, 9 were TREK 565, 4 were TREK 344, and 2 were TREK 347. After validating the proper operation of equipment and making the connections, we proceed to acquire 15 IV-curves simultaneously in one single IV-curve sweep.

Test Results: In this section, the results obtained for the test setup are shared. Figure 1-14 shows the IV curve obtained on sweeping the IV curve at 1:23 pm (MST time) using the solmetric IV curve tracer with other string details.

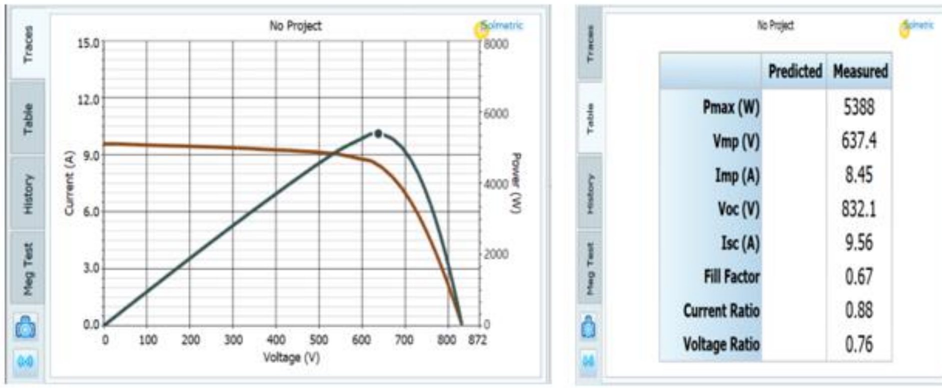


Figure 1-14: IV and PV Curves - Solmetric IV Curve Tracer

Figure 1-15 shows the screenshot of the DAQ screenshot with signal versus time responses for 15 voltages and currents. The signal versus time data were saved to a .txt file which was used later to get IV and PV plots.

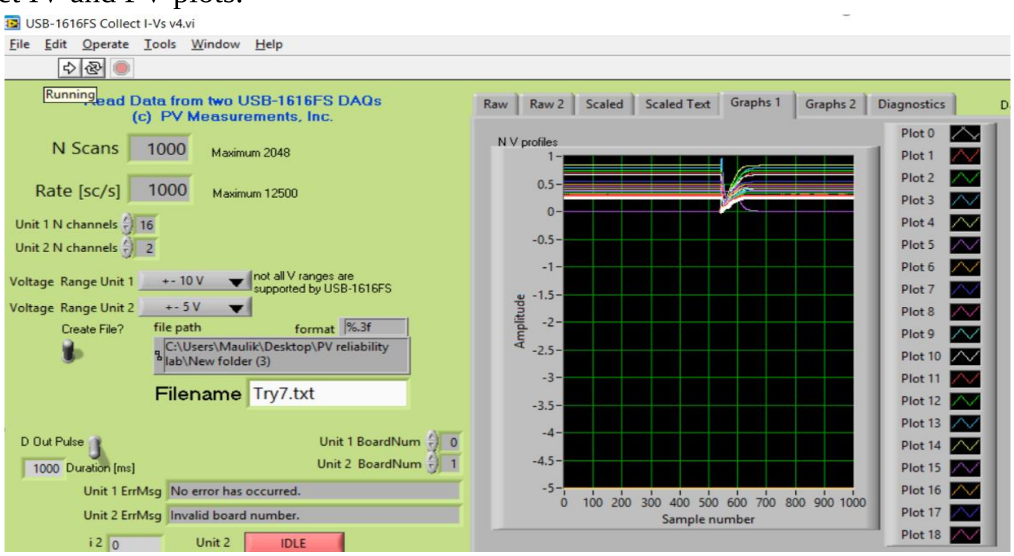


Figure 1-15: DAQ Software - Signal Vs Time response

In the experiment, TREK make ESVs were used for direct voltage measurement of the module voltages. Table 3 includes the details of ESVs connected to the specific modules.

Table 3: ESV and Module Details

Module 6 to Module 13	TREK 565 (8 no.)
Module 14 to Module 17	TREK 344 (4 no.)
Module 18 and Module 19	TREK 347 (2 no.)
Module 20	TREK 565 (1 no.)

Figure 1-16 highlights the IV plots for the string. The module number in the figure signifies the IV curve for an entire string including modules through the first module in the string to the specific module number. For example, Module 6 plot is the IV curve of the first 6 modules in the string.

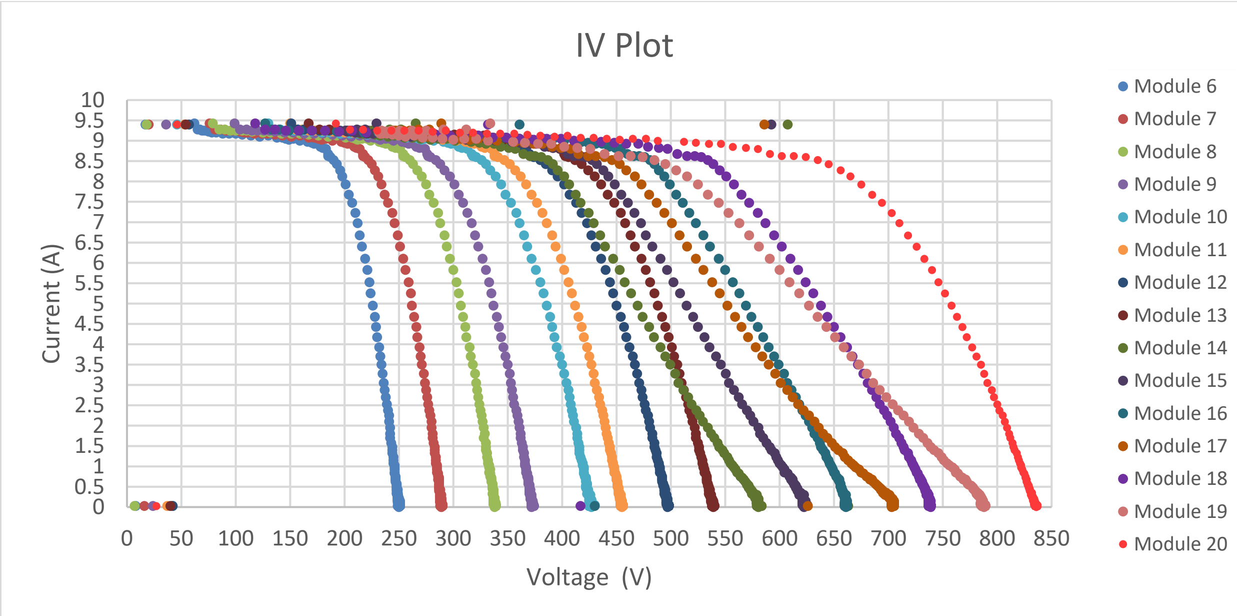


Figure 1-16: Non-contact I-V curves of the String and Substrings - 1000V String (DayStar load)

Table 4 provides a comparison between the string I-V parameters recorded by the Solmetric curve tracer and the ones obtained using DAQ along with the percentage difference between those values which is calculated as the absolute percentage difference between values recorded on solmetric curve tracer and DAQ with respect to the value recorded by the Solmetric curve tracer . It is found that the recorded values are very close to each other.

Table 4: Accuracy Comparison of IV Parameters between Solmetric Tracer and NCIV Tracer

	Solmetric Curve Tracer	NCIV Curve Tracer	Difference
Pmax (W)	5388	5350	0.7 %
Vmp (V)	637.4	635.0	0.37 %
Imp (A)	8.45	8.43	0.29 %
Voc (V)	832.1	837.0	0.58 %
Isc (A)	9.56	9.45	1.15 %

Individual voltages for a specific module are obtained by taking the voltage differences between adjacent voltage columns of the string and is plotted with the string current to get module IV curve.

Figure 1-17 shows the IV curve for Module 7 in the string. Similarly, IV curves for all other modules were obtained. Proper individual module IV curves are not obtained Module 14 onwards because of the mismatch in the response time of the ESVs, because of which the difference taken between the voltage data points is not correct.

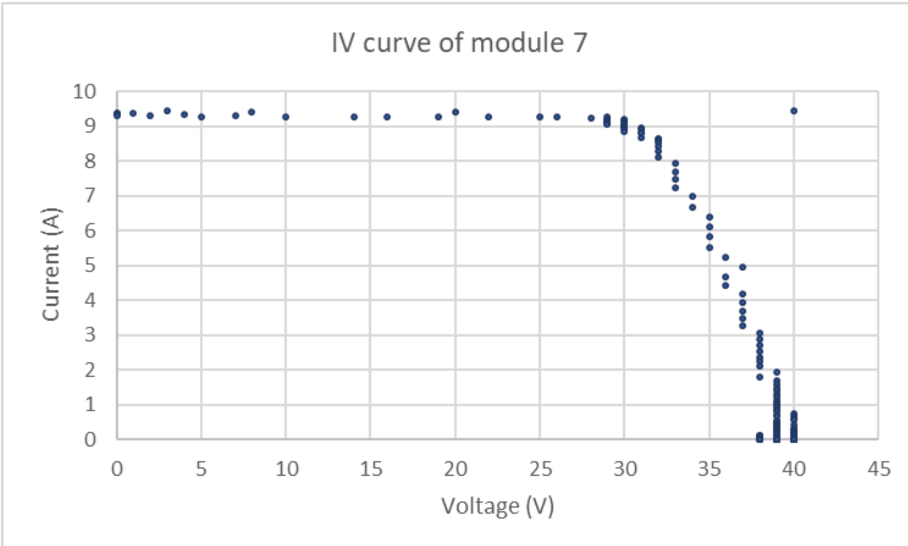


Figure 1-17: IV Curve using ESV - 7th Module

Aged connectors testing

PV connectors used in the solar industry age/detoriate with years of operation in the field and they have an impact on energy production at various Solar PV installations. In order to test the capability of Non-Contact Simultaneous IV curve measurement test setup (developed jointly by ASU-PRL and PV Measurements, Inc.) in identifying the impact of aged connectors, test with aged connectors from Damp Heat and Thermal Cycling chamber tests were conducted at ASU-PRL on 03/01/2019. The test setup with fresh connectors is shown in Figure 1-18.

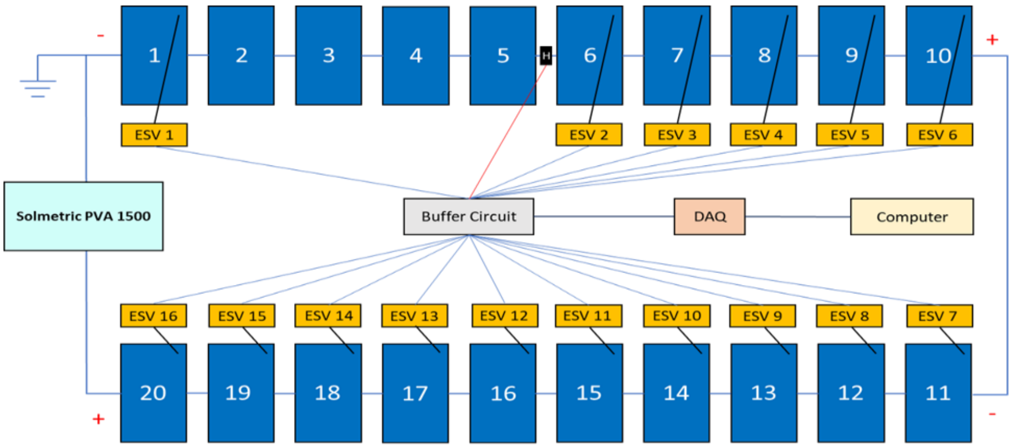


Figure 1-18: Test Setup - Fresh Connectors

The test setup with damp heat chamber aged connectors is shown in Figure 1-19. Total resistance of the aged connectors was around 30mΩ. Fresh connectors refer to connectors in the PV Module. Their resistance was not measured.

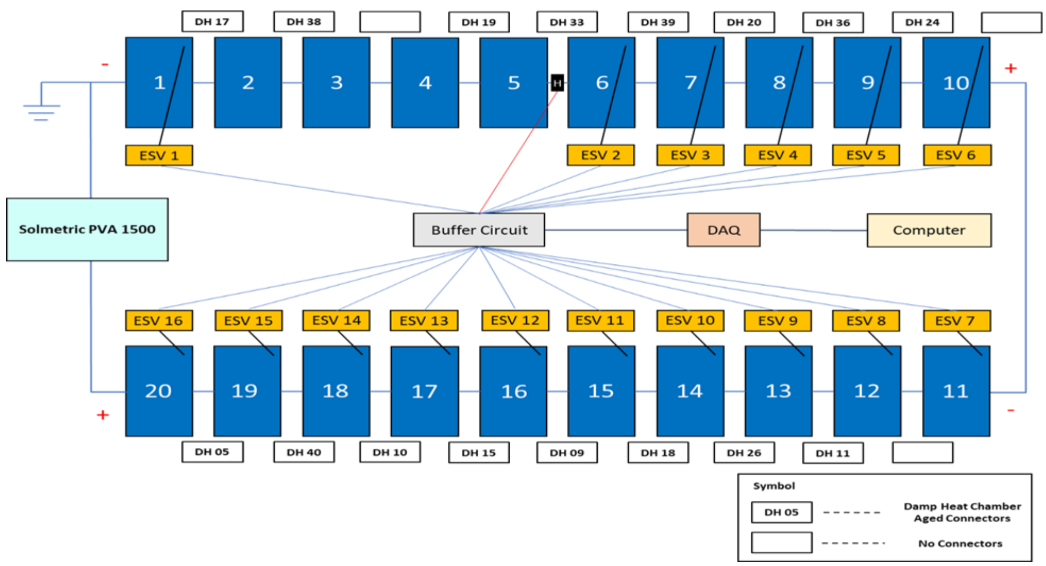


Figure 1-19: Test Setup - Damp Heat chamber aged connectors

The test setup with thermal cycling chamber aged connectors is shown in Figure 1-20. Total resistance of the aged connectors was around 30mΩ. Fresh connectors refer to connectors in the PV Module. Their resistance was not measured.

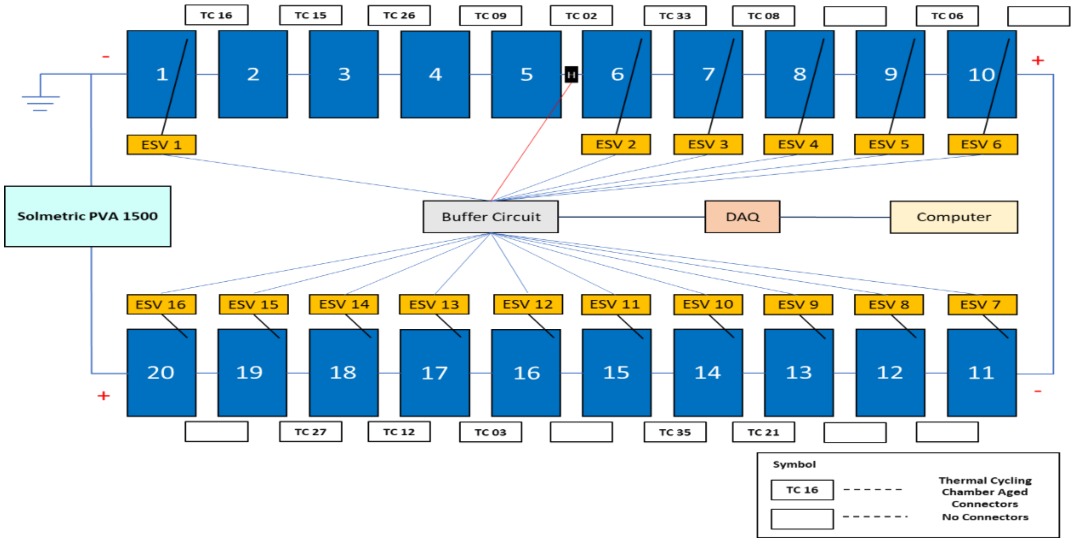


Figure 1-20: Test setup - Thermal Cycling aged connectors

Due to bad weather conditions at Mesa (Arizona) in February 2019, tests were postponed until March 1, 2019. The Test setup was carried out on March 1, 2019 from 8:30 AM to 9:45 AM. There was high cloud coverage till 12:00 PM, so the actual tests were not conducted during that time period. Tests commenced once the cloud coverage was minimal. Different sets of tests were conducted at different times as shown in able 1 below. All tests were conducted between 12:30 PM to 1:30 PM. Following parameters were noted down while performing the tests – Reference Cell Irradiance (Mono-Si/Poly-Si) and Module Temperature (Mono-Si/Poly-Si).

Data obtained from different sets of tests were analyzed. Current data from ESV-Hall sensor setup was identified to be leading the ESV-voltage data, mainly due to slower response of the ESVs when compared to the Hall sensor. Also, only String level data (i.e. data from last module – Module 20) was analyzed, as module level data was affected by delay response issues between ESVs.

Pmax data collected from testing fresh connectors, aged damp heat connectors and aged thermal cycling connectors were compared with Pmax from Solmetric test data to find the impact of current data points (from ESV – Hall Sensor based test setup) delayed by 5ms, 6ms, 7ms and 8ms respectively.

From Figure 1-21 and Table 5 below, it is evident that current data points delayed by 7ms produced results close (within allowed ±1.5% deviation) to Pmax data points obtained from Solmetric IV curve tracer.

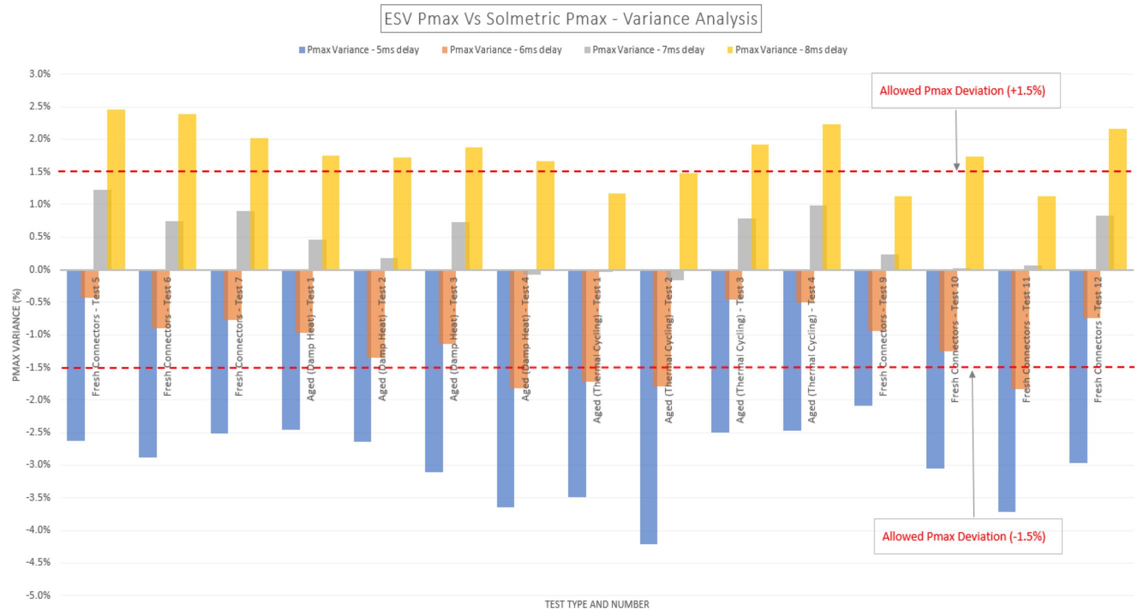


Figure 1-21: Pmax Variance Analysis

Maximum and Minimum Pmax deviation (%) obtained from delaying the current points at different time intervals (5ms/6ms/7ms/8ms) are shown in Table 5 below. It can be seen that 5ms delay had the worst results followed by 8ms delay. 6ms delay yield results which were marginally outside the allowed Pmax deviation, when compared to 7ms delay results (best result).

Table 4: Pmax deviation - Min/Max

Pmax Deviation	5ms delay	6ms delay	7ms delay	8ms delay
Minimum	-4.2%	-1.8%	-0.2%	1.1%
Maximum	-2.1%	-0.4%	1.2%	2.5%

IV curve for fresh connectors from Solmetric IV curve tracer were compared with IV curve from ESV setup (current data points delayed by 7ms) as shown in Figure 1-22. Both the curves are similar, with slight deviation observed towards the voltage end of the curve. Similar results were observed with chamber aged connectors.

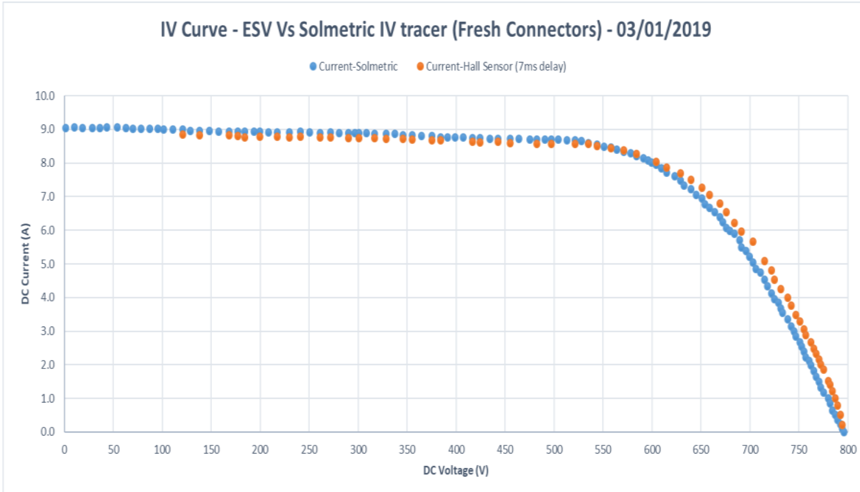


Figure 1-22: ESV Vs Solmetric IV Tracer - fresh connectors

From Figure 1-23 below, we can clearly see how the IV curve looks when current data points are not delayed compared to current data points delayed by 7ms. Similar results were observed with chamber aged connectors.

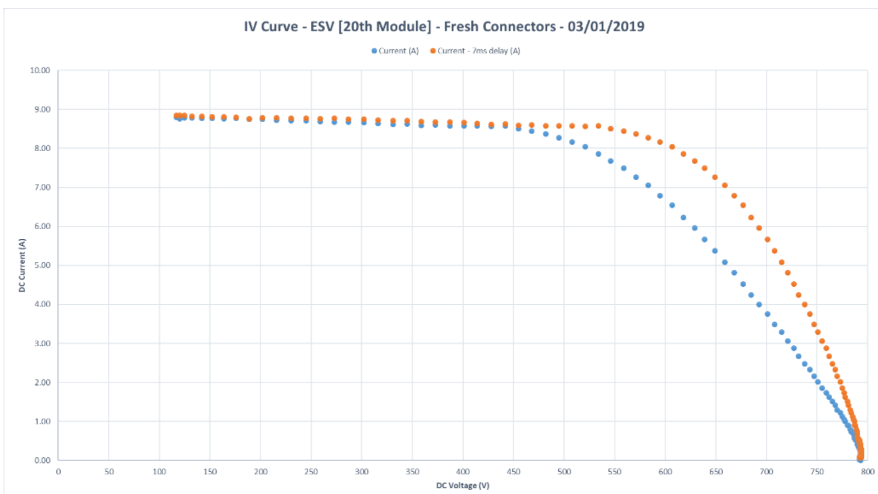


Figure 1-23: Fresh Connectors - 7ms data delay

Results from Fresh Vs Aged Thermal Cycling Vs Aged Damp Heat Connectors were compared to understand if the ESV test setup would be capable of identifying the impact of aged connectors.

From Figure 1-24 and Figure 1-25 below, it is evident that there is an impact of aged connectors when compared to the use of fresh connectors (Data points – Normalized/Not Normalized for Module Temperature/Irradiance) as the data points near Voc are observed to be strongly affected due to series resistance impact due to introduction of chamber aged connectors in the circuit. Here, normalized refers to data points normalized for module temperature of 25°C and Irradiance of 1000 W/m^2. It is to be noted that for comparison of all three test results (as shown in Figure 28, 29 and 30), only voltage values in 50V increment were selected and compared as three tests were done at different time.

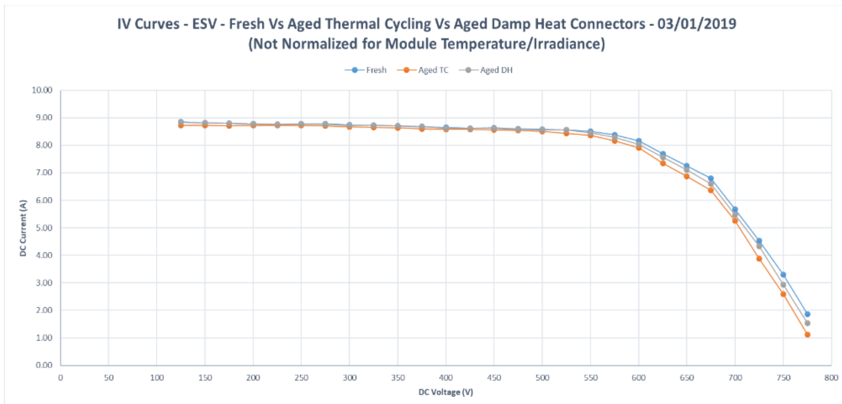


Figure 1-24: ESV - Fresh Vs Aged thermal cycling Vs Aged damp heat connectors (Not Normalized)

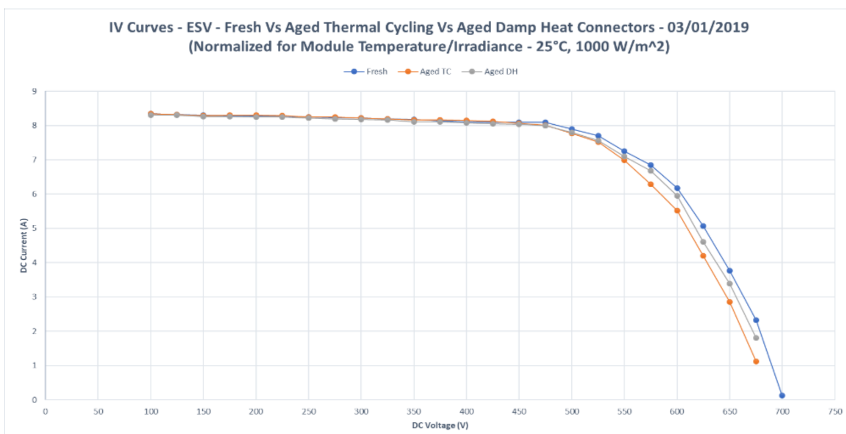


Figure 1-25: ESV - Fresh Vs Aged thermal cycling Vs Aged damp heat connectors (Normalized)

Similar results were observed when normalized data points (Fresh, Aged Thermal Cycling and Aged Damp Heat Test) from Solmetric IV curve tracer were compared as shown in Figure 1-26.

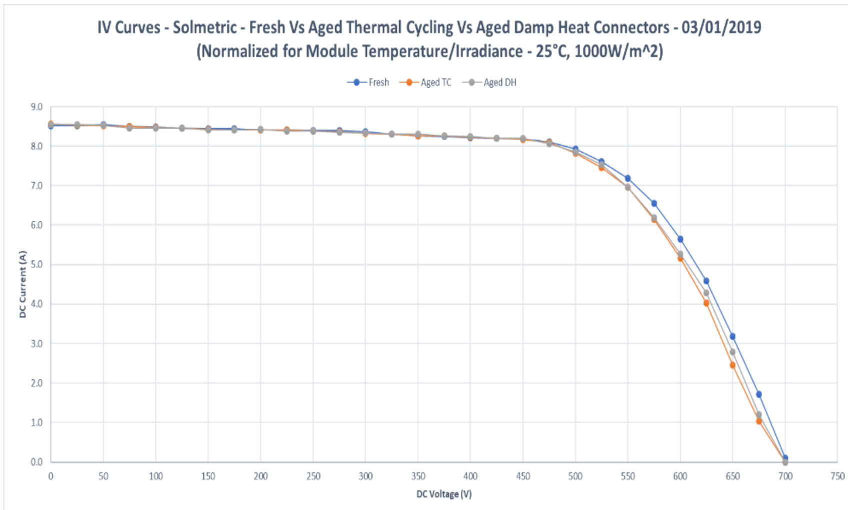


Figure 1-26: Solmetric - Fresh Vs Aged thermal cycling Vs Aged damp heat connectors (Normalized)

Soiling and Shading test

Soiling and Shading are major problems experienced by solar installations all over the world. In order to test the capability of Non-Contact Simultaneous IV curve measurement test setup in identifying the impact of soiling and shading on PV Modules, different tests were conducted at ASU-PRL.

Test setup for soiling/shading test is shown in Figure 1-27.

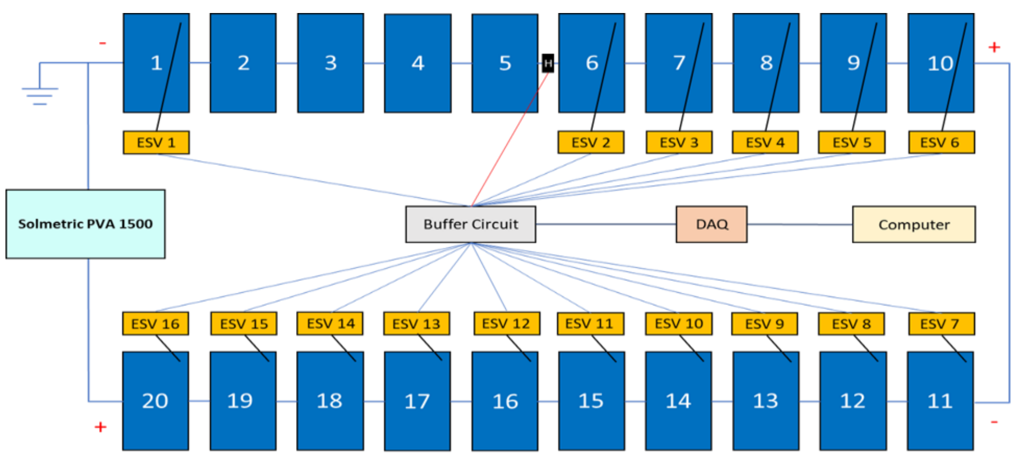


Figure 1-27: Test Setup - Soiling/Shading

Following are the details of how the shading tests were carried out.

Cardboard of dimension 38.3 ft * 7 ft was used to shade the PV module as shown in Figure 1-28 below.

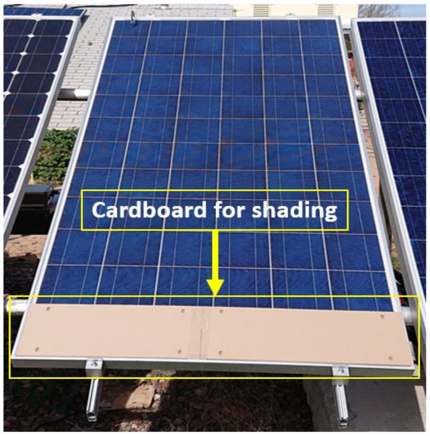


Figure 1-28: Experimental setup of shading experiments

Selected locations of the array were shaded, and results were collected. Locations are as follows:

- Module 20 – bottom row (last module on the PV Array)
- Module 20 – vertical (last module on the PV Array)
- Module 1 – bottom row (first module on the PV Array)
- Module 10– bottom row (tenth module on the PV Array)

Following are the details of how the soiling tests were carried out.

Water was sprayed onto the selected module for conducting soiling tests using a water spray bottle as shown in Figure 1-29 below.

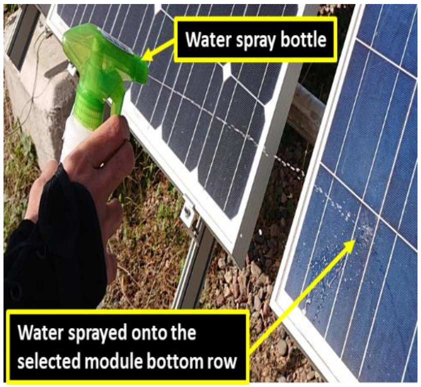


Figure 1-29: Soiling - Water sprayed

Subsequently, soil dust was gently dusted onto the water sprayed portion of the PV module using a cheese cloth as shown in Figure 1-30 and Figure 1-31 below.

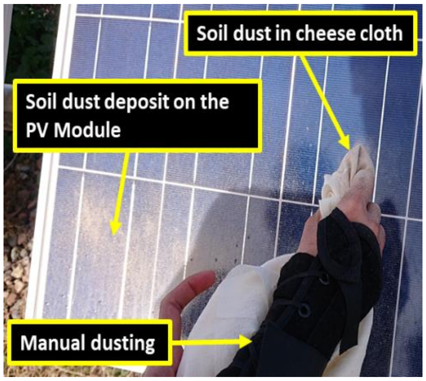


Figure 1-30: Soiling - Manual dusting

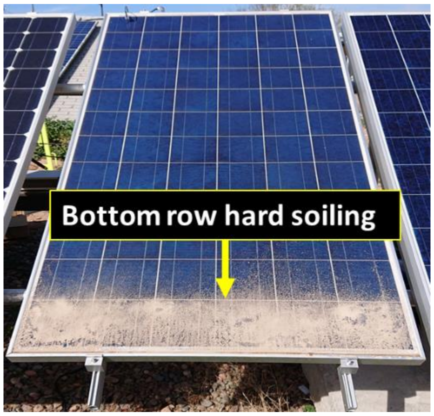


Figure 1-31: Soiling - Hard Soiled Module

The test setup was carried out on March 1, 2019 from 8:30 AM to 9:45 AM. There was high cloud coverage (>80%) till 12:00 PM, so the actual tests were not conducted during that time period. The tests commenced once the cloud coverage was minimal (< 25%). Different sets of tests were conducted between 1:45 PM to 2:44 PM. Following parameters were noted down while performing the tests – Reference Cell Irradiance (Mono-Si/Poly-Si) and Module Temperature (Mono-Si/Poly-Si).

The bottom row of Module 20 (last module in the PV Array) was shaded using a cardboard, as shown in Figure 1-32 below.

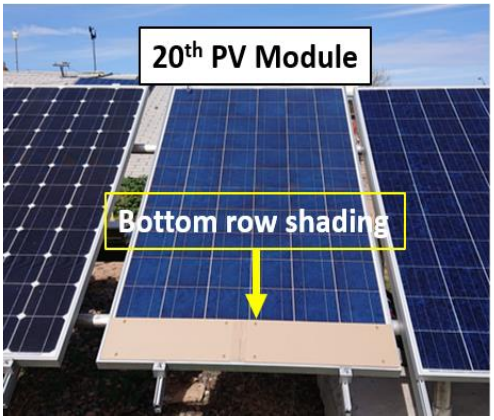


Figure 1-32: Shading - Module 20 (bottom row)

Test results from Non-Contact Simultaneous IV curve measurement test setup was compared with Solmetric IV tracer. As indicated in Figure 37 below, it can be clearly seen that IV curves from test setup matched with Solmetric IV tracer test results at the string level. It is to be noted that a 7ms delay was applied to the current data from the test setup in order to account for the response delay issue between ESVs and Hall sensor, as identified in the aged connectors testing report. Also, due to the response delay issue between the modules (which is under investigation), individual module level data were not analyzed. It is to be noted that for comparison of the test results (as shown in Figure 1-33), only voltage values in 50V increment were selected and compared as three tests were done at different time.

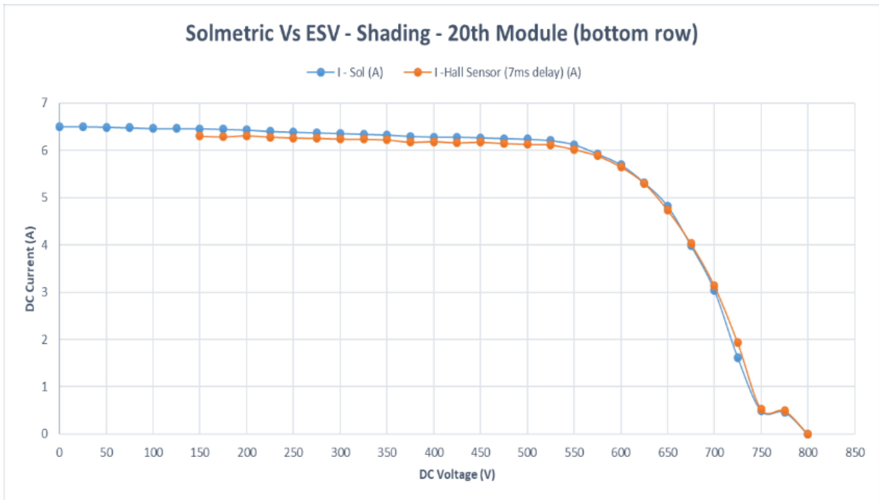


Figure 1-33: Solmetric Vs ESV - Shading - Module 20 (bottom row)

Similar results were obtained for the following shading tests: Module 20 – vertical, Module 1 – bottom row and Module 10 – bottom row and so they are not discussed here.

Module 20 (Last module in the PV Array) – bottom row was soiled as shown in Figure 1-34 below.

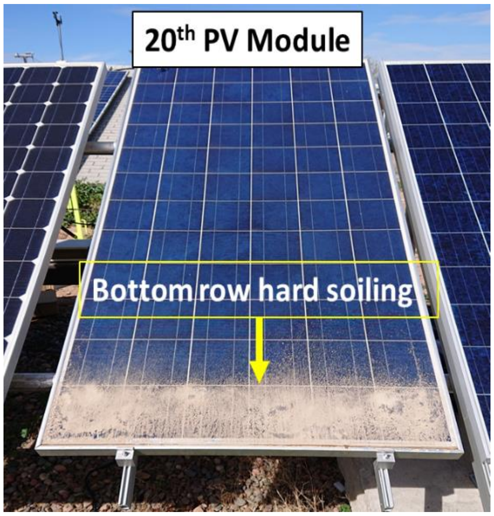


Figure 1-34: Soiling - Module 20 (bottom row)

Test results from Non-Contact Simultaneous IV curve measurement test setup was compared with Solmetric IV tracer. From Figure 1-35 below, it can be clearly seen that IV curves from test setup matched with Solmetric IV tracer test results at the string level. It is to be noted that for comparison of the test results (as shown in Figure 1-35), only voltage values in 50V increment were selected and compared as three tests were done at different time.

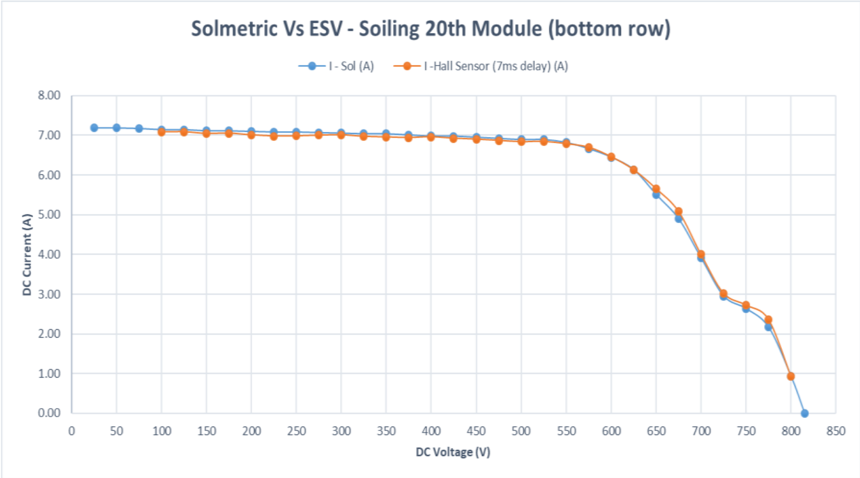


Figure 1-35: Solmetric Vs ESV - Soiling - Module 20 (bottom row)

Simultaneous IV-curve tracing in 1500V string

As proposed to DOE previously, the original planned homemade ESV probe deliverable was replaced by a 'switchbox' system. The details on the switch-box development is provided in Part 2 of this report.

ASU-PRL did not receive all 15 ESV probes ordered from Trek. Only 5 have been received at the time of testing. So, test was conducted with 21 ESVs of model 344/347 and 9 ESVs of model 565. While conducting the test on 04/26/2019, it was identified that five ESVs of model 565 were reading erroneous values along with one ESV each of model 344/347. So, they were turned off during the testing and only 23 module IV data were recorded.

The test setup is similar to Figure 1-13, but 30 PV modules were connected instead of 20 PV Modules. String level IV curves obtained from 23 PV Modules are shown in Figure 1-36.

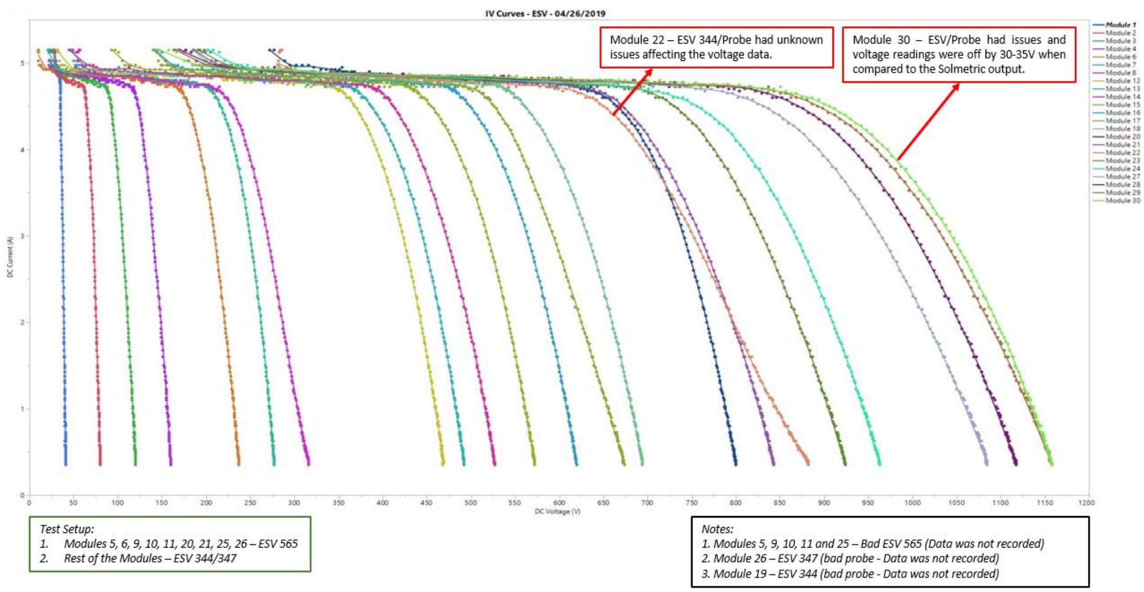


Figure 1-36: Non-contact I-V curves of the String and Substrings - 1500V String (Solmetric load)

Following were the key conclusions:

- The hall sensor data from DAQ was off by a factor of 10 while conducting the test. One of the PV Module in the field was short circuited and Hall sensor was connected to it to test if the hall sensor was working fine. Hall sensor was reading close to the short circuit current of the PV Module and so it was concluded that there is some issue with the DAQ, which is currently under investigation.
- The ESV/Probe connected to Module 30 had unknown issues affecting the voltage reading. The voltage was off by 30-35V when compared to the Voc reading from the Solmetric IV Tracer. It is to be noted that this ESV/Probe were working fine when they were initially connected to the PV Module before the readings were taken. This issue was investigated later.
- The ESV/Probe connected to Module 22 had some unknown issues which affected the IV data as shown in the plot above. This issue was investigated later.
- The test setup is capable of measuring 30 PV Modules although there were still accuracy issues associated with them.

Switchbox testing

We reported to DOE that our goal in quarter 5 will be performing switchbox testing using 1500V array system (30 PV Modules). To reduce the tracer cost, we decided to introduce a multiplexing scheme to reduce the number of ESVs from 30 to 6 using 5 switchboxes with 6 modules per switchbox. To achieve the quarter 5 goal, we undertook a two-step approach. In the first step, we decided to test only one switch box. In the second step, based on the first step experience, we will test all the five switch boxes. PV Measurements designed and built the first prototype switchbox. The switchbox capability was tested outdoor at ASU-PRL in the first week of June 2019 as shown in Figure 1-37.

The main objective of the test was to find whether the switchbox prototype works as designed, in particular:

- Test the switchbox prototype in a 7-module array (six test modules plus one pre-module) and confirm if it is working as designed.
- Verify if the IV curve parameter data via the switchbox meets the accuracy requirement by comparing with conventional IV tracers.

Test procedure:

- Connect the power supply to the power supply connector.
- Connect the ESV A to the ESV A connector on the end of the switchbox using a patch cable. The end of the patch cable with a piece of grey duct tape must connect directly to the ESV.
- Similarly, connect the ESV B.
- Connect the output from the ESV monitoring the module "below" (closer to ground than) the first module in the switched set to the connector marked "Prev ESV".
- Connect ESV A's output to the BNC jack on the switchbox marked "ESV A".
- Similarly connect ESV B's output to the switchbox.
- Connect probes to the modules to the 6 module jacks. The module numbers are written on the box. 2 4 6 5 3 1
- Connect an accurate handheld meter and the DAQ, in parallel, to the DAQ Output BNC connector.
- Connect the grounds of the switchbox, ESVs, and the ground of the PV module or string of modules to each other.

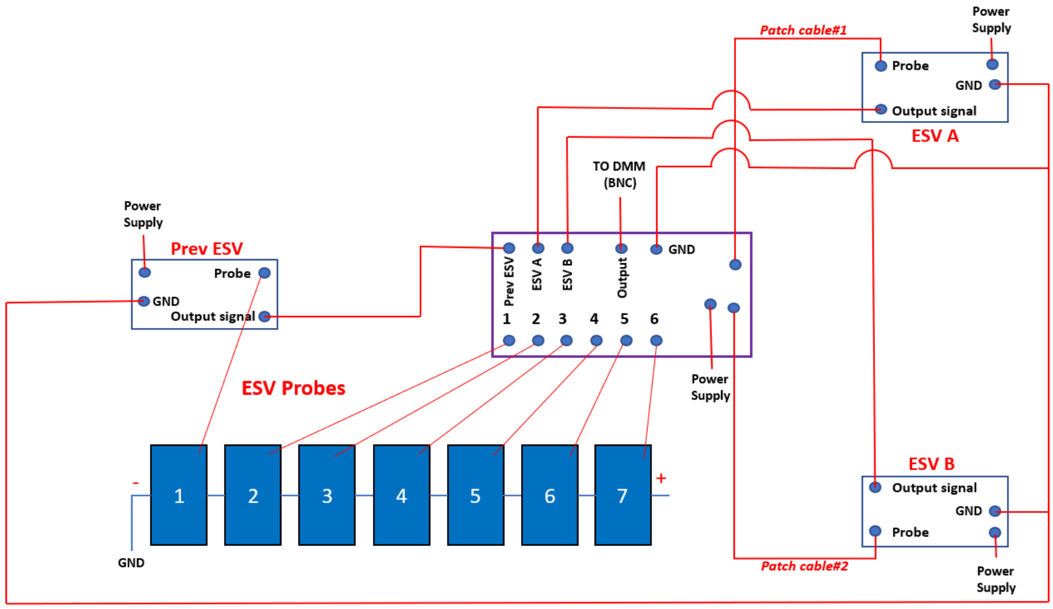


Figure 1-37: First Prototype Switchbox - Circuit connection

Switchbox probe offset correction (Figure 1-38):

- Remember to turn off the ESVs when switching the PV modules.
- Mount all the probes so that they probe a region of a module that is at ground potential.
- Set the switch to position 2.
- Turn on the ESVs
- Adjust the ESV "Zero" control for a zero front panel reading. Do not change the position of the Zero controls after this. Maybe apply tape to the control to make sure it doesn't inadvertently get turned.
- Turn the ESVs off.
- Connect a shunted BNC plug to the "Prev ESV" input.
- Set the switch to position 1.
- Turn on the ESVs
- Record the reading from the meter. This is the offset for Module 1.
- Turn off the ESVs.
- Similarly, measure and record the offsets for modules 2 through 6.
- Change the voltage where the probes are mounted to something greater than 20 VDC.
- Repeat steps 7-11, recording what the meter indicates.
- Compare the readings from grounded and ungrounded probes. Make sure that these readings are 1/100th of the voltage that was applied in step 12.

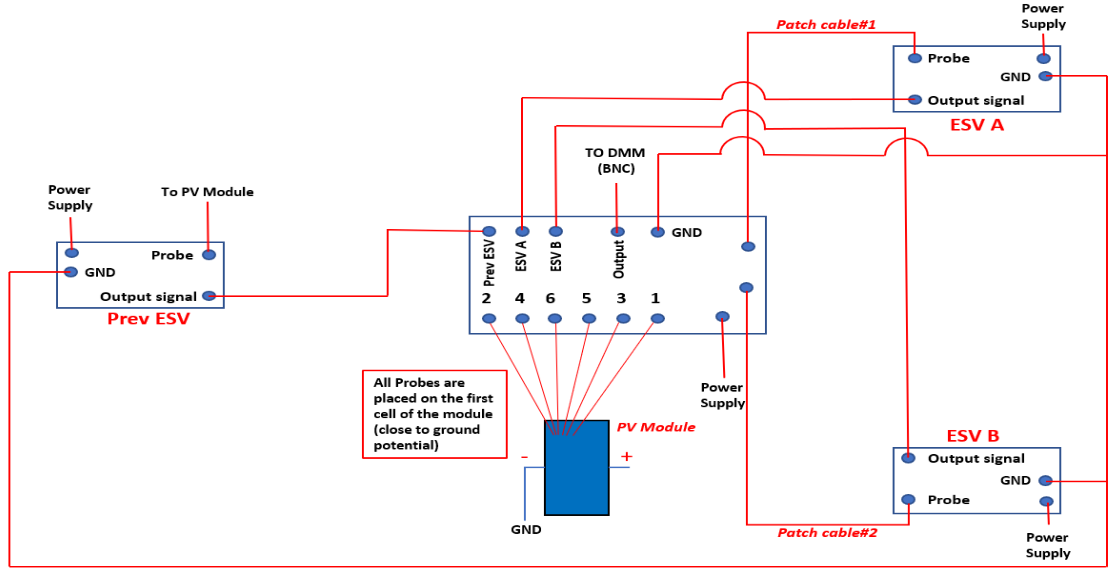


Figure 1-38: First Prototype Switchbox - Probe offset correction

Switchbox operation:

- Note: ESVs need to be turned off every time when switching modules
- Perform steps 1-9 in Switchbox connections.
- Using the procedures learned in Switchbox connections, first set the switch to Module 1, prepare and start the DAQ system, and sweep the string.
- Subtract Module 1's offset from the data obtained.
- Repeat above steps for modules 2-6, remembering to have the ESVs off while selecting the next module.
- The test was carried out on 06/07/2019 from 9:00 AM to 5:00 PM using only fresh connectors (i.e. connectors in the PV module of the array). Data obtained from the test was analyzed and results are as outlined below.

Switchbox – Probe Offsets:

Probe offsets were identified using the procedure outlined under the section “Switchbox probe offset correction”. Later the probe offsets were adjusted based on the data obtained from the test results using the voltage values before the IV curve tracing happened as the probe offsets were slightly different from the ones that were obtained using the procedure outlined to identify the probe offsets. Table 6 below contains the probe offsets information.

Table 5: Probe offsets

Module #	*Offset*
1	-0.337
2	8.821
3	7.811
4	-2.32
5	6.712
6	-2.748

Switchbox - Module IV curves:

Module IV curves (Module 1 to 6) measured using the switchbox are discussed below. Data obtained for each module from the switchbox were corrected for the offsets using the Table 6 above.

Individual module IV curves (Figure 1-39 through 1-44) obtained from the switchbox are provided below for reference.

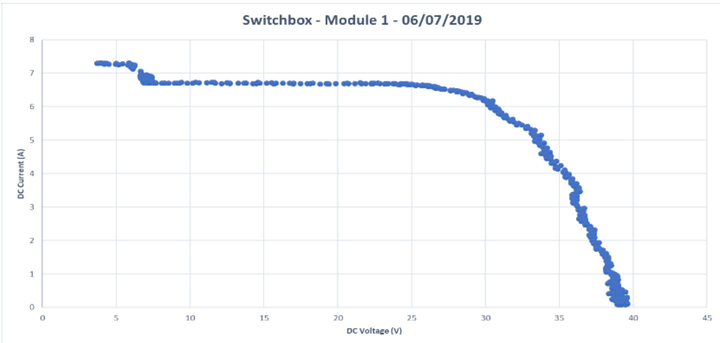


Figure 1-39: Switchbox - Module 1 IV Curve

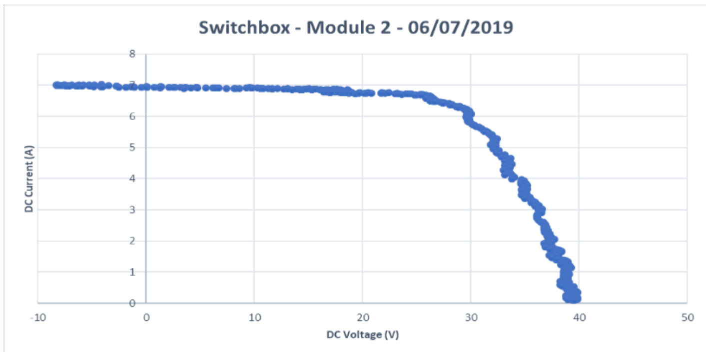


Figure 1-40: Switchbox - Module 2 IV curve

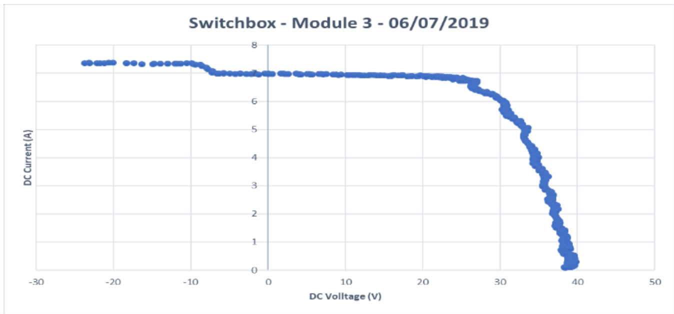


Figure 1-41: Switchbox - Module 3 IV curve

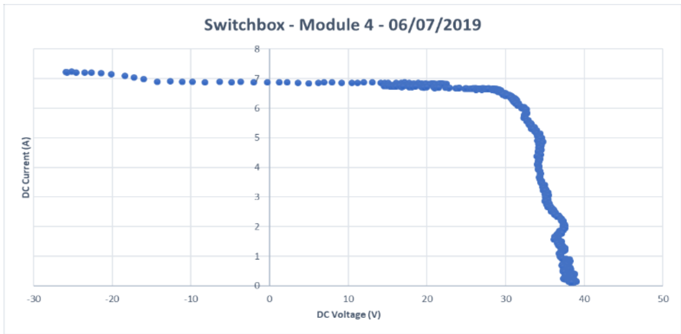


Figure 1-42: Switchbox - Module 4 IV Curve

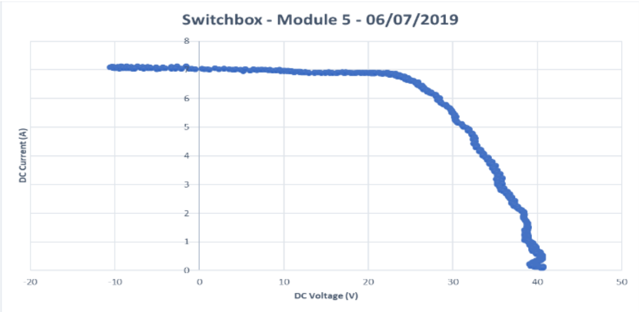


Figure 1-43: Switchbox -Module 5 IV Curve

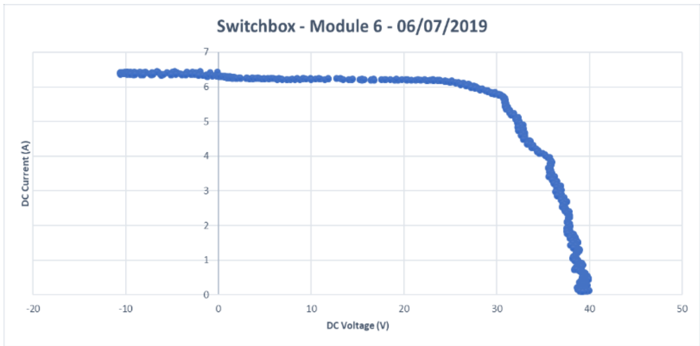


Figure 1-44: Switchbox - Module 6 IV curve

Switchbox – Accuracy of the IV curve parameters:

To quantify the accuracy of the IV parameters obtained from the test setup, following steps were carried out:

- Module IV curve was obtained using the Switchbox-ESV-Hall sensor setup.
- Individual module IV curve were obtained using the Solmetric IV curve tracer immediately (within 1-2 minutes) after a module IV curve was obtained using the Switchbox-ESV-Hall sensor setup.
- Another IV curve was traced using the Switchbox-ESV-Hall sensor setup after the individual module IV curve was obtained using the Solmetric IV curve tracer.
- Current data obtained from the Switchbox-ESV-Hall sensor was later adjusted for irradiance using the ratio of Isc reading from the Solmetric IV curve tracer during measuring individual module IV curve to the Isc reading from the Solmetric IV curve tracer, when Switchbox-ESV-Hall sensor setup was used for measuring the IV curve.

IV curve parameters (Vmax, Imax and Pmax) for the individual modules obtained from both the Solmetric IV curve tracer and the Switchbox-ESV-Hall sensor setup were compared, and results are presented below.

Vmax accuracy:
Vmax was determined to be accurate within 1.5% of the Solmetric measured data. The deviation for all the six modules is shown in Table 7 below. It is to be noted that Vmax value from the curve (for the curve obtained via Switchbox-ESV-Hall sensor setup) was selected as close as possible to the Solmetric tracer IV curve results in order to quantify the accuracy of the IV parameters. Vmax values were not always close to the knee region of the IV curve.

Table 6: Vmax accuracy

	Module 1	**Module 2**	**Module 3**	**Module 4**	**Module 5**	**Module 6**
Vmax - Solmetric (V)	**29.2**	**28.4**	**28.7**	**28.4**	**27.7**	**28.5**
Vmax - ESV (V)	**29.3**	**28.2**	**28.5**	**28.1**	**28.0**	**28.3**
Difference between Switchbox and Solmetric Vmax (%)	**0.1%**	**-0.8%**	**-0.6%**	**-1.0%**	**1.0%**	**-0.4%**

Imax accuracy:
Imax deviation was outside of 1.5% goal for all six modules as shown in Table 8 below. This higher deviation is attributed/suspected to the lower current measurement capability of the Hall sensor. A high accuracy Hall sensor needs to be explored and purchased. 7ms delay was applied to current data, but it is suspected that the delay may be higher than 7ms. This could be another reason for the high deviation with respect to Imax along with the hall sensor accuracy issues.

Table 7: Imax accuracy

	Module 1	Module 2	Module 3	Module 4	Module 5	Module 6
Imax-Solmetric (A)	6.9	7.0	6.9	6.8	6.9	6.4
Imax-Hall sensor (A)	6.3	6.4	6.3	6.6	6.1	5.9
Difference between Switchbox and Solmetric Imax (%)	**-9.1%**	**-8.8%**	**-9.8%**	**-3.7%**	**-11.6%**	**-7.6%**

Pmax accuracy:
Pmax deviation was outside of 1.5% goal for all six modules as shown in Ttable 9 below. This higher deviation is predominantly attributed to the lower current measurement capability of the Hall sensor. A high accuracy Hall sensor needs to be explored and purchased. 7ms delay was applied to current data, but it is suspected that the delay may be higher than 7ms. This could be another reason for the high deviation with respect to Pmax along with the hall sensor accuracy issues.

Table 8: Pmax accuracy

	Module 1	Module 2	Module 3	Module 4	Module 5	Module 6
Pmax-Solmetric (W)	202.9	198.1	199.2	194.0	192.4	182.6
Pmax-ESV (W)	184.6	179.2	178.7	184.9	171.8	168.1
Difference between Switchbox and Solmetric Pmax (%)	**-9.0%**	**-9.5%**	**-10.3%**	**-4.7%**	**-10.7%**	**-8.0%**

Following are the conclusion from this accuracy test.

- Vmax is within the 1.5% deviation goal.
- Imax and Pmax are beyond the 1.5% goal.
- The current and Pmax accuracy issues were confirmed with both Solmetric and DayStar tracer. Current shunt did not work properly with the test setup and thereby affected the current accuracy measurement testing.
- A new high accuracy Hall sensor will be explored and purchased.
- Delay in current data points needs to be addressed before quantifying the accuracy of the IV parameters.
- Once we are successful with the first six IV curves using the first switch box, we will immediately build the remaining five switch boxes to measure the IV curves of all 30 modules in a 1500V system.

ESV/Probe operational capability tests

Electrostatic Voltmeters (ESVs) and Probes used in the Non-Contact Simultaneous IV Curve Measurement (NCIV) Test Setup (developed jointly by ASU-PRL and PV Measurements Inc.) are designed and manufactured to be operated in specific operating conditions. For Example, Trek ESV Model 344 is rated for the following operating conditions: Temperature – 0°C to 40°C and Relative Humidity – to 90%, non-condensing. But, the Ambient/Module Surface Temperature in the field can exceed the 40°C range easily. So, to test the reliability of the ESVs and the Probes during high temperature operating conditions in the field, reliability testing of ESV/Probe was conducted at ASU-PRL on 04/03/2019. The test setup is as shown in Figure 1-45.

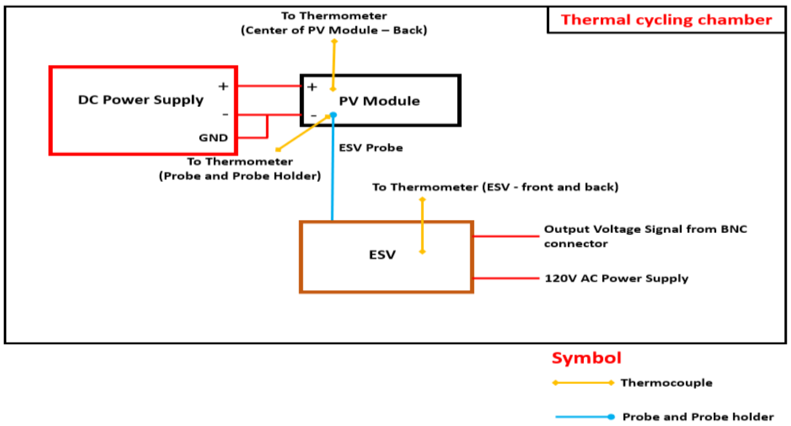


Figure 1-45: ESV/Probe Reliability test setup

The test setup was completed and tested for issues on April 2, 2019. The test was conducted on April 3, 2019, from 12:30 PM to 3:00 PM. Chamber temperature (°C) was controlled in 6 intervals as shown in Table 10.

Table 9: ESV/Probe Reliability test - Chamber temperature intervals

Interval	Start Time	End Time	Duration	Chamber Temperature (°C)	Ramp Rate (°C/minute)
1	12:40 PM	1:09 PM	30 minutes	25°C to -5°C	-1
2	1:10 PM	1:24 PM	15 minutes	-5°C	Constant (no ramp rate)
3	1:25 PM	2:19 PM	55 minutes	-5°C to 50°C	1
4	2:20 PM	2:34 PM	15 minutes	50°C	Constant (no ramp rate)
5	2:35 PM	3:00 PM	25 minutes	50°C to 25°C	-1
6	3:00 PM	3:00 PM	0 minutes	NA	NA

It is evident from Figure 1-46 that the ESV and Probe used in the test setup were operational at a very low chamber temperature of -5°C as well as at a high chamber temperature of 50°C, considering the manufacturer outlined operating temperature range of 0°C to 40°C. So, this ESV/Probe setup can operate in the field at ambient temperature of -5°C to 50°C without any problems. Only one ESV/Probe were tested to avoid damaging the available ESVs/Probes during the testing. Low chamber temperature of -5°C and high chamber temperature of 50°C were chosen in consideration to the operational and design margins of the ESV/Probe. This result is only applicable to the Trek ESV Model 344 and 555P-4, End-View, Miniature Probe. Other ESV/Probe models must be tested before employing in the field. Also, it was assumed that all units of Trek ESV Model 344 and 555P-4, End-View, Miniature Probe would work fine based on this test as more samples were not tested.

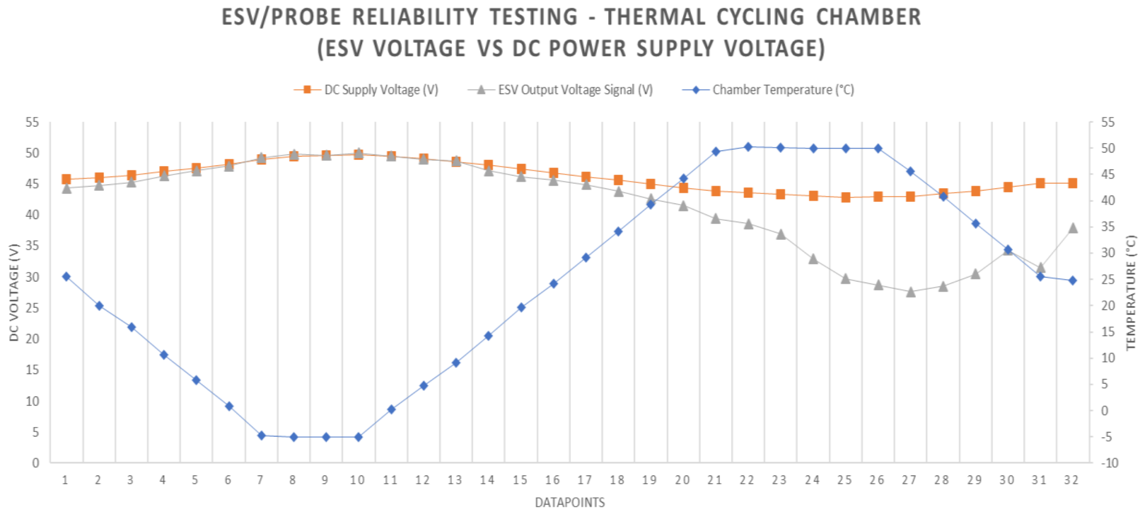


Figure 1-46: ESV Voltage Vs DC Power Supply Voltage

ASU-PRL identified that ESV and Probe needs to be calibrated together as a pair after several tests in the field as they observed that offsets changed with switching Probes from the same ESV or switching ESVs for the same probe. Then, we went with testing for verification of the ESV-Probe pair under the following conditions:

- Verification with using PV module in the field
- Verification with using control PV module in the lab under forward bias
- Verification with using control PV module in the lab under GND potential

Only results from "Verification with using PV module in the field" is discussed below as they provided better verification results when compared to the other tests.

Verification test #1: Using the PV module in the field for verification
Verification setup (Figure 1-47):

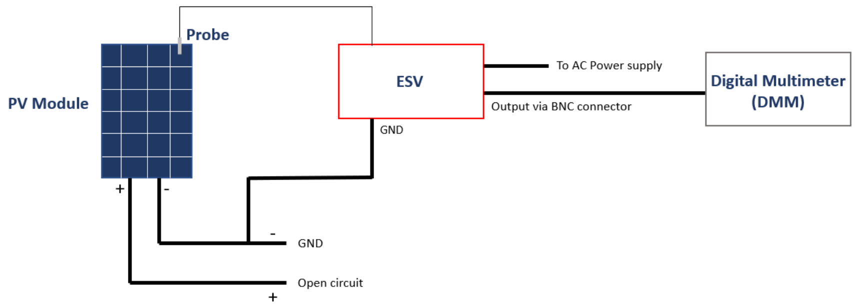


Figure 1-47: Verification test setup 1

Verification procedure:

- Select one PV module in the field.
- Select one ESV/Probe as a pair for verification.
- Connect a Digital Multimeter (DMM) between the positive and negative terminal of the PV module.
- Note down the PV module voltage shown in the DMM.
- Place the ESV probe on to the center of the last cell of the PV module.
- Make sure the ESV response gain is 0.
- Connect the ESV to a power supply and turn it on.
- Allow the ESV to stabilize (settle down on a value) for a time period of 10 seconds.
- Adjust the ESV offset so that the ESV reads the same voltage value (as close as possible) as shown in the DMM connected to the PV module. Make sure to connect a calibrated DMM (Digital Multimeter) to the output of the ESV using a BNC connector for measuring the DC voltage output signal from the ESV.
- Turn off the ESV and disconnect the DMM from the PV module.
- Compare the voltage values from the ESV and the PV Module. Make sure it is the same.

Thus ESV/Probe as a pair can be calibrated. Consider the tested ESV/Probe as a pair for all testing going forward. This verification test has to be performed for all the ESV/probe pairs before employing them in the field to mitigate accuracy issues.

Result:

Five pairs of ESV/probe were selected for this test. They were calibrated as outlined earlier in the verification procedure with respect to a single PV module in the field. To further confirm the verification accuracy, calibrated ESV-Probe pairs were tested as follows:

- Test with single PV module
- Test with two PV module string
- Test with three PV module string

Test with single PV module:

After verification, the calibrated ESV-probe pairs were tested for accuracy on a single PV module. ESV/Probe pairs were accurate within 1.5% allowed accuracy deviation as shown in plots below (Figures 1-48 and 1-49).

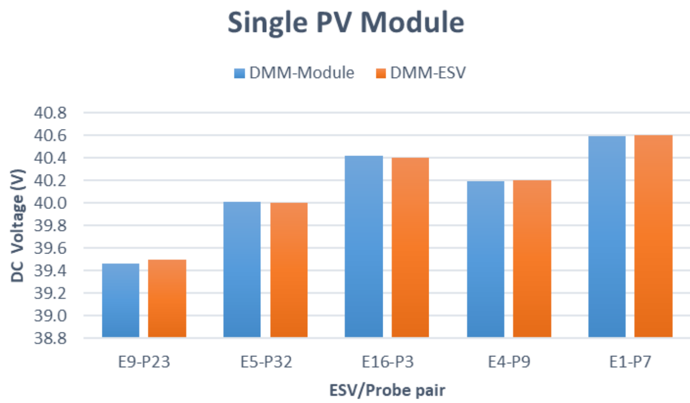


Figure 1-48: DC Voltage - ESV-Probe Pairs - Single PV Module

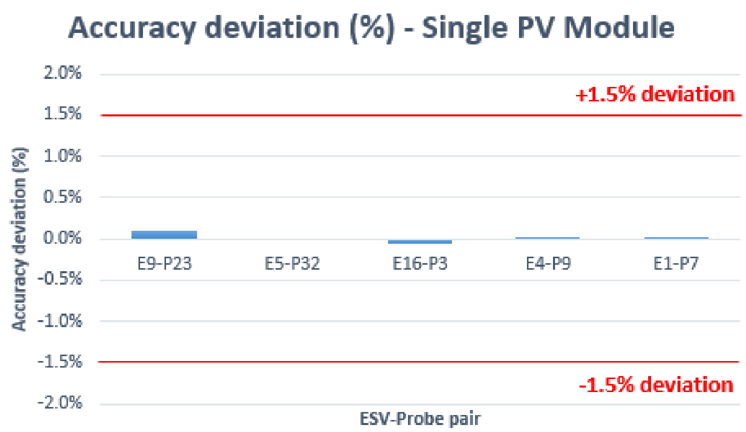


Figure 1-49: Accuracy deviation - ESV-Probe pairs - Single PV Module

Test with two PV module string:

Then, the calibrated ESV-probe pairs were tested for accuracy on a two PV module string. One ESV/Probe pair was not accurate as shown in the results below (i.e.) One ESV-Probe pair showed voltage values with accuracy deviation (1.6%) greater than allowed 1.5% accuracy deviation. All other four ESV-probe pairs were within the allowed 1.5% accuracy deviation (Figures 1-50 and 1-51).

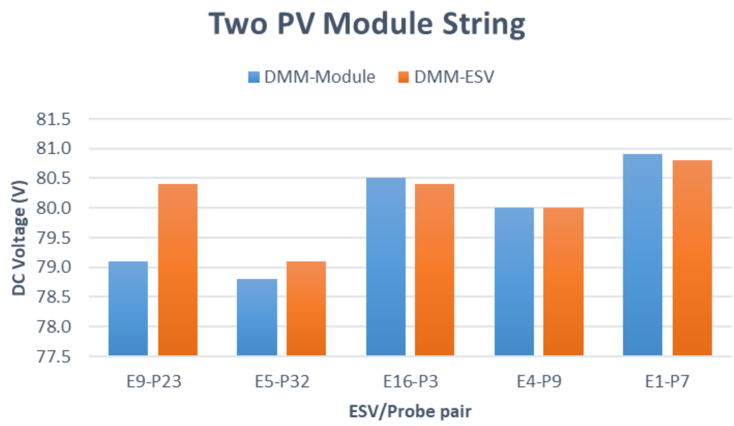


Figure 1-50: DC Voltage - ESV-Probe Pairs - Two PV Module String

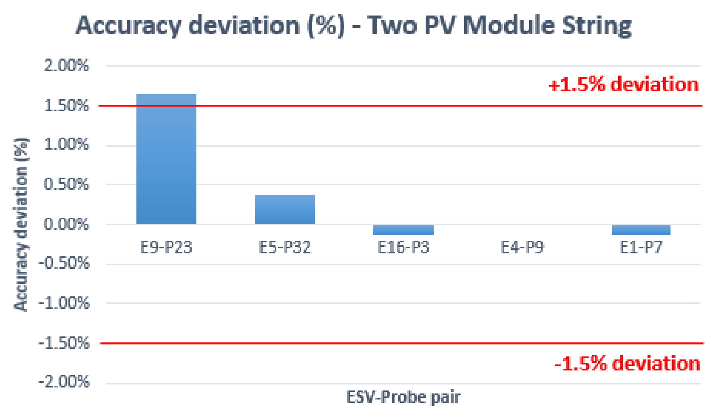


Figure 1-51: Accuracy deviation - ESV-Probe pairs - Two PV Module String

Test with three PV module string:

Then, the calibrated ESV-probe pairs were tested for accuracy on a three PV module string. One ESV/Probe pair was not accurate as shown in the results below (i.e.) One ESV-Probe pair showed voltage values with accuracy deviation (1.7%) greater than the allowed 1.5% accuracy deviation. All other four ESV-probe pairs were within the allowed 1.5% accuracy deviation (Figures 1-52 and 1-53).

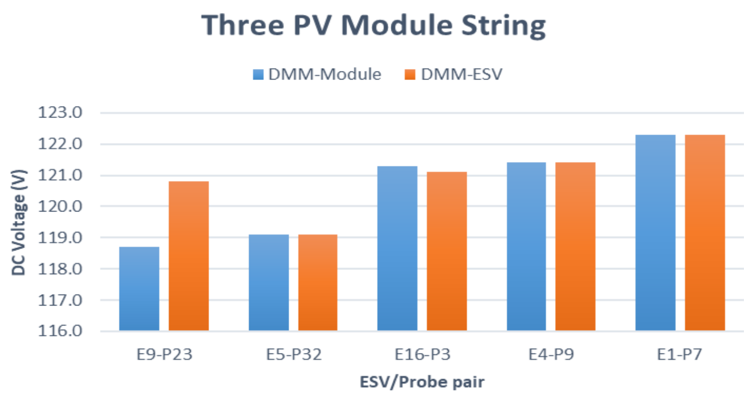


Figure 1-52: DC Voltage - ESV-Probe Pairs - Three PV Module String

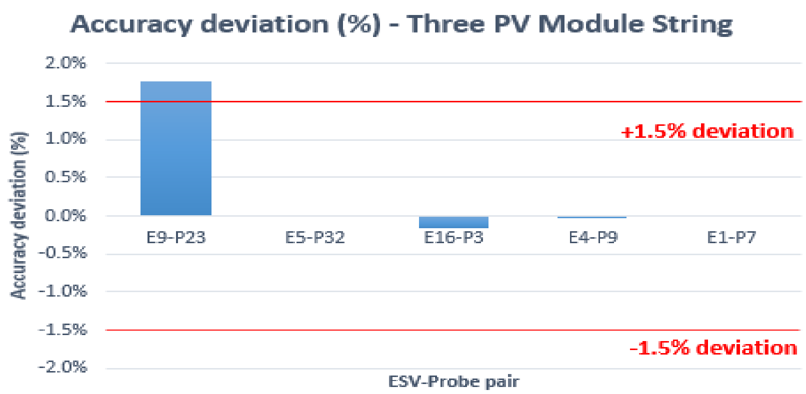


Figure 1-53: Accuracy deviation - ESV-Probe pairs - Three PV Module String

Repeatability of the measurement (same probe, same placement)

Setup (Figure 1-54):

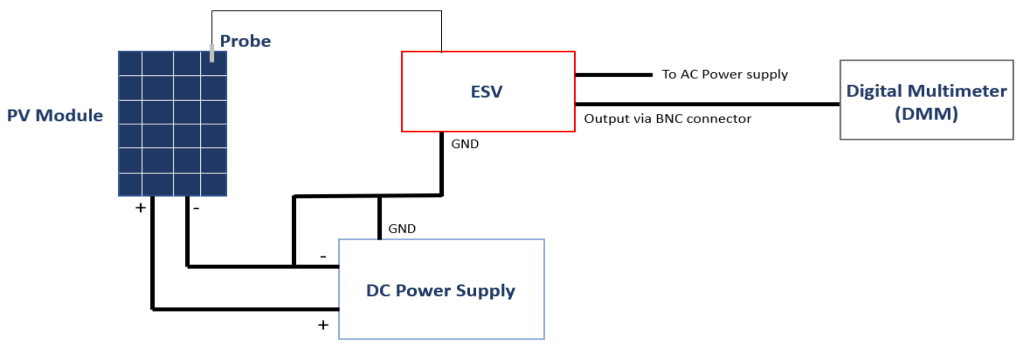


Figure 1-54: Test setup - Repeatability of the measurement – Control Module - Same Probe, Same placement

Procedure:

- Calibrate one ESV/probe pair as per the verification guidelines identified using a control module under forward bias.
- Care should be taken not to change any setting for the ESV/Probe pair after verification.
- Select one PV module for the testing purpose.
- Select a DC power supply with ground capability.
- Connect the DC Power supply to the PV module. (i.e.) positive to positive, negative to negative.
- Make sure the negative terminal of both the PV module and DC power supply are grounded. Connect the ESV ground to the same ground terminal where the PV module and DC power supply negative terminals are connected.
- Place the calibrated probe onto the last cell of the PV module and connect it to the ESV.
- Forward bias the PV module using the DC power supply.
- Note down the DC voltage at the power supply.
- Turn on the ESV and note down the value.
- Compare the value between the ESV and the DMM.
- Turn off and turn on the ESV 10-20 times and note down the voltage values from the DC power supply and the ESV.
- Repeat this test with a sample of 5-10 ESV/Probe pair to confirm the results.
- Analyze the test results and produce a report.

Result:

Five pairs of ESV/probe were selected for this test. Verification of ESV/Probe pair was done with respect to the probe position to be tested. Testing was done with respect to the steps identified above. Test was repeated for 10 times at the same probe position (calibrated position) for all five ESV/Probe pairs (Figures 1-55 and 1-56). DC voltage was maintained at 22.5V at the PV module using a DC power supply.

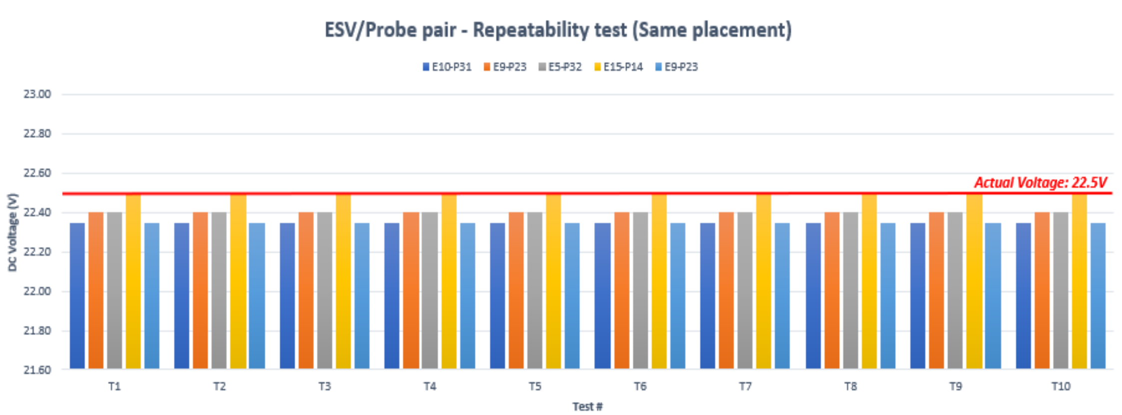
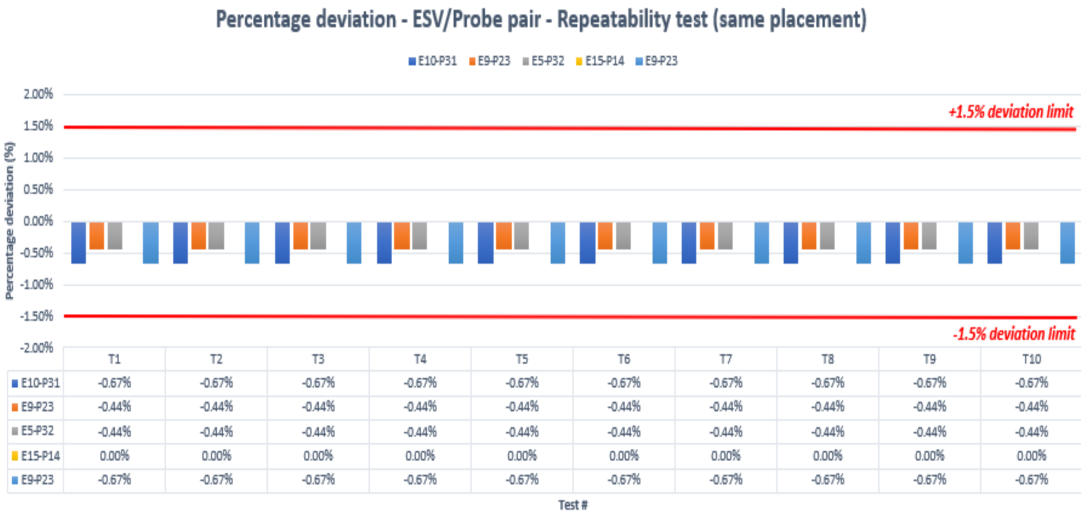


Figure 1-55: DC Voltage - same placement



	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
E10-P31	-0.67%	-0.67%	-0.67%	-0.67%	-0.67%	-0.67%	-0.67%	-0.67%	-0.67%	-0.67%
E9-P23	-0.44%	-0.44%	-0.44%	-0.44%	-0.44%	-0.44%	-0.44%	-0.44%	-0.44%	-0.44%
E5-P32	-0.44%	-0.44%	-0.44%	-0.44%	-0.44%	-0.44%	-0.44%	-0.44%	-0.44%	-0.44%
E15-P14	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
E9-P23	-0.67%	-0.67%	-0.67%	-0.67%	-0.67%	-0.67%	-0.67%	-0.67%	-0.67%	-0.67%

Figure 1-56: Accuracy deviation - same placement

Results prove the repeatability of the measurements (after verification) as the results from each ESV/Probe pair didn’t change throughout the testing. Results are also within 1.5% accuracy deviation limit as the maximum accuracy deviation observed was around -0.67% for two ESV/probe pairs.

Repeatability of the measurement (same probe, different placement)

Setup (Figures 1-57 and 1-58):

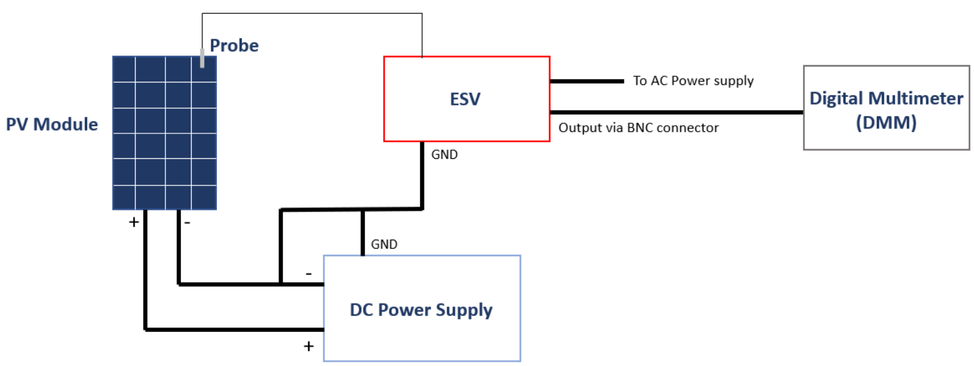


Figure 1-57:Test setup - Repeatability of the measurement – Control Module - Same probe, Different placement

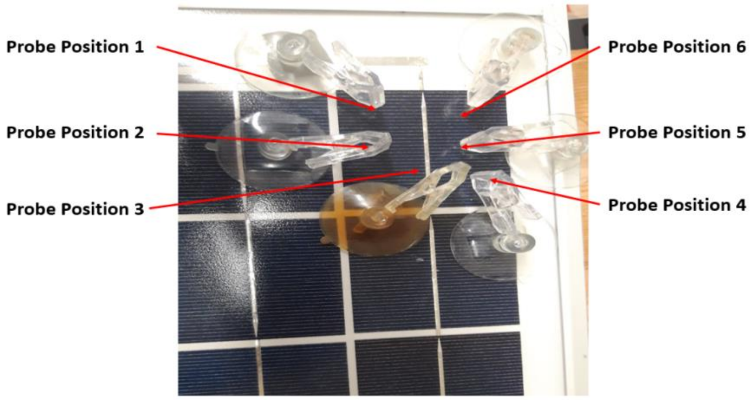


Figure 1-58: Probe position

Procedure:

- Calibrate one ESV/probe pair as per the verification guidelines identified. Care should be taken not to change any setting for the ESV/Probe pair after verification.
- Select one PV module for the testing purpose. (Here, instead of using a string, only one PV module was used but different positions were identified for the testing from the last cell of the PV module to prove the repeatability of the measurement with respect to placement variation).
- Select a DC power supply with ground capability.
- Connect the DC Power supply to the PV module. (i.e.) positive to positive, negative to negative.
- Make sure the negative terminal of both the PV module and DC power supply are grounded. Connect the ESV ground to the same ground terminal where the PV module and DC power supply negative terminals are connected.
- Place the calibrated probe onto the last cell of the PV module and connect it to the ESV.
- Forward bias the PV module using the DC power supply.
- Note down the DC voltage at the power supply.
- Turn on the ESV and note down the value.
- Compare the value between the ESV and the DMM.
- Repeat the steps above with placing the probe onto 5-10 different places within the last cell of the PV module.
- Compare the results and produce a report.
- Repeat this test with a sample of 5-10 ESV/Probe pair to confirm the results.
- Analyze the test results and produce a report.

Result:

Five pairs of ESV/probe were selected for this test. Verification was done with respect to the probe position 1. Testing was done with respect to the steps identified above. Test was conducted for six different probe position for all the five ESV/Probe pairs selected.

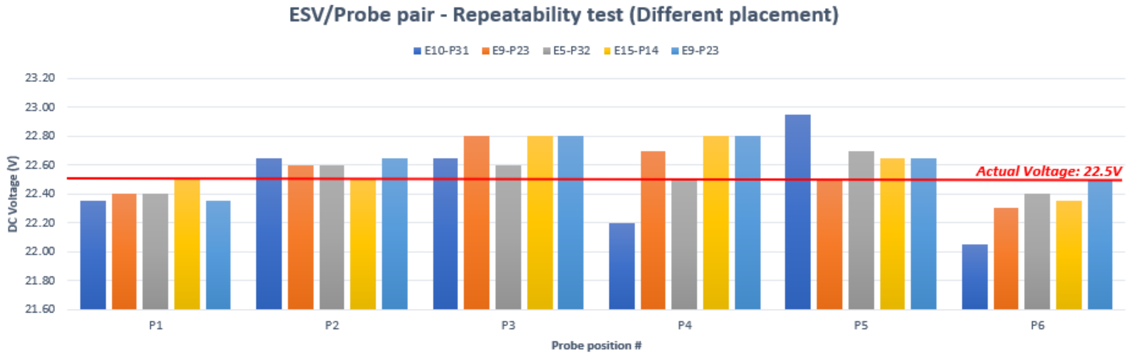
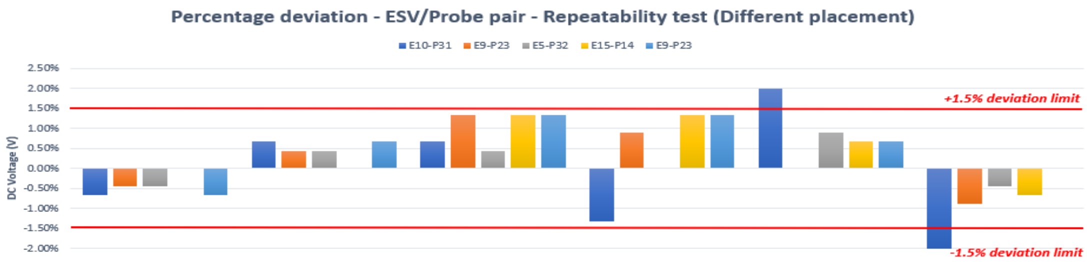


Figure 1-59: DC Voltage - different placement



	P1	P2	P3	P4	P5	P6
E10-P31	-0.67%	0.67%	0.67%	-1.33%	2.00%	-2.00%
E9-P23	-0.44%	0.44%	1.33%	0.89%	0.00%	-0.89%
E5-P32	-0.44%	0.44%	0.44%	0.00%	0.89%	-0.44%
E15-P14	0.00%	0.00%	1.33%	1.33%	0.67%	-0.67%
E9-P23	-0.67%	0.67%	1.33%	1.33%	0.67%	0.00%

Figure 1-60: Accuracy deviation - different placement

Results (Figures 1-59 and 1-60) are slightly different with respect to different probe positions. They are not the same as identified during the testing with same probe placement. Maximum deviation that was observed with respect to six different probe positions and different ESV/probe pairs was around ±0.45V with respect to the DC voltage maintained at the PV module using a DC power supply.

It is to be noted that the test results from the probe position (probe position 1) that was used for verification was well within 1.5% accuracy deviation limit. As probe position changed from 1 to 6, observed accuracy deviation (%) was higher at probe position further away from the probe position at which the verification was done. So, it can be understood that the probe should be placed as near as possible to the same position at which the ESV/probe pair was calibrated to get more accurate results.

Dark IV (to avoid light variation)

Setup (Figure 1-61):

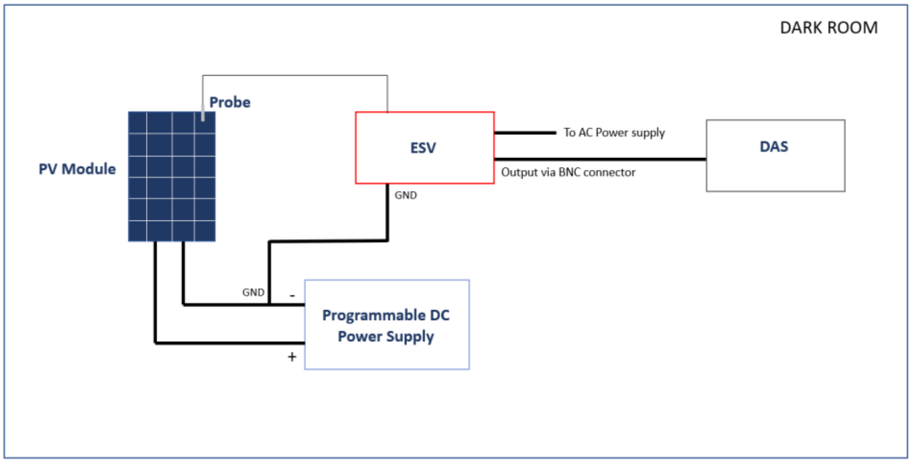


Figure 1-61: Dark IV test setup

Procedure:

- Select one PV module of known short circuit current and set it up for Dark IV measurement.
- Connect the positive and negative ends of the module with the positive and negative ends of the junction box used in Dark IV measurement.
- Take one calibrated pair of ESV and probe. Attach the probe to the last cell of the module using probe holder. Connect the ground of the ESV to the negative end of the PV module.
- Connect the output of the ESV to the DAS to record voltage.
- Connect a hall sensor in the circuit and connect its output to the DAS to record current.
- Switch on the ESV and check the voltage on the display. It should read zero.
- Switch off the lights and make sure no light is falling on the PV module. Cover the module with a blanket if needed.
- Set the saturated current on the DC power supply equal to the short circuit current of the PV module. Switch on the DC power output.
- Set a recording time of 10 seconds on the DAS. Start recording.
- At the same time, gradually increase the voltage from zero to the maximum value that it can reach. Make sure to do this in 10 seconds.
- Once the DAS stops recording, turn the DC power output back to zero and switch off the power output.
- Turn off the ESV.
- Repeat the entire measurement procedure for 3-5 pairs of ESV/Probe.
- Analyze the data from the DAS and produce a report.

Result:

Results (Figure 1-62) from three pairs of calibrated ESV/probe are provided below. Testing was done with respect to the steps identified above. Results are provided below.

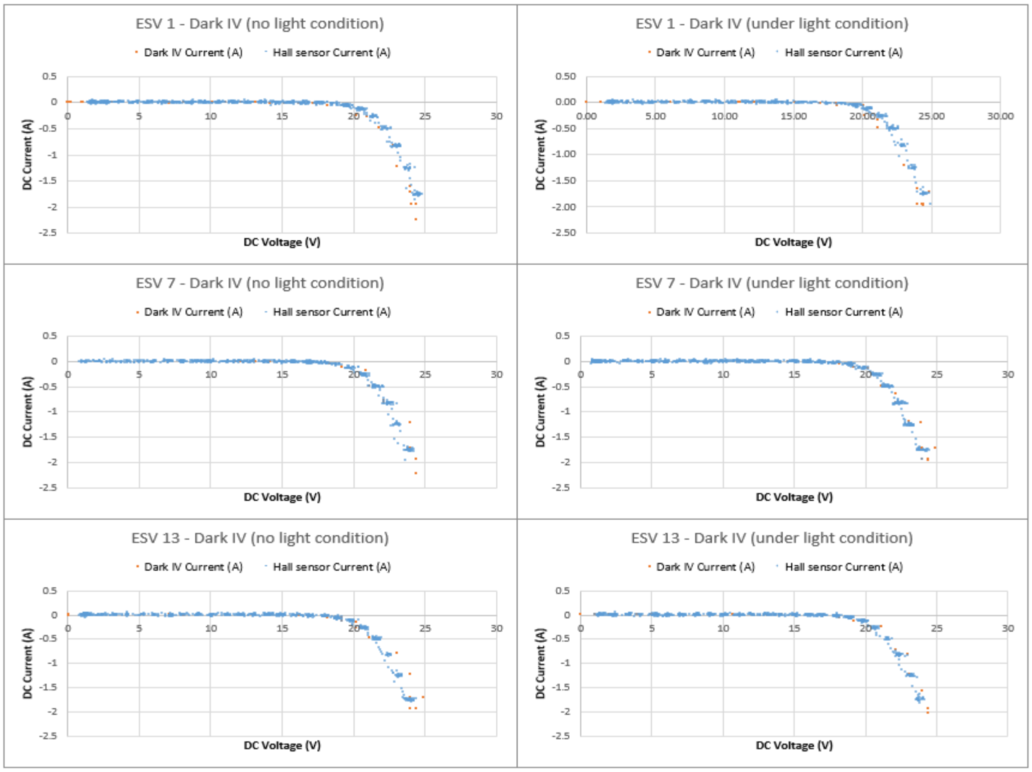


Figure 1-62: Dark IV test results

Based on the results above, it can be identified that light is not causing any visible variation during the measurement.

Effect of glass on ESV drift

In order to identify if the ESV drift phenomenon is caused due to the presence of glass, ASU-PRL conducted the following test. We tested the 5 ESV-Probe pairs on metal surface which was energized and repeated the test with glass surface on the metal plate similar to the test setup as shown in the chamber tests.

Oscilloscope results on testing the metal plate:

It is stable with metal plate based on the plots below (Figure 1-63). Variations we are seeing are mostly due to changes in the metal plate voltage. (i.e.) ESV follows whatever the metal plate voltage is. It does not change some time with respect to the metal, but 95% of the time it does if you look at the plot.

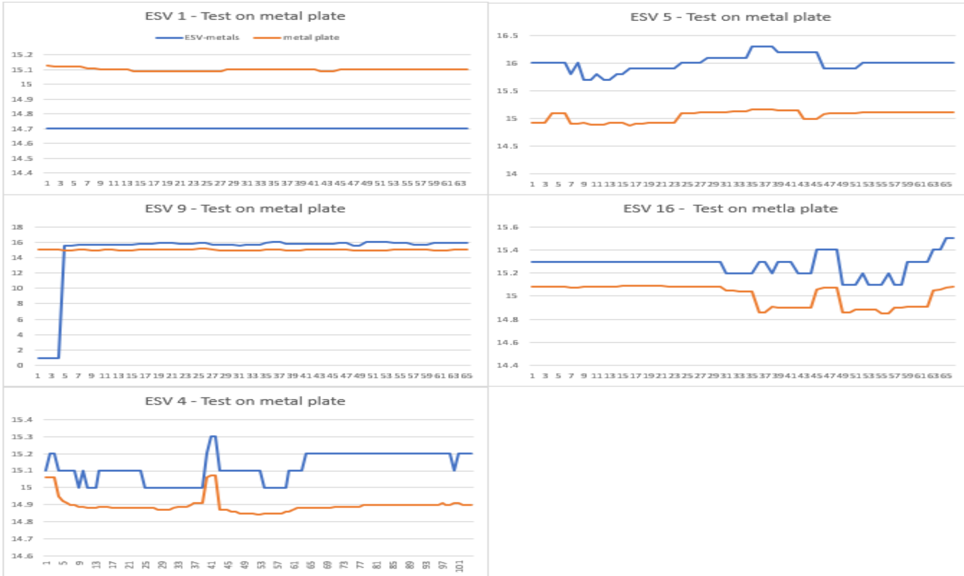


Figure 1-63: ESV drift - Metal plate

(X axis – Time (0.2s), Y -Axis – DC Voltage (V))

Oscilloscope results on testing the metal plate with glass surface over it:

Based on the plots below (Figure 1-64), it can be inferred that the ESV readings are definitely not stable with glass surface on the metal plate. It varies heavily and it is definitely not following the metal plate voltage trend.

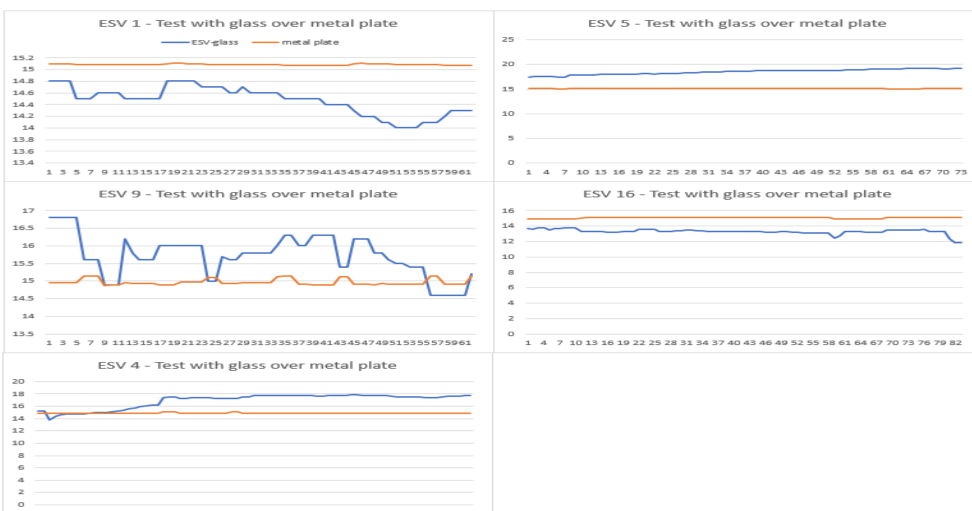


Figure 1-64: ESV drift - glass surface

(X axis – Time (0.2s), Y -Axis – DC Voltage (V))

Based on the results above, it can be inferred that there is something going on with introducing the glass surface. Either some glass property affects the ESV results or the distance of 3.2mm (glass width) at which the ESV is placed is creating the issue. But the same phenomenon was not seen with the testing carried out with the PV module in the field although the glass surface is more or less the same. This makes us believe that the glass surface may not be the issue or the distance of 3.2mm (glass width) from the cell surface. Something else is happening with glass and metal combination, which is not happening at the PV module

ESV Stabilization Vs Response Gain

In order to understand the time taken for the ESV to stabilize with respect to different response gain, test was conducted at different ESV response gains – 4, 7 and 9.

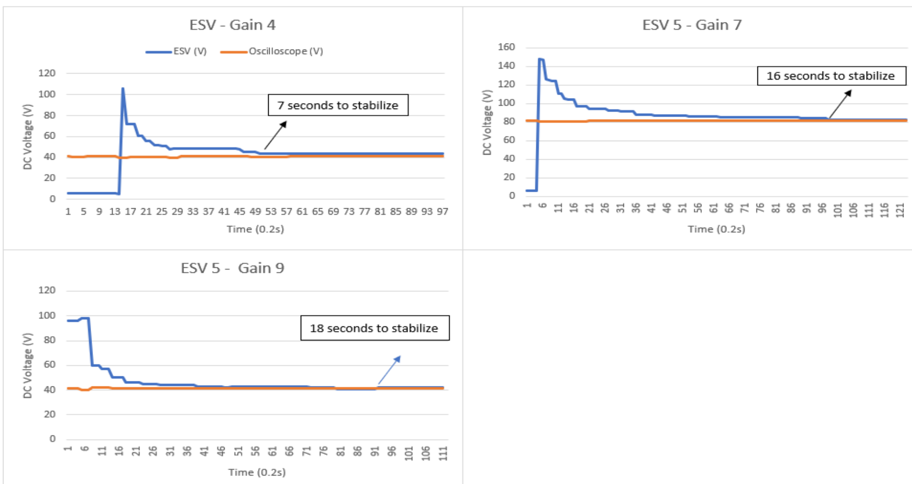


Figure 1-65: ESV Response gain Vs Stabilization

Following are the inference based on the plots above (Figure 1-65):
1. As response gain increases, time to stabilize increases.
2. To work around this stabilization issues, we have to turn the ESVs on before the IV tracing happens to let them stabilize for a period of around 10 seconds with the response gain setting as 0 in the ESVs.
3. During verification, we have to let the ESVs stabilize before adjusting their offset if required.

IV curve testing using an electronic load

Setup (Figure 1-66):

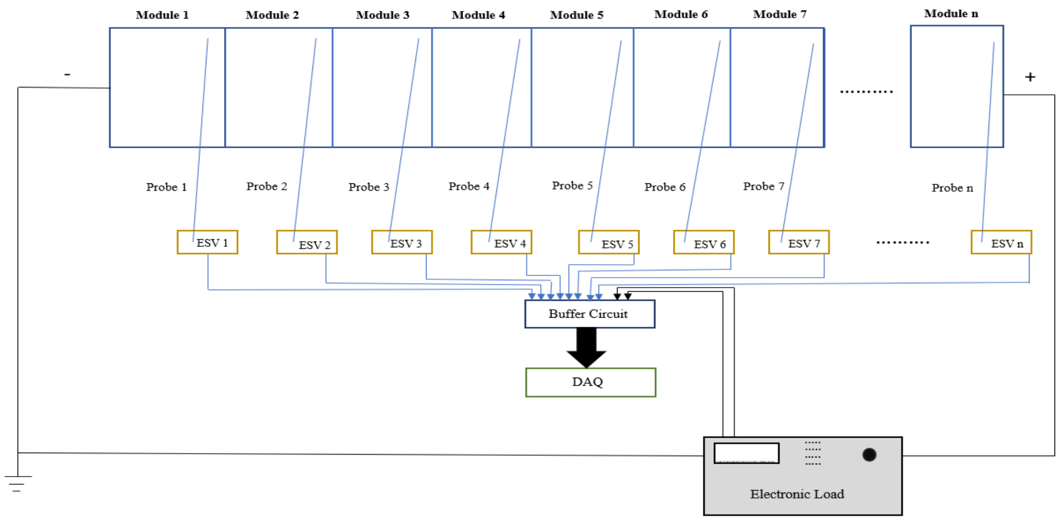


Figure 1-66: NCIV test setup using electronic load

Procedure:

- An electronic load (Chrome - model number 63206A-1200-240) is used instead of conventional IV curve tracers in order to achieve slow speed IV tracing as most conventional IV tracers don't have the ability to control the IV curve tracing speed.
- An electronic load is operated in the constant resistance mode - high range, capable of handling up to 1200V.
- The resistance of the load is constantly varied manually by turning a knob present in the front panel of the electronic load. Currently, this is a manual process until the load is programmable to change the resistance at regular intervals depending on the IV curve tracing time required by the operator.
- The voltage and the current across the load are collected from the current and voltage monitor ports of the electronic load using coaxial cables and fed into the DAQ from the NCIV setup.
- The ESV/probe pairs are also placed on selected modules to collect the I-V data without disturbing the PV module leads in the string.
- The data from the ESV is also collected using the coaxial cables and fed into the DAQ.
- As the values of the resistance is changed in the electronic load from low to high, the operating current and voltage of the PV modules/string changes.
- This change in voltage is captured by the ESV and recorded by the DAQ associated with the NCIV setup.
- The DAQ present in the system collects n data points from each node at the rate of R samples per second. These parameters are chosen by the users.

- The operating points of the string (voltage/current) can be seen in the front panel of the electronic load. This display helps the operator of the electronic load to time the rate at which the load value is changed.

Operation:

- Six modules were connected in a string to the load for this test.
- Six ESV/Probe pairs were calibrated with respect to a PV module in the field.
- Probes from the calibrated ESV/Probe pairs were then placed on each PV module in the six-module string.
- ESVs were turned on and allowed to stabilize for a period of 10 seconds.
- After ESV/Probe stabilization, resistance is changed in the load gradually by the Operator.
- Data is recorded in the DAQ from both the ESVs and the load.
- As the string reaches its open circuit voltage, test is stopped.

Result:

Data collected was analyzed and results are provided below (Figures 1-67 and 1-68). As we used current data from the load, we have completely removed the uncertainty in recording the current values using the hall sensor which had error up to ±4% based on the verification results from last quarter. We were successfully able to obtain good IV curves using an electronic load. There were limitations with respect to resistance ranges in the load and availability of manual to program the resistance change so that tracing can happen automatically (for the test, resistance was changed manually), which resulted in incomplete IV curves for the PV modules around Isc to Imax region, but the accuracy of the data collected was not affected. Following was observed:
IV curve from the ESV-sixth module (string) matched with the load IV curve. There were no visible deviations.
PV curve from the ESV-sixth module (string) also matched with the load PV curve. There were no visible deviations.

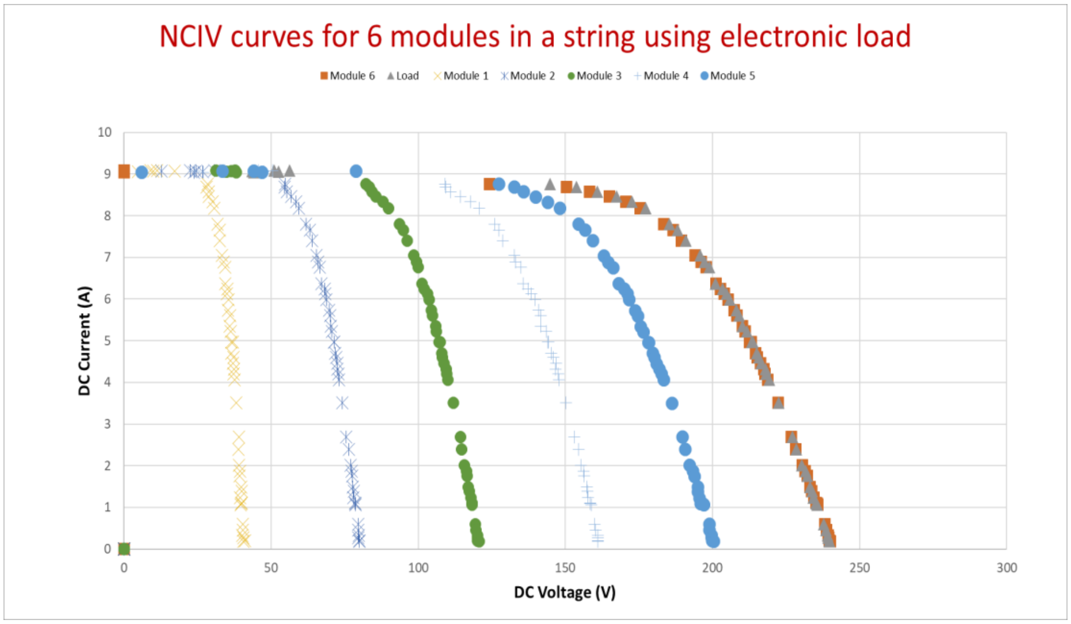


Figure 1-67: NCIV curves for 6 modules in a string using electronic load

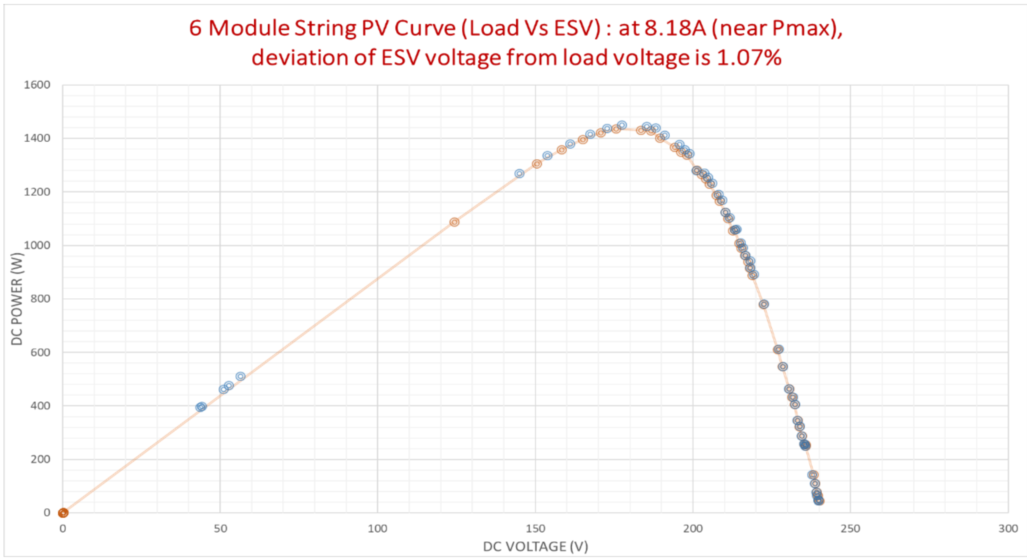


Figure 1-68: PV curve - 6 modules string

Accuracy of the IV parameters:

From the Table 11 below, it is evident that all three major IV parameters (Vmax, Imax and Pmax) are within the allowed accuracy deviation limit of 1.5%. This is a great result confirming the accuracy of the test results as well as proving that the verification methodology using the field PV module produces high accuracy results well within the allowed accuracy deviation limit of 1.5%.

Table 10: IV Parameters Accuracy Information

	IV Parameter		
Component	**Pmax (W)**	**Vmax (V)**	**Imax (A)**
Load	1435.63	175.47	8.18
ESV	1450.92	177.34	8.18
Accuracy deviation (%)	1.07%	1.07%	0.00%

New Probe Exploration:

ASU-PRL attempted to explore other probes available to be used with Trek 344 ESV model in order to fix the accuracy related issues. ASU-PRL went ahead with placing order to TREK for a single probe of model 555-P-1 to further investigate if it could help us alleviate the accuracy related issues.

Decision to go ahead with the new probe was based on the intuition that the bigger sensor diameter would provide better results than the old probe (Model: 555-P-4). Model 555-P-1 probe has a sensor diameter of 2.56mm, whereas Model 555-P-4 probe has a sensor diameter of only 1.17mm (Figure 1-69). So, it is evident that Model 555-P-1 probe has a bigger sensor diameter than Model 555-P-4.

Figure 1-69: P1 Probe (2.56mm aperture diameter; side face) and P4 Probe (1.17mm aperture diameter; front face)

New Probe Vs Old Probe – Technical details:

Model 555-P-4 probe is an end-view probe (i.e.) It has sensor at the bottom. Speed of response of the probe is around less than 4.5ms. Noise from the probe is around less than 4mV.

Model 555-P-1 probe is a side-view probe (i.e.) It has sensor at the side. Speed of response of the probe is around less than 3ms. Noise from the probe is around less than 3mV.

Based on the information provided above, it is evident that the new probe has a higher speed than the old probe. Also, noise from the new probe is less than the noise from the old probe. Technically, new probe sounds better than the old probe.

New Probe Vs Old Probe – Test Results #1 – Probe Response Time:

In order to test the new probe, initial tests were carried out on a single mono-Si PV module with both new probe and old probe attached to the last cell of the same PV module. Following were the results obtained as shown in Figure 1-70.

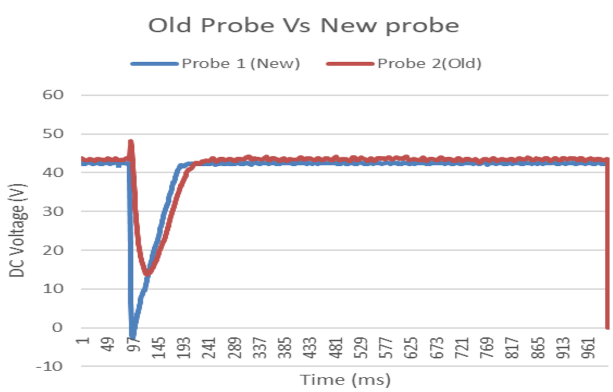


Figure 1-70:Test 1 - Old Probe Vs New Probe

New Probe (555P-1) seems to be faster than Old Probe (555P-4).
New probe reaches 0V (representation of short circuit condition) for voltage less than 50V, which was not possible with the old probe as evident from this plot as it only reached a lowest of 15V.

These readings were taken with response gain 0. Accuracy was not determined as current sensor was not operational during the test.

Test Results #1– Solmetric Tracer as Load:

After receiving encouraging test results as explained above, ASU-PRL conducted further experiments with Solmetric Tracer and also after replacing the bad current sensor. This experiment was conducted to identify the accuracy of the IV parameters obtained using the new probe. Following are the preliminary results obtained. It is evident from Figure 1-71 that new probe is faster than the old probe as identified in earlier results. IV curve from the NCIV setup matched with the IV curve from Solmetric tracer with accuracy of all IV parameters within allowed accuracy deviation limit of 1.5%

Also, we got complete IV curves under certain adjustments as discussed below.

Adjusting hall sensor data for its accuracy issues. This new hall sensor needs to be calibrated.

Current data from the hall sensor needed to be moved by 4 data points (4ms) as voltage data was falling behind similar to what we observed in the past experiments with Solmetric/Daystar. This can be mitigated by using electronic load/slow IV sweeper.

ESV with the new probe maxed out even after maximum zero offset adjustment during calibration at 42.45V, whereas the DMM connected to the PV module was reading 42.67V. So, we manually added a constant of 0.22V to the measured ESV voltage value, as shown in Figure 1-72, before analyzing the data (Table 12).

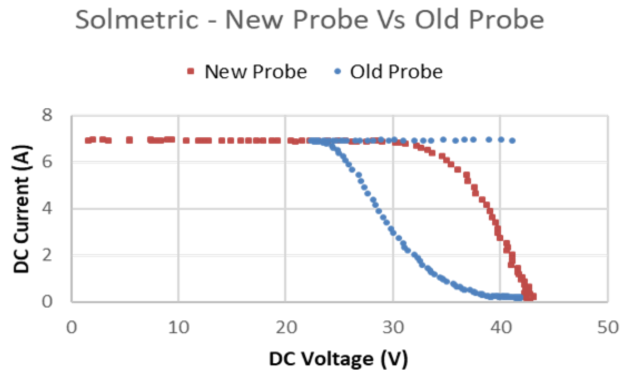


Figure 1-71: Test 2 - New Probe Vs Old Probe (Solmetric load curve not shown) at the Module Level

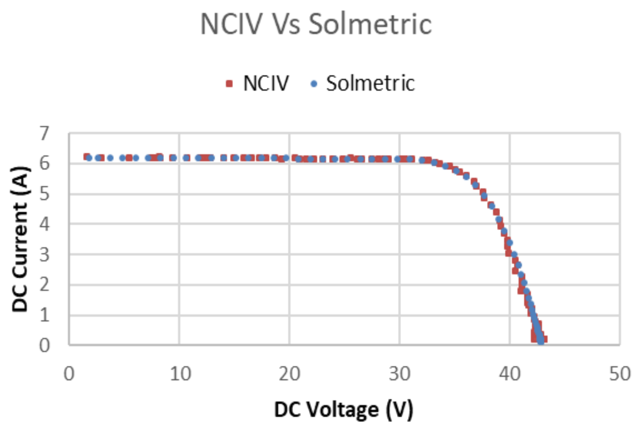


Figure 1-72: Test 2 - NCIV with new probe Vs Solmetric at the Module Level

Table 11: Test 2 - IV Parameter Accuracy

IV Parameters	Solmetric	New Probe	Accuracy deviation (%)
Vmax	34.67	34.57	-0.30%
Imax	5.87	5.92	0.93%
Pmax	203.37	204.65	0.63%
Isc	6.20	6.21	0.11%
Voc	42.93	42.82	-0.25%

Test Results #3 – Daystar Tracer as Load:

ASU-PRL conducted further experiments with the Daystar tracer like the tests with the Solmetric tracer. This experiment was conducted to identify the accuracy of the IV parameters obtained using the new probe with respect to the Daystar tracer.

Following are the preliminary results obtained. It is evident from the figure that new probe is faster than the old probe as shown in Figure 1-73. IV curve from the NCIV setup matched with the IV curve from Daystar tracer with accuracy of all IV parameters within allowed accuracy deviation limit of 1.5%

Also, we got complete IV curves under certain adjustments as discussed below. Adjusting hall sensor data for its accuracy issues. This new hall sensor needs to be calibrated. Current data from the hall sensor needed to be moved by 3 data points (3ms) as voltage data was falling behind similar to what we observed in the past experiments with solmetric/daystar. This can be mitigated by using electronic load/slow IV sweeper. ESV with the new probe maxed out even after maximum zero offset adjustment during calibration at 42.45V, whereas the DMM connected to the PV module was reading 42.67V. So, we manually added a constant of 0.22V to the measured ESV voltage value, as shown in Figure 1-74, before analyzing the data (Table 13).

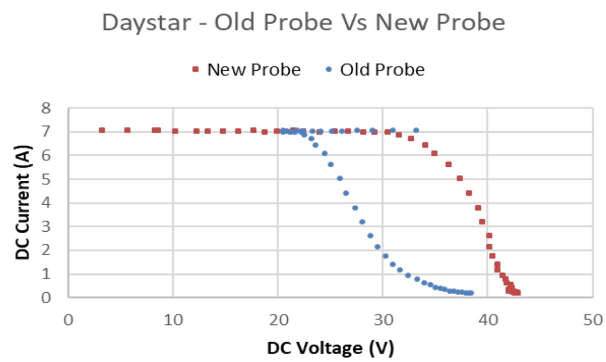


Figure 1-73: Test 3 - New Probe Vs Old Probe (Daystar)

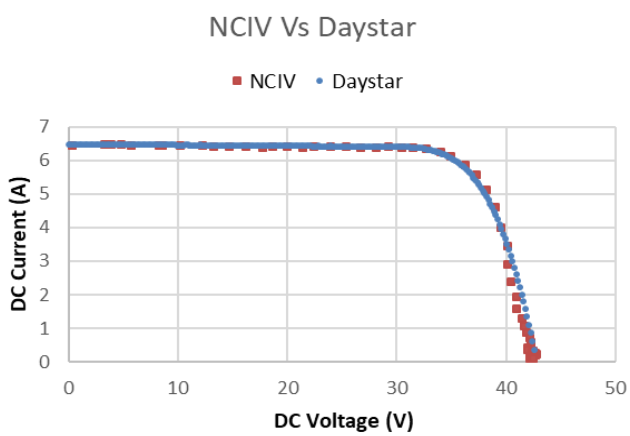


Figure 74: Test 3 - NCIV Vs Daystar

Table 12: Test 3 - IV Parameter Accuracy

IV Parameters	Daystar	New Probe	Accuracy deviation (%)
Vmax	34.68	34.96	0.80%
Imax	6.12	6.11	-0.20%
Pmax	212.30	213.64	0.63%
Isc	6.47	6.46	-0.23%
Voc	42.77	42.48	-0.69%

Order for new probes and project termination:

After seeing encouraging results from the new probe, ASU-PRL requested a quote for three additional new probes from Trek in January 2020 with request for expedited delivery. But Trek provided the quote only with a lead time of about 12 weeks, i.e. the new probes was expected to be delivered to PRL only by May 2020. Due to the prolonged COVID-19 situation, the new probe delivery was postponed by Trek to arrive only in November 2020, but the project ended in September 2020 itself.

Due to the prolonged COVID-19 issue, only limited progress was made in the last two quarters of the contract and the project was stopped prematurely. In this quarter, our efforts were focused on two tasks.

- Building switchboxes: PV Measurements built five 6-1 switchboxes which would have the capability of testing 30 modules in a 1500 V string
- Writing final report and conducting stakeholder survey: During this quarter, the final report was written, and the stakeholder survey was completed as indicated below.

Stakeholder Survey

A 5-question stakeholder survey was developed and sent to the stakeholders to assess the potential of the NCIV in the marketplace (usefulness to plant owners and O&M companies). The responses from the stakeholders are provided below:

1. *Do you believe that the NCIV developed in this project would potentially be useful to the plant owners and O&M companies?*
    - Three responders said “yes”. The fourth responder said “unsure”

2. *If your answer is “Yes” or “No”, please briefly explain why.*
    - Response 1: Yes, the operator can find the underperforming module within the string quickly and perform mismatch study in the field.
    - Response 2: Yes, a consistent environment for comparing module performance is important. For O&M it is preferable not to disconnect modules.

- Response 3: Yes, this could potentially be a much faster and streamlined operation without high-voltage safety risks, or problems with disconnection of strings. In particular, fragile connectors could be broken, or personnel put at risk of high-energy Arc by working inside combiner boxes, which are notorious for being fragile and a high-voltage risk. Also, the speed at which measurements could be taken throughout the system would be dramatically increased. Also, if spot measurements are taken at actual PV modules, you remove the need to track down which strings are actually connected to which modules, and avoid the risk of thinking that you're taking a string offline, but in fact you disconnected the neighboring string.
- Response 4: I am unsure if it makes economic sense as aerial IR can also detect issues. Personally, I am on the fence. However, this approach may be better if going after modules in a localized area as it gives more information than aerial IR. This tool can be used to zoom in and get enhanced clarity.

3. *Are measurements of 6-module substrings within a longer string useful?*
    - Response 1: No
    - Response 2: Yes, we think covering the highest, middle, and lowest system voltage modules in a string is useful. I don't think every module in the string is necessary for almost all cases. Unless you are getting individual performance for warranty or performance guarantees
    - Response 3: Sort of, any way to further segment a system quickly, even if it's not exactly at a module level would help to isolate and locate failures. However, it's less useful if O&M folks need to keep two instruments on hand – a module-level and string-level unit. Also, when you combine 6 modules, you're starting to obscure individual module-level problems. Maybe a 3-module (~100V) segment would be a better compromise between cost and resolution.

4. To what extent would it be more useful if the instrument could obtain accurate measurements at the single-module level?
    - Response 1: Understanding the underperformance of the module in the field will limit the risk to the contractors, operators and owners as they are able to identify these issues earlier in the life of the plant and quickly.
    - Response 2: Useful when evaluating performance guarantees.
    - Response 3: It's important to have enough resolution to identify a failed bypass diode or under-performing module substring. If you can still do that with a 3-module or 6- module unit, then it would be ok, but part of the purpose here is to screen for failed or degraded modules in the field

5. At what price point does the apparatus begin to make sense economically?
    - Response 1: As this will be a risk mitigation tool and not an everyday tool, $20,000 -$40,000 price for this kind of tool would be reasonable depending on capability and accuracy of the measurement.
    - Response 2: less than $20,000
    - Response 3: You should be able to compete with conventional string-level IV tracers, which are in the $5k-$20k price range.

PART 2: INSTRUMENTATION AND DEVELOPMENT

Quarter 1 (October - December 2017)

PV Measurements (PVM) began technical work on this project in December 2017. October and November were consumed by various paperwork items required by ASU and DOE.

In December, PVM finished the paperwork and participated in a team planning meeting with a view towards the initial subtasks and the **first milestone of reporting on the theoretical limits and geometry of non-contact voltage sensors, a survey of equipment available in the market, and purchase of equipment deemed likely to be suitable.** PVM then added extensive criteria to a list that ASU-PRL had started for use as a filter to select candidate equipment from market offerings. Details of these criteria appear in Part 1 on page 14.

During project proposal, the vision included affixing non-contact probes to the cables that connect PV modules within a string. This was the initial configuration used in evaluating two systems that ASU-PRL had already purchased. The initial findings were:

1. Readings highly variant while probing insulated cables; this configuration deemed to be problematic.
2. Readings facing a flat surface were within a few volts of the correct voltage; deemed this to be likely sufficient.
3. One system's analog output has noise of amplitude on par with the instrument's full scale range, rendering it ineligible for further consideration.

This initial experiential knowledge with these instruments helped PVM to refine the proposed criteria list. PVM's expertise with instrumentation development and interfacing contributed to the expression of detail in the list. Ultimately, the list could only pass instruments that are likely capable of meeting the project's accuracy requirements; here PVM's understanding of combining uncertainties in complex measurements enabled quantities to be expressed in the list with confidence. This list acknowledged that cost is limited but did not require that instrument prices be below a stringent threshold, as we envisioned that once the technology was selected, other efforts could be applied to lower cost, such as economies of scale or removal of unnecessary features.

PVM then made a survey of the instruments in the market, selecting one system that appeared to meet project requirements. PVM also engaged in a conversation with another manufacturer, sending cable samples to support a demonstration measurement. Unable to provide a useful measurement, this manufacturer's products were not included in the list for evaluation, as we were still hopeful that we would find an instrument compatible with the initial vision of probing module interconnection cables.

The **first year milestone is to identify and validate an instrument that can meet our accuracy goal of 1.5%.** If the validation succeeds, we will be able to proceed with further development. If we fail, we'll have to stop. To support this, PVM began to prepare for rigorous evaluations at this level of precision and accuracy. PVM selected and purchased an externally-controllable high-voltage power supply to support ongoing instrument evaluations, testing, and calibrations. PVM also made a top-level design of a device that would provide accurate voltage readings from modules by electrical contact and provide the data wirelessly to serve as a comparison reference.

Quarter 2 (January - March 2018)

In December we had removed one manufacturer's products from our list for evaluation. In this quarter, we saw that this company is a major supplier in the market and that many of their products are available in the surplus market. To ensure completeness in our survey without substantial expenditure, and to learn more about this product line's principles of operation, we purchased some units of the latest models we found on the surplus market.

In this quarter, we learned more about the **practical accuracy and geometry** issues involved with using the non-contact voltage sensing instruments, which is one of our **subtasks**.
Because our initial plan to measure through the insulation on interconnection cables was found to be unworkable by that manufacturer and we could not make it work with other units tested, the project team considered other ways we could still achieve non-contact voltage measurements in this application. Thus, we included the notion of measuring flat, equipotential surfaces such as cell interconnection ribbons and fronts and backs of solar cells through front glass or backsheet materials. This broadened the scope of our ongoing search for candidate non-contact voltage measurement instruments.

PVM's work in the second quarter also attended to **our year-end and project goals of achieving measurements within 1.5% of the true quantities**.

To know that our non-contact measurements are accurate, we must compare them to trusted measurements. To reduce the chances of erroneous assumptions or introduction of hard-to-control variables, we wish to make the "trusted" measurements in the same conditions as will exist in actual use of the non-contact instrument we are developing. For highest confidence, we should measure voltages at individual modules at the same time that our non-contact instrument is measuring them. PVM has experience in simultaneous measurements of voltages within a PV module string, having developed and sold its Multi-Module I-V tester (MMIV). The MMIV instrument enables simultaneous measurement of the I-V curves of all the individual modules in a string at the same time as each other and the measurement by the I-V sweeper that provides the voltage-sweeping load for the string. This enables PV module performance to be tested under identical irradiance and spectral irradiance conditions, and to the extent that all modules in a string operate at the same temperature, the same temperature as well. To the extent that the string's modules are mounted in the same plane as each other, the angle of incidence (AOI) is the same for all the modules. However, this instrument is not yet in widespread use, in part because it uses direct electrical connections to the string's individual modules by inserting tee connectors in the string wiring. To accumulate further experience and confidence with this technique before it is needed for this project, PVM developed the "RadioVoltmeter". The initial design is meant for static voltage measurements, but it may be expandable for dynamic measurements as well. Per a request from ASU-PRL, PVM accelerated the development of this instrument, as ASU-PRL had another current project that would be able to utilize the static measurement feature and provide performance feedback. The device uses a transmitter at the PV panel and a receiver connected at a computer. Data transmit by radio. Initial tests showed data transmission over 10 meters and through a house wall, indicating that it is sufficient for transmission in a compact PV array environment. Further development demonstrated accuracy of voltage measurements and the ability of a single computer to receive voltage readings from multiple senders. ASU-PRL requested a set of 12 units.

PVM developed a plan to evaluate the performance of non-contact voltage sensors that are measuring changing voltages, as this will be required for I-V curve measurements. The need to evaluate such performance at very high test voltages complicates the task as the direct measurements must also be made with great accuracy. PVM found suitable voltage divider resistors with low voltage coefficient of resistance (VCR) for this task. Summarily, a data acquisition system will simultaneously measure the voltage directly and via the sensor system under test. The computer will vary the voltage by providing a waveform to the high-voltage power supply procured earlier.

Quarter 3 (April – June 2018)

During this quarter, PVM's work attended to the upcoming need to **prove that I-V curve measurements made using non-contact sensors are accurate at the 1.5% level**. The first two radiovoltmeter prototypes worked well at PVM with a transmitter-receiver distance of 200 meters, so PVM sent them to ASU-PRL for their use and further evaluation. PVM then designed a printed circuit board for the instrument and ordered several boards. This result also gave ASU-PRL confidence that they would work well at ASU-PRL as well. ASU-PRL temporarily prioritized PVM's RadioVoltmeter effort over the other work PVM was doing to design and build the instruments needed to assess the accuracy of the non-contact voltage sensing instruments. ASU-PRL offered assistance from their staff to manufacture the remaining units for the initial set of 12. PVM provided components and instructions to ASU-PRL and received subassemblies in return.

Experiments to assess the performance of the non-contact sensing instruments continued, using actual PV modules in the field. By this time, the team had decided that one of the probing configurations we would consider would be that of a probe in front of the solar cell on the module. This configuration introduces an accuracy problem – the apparatus will reduce the amount of light reaching the cell being probed, thus distorting the performance of the modules under test. We had to consider this configuration anyway because the other probing options were giving inferior results. Unable to eliminate this source of error, we strove to minimize it. The probe would have to cast minimal shadowing on the cell being probed.

PVM made another effort to discuss probing options with an engineer working at one of the leading manufacturers of these instruments. The engineer helped us select the most likely-to-be-suitable instruments and revealed some of the operational principles of their products. ASU-PRL subsequently ordered the recommended equipment.

The probe detects an electric field by vibrating a sensor positioned between the field to be sensed and a reference potential. It then adjusts its own reference potential to reduce the magnitude of the sensed signal. By using a control loop circuit, it nulls out the electric field, using its sensor to "know" that the field has reached zero. The potential that was applied to achieve that null is considered to be the potential of the surface to be measured. This process happens so quickly that the unit is able to measure a voltage in less than 10 milliseconds.

Halden Field of PVM traveled to ASU-PRL to meet the rest of the team and work on the project's current top priorities. The most significant achievement of this trip was the initial evaluation of a non-contact instrument's dynamic voltage measurement capability. We faced its probe to a surface energized with 114 VAC at 60 Hz through a sheet of glass. A Keithley 2700 DMM connected to the instrument's monitor output indicated 114 mV RMS while a Fluke handheld DMM indicated 114 V RMS applied to the metal plate. The ratio of these readings is 1:1000, consistent with the instrument's intended output. The ability of the instrument to follow the 60 Hz sine wave gave us confidence that it will also be able to follow a swept voltage of a PV module under test.

The other task performed during this trip was to perform a comparison between I-V curves made using conventional instruments and one of our non-contact voltage sensor instruments. Although we did not have data acquisition instruments compatible with the commercial sweeper that was available, we did achieve some crude results using a rheostat and the Keithley 2700 DMM/data acquisition unit. This enabled the ASU-PRL technicians understand the concepts of I-V curves generally and comparing two different measurement techniques on PV modules specifically.

During this trip, PVM also obtained initial feedback on the performance of the two RadioVoltmeters under trial. They were not performing as well at ASU-PRL as they did at

PVM. The usable working distance turned out to be 10 meters line-of-sight with no obstacles and 3 meters through a residential-style roof with aluminized insulation. This range is usable, but the ASU-PRL user said that longer range was important. PVM concluded that the RadioVoltmeter range difference was probably due to interference at the ASU-PRL site, as it has multiple cellphone towers and a nearby commercial airport. In contrast, PVM’s site has poor cellphone service, one known cellphone tower about 1 km away from PVM, and its airport lacks radar or other communication facilities. PVM obtained a Yagi-Uda directional antenna for the base unit’s data transceiver to improve the signal strength.

At this point, meeting the **M9 milestone** had become urgent. We needed to evaluate whether **our technique could achieve 1.5% accuracy within a 1000V system.** Creating the data acquisition equipment to perform this evaluation was prioritized over further development of the laboratory-level equipment evaluation system at PVM. PVM’s perspective was that from a product development perspective, we needed additional effort to achieve the needed accuracy in laboratory environment before introducing the additional variables offered in the field. But the contract obligated us to do the measurements in the field, even if those measurements would show that we had not achieved the accuracy goal. There is value in **proving that we have the capability of performing the field evaluation**, and that interpretation of the M9 milestone is consistent with this prioritization.

In support of **milestone M9**, PVM designed a data acquisition system combining custom signal conditioning circuitry with an off-the-shelf data acquisition unit to collect data from both non-contact voltage sensors and conventional voltage measurement connections for this comparison (Figure 2-1). A capacitive load swept the voltage without pre-sweep reverse bias. Multiple capacitors permitted variations in sweep rate. PVM connected this apparatus to one and two Photowatt PV modules (ca. 2001) that PVM had available from a prior project.

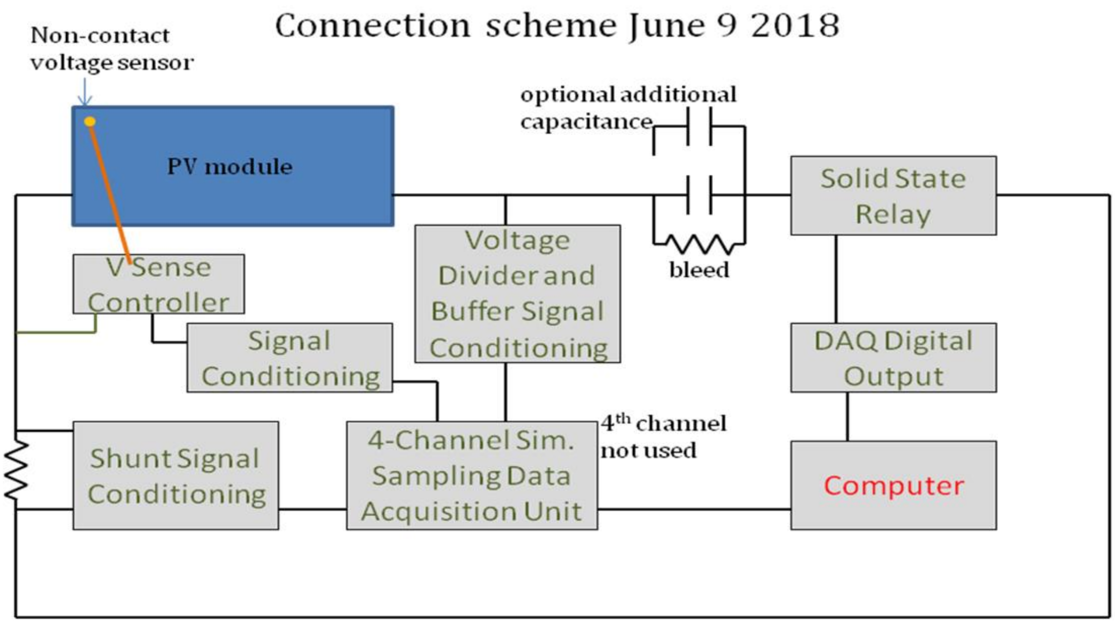


Figure 2-1: Connection scheme developed by PVM

The test sessions involved multiple voltage sensing instruments which revealed their differences, performance nuances, and some malfunctions.

The test generated several well-matched voltage sweeps with the exception of voltage offsets that were substantial enough to prevent consistent achievement of our 1.5% maximum deviation goal. PVM observed some aspects of measurement configuration that appeared to correlate with these voltage offsets and proposed some ways to try to mitigate them. The most prominent need was for rigid probe holders, as the holder fabricated from a polystyrene music CD enclosure could not hold the probe in position for very long (Figure 2-2). Voltage offsets varied with probe position and, it appeared, other factors as well. A second was the temporal lag of voltage data from the non-contact instrument relative to that from the direct connection. This can be reduced in magnitude by using a faster sensor-controller system. Its consequence can be reduced by slowing down the voltage sweep rate. It can be mitigated by advancing the voltage data (or retarding the current data) during data processing and presentation.

Figure 2-2: Probe holder

Although several opportunities for improvement were noted, this measurement of two PV modules connected in series showed that our project can succeed. An I-V measurement comparing direct and non-contact voltage sensing showed almost the same result (Figure 2-3). Once we understand and mitigate the unpredictable voltage offset, we'll be ready to scale this up to the string level.

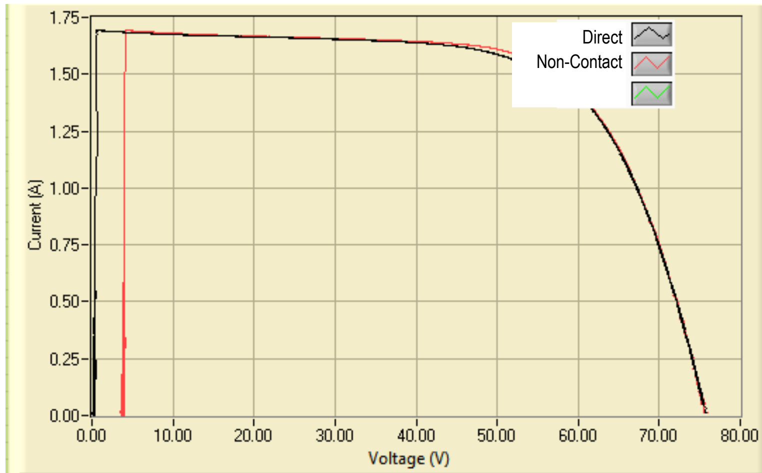


Figure 2-3: Connection scheme developed by PVM

However, for reasons explained above, we moved to the string level right away. PVM next designed a more-versatile data acquisition system that would record 4 channels of simultaneous data with inputs selectable between contact and non-contact methods. Its signal conditioning circuitry included appropriate voltage dividers, buffers, and switches. This would enable some experimentation with different configurations so we could learn more while doing the comparisons.

PVM designed modifications to ASU-PRL's multi-module I-V testing (MMIV) system to enable some of its units to receive voltage readings from the noncontacting sensor instrument outputs. With such a modification, this system could serve to collect data to compare contact and non-contact voltage measurements within a string of modules.

By the end of this quarter, the domestic, dominant manufacturer of non-contact voltage sensors had garnered the team's attention as the other makers' instruments were falling out of favor for their inaccuracies and lack of fast response to changing voltages. **Looking forward to the next year's tasks and milestones**, PVM enquired with that manufacturer about the possibilities of an OEM version of their instrument, **as our application would need many units but the application cannot support the cost** without substantial economies of scale. The manufacturer expressed that such an OEM device was in the works but with a specification that was not firm. PVM asked for the draft specifications and encouraged them to move the project forward. During this quarter, PVM also requested quotes for the additional probes that the team needed. They did not arrive despite multiple reminders.

Quarter 4 (July – September 2018)

Halden Field traveled to ASU-PRL to lead the I-V tests for the **milestone M9 goal**. In the furnace-like conditions at ASU-PRL, most of our non-contact voltage sensing instruments failed.

The one instrument that kept working enabled us to achieve data showing close agreement between conventionally measured I-V curves and those using non-contact voltage sensing.

During this trip, ASU-PRL requested quotes for the probes requested of the non-contact voltage sense instrument manufacturer by PVM during the prior quarter. The quotes arrived within 2 hours. This confirmed Halden Field's suspicion that the manufacturer prefers to work with ASU-PRL, not PVM. ASU-PRL placed that and future orders with this manufacturer.

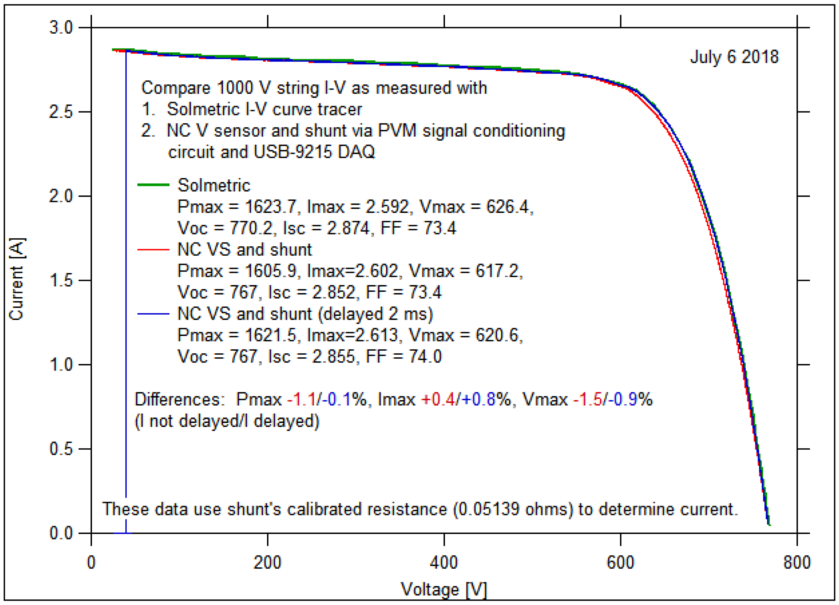


Figure 2-4: Accuracy at the string level

Also during this trip, PVM also evaluated the Yagi-Uda antenna for the RadioVoltmeters and showed the user how to set it up. It achieved 60 meters range which was deemed sufficient. Upon return to PVM, PVM completed final assembly of more units and sent them to ASU-PRL. A month later, PVM completed the last of the requested units and provided them to ASU-PRL as well. PVM received and utilized the first user feedback – the need for a logging function in the host computer software.

After the trip, PVM performed calibrations on the shunt and voltage divider resistors that had been used for the tests at ASU-PRL. The initial results used computations based on nominal component values. PVM later calibrated the voltage dividers and shunt and revised the results accordingly. The graph also shows the consequence of retarding the current data by 2 ms to compensate for the lag in the non-contact voltage measurement instruments. Performing this step improved the match even further.

This result showed that we met the 1.5% accuracy goal at the string level (Figure 2-4). The text of the M9 goal does not indicate whether the goal pertains to module-level or string-level measurements. Thus, with selective interpretation, **these data indicate that we have achieved the M9 goal**. However, PVM's perspective is that a usable and sellable product must achieve the 1.5% goal at both the module and string level, and continued to pursue this aspect of accuracy improvement.

Encouraged by the positive results of the July work session at ASU-PRL and discouraged by the instrument manufacturer's failure to deliver ordered equipment on time, PVM procured several units from the surplus market, as **we must have them to complete tests to fulfill urgent project milestones**. The shortage of equipment, and the fact that the eventual product apparatus configuration involves many instruments that are idle most of the time, inspired Halden Field of PVM and Dr. TamizhMani of ASU-PRL to think about ways we might multiplex equipment. Anticipating the **task requirement to drastically reduce product cost during the project's second year**, we chose to begin acting immediately. PVM worked out the details of how this could be done. Multiple string I-V sweeps would be performed in rapid succession and voltage sensing instruments would be switched between module probes between sweeps. The setup would be more complex and involve more cables, but the equipment cost would be much lower and closer to the project's goals. PVM created a customer requirements document for this and shared it with the team. PVM designed the necessary switchbox and data acquisition equipment configuration that would be needed and began ordering parts for the first prototype. The switchbox will be rather elaborate because all wires in the voltage sensing probe operate near the probed voltage, which can be dangerously high. Thus, the switchbox must have guards to prevent worker exposure to high voltages.

PVM introduced, with the support of the project's PI (Dr. Tamizhmani) at ASU-PRL, the concept of an engineering requirements document to the team, applying it to the probe holders that the project requires in order to obtain more consistent measurements during field trials. This is an essential component of module-level accuracy improvement **for which goals are quantified in the M9 and M12 milestones**. It is also needed for product usability. The team agreed to use this process and made initial contributions to the customer and engineering sections of the documents. The ASU-PRL team accepted the task of designing and building the probe holders in part due to the presence of a mechanical engineer on the team. PVM also created a draft of the customer requirements document for the multiplexing scheme introduced above to which the ASU-PRL team members contributed. PVM derived an engineering requirements document from the agreed-upon customer requirements and provided it to the rest of the team for further review.

Per a request from the ASU-PRL side of the project team, PVM provided support for a 16-channel data acquisition system that would record data from as many voltage sensing units simultaneously. Support included top level system design, signal conditioning circuitry design, choice of hardware, and a program to collect and present the data.

During this quarter, the ASU-PRL side of the team worked with PV connector aging in order to have some aged connectors on hand for the upcoming milestone test requirements. One of the failures that can occur in the field is in the connectors between modules. Some installers use connectors that fit together but are not made by the same manufacturer. At least one manufacturer recommends against using other manufacturers' connectors with their own. The industry uses the misnomer "compatible" to describe this risky practice. Regardless of whether the failure is caused by "compatible" connectors or connectors from the same manufacturer, what ultimately can occur is that the resistance at the interface rises, causing energy to be dissipated at the connection point. That resistance may or may not be ohmic. If the resistance is high enough, failure can be catastrophic, generating a fire. The instrument we are developing will be valuable to its users if it can help users identify interconnections that are progressing towards failure. Early identification and mitigation of such problems can avert expensive and unsafe failures later on. The **M12 and M18 milestones** pertain to ensuring that our instrument can do this.

Halden Field of PVM contributed his perspective to the ASU-PRL side of the team working on the connectors issue. If connectors are simply aged in a chamber, they should have intermittent, heavy current running through them as would occur in a PV field, in order to generate the kinds of corrosion that would occur in the field and cause the failures. After aging, the connectors should not be exercised, as moving the contact surfaces may scratch off the corrosion material that has developed, restoring the aged connector to proper function. A much simpler way of demonstrating that our instrument can detect such failures is to determine what resistance would be associated with substantial heating at the interconnection and making simulated connector problem cables containing that resistance.
The following calculation illustrates how this might work out. At 8 amperes, a 0.125 ohm resistance would cause a 1-volt drop and 10 watts of dissipation. This would probably be sufficient to soften or melt the plastic connectors unless the cables themselves conduct the heat away from the connection. But it would not be enough to start a fire. Thus, 0.1 ohms is an order-of-magnitude approximation of the resistance one might use. PV module installation design experts have probably investigated this issue more thoroughly and developed a tolerable resistance threshold for connections. Can our instrument enable a user to detect such a loss in a string? A 1-volt drop on a module operating at 30 volts would constitute a 3% decrease in module-level voltage. If we have achieved our 1.5% accuracy goal, our instrument should reveal that to a user who analyzes the data carefully. It would appear as a lower-than-normal Voltage at the string's operating current and a similar drop in Vmax as determined from the module's I-V curve. Testing an array with and without such an interstitial resistance should enable us to demonstrate this aspect of the product's utility.

Unfortunately, these many tasks left no time for PVM to further develop the laboratory-based equipment to evaluate the voltage sensing instruments for speed and accuracy. Deferring this necessary work is starting to impair our progress, as **the M12 goal requires us to show that we actually do meet the 1.5% accuracy goal before we can continue to second year tasks**. PVM prefers to interpret the 1.5% goal as pertaining to module-level measurements because our instrument won't be accepted in the market without it.

Quarter 5 (October-December 2018)

In Quarter 5, PVM continued to provide support the 16-channel data acquisition system requested by ASU-PRL. PVM configured two 8-channel DAQ units in master-slave configuration, wrote software to operate it, and designed circuits to protect the DAQs from destruction if overvoltages were inadvertently applied. The ASU-PRL side of the team built the protective circuits with PVM guidance.

The team discussed the direction of the technology we are developing as it relates to the direction we envisioned it would take when the project was proposed. We expected at this time to launch the process of having companies design PV-specific voltage sensing probes and also figure out how to make them ourselves. However, we have found that the standard probes seem sufficient for our application and the cost is consistent with the cost goals of the instrument we are developing. However, the controllers and readout instruments are more costly than probes, are bulky, and seem to contain components that are within our capability to build ourselves. The primary sensor manufacturer has mentioned that they are developing a smaller and less-expensive version of the controller, so we're not sure that we need to make our own. What we can do now is **reduce system cost** by making a switching system that switches each controller between multiple probes. We foresee that this can be done in a way that saves significant amounts of money while still achieving the accuracy and speed goals. Thus, we are **modifying our year 2 subtasks to refer to multiplexers instead of homemade probes**.

Halden Field of PVM led the review of the Engineering Requirements document for building the multiplexing system. This included comments, questions, and discussions by email and phone. PVM integrated the conclusions into a new document and circulated it to the rest of the team to verify that it incorporates the team's decisions. PVM also provided an initial system configuration sketch to the team that shows how the system can be deployed with a minimal number of long wires and multiple DAQs that send their data to the central computer by radio telemetry.

Individual voltage sensors measure the I-V curve of the string of PV modules defined from the reference point (negative end of string) up to the module under test. The user needs the I-V curves of the individual modules. When string I-V curves at adjacent modules are simply subtracted to determine individual module I-V curves, the noise in both measurements is retained while the voltage of interest is but a fraction of the voltage measured. To obtain usable accuracy, we must minimize the amount of noise that propagates to the final result.

PVM explored two ways of achieving this. Connecting the outputs of adjacent sensors to a DAQ input in differential mode can eliminate many error sources, but requires two sensor controllers at each switchbox instead of one. Synchronizing the measurements and performing the subtraction after the acquisition would be less costly but would retain more noise sources and require more resolution in the initial measurements. PVM presented these options to the team. To **minimize risk of not meeting the accuracy requirements of the M15 test**, the team selected the former option.

Halden Field reviewed the system cost using the chosen method. It meets the goal, but with little room for manufacturer profit. Other cost reductions will be required, and they seem potentially possible.

PVM supported the ASU-PRL side of the team as it prepared to perform measurements pertaining to the M15 goal. It turned out that ASU's MMIV equipment had been damaged a few months ago due to inadvertent application of excessive voltage. Units that had been modified to receive low voltages (and marked as having been modified) had been connected directly to PV modules. PVM assessed the repairs that would be needed and conveyed an estimate of the repair effort that would be needed to the ASU-PRL side of the team.

Quarter 6 (January-March 2019)

PVM repaired the equipment (MMIV unit) that had suffered an internal fire due to misuse during Quarter 4, calibrated it, and returned it to ASU-PRL so that it could be used to perform the M15 test. PVM also developed the equipment configuration that would be needed to demonstrate that the non-contact voltage measurement technique with switchboxes can achieve the project goals. The configuration is shown below (Figure 2-5):

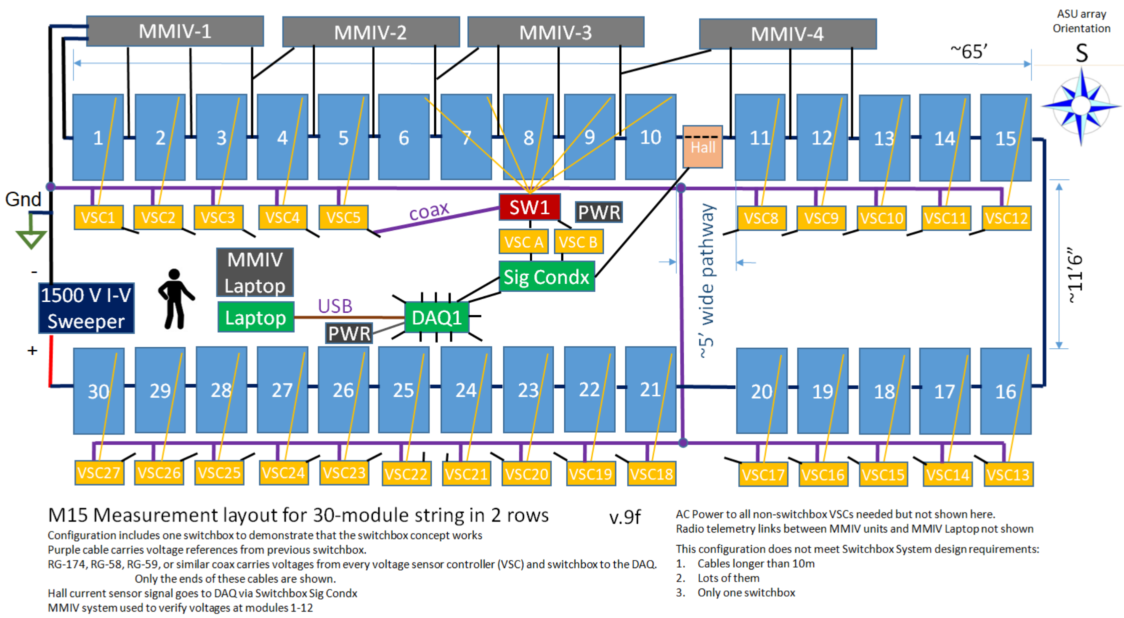


Figure 2-5: Equipment configuration for non-contact voltage measurement technique with switchboxes

Here, we evaluate one switchbox measuring 5 modules while individual non-contact voltage sensors measure the rest. Data from this test should show to what extent the switchbox adds uncertainty, noise, or any other problems to the system.

PVM acquired additional Voltage Sensor Controllers (VSCs) and other equipment for this test, learned about the special circuitry required for the switchbox, designed the switchbox, and ordered its components.

The voltages in the voltage sensing probe wires all operate near the voltage of the surface being sensed, meaning that strong dielectric isolation between contacts and relay circuits would not be required. However, all conductors would operate at hazardous voltages most of the time. PVM built the relays into a metal box that will be held at one of the voltages in the probe wiring to minimize the chance of noise interfering with probe operation. A grounded box surrounds this box to isolate personnel and equipment from the high voltages during operation.

Quarter 7 (April - June 2019)

PV Measurements built the first prototype switchbox needed for the **milestone M15** test. Assembly and initial testing revealed some oversights in the initial design, quickly remedied due to availability of parts in PVM's inventory that it uses for its products. Halden Field travelled to ASU-PRL to test the switchbox further and to help prepare for and perform the M15 test.

At ASU-PRL, Halden Field provided guidance in preparing equipment for the M15 test. ASU-PRL team members aggregated the signal connection, conditioning, and digital conversion equipment onto a single board so that it would be robust for work outdoors while Halden Field soldered several connections. He provided guidance on how to order replacement cables for the repaired MMIV system.

Halden Field also connected the switchbox to actual voltage sensing probes mounted to a PV module indoors to look for problems that might appear during later, more complex tests. He identified several problems with the probes, probe mounts, interconnection cables, and the switchbox itself. While the switchbox worked in a limited way, it was not robust enough to withstand an excessive voltage applied to it by the sensor controller units when no probe was connected or when the probe's mount had fallen off the module. The evaluation involved use of several voltage sensing probes at once, revealing that probe offset voltages depend on the probe, which controller box the probe is connected to, which circuit path in the switchbox is in use, unknown factors regarding how it is mounted to the PV module, and probably other factors that we don't know of, as evidenced by our inability to get reliably repeatable measurements.

The team discussed what its members learned and developed a list of action items to make our apparatus more robust, understand probe offset voltages further, and add a procedure to accommodate probe offset voltages during testing. Halden Field insisted in the team meeting that we fulfill the probe holder design we developed in the prior year, since the tendency of the suction cup probes to fall off and allow the probes to vary in angle and distance from the PV module is contributing to the variations in offset voltage.

In the next months, switchboxes were broken and repaired, and PVM built another prototype. Attempts to measure modules proceeded and the mysterious voltage offset problem continued to challenge our work. ASU-PRL team members and Halden Field of PVM all observed the offset voltage and noticed factors that seemed to influence it. While the offset voltage depended on the probe's physical position relative to the module under test which could not be adequately controlled by the suction cup mounts, it also depended on temperature, wind speed, and weather!

This was a very significant quarter for the course of the overall project. The prototype switchbox testing had revealed the extent to which the voltage offset problem would prevent accurate measurements and that the team did not understand the physics or magnitude of the voltage offset problem nor how to mitigate it. Prior measurements had not addressed the offset problem other than by trying to select days of optimum humidity and wind speed to collect data. Measurements of modules in a string had been presented as measurements of strings of *n* modules rather than measurements of the *nth* module. Halden Field explained his perspective to the rest of the team that our project cannot succeed without solving this problem, and began to form a plan for how to solve it.

Quarter 8 (July - September 2019)

Initial non-contact voltage sensor evaluations at PVM in the summer of 2018 had shown good performance, but those analyses did not have high precision nor multiple modules. They had shown that the sensors *can* work well for measuring PV module I-V curves. Details had to be developed, the concept had to be scaled up, and unknown challenges remained, but success seemed within our reach. Unpredictable voltage offset grew to be our biggest challenge in the months that followed. To meet it, PVM proposed a "Sweeper-DAQ" instrument that would enable us to explore the voltage offset issues on an array of 3 PV modules at the PVM site. PVM's perspective is that we must first demonstrate accurate, non-contact measurements on an array of 3 modules before we should spend any further effort trying to make this measurement on a 30-module array. PVM received immediate support from ASU-PRL in the form its agreement with the strategy, a shipment of PV modules to populate the array, plus voltage sensing controllers and probes. While PVM focuses on reaching the **accuracy goals contained in the M9 and later milestones** in the laboratory, ASU-PRL can continue pursuing field-specific improvement ideas, design and build probe holders, and further develop the team's capability to evaluate instrument performance in the field.

Priorities Shift

The dominant factor in our instrument accuracy is the voltage offsets, which seem to pertain to both the environment of the measurements and the internal function of our equipment. Thus, the instrumentation PVM set out to build earlier in the project has become lower priority, as it will only become useful once the voltage offset problem is solved. The highest priority at PVM has become mitigating and/or reducing the voltage offset.

Instrument Description

The Sweeper-DAQ instrument combines a PV string I-V tester with an 8-channel data acquisition system. The sweeper's operation principle involves storing energy from the string under test in a capacitor and collecting current and voltage measurements as the capacitor charges. Between measurements, the sweeper discharges the capacitor through resistors, which in turn dissipate the energy into circulating air. This is the principle upon which several commercial I-V testers work.

The data acquisition component provides high-accuracy, direct measurements of string current and voltage at each of the 3 modules in the string. The other four inputs that it reads simultaneously with the direct-measurement data record readings from the non-contact measurement devices - the Hall sensor and three non-contact voltage sensors. The initial version of the instrument sweeps I-V curves more slowly than the Solmetric and Daystar testers the project has been using. It is amenable to addition of more capacitance to reduce the sweep rate further. The data acquisition system uses 16-bit ADCs and signal conditioning circuitry that scales the measured signals for compatibility with the ADC ranges to optimize the data precision. The sweeper firmware supports a wide range of sampling rates. It delivers data to the user-interface in text format over a USB serial port. A measurement can include 1000 measurement points and, in some cases, even more. For each measurement point, it provides a timestamp along with the 8 channels of measured quantities.

The Sweeper-DAQ is meant to be a versatile tool to enable rapid, precise comparison of actual (directly-measured) quantities to those measured by non-contact methods. By displaying all data graphically and numerically immediately after measurement, it should enable its user to evaluate test outcomes and make quick, well-informed decisions regarding next tests that may be appropriate while exploring the effects of various factors on voltage sensor accuracy.

At the time of initial operation, the Sweeper-DAQ's user software provided several graphs that enable immediate interpretation of measurement results. Graphs include I-V curves for each of the 3 modules that include both the direct and the non-contact voltage measurements. Voltages and currents also display as a function of time. The program has a feature to save the full text data from the Sweeper-DAQ in a text file in case the user wishes to perform further analysis.

PVM PV Array

PVM built a PV module rack from framing lumber and applied one layer of varnish to help it survive the upcoming rain and snow season. PV modules are now held to the rack with C clamps (Figure 2-6). To minimize risk of high voltage exposure to passing animals or trespassing humans, PVM leaves the modules disconnected from each other between work sessions.

Figure 2-6: PVM 3- PV module string

Voltage Sensor Calibrations

To evaluate the accuracy of the non-contact voltage measurements in the dynamic condition of voltage sweeps, we must know the calibration factors of all the apparatus involved in the voltage sensor measurements. These calibration factors will be determined in a static condition with the anticipation that the static condition calibrations will be valid in the dynamic measurement conditions as well. During calibrations, PVM made additional tests to ascertain whether the equipment has low-enough noise and sufficient resolution, as designed, to fulfill the measurement requirements.
The apparatus measures the voltage quantities both directly and via non-contact voltage sensors. Because they are more complex and not fully understood, PVM focused first on the voltage sensor measurements.
In the final product, the measurements of PV module voltage using non-contact voltage sensors will involve 5 basic components that can affect measurement accuracy:

1. Voltage sensing probe, including characteristics of the materials and air between the PV cell and the probe tip
2. Wiring between probe and controller (may include switchbox)
3. Voltage sensor controller
4. Signal conditioning circuitry
5. Data acquisition Unit

Since these components will always be used together, they need not be calibrated individually. With this in mind, PVM created a procedure for calibrating Probe - Controller - DAQ channel combinations and shared it with the ASU-PRL side of the team.

PVM next built and utilized an apparatus (Figure 2-7) to calibrate the Probe - Controller - Signal Conditioning - DAQ system as a whole, according to the written procedure. This system uses a high-voltage power supply and an outdoor reference cell (RCO) to provide a known voltage to the probe. The probe affixes to the RCO as it would to a PV module. Its cable goes to its controller, which in turn provides its analog output signal to the I-V tester's signal conditioning circuitry. That circuitry feeds the tester's DAQ which communicates its measurements to the calibration and testing software.

Figure 2-7: Calibration apparatus

Once built, the first task in using a calibration apparatus is to determine if it's working. Part of this involves evaluation of the noise in the readings. If the noise is greater than the uncertainty performance that the application needs, then it's not working. The following graph (Figure 2-8) shows readings from a zero voltage as measured directly (black) and via a non-contact voltage sensor (red).

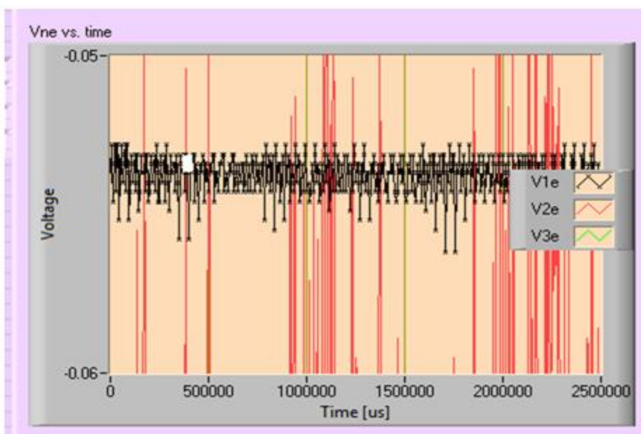


Figure 2-8: Noise - Zero voltage

The quantization of the readings shows that the noise contributed by the signal conditioning circuitry and the DAQ itself is several LSBs. The full range is 12 LSBs spans about one third of the window. This range is about 0.01V/3 = 3.3 mV. Scaling this up by a factor of 21 since 10 V represents 210V in the outside world gives a noise contribution of +/- 35 mV, or +/- 0.017% of full scale. This is an insignificant component of our 1.5% uncertainty goal. The graph (does not contain the noise from the voltage sensor's controller; it's much greater.
The next step was to evaluate the noise levels with voltage sensors connected to actual high voltage with the controller output feeding the signal conditioning equipment.

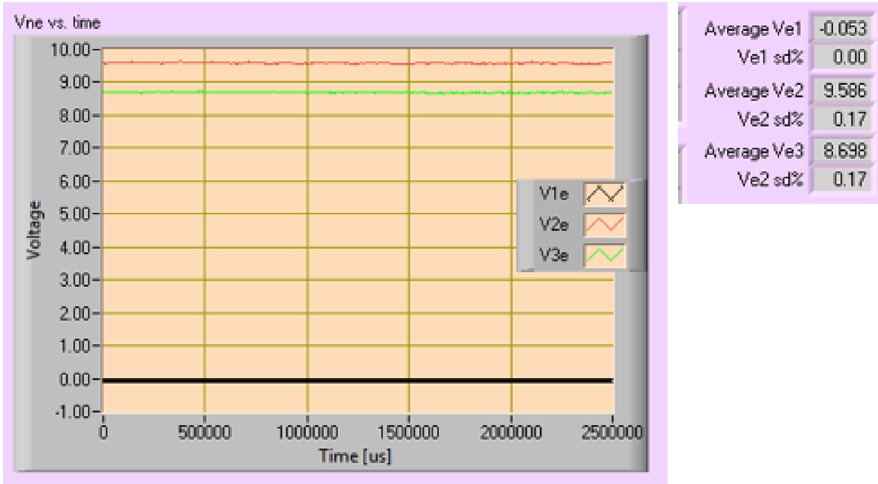


Figure 2-9: Sample controller output signals

Figure 2-9 shows the non-contact voltage sensor's signals while probing the RCO held at 194.78 V. The black line represents the shunted input since only two voltage sensing instruments were available for this test. Figure 2-10 expands the scale of the red line in Figure 32 to illustrate the nature of the reading noise:

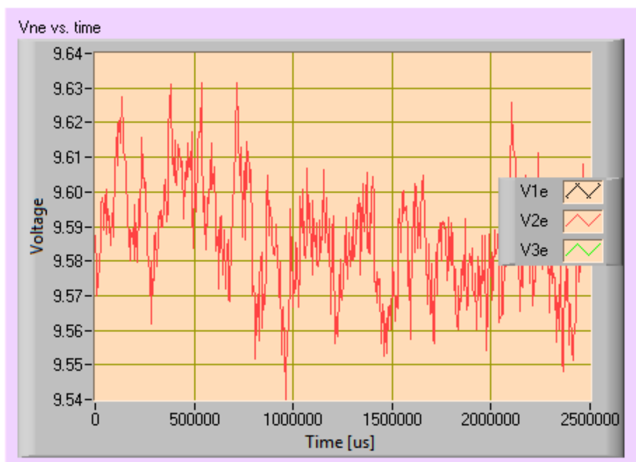


Figure 2-10: Voltage signal from one voltage sensor probing 194.78 V through the RCO's glass

A visual estimate of the standard deviation of this data is 2 divisions in the graph, which is 0.02 volts. This represents 0.2% of full scale, which is close to the 0.17% reported in the software. This confirms that the software is giving a reasonable report. The total range of these voltage readings is 0.091 which represents +/- 0.46% of the reading. Both these numbers are within the 1.5% uncertainty goal and a significant contributor to it.

Since the apparatus' noise performance is consistent with the project's uncertainty goals, PVM proceeded with tests intended to generate a calibration factor for each Probe / Controller / Signal Conditioning Channel / DAQ Channel combination. Calibration tests consist of recording a zero reading, applying a known voltage, recording the reading again, and comparing the difference to the actual voltage. The first several cycles of tests revealed that voltage sensor measurement results drift with time after a large change in probed voltage. The set of graphs in Figure 2-11 illustrate the nature of the offset voltage drift (graphs sized to equalize the scale across the page). Note that the drift initially goes up but later falls. The probe/controller combination with the fastest offset drift also has the largest.

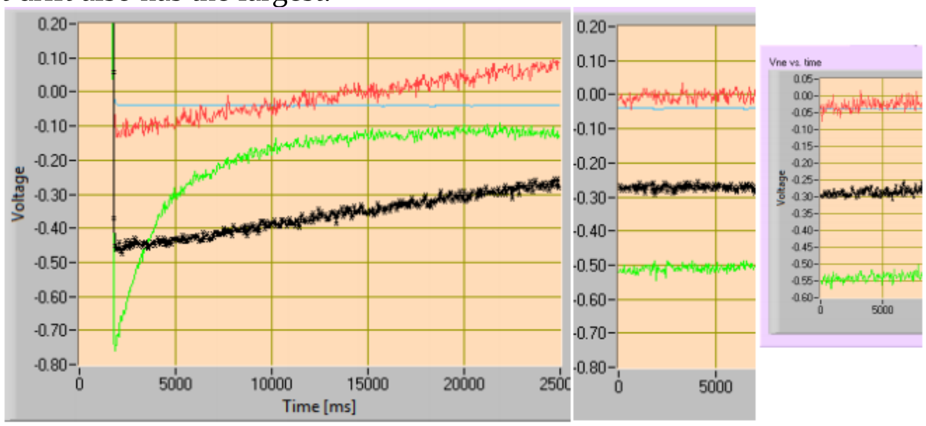


Figure 2-1175: Voltage sensor readings 0, 2, and 10 minutes after voltage change

This complicates the calibration because it is not possible, under currently envisioned procedures, to expose the probes to the zero-voltage condition immediately prior to or after the I-V measurement. However, PVM continued with the calibrations in order to ascertain whether calibration results are the same when the zero comparison is performed immediately prior to and immediately after the high-voltage measurements. By comparing the controller's output voltages before and after transitions of the measured voltage between zero and 194.78 volts, PVM determined the calibration factors to be 20.122 and 20.304 (0 to 194.78V) and 20.128 and 20.212 (194.78 to 0). The differences between the two calibrations with different voltage shift directions are 0.03 % and 0.46 %, respectively. One is insignificant; the other is a significant component of the uncertainty budget, but still within it. The calibrations show that both zeroing methods provide nearly the same calibration factors, which adds to confidence that the calibrations are valid.

Quarter 9 (October - December 2019)

During this quarter, PVM developed and used the non-contact voltage sensor calibrator and the Sweeper-DAQ to further our understanding of voltage offset. As a reminder, solving the voltage offset issue is essential for achieving the **1.5% accuracy goal of the M9 and later goals** when those goals are interpreted as pertaining to single-modules within strings and as will be required for product success in the market.

<u>Exploring voltage sensor offset voltage drift dependence on feedback loop gain</u>

The voltage sensor controller the project has been using has a user-settable feedback loop gain. The controller uses a feedback loop to adjust its reference voltage in response to the signals coming from its sensor. A higher gain can improve response speed while risking ringing and instability in the output signal. It's labeled as "RESPONSE" on the instrument's front panel. The ASU-PRL side of the team has reported that a RESPONSE setting other than zero provided better results in their experiments. Therefore, PVM proceeded to explore how the RESPONSE setting changes the offset drift characteristics. Figure 2-12 shows the voltage readings after turning the test voltage on, and about 2 minutes later, changing the RESPONSE settings at all three controllers from 0 to 1, about 1/2 second apart.

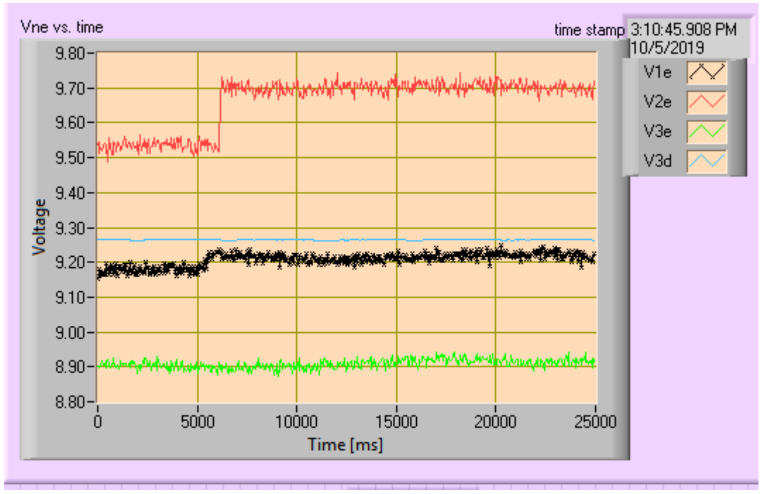


Figure 2-12: Controller Output as the RESPONSE setting changes from 0 to 1

The voltage reading changed most on channel 2, less on channel 1, and imperceptibly on channel 3. We don't know if this is a change in the scaling or offset. To explore this question, PVM examined what happens to the readings when turning off the test voltage while all controllers are set for RESPONSE 1. See Figure 2-13.

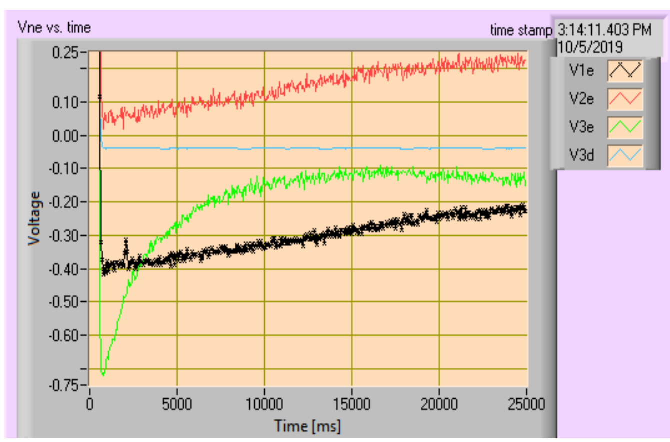


Figure 2-13: Controller Output – Turn OFF - RESPONSE setting 1

The drift slopes appear similar. But the initial offset magnitudes are different from the RESPONSE=0 case. Ve2, which rose 0.18 V when RESPONSE changed, is now 0.15 V higher. Ve1, which rose about 0.04V upon changing the RESPONSE setting, rose about 0.05V here. Ve3 changed very little in either case. This suggests that the RESPONSE changes the offset, not the scaling. PVM explored the effects of additional RESPONSE settings. These caused further changes in the offset voltages but no changes in the scaling of the output voltage. Anticipating that we might use RESPONSE 8 going forward, Figure 2-14 shows some data to characterize the drift.

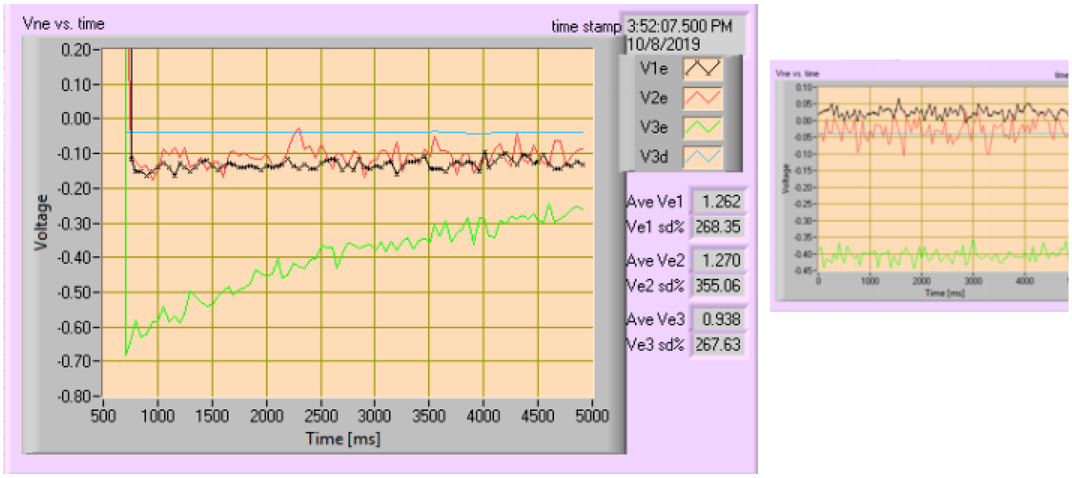


Figure 2-1476: Controller Output - Response Gain 8

The left graph in Figure 37 shows the first 5 seconds. The graph on the right shows readings taken about 6 minutes later. The latter image is smaller in order to align the Y-axes.
V1e drift -0.15 to +.02 | 0.17/(9.52+0.15) = 1.8%
V2e drift -0.14 to -0.03| 0.11/(9.58+0.14) = 1.1%
V3e drift -0.65 to -0.4 | 0.25/(9.10+0.5) = 2.6%

PVM performed further calibrations which revealed:
1. The Controller - Probe combinations do give output that is linear with the voltage probed up to 400V. Calibrations without the DAQ at various voltages spanned + to - 0.5% which portray the random component of instrument uncertainty.
2. Calibration factors are about 4% from nominal on the controllers.
3. Offset drifts seem larger when the probe touches the glass.
4. Offset drift is greater immediately after measuring a high voltage.
5. Offset varies with probe-glass distance.
6. Offset contributes a substantial component to the uncertainty but doesn't render the technique useless.
7. If we can reduce the offset drift, we can make even better measurements.

Since we must resolve the offset drift issue for this technique to meet the project's uncertainty goals, this became the primary area of attention for the rest of the period. Since the phenomena of offset drift and response time appear under the same and similar test conditions, PVM explored both simultaneously.

<u>Exploring instrument response time</u>

PVM explored the response of the controller output on sudden changes to the sensed voltage. The graphs in the figures below illustrate the observed phenomenon (Figures 2-15 and 2-16). The blue line indicates the actual voltage being sensed, which does not change instantaneously.

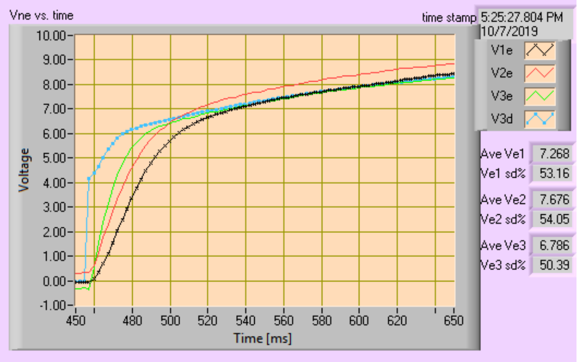


Figure 2-15: Controller reading response time for a positive-going measured voltage (blue line) transition

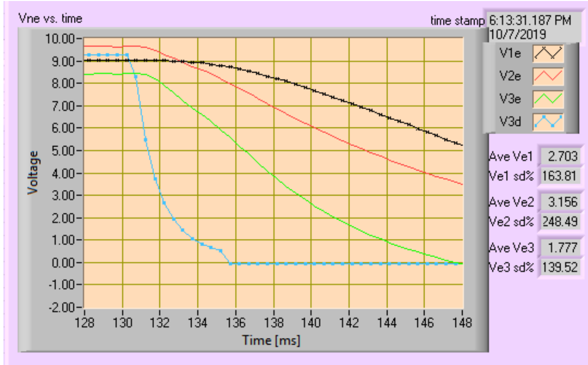


Figure 2-16: Controller reading response time for a negative-going measured voltage (blue line) transition

Note that the time scale is very different for these two graphs. Since the transition characteristics are similar for positive- and negative-going transitions and the transition to zero is sharper than the upward transition, PVM focussed on experimenting with negative-going transitions. The graph below illustrates the analysis of one studied transition (Figure 2-17).

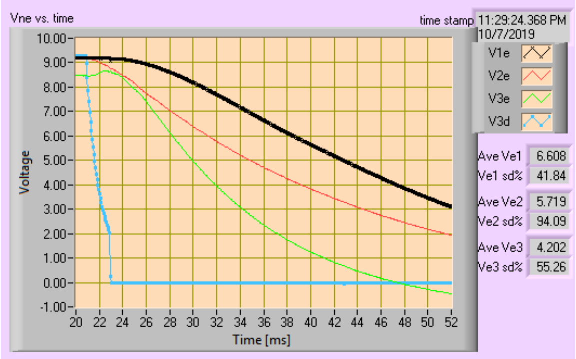


Figure 2-17: Controller Output at high voltage turn-off - RESPONSE setting 1

Off at 20.8 ms
V1e from 9.2 to -0.5. 37% of 9.7 is 3.6. -0.5 gives 3.1. Crosses at 51.8 31 ms
V2e from 9.2 to -0.5. 37% of 9.7 is 3.6. -0.5 gives 3.1. Crosses at 43.8 23 ms
V3e from 8.5 to -1.1. 37% of 9.6 is 3.55. -1.1 is 2.5. Crossed at 35.8. 15 ms
PVM also explored how long it takes for the controller output to begin changing after the sensed voltage changes. The graph below provides an example of this analysis (Figure 2-18).

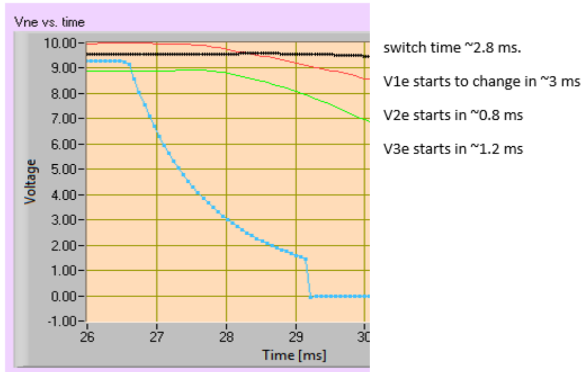


Figure 2-18: Contoller Output when at high voltage turn-off - RESPONSE setting 9

After exploring transition times with RESPONSE settings up to 9, PVM concluded that higher RESPONSE settings generate faster transitions. However, the highest RESPONSE settings also came with the cost of more noise in the analog signal.

<u>Understanding system component contributions to temporal response factors</u>

Next, PVM performed experiments to find out whether response time, response delay, and/or offset voltage can be associated to parts of the apparatus "before" or "after" the Probe/Controller connection. On the Probe side ("before") is the probe assembly, its mounting mechanism, its spacing, its position on the RCO, the RCO itself, and the connection between the RCO and the HV supply. On the Controller side ("after") is the controller, signal conditioning, and DAQ. PVM cycled the probes between controllers to find out which characteristics moved with the probes and which remained with the controller. As required, PVM adjusted offset potentiometers on the controllers to bring readings into the range of the DAQ channels. The graph below illustrates the initial finding (Figure 2-19).

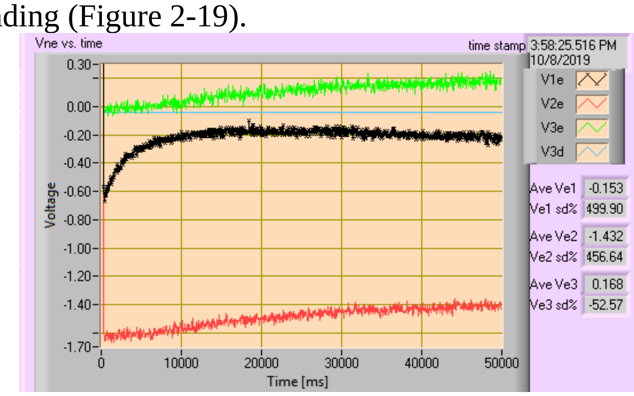


Figure 2-19: non-contact voltage sensing controller offset and drift

The fast offset drift moved with the probe and/or the probing environment from controller 3 to controller 1. Noise characterizations indicate that the noise level is a property of the controller. Comparisons of response speed indicate that this is also a property of the controller. The time needed to begin responding to a change in voltage is a property of the controller.

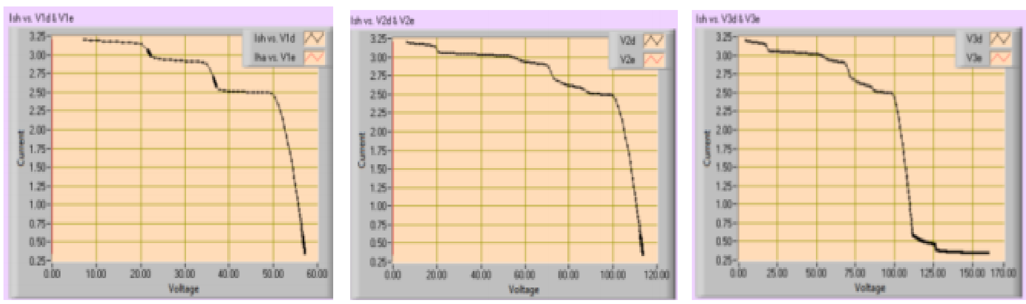
Finally, PVM performed a calibration with a RESPONSE setting of 8 on the new configuration. The results are:

V1e 9.07 to -0.66. 194.92/9.73 = 20.032
V2e 7.98 to -1.85. 194.92/9.63 = 20.241
V3e 9.69 to -0.01. 194.92/9.70 = 20.095

The calibration factors from channels 2 and 3 determined earlier were 20.122 (V2e) and 20.304 (V3e). The new value for V3e resembles the prior value for V2e which suggests that the calibration moved with the probe. But the new value for V1e is far from the prior value for V3e which suggests it doesn't. Thus, the calibration factor is either a property of both the controller and the probe, or the calibration factor is different for different RESPONSE settings. Earlier data suggest that the latter is not the case, so the tentative conclusion is that calibrations need to utilize the same equipment combinations that will be used in the field.

<u>Outdoor tests</u>

The graphs in Figure 2-20 show data taken on October 26, illustrating the functioning of the Sweeper-DAQ with the array illuminated with partial shading and voltage measured by the direct connection method.



Module 1 | Modules 1 and 2 in series | Modules 1, 2, and 3 in series

Figure 2-20: String level test results – first tests with new Sweeper-DAQ

With proper functioning of the I-V tester at substantial current now verified, PVM added one controller with probe to the apparatus. PVM set the RESPONSE control to 0. First, PVM attached its probe to the bottom cell of the array to determine its offset voltage. The left graph below shows the voltage reading during a sweep of the I-V curve. The center voltage is 35.8V. The change during the many samples is around +/- 0.8 V. The graph on the right shows the measurement result after subtracting the offset voltage (Figure 2-21).

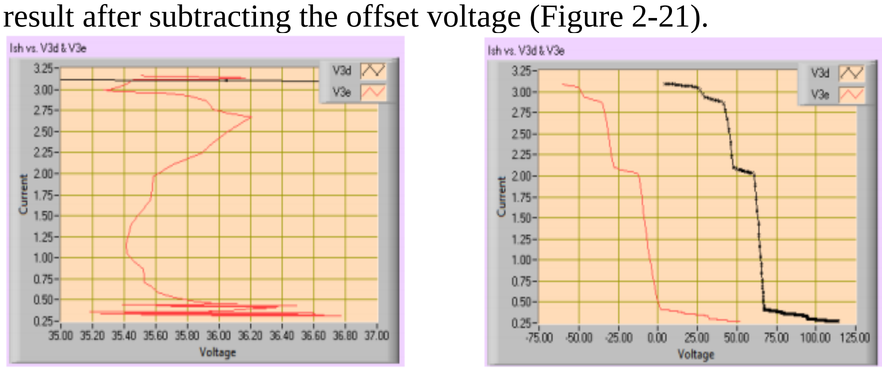


Figure 2-21: IV curve result comparing direct (black) and non-contact (red) measurements

The non-contact reading seems to follow the direct measurement quite well, but the offset is higher than expected - about 74 volts. After trying other offset voltage settings, PVM obtained the following graphs that illustrate how well the non-contact voltage follows the directly measured voltage (Figure 2-22).

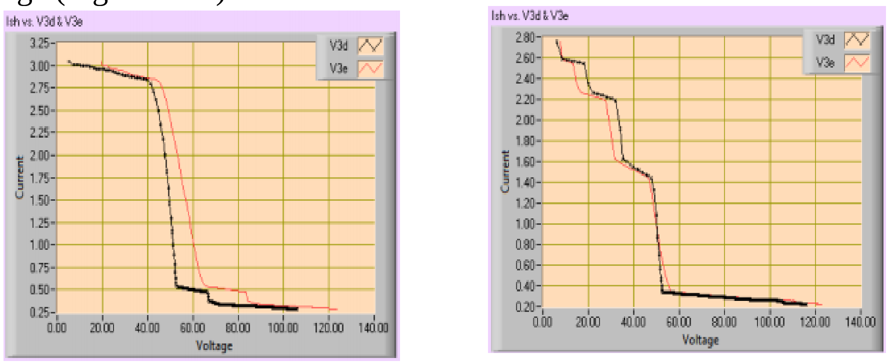


Figure 2-22: IV curve results with lower offset voltage

The tracking shows substantial errors in the non-contact reading. It also shows substantial drift in the offset voltage. The errors in reading might be due to rapid drift in the offset voltage during the voltage sweep.

The graph below shows how well the Hall sensor's output is tracking the directly measured current quantity (Figure 2-23).

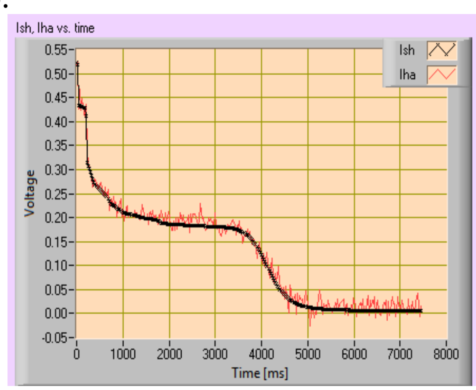


Figure 2-23: Hall sensor noise

The Hall sensor is tracking well; it's just noisy. The noise is about 1 division wide, which is +/- 25 mA. This is 0.25% of the full-scale range of 10 A. When measuring a 5A current, it would be 0.5%, a large share of the uncertainty budget.

As the sky darkened at the end of the day, the illumination also became more uniform, causing I-V curves to appear more ideal. Also, the offset voltage drifted less during a measurement. The next figure shows a measurement with a 50 ms period between points and offset voltage set at -30 volts (Figure 2-24):

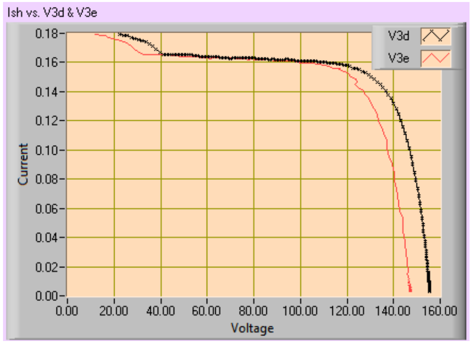


Figure 2-24: IV curves - Offset voltage at -30 Volts

After chasing the offset voltage moving target for a few more curves, PVM achieved the result shown below (Figure 2-25).

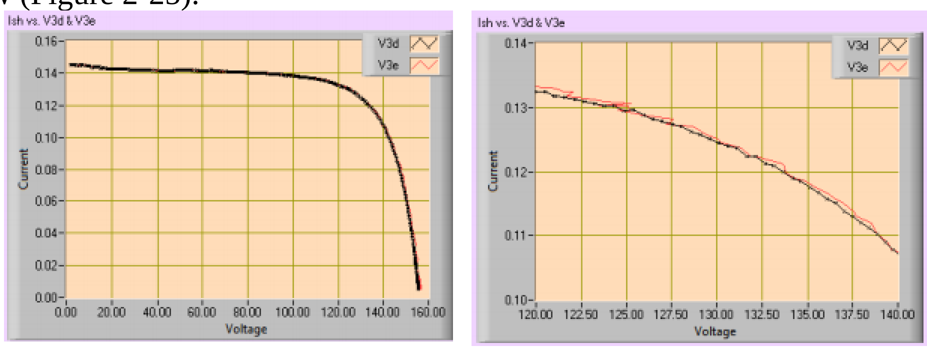


Figure 2-25: IV curve result #3

The curve on the right is a zoom-in on the knee of the curve on the left. This shows that once we figure out the offset voltage and slow down the sweep rate, we can achieve very good results!

Immediately following the measurement shown here, PVM re-measured with the probe on the bottom cell. Multiple measurements yielded multiple, drifting results. Knowing that there are more variables outdoors at this time than there were in the lab where the offset voltage was on the order of 1-2%, PVM tried changing the distance between the probe and the glass. The graphs below contain some examples from the study (Figure 2-26).

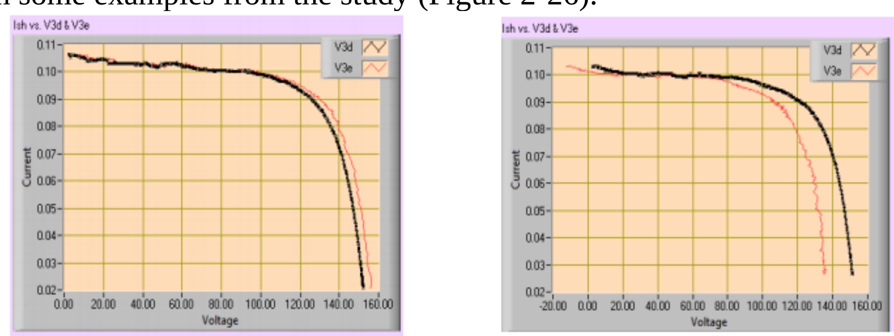


Figure 2-26: IV curve result #4

The study probing at the top cell and additional measurements at the bottom cell indicate that the probing distance does contribute several volts to the offset, but there are other factors as well. It was cold (5-10 C) outside, getting colder fast, and relative humidity (RH) was probably close to 100%.

I-V Sweeper Design
Though we have not yet solved the voltage offset problem, we have learned that slow sweeps of string voltage are very likely to be part of our solution. PVM made a conceptual design of such a sweeper, minding the need to manage and dissipate the vast quantities of energy produced by the string under test during its measurement. Halden Field selected some of the critical system components and ordered them.

Quarterly review for project planning
PVM proposed a detailed list possible "next steps" for the team's consideration as we **compare where we are now with where we need to be according to our project milestones** and plan what to emphasize in the little time remaining. PVM expressed its perspective that we should solve the problem of unstable probe mounting, implement low-pass filtering for the current sensor signal, and resume experiments and begin consultations with others to help us understand voltage offset drift. The mechanical position of the probe relative to the test device clearly influences our voltage drift and it is something we can understand and control. Someone with extensive, deep experience and knowledge of physics may help us prioritize our investigations and help us find the answers sooner.

ASU-PRL visit
Due to the Sweeper-DAQ's completion during a rainy season at PVM and the need to evaluate and utilize it under realistic conditions, Halden Field traveled to ASU-PRL to use it with modules in the project's field string. Halden Field spent days with the array, trying various combinations of modules and probe positions, including probing the module backsheet. Probe holders for which the requirements had been developed last fall were still not available, so the variable of suction cup mounted probes falling off and changing orientation and position continued to slow down and complicate the work. These trips generated further observations about the nature of the voltage offset problem and revealed some additional features that the Sweeper-DAQ needed. PVM implanted the needed features and made needed modifications to the Sweeper-DAQ. As we had observed that voltage offset and its drift seems to depend on humidity, we tried to make a measurement while excluding humidity from the probed region by running helium through a transparent chamber mounted to the PV module. We concluded that we should design and build better apparatus to manage the flow and repeat the experiment.

Quarter 10 (January - March 2020)

Halden Field learned that in discussion with the non-contact voltage sensing equipment manufacturer during the previous period, ASU-PRL team members received a recommendation to try "ionizers" to reduce the effects of static electricity in our measurements. Therefore, in this period, Halden Field began by reading about what ionizers are and how they might help. Anticipating that the final product of this project must be field-usable, Halden Field purchased some small ionizers that could fit inside the enclosure boxes ASU-PRL had purchased to moderate the environmental contributions to the measurement offset that is now our greatest challenge.

During the consultant visit, Halden Field, along with the entire team, learned very relevant lessons from the consultant. He helped us understand why the static electricity is present in our apparatus, where it probably is, and how various mitigation techniques work. Halden Field worked with the consultant at the outdoor PV array, trying and evaluating measurements using various probing sites and trying the various mitigation techniques the consultant had introduced. In these measurement sessions, Halden Field prioritized learning about and evaluating the techniques over achieving a measurement with 3 modules all within the 1.5% accuracy limit goal. During the trip back to PVM and afterwards, Halden Field wrote notes describing details of experiments performed during the consulting session. ASU-PRL supported PVM's upcoming in-depth experiments with ionizers by providing mini-environment chambers, antistatic spray, and flexible hose for use with displacement gas.

Since PVM must make I-V measurements while using the Sweeper-DAQ and the weather conditions at PVM do not support making such measurements outdoors, PVM must do this work indoors using simulated sunlight. With a module-level continuous solar simulator being outside the scope of this project, PVM considered using a tungsten "shop light" as a solar simulator. But as expected, the 60 Hz ripple in the light intensity itself obscures the features we need to see on the I-V curves. Therefore, PVM built a DC power supply for the "shop light" lamp that will be used for indoor non-contact measurement experiments oriented towards developing static electricity mitigation and avoidance techniques to achieve accurate single-module I-V measurements with the non-contact voltage sensors. PVM put this power supply into service to evaluate the performance of the miniature air ionizers PVM had procured for this purpose (Figure 2-27). The ionizers charged the PV surface to more than 2000V as measured by the voltage sensor within a few seconds of being energized. Halden Field concluded that these ionizers are capable of providing ions well beyond the level needed for our application. This is good news because the miniature ionizers can mount on the outside of the mini-environment box (no need for air ducts, flames, or cumbersome fan ionizer mounts) and are so small that they won't block very much light from reaching the solar cell. However, the ionizers under test provide only negative ions and our application requires ions of both polarities. PVM attempted to open an ionizer's housing to modify the circuit to provide positive ions, but the thorough potting of the device prevented circuit access. PVM ordered similar ionizers capable of both positive and negative ion generation.

Figure 2-27: Miniature air ionizers inside mini-environment

Prioritization Decision

Dr. TamizhMani (PI) and Halden Field (co-PI) discussed the two ways that PVM can contribute towards the project's upcoming milestones. One of them is solving the voltage offset problem that we have identified to be our major obstacle in the path to achieving 1.5% accuracy at the module level. Another one is demonstrating with actual field measurements that using switchboxes to multiplex the expensive voltage sensor controllers with the non-contact voltage probes actually does work. This second task is important for ensuring that the product we envision will have a price that is acceptable to the market. On one hand, we have some rudimentary data showing that a single switchbox can work, which implies that a set of switchboxes can also work if surprise issues in scaling the multiplexing don't arise. As long as we have a reasonable path to product affordability, we should focus on solving the accuracy problem because without sufficient accuracy the market won't accept the product at any price. On the other hand, the ability to scale up the switchbox concept is not a given and we have the resources now to evaluate a full set of switchboxes in the field. With such a successful demonstration, the rewards of solving the accuracy problem will be imminent and clear. We decided to prioritize the switchboxes over the experimental work and resume the experimental work once the switchboxes are built.

To support ASU-PRL's upcoming field testing activity, PVM modified the current 3-to-1 switchbox design for a 6-to-1 configuration. PVM created the needed PCB design, ordered the PCBs, created the BOM, and ordered the parts to build the first prototype of the switchbox that this activity will require. At the end of this quarter, travel was curtailed by government rules to minimize the spread of the SARS-CoV-2 virus. In addition to the effects known to workers at most companies and academic institutions, this had a more extreme effect on PVM. Halden Field lost practical access to PVM facilities during most of March.

Quarter 11 (April - June 2020)

PVM planned with Dr. Mani how the project can continue with the constraints on travel and working during the pandemic. Dr. Mani indicated that he expects that the 6-to-1 switchbox will still be needed and used even if the pandemic delays their construction. Without access to PVM facilities, Halden Field was unable to build the switchboxes during April or May. He was able to gain brief access in June, during which he began building the first 6:1 switchbox.

Quarter 12 (July - September 2020)

Halden Field's access to PVM facilities increased during this quarter in part due to a supporting letter from ASU-PRL that convinced the border officers that his travel was "essential" (PVM is approximately a mile from the border with Canada and Halden has to cross this border when working at PVM).

Halden Field was able to build the initial switchbox prototype, test it using a PV module at Voc, and send it to ASU-PRL. Initial feedback generated only a few design changes, so PVM ordered the parts to build 4 more units. By the end of this quarter, all five switchboxes were built, tested, and packed for shipment to ASU-PRL (Figure 2-28).

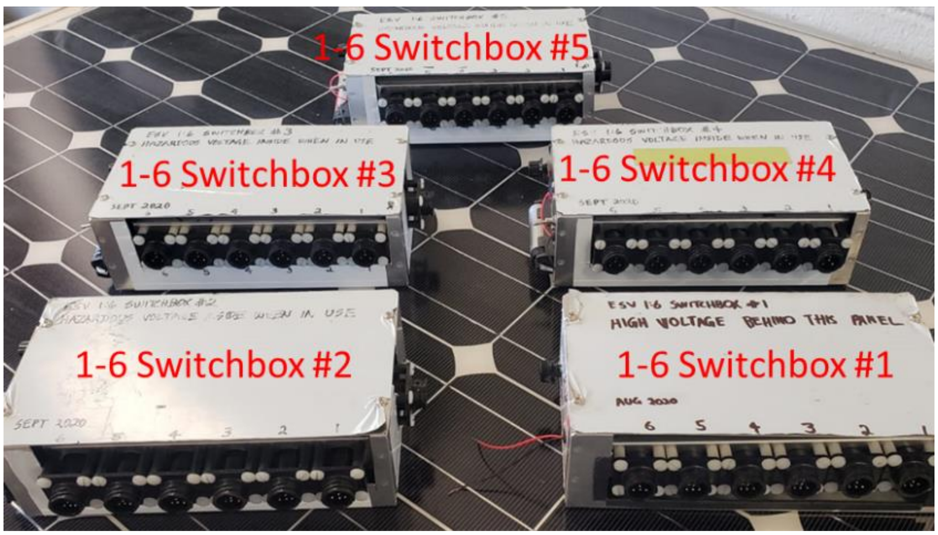


Figure 2-28: Five 1-6 Switchboxes built for non-contact I-V tracer

KEY ACHIEVEMENTS

- Identified a large number of commercial ESV models and probe models (from multiple manufacturers in the United States, Europe and Japan) that can potentially meet the intended PV-specific application requirements
- Down-selected appropriate ESV models and probe models which would meet three major requirements: ensure that the selected ESV and probe models will be commercially available now and in the future; ESV models and probe models that can withstand high testing voltages, as high as 1500V; Probe models that casts minimum shadow on the PV modules during the measurements.
- Installed a 3-row PV racking system at a fixed tilt angle of 33^{o} (local latitude)
- Installed and commissioned a 30-module string on the racking system
- Demonstrated the operation of 15 ESV-Probe sets in a 20-module string (1000V) using an electronic load to obtain simultaneous I-V curves of 15 modules of the 20-module string
- Demonstrated the operation of 24 ESV-Probe sets in a 30-module string (1500V) using an electronic load to obtain simultaneous I-V curves of 24 modules in a 30-module string.
- Designed and developed five switchboxes to reduce the number of ESVs from 30 to 5.
- Conducted the high and low temperature operational capability testing of ESV/Probe setup using an environmental chamber
- Through an extensive down-selection process and enormous amount of field testing, two ESV-Probe pairs were finally used to obtain simultaneous the I-V curves of string, substring and modules. Using the first ESV-Probe pair, it was demonstrated that the 1.5% accuracy requirement can be met for the strings and substrings having four or more modules. However, the 1.5% accuracy requirement could not be met for the individual modules using the first ESV-Probe pair due to the voltage offset drift issue. Using the second ESV-Probe pair, it was demonstrated that the 1.5% accuracy requirement can be met even at the individual module level. Unfortunately, we had only one probe for testing using the second pair. We placed order for additional probes for testing using the second pairs but did not, due to COVID-19 related delivery delay from the probe manufacturer, receive the probes on time to complete the project before the end date
- Obtained experience with and developed understanding of, the influence of static electricity on the offset voltage drift phenomenon and the ability of ion introduction to influence this effect.
- Our goal was to reduce the equipment price close to $60,000 (the commercial multi-curve tracer available from a commercial vendor for 16 modules costs about $60,000). Five battery powered 1-6 switchboxes were fabricated with double enclosures for safety. Each switchbox accommodates 6 probes (each probe costs about $700) and a 30-module string requires only 5 switchboxes so the cost of ESV units is reduced from $120,000 (for 30 units) to $20,000 (for 5 units). So, the total cost of ESVs and probes is reduced from $141,000 to $41,000 (more than 70% cost reduction). We believe that it is possible to maintain the price close to $60,000 which would include other components (slow sweeper, DAS and buffer circuit).

Budget

FEDERAL FINANCIAL REPORT
(Follow form instructions)

1. Federal Agency and Organizational Element to Which Report is Submitted DOE - Office of Energy Efficiency and Renewable Energy (EERE)	2. Federal Grant or Other Identifying Number Assigned by Federal Agency (To report multiple grants, use FFR Attachment) DE-EE0008165	Page 1	of 1 pages
3. Recipient Organization (Name and complete address including Zip code) Arizona State University - Award Management PO Box 876011 Tempe, AZ 85287-6011			

4a. DUNS Number 943360412	4b. EIN 86-01-96696	5. Recipient Account Number or Identifying Number (To report multiple grants, use FFR Attachment) AWD032079 FSR 093020F	6. Report Type ☐ Quarterly ☐ Semi-Annual ☐ Annual ☑ Final	7. Basis of Accounting ☑ Cash ☐ Accrual

8. Project/Grant Period From: (Month, Day, Year) 10/01/17	To: (Month, Day, Year) 09/30/20	9. Reporting Period End Date (Month, Day, Year) 09/30/20

10. Transactions	Cumulative
(Use lines a-c for single or multiple grant reporting)	
Federal Cash (To report multiple grants, also use FFR Attachment):	
a. Cash Receipts	$709,999.00
b. Cash Disbursements	$696,028.08
c. Cash on Hand (line a minus b)	$13,970.92
(Use lines d-o for single grant reporting)	
Federal Expenditures and Unobligated Balance:	
d. Total Federal funds authorized	$709,999.00
e. Federal share of expenditures	$696,028.08
f. Federal share of unliquidated obligations	$0.00
g. Total Federal share (sum of lines e and f)	$696,028.08
h. Unobligated balance of Federal funds (line d minus g)	$13,970.92
Recipient Share:	
i. Total recipient share required	$79,000.00
j. Recipient share of expenditures	$80,523.32
k. Remaining recipient share to be provided (line i minus j)	($1,523.32)

Path Forward

PVM's perspective is that the next tasks should be, in priority order:

1. Design and make a probe holder for use in the laboratory that includes or supports these features:
    A. Settable and measurable probe/glass distance
    B. Temperature sensor that presses against probe, optionally readable by computer
    C. Humidity sensor near probe, optionally readable by computer
    D. Amenable to adding temperature control for the probe later
    E. Supports quick probe exchange
    F. Compatible with blowing air from controlled temperature and humidity source onto probe.
    G. Maybe put it into environmental chamber described below
2. Perform measurements on a cell in a module with the mini-environment box
    A. Monitor how well the measured voltage responds to various durations and power applied to a dual-polarity ionizer.
    B. Try different types of dual-polarity ionizers
    C. Try other methods of generating ions
    D. Try this with the dehumidifier operating

   E. Try this on the back of the module

3. Evaluate performance of the new probe card with probe.
   A. Offset voltage drift
   B. Calibration linearity
   C. Calibration stability
   D. Calibration sensitivity to temperature
   E. Calibration and offset voltage sensitivity to probe distance
   F. Noise on output signal
4. Perform other experiments inspired by results obtained from items listed above until repeatable, reliable measurements are achieved at the single-module level.
5. Make a 1500 V string slow sweeper (parts are already on hand):
   A. Build a prototype of the circuit for slowly sweeping the 1500 V string (with or without data acquisition).
   B. Let it run, automated, for a few weeks on the 200 V string to make sure it works.
   C. Build it into a suitable(safe!) enclosure for operation in a 1500 V environment.
   D. Take it to ASU and set it up on the project's 1500 V string and see if it works there, too.

PVM might continue to further develop this technique outside the context of the ended DOE project. Funding and/or access to this project’s leftover tools, apparatus, supplies, and controllers would encourage such work.

Publications Resulting from This Work

Based on the work performed in this project, two papers will be prepared and submitted to IEEE Photovoltaic Conference, 2021

1. *“Accuracy Challenges in Non-contact Module I-V Measurements”*, IEEE Photovoltaic Specialists Conference, 2021
2. *“Simultaneous Non-contact I-V (NCIV) Measurements of Photovoltaic Substrings and Modules in a String”*, IEEE Photovoltaic Specialists Conference, 2021

References

1. Yoshihiro Hishikawa, Kengo Yamagoe and T. Onuma “Non-Contact Measurement of Electric Potential ofPV Modules”, IEEE Photovoltaic Specialists Conference, 2015
2. Yoshihiro Hishikawa, Kengo Yamagoe, and Tsuyoshi Onuma, "Non-contact measurement of electric potential of photovoltaic cells in a module and novel characterization technologies", Japanese Journal of Applied Physics 54, 2015