

Updated evaluation of shock hazards to firefighters working in proximity of PV systems.

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Abstract — Sandia National Laboratories (SNL) is evaluating a variety of Photovoltaic (PV) operating conditions that have raised concern of shock hazard among firefighters and other emergency responders, including a scenario where the array might be illuminated by high power floodlights in a nighttime firefighting event. Theoretical approaches to determining the shock hazards to firefighters from PV arrays under worst-case daytime conditions are described. In order to evaluate the extend of the hazards in a nighttime fire scenario, experimental tests were conducted under full-moon illumination, specifically under a rare Super Moon event. We have monitored available power levels of a PV array power levels under realistic worst-case illumination conditions. The evaluations considered a variety of PV array sizes, proximity to high intensity flood lamps of the type used by firefighter personnel, as well as full-moon illumination. IV traces from individual modules, as well as PV modules connected in parallel and series, were recorded to determine the available power levels. All conditions tested showed that the shock hazard to firefighting personnel under these worst-case conditions is well below the hazard limits defined IEC TS 60479-1.

I. INTRODUCTION

Recently, there has been an increasing concern regarding the risk of shock to firefighters and other emergency response personnel working in the proximity of PV systems. The data made available to support these concerns is often incomplete, and sometimes results in an overly conservative risk assessment. Understanding exact risks is very important to formulate correct mitigation measures. Actual levels of PV power attainable may dictate safety procedures and requirements, such as voltage levels for Rapid System Shutdown (RSS) [1] and other approach boundary voltages.

NEC Article 690 establishes electrical safety requirements for PV installations in the U.S. The 2017 Revision to NEC 690.12 includes new requirements for RSS protection applied to PV arrays [2]. The revision lists the following options to mitigate shock hazard:

- A. Listed protection system at the PV array level.
- B. 80 V, 30-second limit for controlled conductors internal to the array.
- C. PV arrays with no exposed wiring methods, no exposed conductive parts, and installed more than 8ft from exposed grounded conductive parts or ground.

Methods include limiting access to exposed components that might become energized, reducing the voltage difference between energized components, limiting the electrical current that might flow in an electrical circuit involving personnel by increasing circuit resistance, or by a combination of such methods. It should be noted that NEC Article 690 requirements do not apply to ac PV modules since they do not have dc output.

Accidental contact with a damaged array may expose emergency personnel to shock hazards of unknown voltage. Therefore, the new 2017 NEC update made specific requirements for RSS and safe voltages for personnel operations. According to UL 1310 [3], the safe voltage is $\leq 60V$ in dry conditions and $\leq 30V$ in wet conditions, as listed in 2014 NEC Chapter 9, Table 11(B) [1]. Additionally, UL 62109-1 [4] and 2014 NEC [1] outlined 240 VA as the safe power limit (energy hazard). The 2017 NEC removed the 240 VA reference, but added an 80 V limit.

The 2017 NEC revision prescribes acceptable voltage levels for firefighter personnel for newly installed arrays. However, it does not quantify the hazard to firefighters from arrays commissioned prior to NEC 2017. In order to understand and quantify the hazards of PV arrays (both with 2017 NEC protections and without), Sandia National Laboratories has conducted both theoretical analysis and experimental testing under a variety of environmental conditions. Section II describes the theoretical analysis of worst-case hazards to firefighters under daytime scenarios, Sections III details the results of nighttime lighting tests with worst-case results for ambient illumination (i.e. moonlight) as well as artificial illumination characteristic of a firefighting scenario.

II. THEORETICAL WORST-CASE DAYTIME EVALUATIONS

This section models shock hazard to a firefighter that may come into contact with a PV array under the conditions of the test. Both grounded and ungrounded arrays are considered. The procedure first calculates the effective resistance (R_{eff}), and then uses the result to estimate the current that a firefighter might experience.

A. Ungrounded Arrays

An ungrounded array is disconnected from ground at the inverter (the array is either ungrounded during normal operation or the ground-tie of the inverter is disconnected during isolation.). This means that the only reference to ground is along the module leakage pathway (R_{module}) and the isolation of the ungrounded array (R_{iso}) is a function of the number of modules in series (S) and parallel (P) and is approximately given by (1):

$$R_{iso}^{ungrounded} \approx R_{module} = \frac{(S-1)P}{R_{leak}} + \frac{2P}{2R_{leak}} = \frac{R_{leak}}{S \cdot P} \quad (1)$$

For an ungrounded array with the inverter disconnected from the path of current flow, the fault current path through a firefighter (R_{FF}) is in series with R_{iso} (Fig. 1). Therefore, a large

R_{iso} restricts the amount of current flow through the firefighter (I_{FF}).

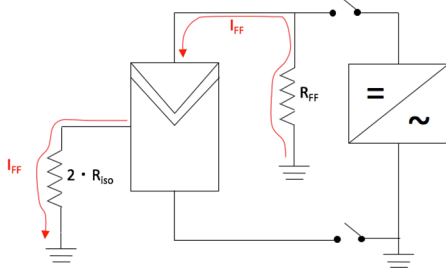


Fig. 1: Simplified diagram of current flow through a firefighter in an ungrounded array. The current flow is in series with the array isolation, R_{iso} .

Since R_{iso} and R_{FF} are in series, the effective impedance of the pathway is equal to (2).

$$R_{Eff} \approx 2 \cdot R_{iso} + R_{FF} \quad (2)$$

B. Grounded Arrays

A grounded array, on the other hand, is not disconnected from ground at the inverter. This means that the array is referenced to ground both along the module leakage pathway (R_{module}) as well via the ground fault protection device (GFPD). Since the module leakage pathway resistance is typically multiple orders of magnitude greater than R_{GFPD} , the isolation of the grounded array (R_{iso}) can be approximated with $R_{GFPD} \sim 0$ so that $R_{iso} \sim R_{module}$. Since R_{FF} is in parallel with R_{module} , a fraction of the current (F) flows through R_{FF} with the remainder flowing through R_{module} . However, as with R_{iso} , typically $R_{module} \gg R_{FF}$ and $F \sim 1$.

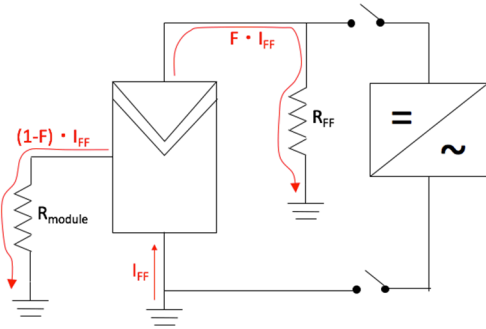


Fig. 2: Simplified diagram of current flow through a firefighter in a grounded array. The current flow is in parallel with the module leakage, R_{module} .

In this grounded case, the effective impedance of the system is equal to (3):

$$R_{Eff} \approx \frac{1}{\frac{1}{R_{iso}} + \frac{1}{R_{FF}}} \quad (3)$$

As $R_{iso} \gg R_{FF}$, (3) reduces to (4):

$$R_{Eff} \approx R_{FF} \quad (4)$$

C. Firefighter hazard as a function of array size

The effective resistance of the system (R_{eff}) determines the

amount of current flow from the array and hence, the amount of current hazard to a firefighter, as it determines the array load line as shown in Fig. 3.

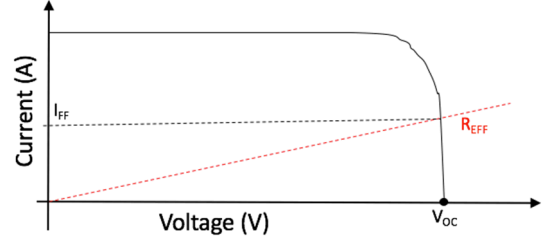


Fig. 3: R_{eff} determines the load line and the amount of current I_{FF} that flows.

If $R_{eff} \gg R_{mp}^{array}$ and the array has a moderate fill factor, then it can be assumed that R_{eff} intersects the array IV curve at array V_{oc} . In this case, the current hazard, I_{FF} can be described by (5):

$$I_{FF} \approx \frac{V_{oc}}{R_{eff}} \quad (5)$$

This approximation is more appropriate for larger values of R_{eff} . As R_{eff} approaches array R_{mp} , the knee curvature of the array IV curve can no longer be ignored and the intersection of R_{eff} with the IV curve cannot be approximated as V_{oc} .

In general, the current hazard to a firefighter is linearly related to the V_{oc} of the array. For small body impedances ($\sim 600 \Omega$ [7]) and large array V_{oc} values, the approximation in (5) tends to overestimate the current hazard. This is due to the fact that as modules are added in series, the value of R_{mp}^{array} decreases. For small values for body impedance and large array V_{oc} , the value of R_{eff} begins to approach R_{mp}^{array} and the knee curvature of the array IV curve cannot be ignored. In this case, the intersection of R_{eff} with the IV curve does not occur at V_{oc} , but at some $V < V_{oc}$ and tends to overestimate the current hazard. If $R_{eff} \gg R_{mp}^{array}$, the current hazard to the firefighters is dependent only on array V_{oc} and not array size (I_{sc}).

As we can see, whether the PV system is grounded or ungrounded has a great impact on the level of current that can be expected. For ungrounded systems, a firefighter in the path from exposed DC conductor to ground would essentially be in series with $2 \cdot R_{iso}$, which can be very large, limiting the current. For grounded systems, the firefighter would instead be in parallel with the module leakage pathway, whose resistance is orders of magnitude larger than body impedance. This means that most of the current would flow through the firefighter.

D. Firefighter danger during daytime operation

To further correctly quantify the electrical hazard to a firefighter, we need to account for additional variables including the following:

1. PV system DC voltage class
2. Isolation from inverter
3. Grounded or ungrounded systems
4. Skin and body impedance
5. Current path through body
6. Duration of contact
7. Surface area of contact

8. Personal protection equipment (PPE) conditions
9. Health and fitness conditions of a firefighter
10. Wet or dry ambient conditions
11. DC physiological effects
12. Fall hazard.

For all our analyses, it is assumed that the inverter is isolated from both the DC as well as the AC sides the array, preventing current flow through the inverter, as is required for “Rapid Shutdown” in [2]. For ungrounded arrays, this would mean the array is disconnected from the inverter ground (GFPD) and the only reference to ground is through the array isolation resistance, R_{ISO} [6]. For grounded arrays, the inverter isolation does not eliminate the connection to ground.

To estimate the current hazard to firefighters, three different PV V_{OC} voltage limits should be considered per [2]:

1. 600 V – small residential PV systems
2. 1000 V – small and mid-size commercial PV systems
3. 1500 V – commercial and utility-scale PV systems

The values for the total body impedance, R_T , as a function of voltage can be found in [7]. R_T can be constructed as a sum of the following components, as shown in Figure 8(b):

- R_{C1}, R_{C2} – Contact resistances (skin)
- R_I – Internal body resistance
- R_{PPE} – PPE resistance

The same R_T calculation can be illustrated in a simplified equivalent circuit diagram shown in Figure 4(a).

The R_T reduces as touch voltage increases. Statistical data exists [7] quantifying R_T for general population, starting from an “average” person, to 5% and 95% percentiles of the population. The 5th and 50th percentiles were considered most appropriate to the average firefighter and are used for further calculations in this work.

To properly apply the effects of direct current passing through the human body per [7], it is assumed that all DC

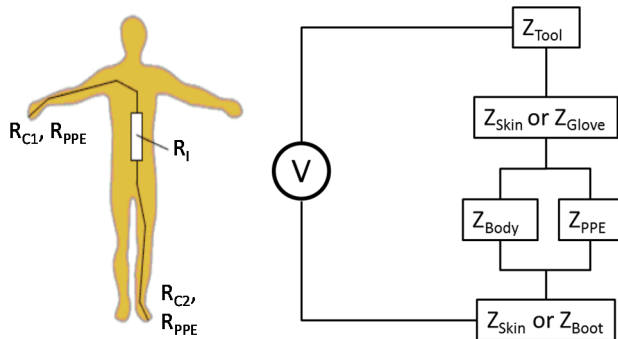


Fig. 4. (a) Illustration of components considered in calculation of the total body impedance, R_T . (b) Simplified equivalent circuit representation of different components of total body impedance and PPE.

currents from PV arrays contains a sinusoidal ripple of no more than 10% r.m.s. Since voltages 600V and above are under consideration, the surface areas of contact defined in [7] become inconsequential. It does however matter when

considering the breakdown of skin, which is dependent on current density (mA/mm^2) and duration of current flow. For contact greater than 10 seconds, currents greater than 4800 mA, and small surface areas of contact (100 mm^2), the skin can be expected to break down and total body impedance becomes just the internal body impedance, which can be considered the worst case [7].

Physiological effects that can be expected per [6], depending on the contact duration. The thresholds vary up to 2 seconds, after which the physiological effect does not change as a function of time. There are seven different physiological effect zones that can be considered, although some, especially those with no lethal potential, can be evaluated as a group, for simplicity.

The current path through the body can have a large impact on the physiological effects expected [7]. For instance, all possible combinations from hands to feet (left/right, one/both) are considered the baseline path. Other variations, such as left hand to right hand, must consider a “heart-current factor” resulting in greater current tolerance, or chest to left hand resulting in lower current tolerance.

The impedance of the body is reduced if the skin is assumed to be broken. As was previously mentioned, this would require quite an extreme current density, 4800 mA for a contact surface of 100 mm^2 , for greater than 10 seconds. None of the scenarios summarized in Tables I and II came anywhere near being able to provide that level of current, therefore the body impedance with skin intact was assumed.

Finally, the level of PPE was considered, as it also has a tremendous impact on the expected current. Ideally, the probabilities of the following would guide assumptions:

1. Firefighter not wearing boots
2. Firefighter contacting exposed DC conductor with one hand and ground with other body parts other than booted feet
3. Firefighter not wearing gloves
4. Firefighter wearing wet gloves
5. Firefighter not able to cease contact in less than two seconds (different physiological effects) or 10 seconds (skin breakdown)

For this study, the possibility of a firefighter not wearing boots was not considered, as a practical case. Therefore, a left-to-right hand path was investigated initially.

Given all the considerations above, Table I and Table II summarize calculated worst case DC currents (in mA) under different PPE conditions for the different voltage classes, for grounded and ungrounded systems, respectively. The colors associated with Tables I and II correspond to the physiological effects in [7]. The applicable hazard classifications and corresponding thresholds are summarized in Table III.

The currents were calculated with the assumptions listed in Table IV. The impedance percentiles were obtained from [7], which lists impedances not to be exceeded by the given percentage of the population.

Calculation results summarized in Table I and II do indicate potentially high hazard levels for bare hand assumptions at the

TABLE I.
POTENTIAL DC CURRENTS (IN mA) FOR UNGROUNDED SYSTEMS
UNDER DIFFERENT PPE CONDITIONS FOR DIFFERENT PV SYSTEM
DESIGN VOLTAGES

50% Imp	Voltage Class		
PPE	600	1000	1500
Bare Hand	308	513	770
Wet Glove	41	69	103
Dry Glove	2	4	6

TABLE II.
POTENTIAL DC CURRENTS (IN mA) FOR GROUNDED SYSTEMS
UNDER DIFFERENT PPE CONDITIONS FOR DIFFERENT PV SYSTEM
DESIGN VOLTAGES

50% Imp	Voltage Class		
PPE	600	1000	1500
Bare Hand	135	225	338
Wet Glove	35	59	89
Dry Glove	2	4	6

TABLE III.
PERCEIVED SENSITIVITY ZONES BASED ON CURRENT

Current	Effects
< 150 mA	Slight pricking sensation to strong involuntary muscle contractions, no organic damage expected.
150-175 mA	≤ 5% probability of ventricular fibrillation.
> 175 mA	Probability of ventricular fibrillation ≥ 50%

TABLE IV.

Variables	Value
50th percentile impedance	775
Bare hand added impedance (Ω)	0
Wet glove added impedance (Ω)	5000
Dry glove added impedance (Ω)	100000
Heart-current factor for hand-to-hand	0.4
Parallel resistance factor for R_{ISO} of 100 k Ω (grounded systems)	0.994
Series resistance R_{ISO} (Ω , for ungrounded systems)	1000

higher voltage classes. However, it is very important to understand the unlikelihood of this scenario, given both standard operating procedures of firefighters and standard cabling and wiring methods of PV systems. Further work will report on statistical likelihood of such scenarios.

III. NIGHTTIME LIGHTING TESTS

Sandia National Laboratories conducted independent tests to verify maximum (worst case) power generated by a PV system under moonlight conditions. Figure 5 shows a photo of the nighttime testing.

A. Setup

The system used for nighttime testing consisted of a PV array with a single string of 16 modules connected to a grid-tied inverter. The array is installed at a tilt angle of 35 deg. The relevant module and array ratings are listed in Table V.



Fig. 5. Photo of the test setup.

TABLE V.
MODULE AND ARRAY PARAMETERS UTILIZED IN TESTING.

Module Rating (W)	245
Module I_{sc} (A)	8.25
Module V_{oc} (V)	37.7
Module V_{MPP} (V)	30.8
Module I_{MPP} (A)	7.96

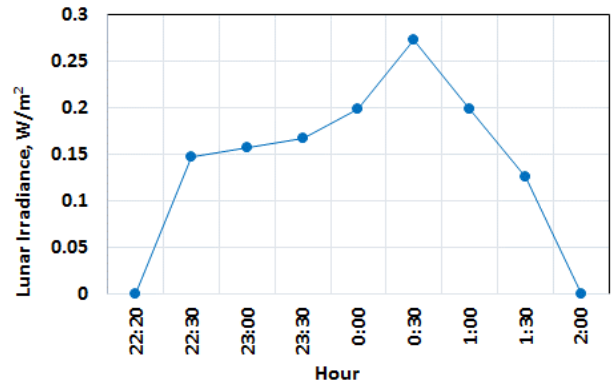


Fig. 6. Measured irradiance during the full ("super") moon in Albuquerque, NM, on November 14th 2016

B. Test conditions

In order to evaluate the worst possible hazards (i.e. the maximum possible power generated by PV panels) presented to firefighters in a nighttime scenario, testing was conducted on a full moon night. The date of testing, November 14th 2016 corresponded to a "Super Moon" event— a full moon closely coinciding with perigee. The November 14th Supermoon was the closest a full moon has been to Earth since January 26th, 1948 and similar event will not occur until November 25, 2034. As such, the test conditions represent the highest moonlight irradiance level contributing to power produced by a PV array. Additionally, lunar "noon" elevation of 70.6°, and azimuth of

180° were optimal angular positions for illumination of our South-facing PV array.

Figure 6 shows measured irradiance during the full moon in Albuquerque, NM, on November 14th 2016. The peak of the irradiance corresponds to the time of lunar “noon” which was at 00:30am local (MST) time. The peak irradiance measured was 0.27W/m². These measurements are consistent with maximum moon power estimates obtained in [5]. Assuming spectral composition of lunar irradiance is the same as solar irradiance, a uniform irradiation of 0.27W/m² would result in less than 10mW of power produced by a typical commercially available Si PV panel. However, spectral composition of lunar irradiance is not identical to that of solar. Further calculations of reduced power produced under moonlight spectra will be reported in a separate publication.

TABLE V
TEST AND CONDITIONS SCHEDULE.

Test	Test Condition	Array Configuration	Floodlight distance
	7 am	3 parallel panels	N/A
	4:30 pm	3 parallel panels	N/A
1	2 x 1000W Halogen	3 parallel panels	56 cm
		single panel	56 cm
2	2500 Lm LED	3 parallel panels	56 cm
		single panel	56 cm
3	2 x 2500 Lm LED	3 parallel panels	56 cm
		single panel	56 cm
4	1000W Halogen 2x 2500Lm LEDs	3 parallel panels	56 cm
		single panel	56 cm
5	2x 1000W Halogen 2x 2500 Lm LEDs	3 parallel panels	56 cm
		single panel	56 cm
6	Full moon only	Super moon, Elevation 70.6, /AZ 180°	N/A

C. Test procedure

Table V lists the test conditions that were used in nighttime testing. In addition to ambient light measurements, panel and array-level measurements were taken for combinations of two different types of floodlights (halogen and LED) that are typically used for nighttime firefighter operations. The lights were installed at a distance of 56 cm from the PV panels. It is important to note that a distance of 56 cm is an extreme worst (and probably, impractical) case of a how close a firefighters’ light source could possibly be to a PV array; in practical firefighting conditions, lights would be on the firefighters’ trucks at least several meters away from a PV array.

For each test, an IV tracer was used to take IV sweeps of individual PV panels as well as PV panels connected in series and in parallel. Current sensitivity of the IV tracer is 30 μ A, which is larger than the photocurrent produced by single module in majority of tests. In these cases, PV panels were connected in parallel in order to increase total measurable current.

In addition to panel and array IV curves, an irradiance uniformity map was recorded using standard LI-COR



Fig. 7. Photos of the test setup: (a) two 1200W halogen lights; (b) one 2500 Lumens LED light; (c) two 2500Lumens LED lights; (d) top view of illumination by two LED lights, showing significant non-uniformity of the illumination

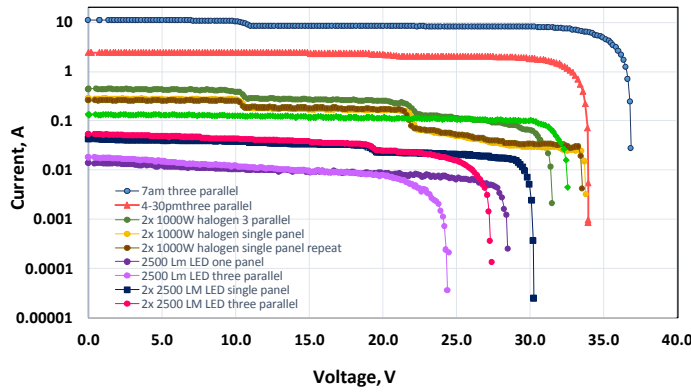


Fig. 8. IV curves recorded under different illumination conditions.

irradiance meter at teach testing condition. As seen from Figure 3, both halogen and LED lights produce localized irradiation patterns. Such non-uniform irradiation results in a classical mismatch case of PV cells within the PV module. As a result, PV power produced is even further reduced due to mismatch.

D. Results and Analysis of nighttime testing.

Figure 8 shows a family of IV traces recorded under different illumination conditions as described in Table II. As can be seen from the plots, illumination by halogen floodlights (green, yellow, and navy-blue traces) resulted in higher current response from the PV array compared to LED illumination (pink, purple traces). This is due to better overlap of the Si PV spectral response with the Halogen emission spectra. It should be noted that the majority of firefighter operations vehicles are switching their lighting equipment from halogen to LEDs. Therefore, the LED illumination results are the more relevant result to current firefighter operations and those in the future.

From Figure 8 we can see that, under illumination by two 2500 Lm LED flood lights (pink trace, circle markers), a single PV panel produced approximately 10 mA at 30 V, resulting in a maximum power of $0.3W_{mp}$. A single 2500 LM LED floodlight yields a hazard of less than $0.1W_{mp}$ or $100mW_{mp}$. More importantly, current levels at the maximum power point condition is under 100mA. As described in Section II, current hazard levels to firefighter will be even further reduced due to PPE and R_{iso} of the array.

IV. CONCLUSIONS

We have assessed the worst case hazards to firefighters under power levels which may be present under fire fighting conditions. Detailed measurements were conducted under nighttime conditions. This work has shown that under work-case ambient illumination (full moon) and typical emergency lighting conditions, the current hazards to firefighters is low. All tested conditions showed that worst-case hazard is well below the limits of the hazard by continuous electrical current set by IEC 60479-1.

The theoretical analysis of specific shock hazards for worst-case daytime conditions have been shown. Unlikely scenarios

with worst case assumptions (e.g. firefighters with no PPE), considering a dozen potential variables and full array V_{oc} exposures, show some potential concerns for higher (> 600 V) PV system design voltages. As these results represent worst-case scenarios, it is extremely unlikely that firefighters would be subjected to the current hazards shown in Tables II and IV. The analysis shows that current hazard is directly related to personnel impedance as well as array maximum voltage. PPE resistance is larger than body impedance. Therefore, minimizing current hazards to emergency personnel is dependent on proper PPE (to increase effective impedance) as well as array segmentation strategies to decrease voltage levels.

The results presented here are preliminary and further work is being undertaken using simulation as well as experimentation. Complete results will be refined, validated, and published in a future publication. This body of work is intended to further clarify the risks posed by PV installation to firefighter and other emergency personnel

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