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A Conservative Approach to Defining Photovoltaic System Hazards to Firefighters

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Abstract

Sandia National Laboratories performed analysis to develop conservative hazard guidelines regarding firefighters working near photovoltaic (PV) arrays. Assuming implementation of NFPA 70 system shutdown requirements, the analysis focused on DC hazards only. Several different PV variables were considered, including system grounding and DC voltage classes. The hazard scenarios considered the contact conditions, current paths through the body, and PPE. Guidelines for the hazard definitions for men and women were based on the IEC TS 60479-1 guidelines. The importance of PPE was illustrated in the results.

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FIGURES AND TABLES

1. INTRODUCTION

Photovoltaic (PV) systems are a relatively new and quickly emerging presence in U.S. society. They are commonly mounted on the rooftops of homes and commercial buildings, presenting a new set of challenges to firefighters. Sandia National Laboratories (Sandia) has performed research regarding concerns of the potential hazards PV arrays pose to firefighters.

Sandia gathered firsthand feedback from the firefighter community to address several concerns, including moonlight and firefighter lighting energization hazards [1]. This report primarily addresses concerns regarding unintended contact with the DC side of PV arrays, taking variations in voltage class, PV system type, personal protective equipment (PPE), and physiological effects of current into consideration. The end goal was to create simple and conservative guidelines defining the potential risks.

1.1. Objectives

Publish a technical report providing conservative and comprehensive risk definitions for firefighters around PV systems. The risk analysis takes various variables considered the most probable risk scenarios into account. The variables and basis of the risk definitions are described.

2. BACKGROUND

2.1. PV and Firefighter Hazard Considerations

PV systems are essentially composed of an array of PV modules that convert sunlight to DC power, which is then converter to AC power by an inverter, allowing it to be utilized by customers on the grid. There are many variations to consider when considering PV safety hazards to firefighters, including:

- Men and women – women typically have a lower body resistance than men
- Grounded or ungrounded systems – this plays a significant role in the amount of current expected (described below)
- Voltage classes – per NFPA requirements [2], PV system DC circuits must be limited to a maximum of:
    - 600 volts or less on one- and two-family dwellings
    - 1000 volts or less on other types of buildings
    - 1500 volts or less where not located on buildings
- Body and PPE impedances, including skin breakdown
- Path of current
- Wet or dry conditions
- Physiological effect of current through the body

Due to the disconnecting means required by the NFPA 70 [2], which if properly installed and utilized eliminate AC power hazards from PV systems, this study focused on DC hazards only. The DC side of PV arrays can continue to be energized after an inverter is turned off assuming continued light energy exposure to the modules. Sandia previously performed testing to quantify the potential risks at night when PV modules are exposed to firefighter lighting and/or worst-case moonlight, such as during a super moon [1]. These were mostly found to be insignificant and were not considered in this study.

PV arrays can be ungrounded or grounded on the DC side. Depending on the type, the amount of current expected differs greatly. There is a fairly large isolation impedance inherent to PV arrays, and whether it is ungrounded or grounded determines whether the impedance is in parallel or in series with a fault. In an ungrounded array, the isolation impedance is in series with the fault, severely limiting the fault current. In a grounded array, the isolation impedance is in parallel with the fault, promoting more current to flow through the fault [3]. Figures 1 and 2 show the fault current flow for both ungrounded and grounded arrays, respectively.

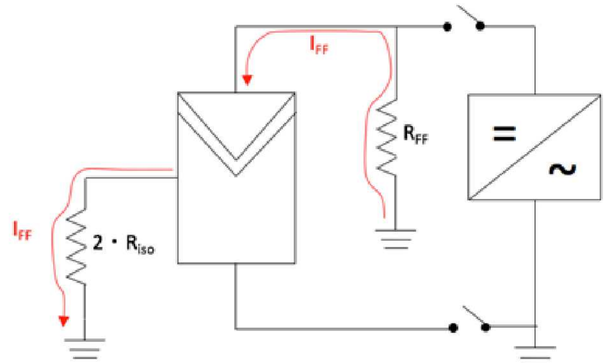

Figure 1: One-line diagram and fault current flow for ungrounded arrays.

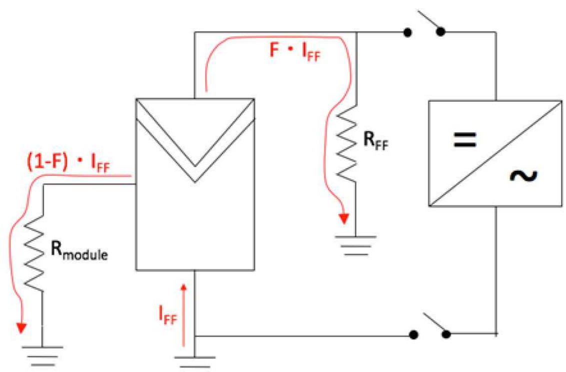

Figure 2 One-line diagram and fault current flow for grounded arrays.

Most PV arrays in the U.S. are grounded. This study focused on both types of arrays and hazards were defined for both. The hazards were also defined at each of the three NFPA 70 [2] DC voltage level limits: 600 V, 1000 V, and 1500 V. As described above, one- and two-family dwellings are limited to 600 volts or less, other types of buildings are limited to 1000 volts or less, and systems not located on buildings are limited to 1500 volts or less. While voltages at each type of system may be below the voltage limit, a conservative approach was taken in calculating the risk at the limit values for each.

Body impedances can vary depending on many factors [4], including:

- Current path
- Voltage
- Duration of current flow
- Frequency
- Degree of moisture of the skin
- Surface area of contact
- Pressure exerted
- Temperature

Core body impedances considered were defined in [4], where values are provided for a variety of conditions and the percentage of the population to which they can be assumed to be applicable

(5%, 50%, and 95%). Hazards were calculated using both the 5% and 50% values for conservancy, as the values of impedance increase as they apply to more of the population. The body impedances are also inversely proportional to the touch voltage. There are then several tables provided for variations in AC versus DC, surface area of contact, and degree of moisture of the skin [4]. Since only DC hazards were studied, only the body resistance was used, as opposed to the impedance with real and reactive components.

However, most of these factors were irrelevant in this study, since regardless of the variables, all tables approached the asymptotic values of 575 Ω for 5% of the population and 775 Ω for 50% of the population. One factor that could further reduce the body impedance is the breakdown of the skin. For this to occur, there must be sufficient current density, approximately 50 mA/mm^2, which depends on the current level and the surface area of contact. In this case, a smaller surface area of contact would be more prone to skin breakdown for a given current level. For the current levels of interest in this study, even assuming a small surface area of contact (100 mm^2), skin breakdown was not a concern.

The impedance/resistance values given in [4] are provided assuming a hand-to-hand current path. Subsequently, a "heart-current factor" (HCF) table is provided with factors to compensate for other current paths through the body and their relation to the likelihood of ventricular fibrillation. While considering a happy medium between realistic and conservative, the likelihood of a firefighter losing his/her footwear or PPE clothing was considered very low and therefore a hand-to-hand path of current was used in the calculations.

For the hand-to-hand current path calculations, bare hand, dry glove, and sweaty wet glove conditions were considered. The bare hand condition was simply calculated using the body impedance values from [4]. The dry and sweaty wet glove conditions were taken from recent UL study values [3]. The lowest measured values available were chosen for conservancy, and extrapolation to 1500 volts was estimated when necessary.

The physiological effects of current on the human body defined in [4] were used as guidance for the hazard risk of each current level. DC is considered less hazardous than AC since it is easier to let go of than AC, and the threshold of ventricular fibrillation is higher [4]. The physiological effects described are slightly time dependent, i.e. the longer the duration of current flow, the lower the current tolerance. Staying in line with conservancy, it was assumed that contact would occur for at least two seconds, which was the threshold of the asymptotic settling of the time dependence.

3. HAZARD CALCULATION RESULTS

The goal for the results of the research done was to provide simple and comprehensive tables clearly conveying the potential hazards, erring on the side of caution and conservancy. The tables are intended to clearly differentiate the hazards for all combinations of the variables described in Section 2. The type of system, ungrounded or grounded, dictated the biggest difference in calculating the current levels to be expected for each.

Equations 1 and 2 were used to calculate the firefighter current, I_{FF}, estimates for the ungrounded and grounded arrays, respectively:

1) Ungrounded:

$$I_{FF} = \frac{V_{OC}}{R_{FF} + R_{PPE} + 2 * R_{ISO}}$$

2) Grounded:

$$I_{FF} = \frac{V_{OC}}{R_{FF} + R_{PPE}} * PRF$$

The variables are defined as:

- V_{OC} is the DC open-circuit voltage of the array
- R_{FF} is the firefighter body resistance
- R_{PPE} is the resistance of the PPE
- R_{ISO} is the isolation resistance of the array used in ungrounded calculations
- PRF is the parallel resistance factor for the isolation resistance of the array

The PPE resistances for sweaty wet and dry gloves were taken from the calculated values in [3]. The dry glove resistances were 35 MΩ at 600 V and 27 MΩ at 1000 V. An estimate for the 1500 V dry glove resistance (17 MΩ) was derived from an extrapolation of the provided values. The resistances for sweaty wet gloves were 450 Ω at 600 V and 380 MΩ at 1000 V. An extrapolated estimate for the 1500 V sweaty glove resistance was defined as 300 Ω.

The isolation resistances used for both ungrounded and grounded arrays was calculated based on the recommendation within IEC 62109-2 [5]. The isolation resistances were calculated as V_{OC}/30 mA, resulting in values of 20 kΩ, 33.3 kΩ, and 50 kΩ for the three voltage levels studied, respectively. Table 1 lists all of the variables considered and values used in the hazard calculations.

Table 1: Current hazard variables and values used for all conditions of interest.

Variables	Value
5th percentile impedance	575
50th percentile impedance	775
Bare hand added impedance (Ω)	0
Sweaty glove added impedance (Ω, voltage dependent)	450/380/300
Dry glove added impedance (MΩ, voltage dependent)	35/27/17
PRFs for 5% Imp, $R_{ISO} = V_{OC}/30mA$ (voltage dependent)	0.972/0.983/0.989
PRFs for 50% Imp, $R_{ISO} = V_{OC}/30mA$ (voltage dependent)	0.963/0.977/0.985
Series resistance 2 x R_{ISO} for UG (kΩ, voltage dependent)	40/66.7/100

The physiological effects were taken from [4], assuming a >2 second contact duration and a hand-to-hand current path. Adjustments for women (x1.33) and men (x2) were also implemented. Tables 2 and 3 list the hazard zone divisions used for women and men, respectively, with color coding, current thresholds, and physiological effects defined. Note the HCF for hand-to-hand current path (x2.5 per equations) was applied to adjust the ventricular fibrillation thresholds (Zone DC-4).

Table 2: Summary of physiological effects and current thresholds applicable to women, as derived from [4].

IEC Zone	Boundaries	Physiological Effects
DC-1	I_{FF} < 2.7 mA	Slight pricking sensation possible when making, breaking or rapidly altering current flow.
DC-2	2.7 mA ≤ I_{FF} < 39.9 mA	Involuntary muscle contractions likely especially when making, breaking or rapidly altering current flow but usually no harmful electrical physiological effects.
DC-3	39.9 mA ≤ I_{FF} < 455.5 mA	Strong involuntary muscular reactions and reversible disturbances of formation and conduction of impulses in the heart may occur, increasing with current magnitude and time. Usually no organic damage to be expected.
DC-4	See below	Patho-physiological effects may occur such as cardiac arrest, breathing arrest, and burns or other cellular damage.
DC-4.1	455.5 mA ≤ I_{FF} < 548.6 mA	Probability of ventricular fibrilation increasing up to about 5%.
DC-4.2	548.6 mA ≤ I_{FF} < 914.4 mA	Probability of ventricular fibrilation up to about 50%.
DC-4.3	I_{FF} ≥ 914.4 mA	Probability of ventricular fibrilation above 50%.

Table 3: Summary of physiological effects and current thresholds applicable to men, as derived from [4].

IEC Zone	Boundaries	Physiological Effects
DC-1	$I_{FF} < 4$ mA	Slight pricking sensation possible when making, breaking or rapidly altering current flow.
DC-2	4 mA $\leq I_{FF} < 60$ mA	Involuntary muscle contractions likely especially when making, breaking or rapidly altering current flow but usually no harmful electrical physiological effects.
DC-3	60 mA $\leq I_{FF} < 685$ mA	Strong involuntary muscular reactions and reversible disturbances of formation and conduction of impulses in the heart may occur, increasing with current magnitude and time. Usually no organic damage to be expected.
DC-4	See below	Patho-physiological effects may occur such as cardiac arrest, breathing arrest, and burns or other cellular damage.
DC-4.1	685 mA $\leq I_{FF} < 825$ mA	Probability of ventricular fibrilation increasing up to about 5%.
DC-4.2	825 mA $\leq I_{FF} < 1375$ mA	Probability of ventricular fibrilation up to about 50%.
DC-4.3	$I_{FF} \geq 1375$ mA	Probability of ventricular fibrilation above 50%.

Tables 4 and 5 show the current calculation results for the firefighter scenarios for women with appropriate color coding for the hazard levels, per Table 2. Table 4 shows the ungrounded array results for the 5% and 50% population impedances, for all voltage levels and PPE conditions. Table 5 shows the results for the grounded array assumptions.

Table 4: Current hazard results for women with color coding for ungrounded arrays under all conditions of interest.

Ungrounded (mA)			
5% Imp	**Voltage Class**		
PPE	**600**	**1000**	**1500**
Bare Hand	15	15	15
Sweaty Gloves	14	15	15
Dry Gloves	0	0	0
50% Imp	**Voltage Class**		
PPE	**600**	**1000**	**1500**
Bare Hand	15	15	15
Sweaty Gloves	14	15	15
Dry Gloves	0	0	0

Table 5: Current hazard results for women with color coding for grounded arrays under all conditions of interest.

Grounded (mA)			
5% Imp	Voltage Class		
PPE	600	1000	1500
Bare Hand	1014	1710	2580
Sweaty Gloves	395	736	1263
Dry Gloves	0	0	0
50% Imp	Voltage Class		
PPE	600	1000	1500
Bare Hand	746	1261	1906
Sweaty Gloves	345	636	1075
Dry Gloves	0	0	0

Tables 6 and 7 show the current calculation results for the firefighter scenarios for men with appropriate color coding for the hazard levels, per Table 3. Table 6 shows the ungrounded array results for the 5% and 50% population impedances, for all voltage levels and PPE conditions. Table 7 shows the results for the grounded array assumptions.

Table 6: Current hazard results for men with color coding ungrounded arrays under all conditions of interest.

Ungrounded (mA)			
5% Imp	Voltage Class		
PPE	600	1000	1500
Bare Hand	15	15	15
Sweaty Gloves	14	15	15
Dry Gloves	0	0	0
50% Imp	Voltage Class		
PPE	600	1000	1500
Bare Hand	15	15	15
Sweaty Gloves	14	15	15
Dry Gloves	0	0	0

Table 7: Current hazard results for men with color coding for grounded arrays under all conditions of interest.

Grounded (mA)			
5% Imp	**Voltage Class**		
PPE	**600**	**1000**	**1500**
Bare Hand	1014	1710	2580
Sweaty Gloves	395	736	1263
Dry Gloves	0	0	0
50% Imp	**Voltage Class**		
PPE	**600**	**1000**	**1500**
Bare Hand	746	1261	1906
Sweaty Gloves	345	636	1075
Dry Gloves	0	0	0

Immediately visible are the higher hazard levels present in the grounded array results. This is due to the high isolation resistance in parallel with the fault in that scenario, forcing most of the fault current through the firefighter. Another significant result is the importance of keeping dry gloves, they have a resistance close to 80,000 times greater than a sweaty wet glove. Since women tend to have a lower body resistance, approximately 2/3 that of men, they are at a slightly higher risk for all effects. For both ungrounded results, there was no risk in the DC-4 ranges (ventricular fibrillation) up to 1000 V.

8. CONCLUSIONS

A conservative approach was taken to define the DC hazards from PV arrays to firefighters. Several variables were considered, including array grounding, voltage classes, body and PPE impedances, path of current, moisture levels, and physiological effects. The results were analyzed assuming suggested adjustments for both women and men. It was found that that significant hazard levels, including a >50% probability of ventricular fibrillation in some cases, especially for higher voltages combined with diminished PPE conditions may exist. It was also observed that maintaining dry gloves eliminates the hazard risks regardless of array grounding and voltage.

It is important to keep the level of conservatism assumed in mind. For example, it is unlikely to expect array types to be at the voltage class limits, as this would require the sum of the array open-circuit voltages to be greater than or equal to the voltage limit with sufficient irradiance conditions. Any reduction in the voltage level would reduce the risk almost linearly. The isolation resistances were chosen per the IEC 62109-2 standard [5]. A less conservative assumption of these variables would directly reduce the hazard levels.

Lastly, it is also important to consider other current paths that would potentially result in a higher risk of ventricular fibrillation, e.g. chest-to-hand. In this study, a logical assumption of the likelihood of certain paths, coupled with a lack of body and PPE impedances for those circumstances, drove the focus on the hand-to-hand current path. Future work may benefit from a probability analysis of all feasible combinations of path of current and PPE conditions to focus on all circumstances with feasible likelihood. This would subsequently require further body and PPE impedance determinations.

9. REFERENCES

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