Measurement of dc Arc-flash Incident Energy in Large-Scale Photovoltaic Plants: A Basis for Standardization

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***Abstract* -- The deployment of high-power dc equipment is increasing in solar photovoltaic (PV) plants, but very few studies have quantified dc arc-flash risks. Currently, PV plant owners and operators rely on theoretical, simplified models, such as those in NFPA-70E and other publications for the assessment of risk associated with dc arc-flash. This paper presents an overview of arc-flash risks in a PV system based on a series of field experiments based on IEEE-1584 in two large-scale ground-mounted PV plants. The experiments include various high-power dc equipment of a PV plant such as central inverters, combiner boxes, recombiner boxes, string inverters, and multiple configurations of electrodes in a 20-inch calibration cube. The study reveals the none of the available dc arc-flash models are applicable for a PV plant. This work is an important first step towards developing an improved model that more accurately assesses dc arc-flash risk in a PV plant.**

***Index Terms*-- Photovoltaic (PV) system, safety, arc-flash, model, incident energy, personal protective equipment (PPE).**

I. Introduction

An arc-flash in an electric circuit can often oucurr when equipment malfunctions or an when an unintentional short oucurss during operation and maintenance. Arc-flashes can release a high amount of energy in the form of intense light, temperature rise, sound and pressure waves, electromagnetic interference, flying shrapnel, molten metal, and vapors, which pose the safety risk. Different categories of personal protective equipment (PPE) are suggested to reduces the effects of arc-flash risk on humans. The PPE is often based on the maximum possible thermal energy also known as incident energy from an arc-flash. The incident energy is "*the amount of thermal energy impressed on a surface, a certain distance from the source, generated during an electrical arc event"* [1], and commonly expressed as cal/cm^2. The incident energy also defines the safe boundary distance from a potential arc-flash hazard.

Section 5(a)(1) of the Occupational Safety and Health Act, OSHA General Duty Clause makes the PV plant owner or operator is responsible for notifying anyone on the site about potential hazards, including arc-flash. The OSHA duty clause, often accomplished by labeling all high-power equipment that contains the incident energy level, required PPE to wear when servicing energized equipment, amongst other label information. A number of models are available to calculate incident energy for a dc, primarily rooted in theory, and various assumptions. The power plant owner should decide which calculation model to use to predict incident energy. The available models have varying degrees of conservatism to ensure that workers have sufficient PPE in the worst-case arc-flash scenario. The overly burdensome PPE may reduce the mobility of workers, decrease productivity, and increase the probability of an accident. Insufficient PPE results in obvious safety hazards.

Arc-flash risk assessments on ac systems are relatively well understood, and the incident energy calculation approaches are applied across a wide range of source voltages and equipment types. The calculation approach is backed up by numerous industrial tests and listed in IEEE Guide for Performing Arc-flash Hazard Calculation, IEEE-1584 [2]. Arc-flash on dc systems is relatively unknown, and the theoretical calculation approaches [3, 4, 5, 6] are yet to be backed by the industrial tests. It is assumed that the risks of dc arc flash are higher than ac as the 60-Hz current will have a current zero every 8.3 milliseconds, and at each current zero, the current will extinguish [7, 8]. If the voltage across the arc is not enough to restrike the arc, the arc will stay extinguished.

Furthermore, the amount of heat flux in dc arc-flash can be 1.25 times higher than ac based on rms and average currents [9]. Available calculation models for dc arc-flash are presumed for a linear dc source, leading to contradictions when applied to a non-linear photovoltaic (PV) array [10]. The amount of current in a PV array is determined the amount of solar irradiance, and the operating point on a non-linear current-voltage (I-V) characteristics curve, unlike the short circuit current and arc-impedance in a linear power source i.e. battery.

This paper discusses the measurement of dc arc-flash incident energy from two sets of experiments in PV plants and provides an overview of arc-flash risk assessment in high-power dc equipment, namely the combiner box, recombiner box, and inverter. The analysis is based on the measurements of arc-flash incident energy in the arc-in-box experiment, as mentioned in IEEE-1584 [2] and various PV equipment powered by a PV-array. The measured incident energy, arc-current (I_{Arc}), and arc-voltage (V_{Arc}) are compared against the available calculation models for the dc system and the source of discrepancies are analyzed. This paper also discusses the applicability of available calculation models for incident energy the arc-flash sourced with a PV-array and proposes a PV-focused model that will more realistically capture the I_{Arc}, V_{Arc}, and the incident energies.

II. EXPERIMENTAL SETUP

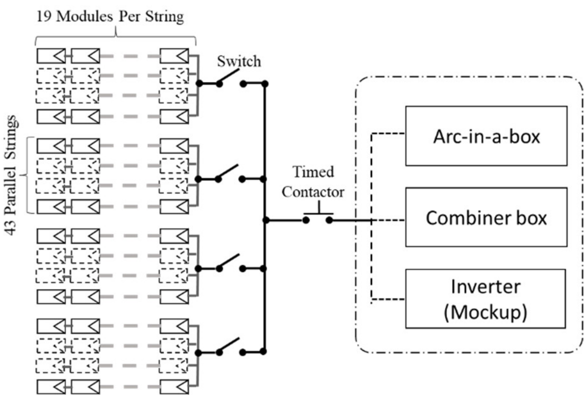

Fig. 1. One-line diagram of the 1 MWdc PV array. Each block is comprised of 43 parallel strings containing 19 PV modules per string. The nameplate ratings of the PV modules are 305W (P_{MP}), 45.4V (V_{OC}), 36.1 V (V_{MP}), 8.93 A (Isc), and 8.45 A (I_{MP}).

Arc-flash experiments were performed on two different ground-mounted PV plants. Both PV plants have designed open-circuit voltage (V_{OC}) of 1,00Vdc with 19 silicon PV modules connected in series. The first PV plant (A) consists of four sub-arrays made up with 43 parallel strings (~250-kWdc) connected with switches. A single-line diagram of the array and the arc-flash test location in the first plant is shown in Fig. 1. The nameplate capacity of the individual module is 305 Wdc.

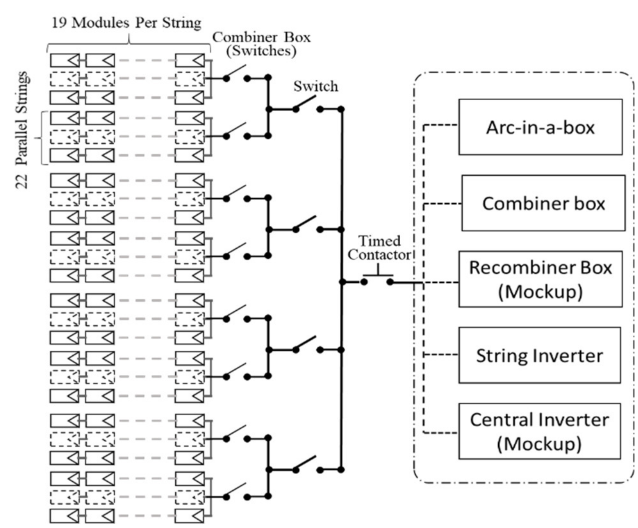

Fig. 2. One-line diagram of the 1,1 MWdc PV array with five test fixtures. Each block is comprised of 22 parallel strings containing 19 PV modules per string. The nameplate ratings of the PV modules are 320W (P_{MP}), 45.3V (V_{OC}), 36.8 V (V_{MP}), 9.3 A (Isc), and 8.7 A (I_{MP}).

The second PV plant consists of an array of approximately 1,100 kWdc with eight sub-arrays (~134-kWdc) made up with 22 parallel strings. The sub-array connected with individual switches to the arc-flash test assembly as shown in Fig. 2. The nameplate capacity of the individual PV module is 320 Wdc.

Fig. 3. Arc-in-box tests with vertical conductors inside a metal box (VCB) orientation.

Arc-flash experiments were designed to measure incident energy, arc-current (I_{Arc}), arc-voltage (V_{Arc}) in six different types of high-power PV equipment, including two types of combiner boxes, one recombiner box, one string inverter and two types of central inverters. Arc-in-box tests with vertical conductor inside a metal box (VCB) orientation [2] were performed in a 20 in × 20 in × 20 in (51 cm × 51 cm × 51 cm) box as calibration tests for analysis. Fig. 3. shows the VCB setup with two electrodes. Insulating support between the electrodes at the top prevents the electrodes from bending or deform due to the magnetic forces created by the arc currents.

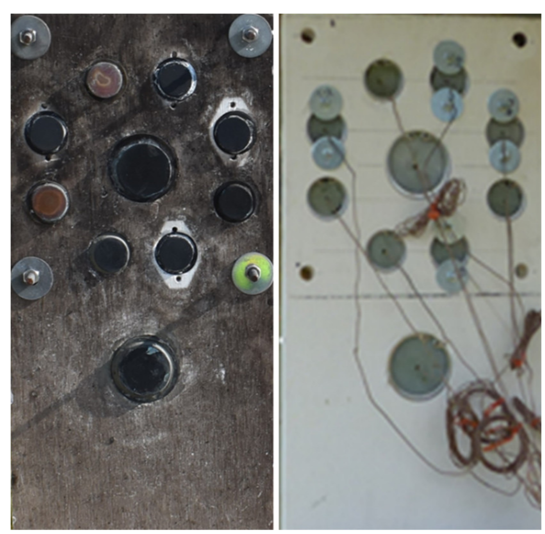

Fig. 4. Multi-sensor calorimeter array front (left) and back (right).

Incident energy was measured at 18 in (46 cm) from the arc-initiation point using a cupper-slug calorimeter panel based on ASTM-1959 [11]. These are copper disks with a thermocouple attached to the back that measures the temperature rise on the disks. Incident energy (cal/cm^2) is calculated by multiplying the temperature rise in degrees Celsius by 0.135 [2]. The calorimeter panel also includes the sensors designed to measure the various components of incident energy. Fig. 4. shows the calorimeter panel used for the tests.

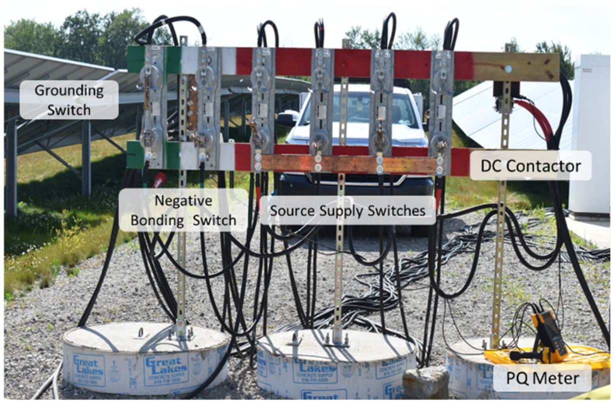

Fig. 5. Switching setup showing the dc contactor and switches for controlling PV array source capacity.

Arc current and voltage were measured at two different points. Fluke i1010 ac/dc current clamp meter and a multifunction power quality (PQ) meter were used after the contactor, as shown in Fig. 5. The second measurement point is close to the arc-electrode of the test fixtures, where a PICO TA167 current probe was used together with BK PRECISION PR-60 differential probe and custom-made data acquisition system. Pyranometer and thermocouples are used to measure the plane of array (POA) irradiance and back of the PV module temperature respectively. High-speed cameras were used to capture arc characteristics. Arc-power (P_{Arc}) was calculated by multiplying I_{Arc} and V_{Arc}. Arc-energy (E_{Arc}) was calculated by integrating P_{Arc} over the arc duration. Arcs were initiated by closing a dc contactor, as shown in Fig. 5. that applies the fault current through the electrodes connected together with a 30 AWG copper bridge wire.

Total 63 arc-flash experiments were performed in the PV plants with 23 tests in the arc-in-box setup, 15 tests in central inverters (mock-up), 11 tests in combiner boxes, 11 tests in string inverter, and 3 tests in recombiner box (mock-up). The nameplate capacity of PV array source power for these tests varies 125-kWdc to 1,100-kWdc. The actual source power was calculated by using the POA solar irradiance and back of the module temperature. The source power ranges from 103-kWdc to 1,017-kWdc. The calibration tests in an arc-in-box setup contain a combination PV array power, electrode spacings (0.5, 2, 4, and 6-inches), durations (0.5, 2, and 10 secs), and electrode orientation (VCB, horizontal electrode facing each other, and vertical electrode facing each other).

III. Result and Analysis

A. *Non-linear IV-characteristics of PV array*

The magnitude of arc-flash risks in a PV equipment depends upon the amount of I_{Arc}, and V_{Arc} that PV array can supply during an arc-flash event. A characteristic equation often describes a PV-array in exponential form, is a non-linear power source. A PV array can behave as a current source or as a voltage source, and the amount of power output varies according to the operating point in the IV-curve. An arc-flash phenomenon is also non-linear, hence the operating point in the IV-curve crucial to predict the available arc energy (E_{Arc}) is variable. An IV-characteristic curve of a PV array adjusted to the irradiance and temperature during the test (blue line) with the measured I_{Arc} and V_{Arc} (red-dots) is shown in Fig. 6.

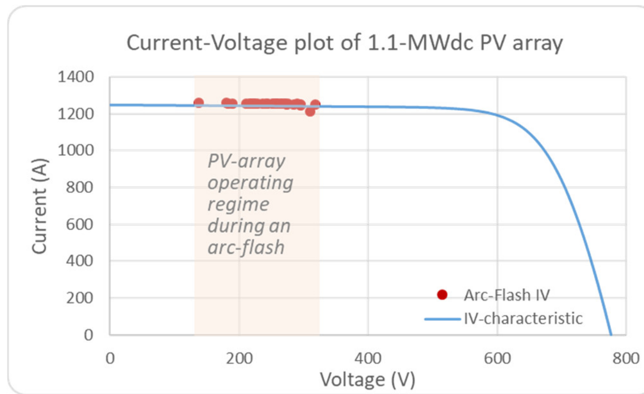

Fig. 6. IV-characteristics of a PV-array (1,100 kWdc-nameplate and 724 kWdc-actual) and overlaid I_{Arc} and V_{Arc} values from the experiment

The PV array operates in a constant-current region of the *IV*-characteristic curve near the short-circuit end of the curve. Fig. 7. shows the power-voltage curve of the same test where the average P_{Arc} is about 45% of the maximum available power (P_{Max}) of the PV-array. It has been found that the P_{Arc} is dependent on the assembly of the test fixture, particularly with different electrode gaps. The P_{Arc}/P_{Max} ratio ranges from 0.11 to 0.57 on 63 arc-flash tests.

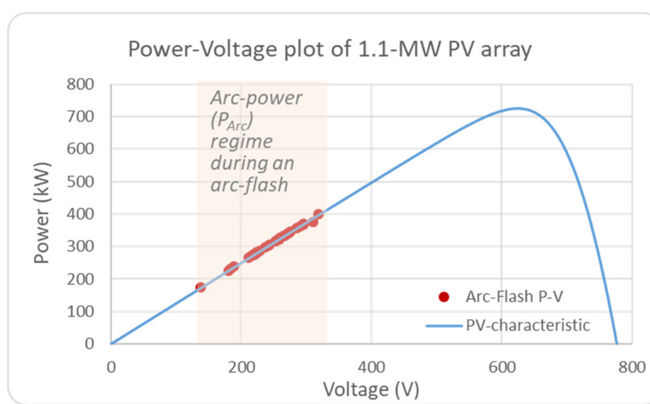

Fig. 7. Arc power and voltage of a PV-array (1,100 kWdc-nameplate and 724 kWdc-actual) and overlaid P_{Arc} and V_{Arc} values from the experiment

B. *The behavior of I_{Arc} and V_{Arc}*

The average I_{Arc} remained almost constant throughout the arcing phenomena, irrespective of electrode geometry and source size. The median value of I_{Arc} was 97% of the short-circuit current of PV array. The measured V_{Arc} fluctuates up to 18 times the minimum value. Fig. 8. shows the typical time response of I_{Arc} and V_{Arc} from the experiment with 724 kWdc source power. The level of fluctuation in V_{Arc} is found lower with the increase in I_{Arc} for the similar test setup. The reason for the fluctuation in V_{Arc} is believed to be the rapidly changing arc geometry at higher I_{Arc}. Similar fluctuation in V_{Arc} with a PV source and dc power supply [3] for an arc-flash was also reported in previous works [12].

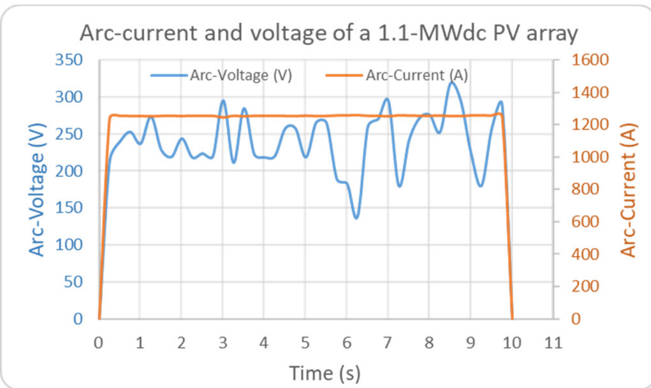

Fig. 8. Arc-current and voltage during an arc-flash event-sourced by a PV-array (1,100 kWdc-nameplate and 724 kWdc-actual)

C. *Sustainability of arc*

Most of the arc event were found sustainable and in line with the findings reported by Sekulic et al. [12] with a 650 Vdc supply from a PV array.. The findings contradicts the observation reported by Stokes and Oppenlander for an arc powered by a dc source, stated as "*the arc will attempt to extinguish and, depending on the current level and the gap, arcs burning with voltages of up to three times the minimum can be interrupted*" [3]. However, the statement is satisfied as the maximum value of V_{Arc} was found to be up to eighteen times higher the minimum. Another reason for a sustainable arc may be the higher voltage (750 V, actual) in comparison to 600 V in the reported work by Stokes and Oppenlander.

As the I_{Arc} is very close to the normal operating current (I_{MP}, current at maximum power) in a PV system, an upstream overcurrent protection is not likely to be activated in the event of an arc-fault. This situation makes the human response time towards the arc-flash as the arc-flash time (t_{Arc}). The t_{Arc} is considered as 2 seconds for the analysis, as in IEEE-1584 [2]. It should be noted that the common types of dc fuse being deployed in large-scale PV plants have response time higher than 2 seconds. Hence a dc arc-fault in a PV equipment can also be fed from one or more parallel PV sub-arrays via downstream switchgear in a PV plant.

The dc side of large-scale PV plants can be found negatively grounded, positively grounded, and ungrounded "floating." The risk of a sustainable dc arc is reduced in an ungrounded system as the equipment case cannot act as a return path for the current during an arc event. Without a return path through the equipment ground, the arc has to maintain a connection to the negative terminal, and the magnetic forces make that difficult to sustain. This is particularly relevant in the high-power PV equipment, i.e. recombiner boxes and central inverters where spacings between the busbars are wide.

D. *Arc Energy and Incident Energy*

The measured incident energy and the arc energy (E_{Arc}) show a linear relation with the PV-array source size.

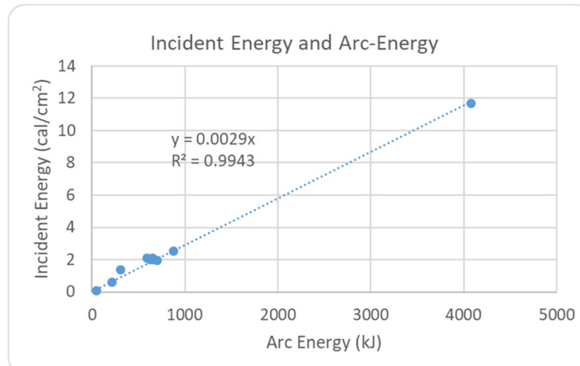

Fig. 9. Incident energy (cal/cm^2) versus Arc-energy (kJ) for VCB setup

Furthermore, the measured incident energy was also found correlating with the E_{Arc} specific to a test fixture and electrode gap. A linear factor of 2.9 (approximate) was observed between incident energy in cal/cm^2 and E_{Arc} in Mega Joule (MJ) for VCB setup, as shown in Fig. 9.

E. *Measured and Calculated Values*

The measured incident energy, I_{Arc}, and V_{Arc} for the arc-in-box test in VCB orientation are compared with the values calculated using the four commonly available dc arc-flash models [3, 4, 5, 6]. All four models require system voltage (V_{System}) and short circuit current (I_{SC}) as the input. Stokes and Oppenlander and Paukert [4] model further require the distance between the electrode. V_{System}, and I_{SC} of the PV array during a particular test is calculated by using the irradiance and temperature coefficients of the PV module and the measured POA irradiance and back of the module temperature data. A uniform irradiance and temperature profile across the array were assumed for the duration of tests.

Fig. 10. shows the measured and calculated I_{Arc} and V_{Arc} from models along with the irradiance and temperature adjusted IV curve of the PV array. None of the models compare well for either I_{Arc} or V_{Arc}. The Stokes and Oppenlander and Paukert et al. models both predict much small arc voltages than were measured. Both models the arc as a straight line from one electrode to another. In the tests, the arc moved and stretched much longer lengths. Doan and Enrique et al. models both overpredict V_{Arc}. Enrique et al.'s model is tailored for a PV array, however, it assumes the I_{Arc} and V_{Arc} as the nameplate current and voltage at the maximum power (I_{MP} and V_{MP}).

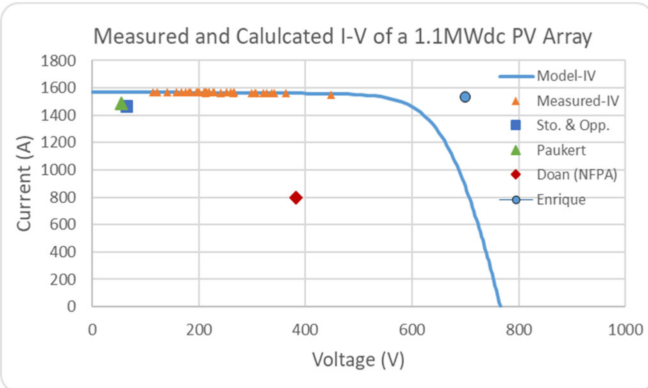

Fig. 10. I-V curve of a PV array (1.1 MWdc-nameplate 874 kWdc-actual). Overlaid I_{Arc} and V_{Arc} values measured from the experiment and predicted using different dc arc-flash models.

The measured incident energy is compared with the calculated incident energy using the same models. Fig. 11. shows the box and whisker plot of measured and calculated incident energies for arc-in-box experiments in the VCB setup. The median incident energy measured is about 15-times smaller than the Enrique model, 5-times than Doan, and about 2-times than Stokes and Oppenlander and Paukert model.

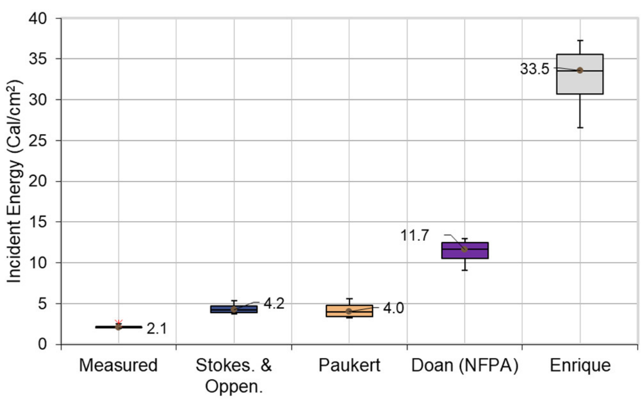

Fig. 11. Measured and calculated incident energy using different dc arc-flash models for arc-in-box VCB setup.

The calculated I_{Arc} and V_{Arc} using the Stokes and Oppenlander and Paukert model is less than the measured. However, the calculated incident energy is almost double than the measured. The assumption made by these models about the energy transfer and the configuration-correction factor made the calculated incident energy higher, even though the calculated I_{Arc} and V_{Arc} are lower than the measured values.

The incident energy (*IE*) and the arc energy (E_{Arc}) in these models can be expressed as:

$$IE = E_{Arc} \times 0.239 \times \frac{1}{4\pi . D^2} \times k_b \quad (1)$$

where *IE* is the incident energy in cal/cm^2, E_{Arc} is the arc-energy in joules, D is the distance to the arc source in (cm) and k_b is the configuration-correction factor. For the VCB experiments in this study, k_b is 2.2 and D is 45.7 cm (18 in), which makes the incident energy in cal/cm^2 is 20 times the arc-energy in megajoules. In the measurements, the incident energy in cal/cm^2 was about 2.9 times the arc-energy in megajoules for the VCB test setup as shown in Fig. 8. The possible reasons for lower conversion factor from arc-energy to incident energy are;

- Some of the arc-energy acts to vaporize the electrodes.
- The box may absorb an appreciable portion of the arc energy.
- The arc moves, and that dynamically changes the distance to the calorimeters. There is no one fixed distance to the arc. Overall, this effect may reduce incident energies.
- The calorimeters may not always be positioned to capture the maximum incident energy.
- The configuration-correction factor may not be appropriate at a working distance as close as 18 in (46 cm).
- Likewise, the squaring term on the working distance may not be appropriate at a distance this close.

F. Model for incident energy estimation in a large-scale PV plant

A PV-focused empirical model based on the test results is considered that will more realistically capture the I_{Arc}, V_{Arc}, and the incident energy. This model is based on the test results use a similar approach applied in IEEE 1584 [2] and assumes 18 in (46 cm) as the working distance. The incident energy is a function of I_{Arc}, V_{Arc}, t_{Arc}, and the factor (k_x) converting arc-energy to the incident at 18 in (46 cm) and can be expressed as:

$$IE = I_{Arc} \times V_{Arc} \times t_{Arc} \times k_x \quad (2)$$

Based on the test results, I_{Arc} is close to the actual value of the short-circuit current (I_{SC}) of the PV array and remains almost constant during the test.

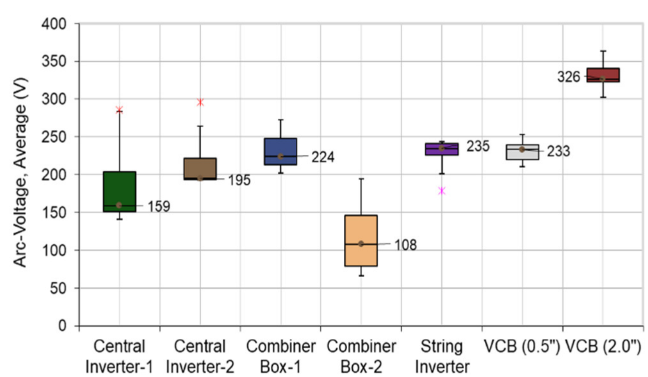

Fig. 12. Distribution of measured arc-voltage (average) for various solar PV equipment and calibration tests (VCB)

The value V_{Arc} is determined primarily by the length of the arc, and the natural length of the arc is determined mainly by the geometry of the electrodes and the equipment. The distribution of measured V_{Arc} for five different types of PV plant equipment and two VCB setups is shown in Fig. 12.

Based on the test results of five different types of PV equipment, 300 V represents the highest possible value for average V_{Arc}. For an array with an open-circuit above 800 V, the 300 V is low enough to draw nearly the short-circuit current from the PV array as shown in the IV-characteristic curve in Fig. 6.

The factor for converting arc-energy to incident energy at 18 in (46 cm) is taken as 2.9 x 10^{-6} cal/cm^2/J based on the test result, as shown in Fig. 9. Hence the equation (2) is simplified as follows;

$$IE = 0.00087 \times I_{Sc} \times t_{Arc} \quad (3)$$

This model only applies to 1000 Vdc plants at a working distance of 18 in (46 cm). For other working distance, a distance factor could be introduced as per IEEE-1584 [2] and the model expressed as follows:

$$IE = 0.00087 \times I_{Sc} \times t_{Arc} \times \left(\frac{D}{45.7}\right)^{-1.6} \quad (4)$$

Where D is the working distance in cm and power -1.6 is known as the distance coefficient.

Fig. 13. shows the measured and calculated incident energy using the PV-sepecific arc-flash model alongwith aviable dc arc-flash model for a VCB setup.

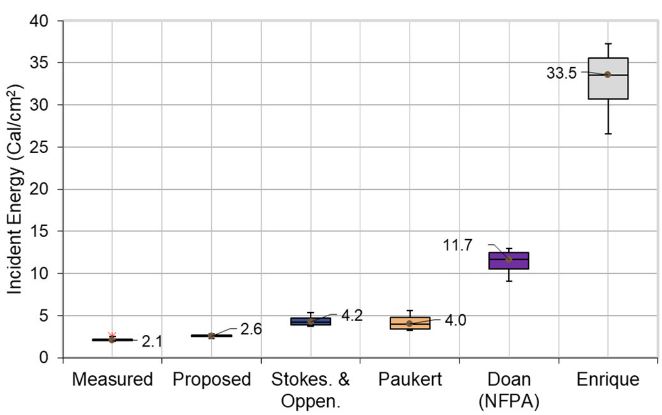

Fig. 14. Measured and calculated incident energy using the PV-specific arc-flash model and other dc arc-flash models for arc-in-box VCB setup.

IV. Discussion

Large-scale PV plants are increasingly being designed and built with higher power equipment. PV plant owners and operators are relying on the available dc arc-flash model to calculate the incident energy and decide the PPE for workers. As none of the simplified dc arc-flash models correctly predict I_{Arc}, V_{Arc}, and the incident energy values for a PV plant, the PPE categories using NFPA-70E [1] and the calculated incident energy for the models range from category 1 to 4 for the same equipment in a PV plant. This situation is creating confusion in the solar PV community and may add undue risk to the PV plant operator.

New PV plants are being built at higher dc voltage (1,500 Vdc) and with storage (i.e., solar-plus-storage), which further increases risks of arc-flash. There is an urgency to quantify the risks of dc arc-flash in the PV plant with new voltage topology and the plant design.

For an adequate template and procedure for an arc-flash risk assessment in a PV plant, further field-data from arc-flash experiments are needed. The experimental data should reflect the components of the PV plant and suitable configurations or specifications, i.e., orientation and distance between the electrodes, voltage, current ranges, and the grounding schemes. Experimental data sensitivity and statistical analysis are also needed to quantify each parameter's contribution to arc-flash risk in a PV plant.

V. Conclusion and Future Work

Adequacy of the simplified dc arc-flash models for PV array as a power source is compared against the experimental data from arc-flash field tests in two large-scale PV plants. I_{Arc} and V_{Arc} of a PV array are verified to follow the IV-characteristics curve in contrast to the predicted values using dc arc-flash models. Existing dc arc-flash models are found to be overly conservative and are not applicable for a PV array as a power source.

More arc-flash experimental data with PV array of different source capacity, voltage level, different system components (i.e., inverters, combiner boxes, and recombiner boxes) in the different configurations are required for comprehensive model development. The development and utilization of robust computer simulation models would be more time- and cost-efficient option in the long-term.

Interaction and partnering among industry members, standards organizations, and research institutes are required to develop and promulgation of much-needed standards or code for dc arc-flash risk assessment in PV plants.

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