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ARC FLASH DETECTION ON PHOTOVOLTAIC SYSTEMS

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Abstract: Photovoltaic (PV) systems are increasingly being used. Because of ageing and the trend toward higher DC voltage levels, incidents of DC arc faults in PV systems are becoming more common, which seriously impacts system stability and human safety. Parallel arcs draw a higher current than series arc faults, so detecting the latter is more challenging. The undetected arc faults pose a severe fire hazard to residential, commercial, and utility-scale PV systems. Such a dangerous event must be detected early to deliver electricity safely and reliably. This paper comprehensively reviews the state-of-the-art techniques for DC arc fault detection in photovoltaic systems (PV). Different methods and the features used for detection are discussed and compared in detail. This paper also emphasizes the importance of DC arc fault simulation for characteristics study and fault diagnosis purposes. Several DC arc fault models have been reviewed and compared.

Key words: risk, evaluation, safety, solar panel.

1. INTRODUCTION

With the advancement of technology and increasing realization of pollution in the environment, clean, renewable sources such as solar energy are gradually replacing traditional fossil fuels. Solar power installation is increasing throughout the world. Residential rooftop solar panels and grid-connected photovoltaic (PV) generation will support the main utility networks and microgrids. The increasing amount of PV systems and the trend toward increasing DC voltage levels can create DC arc faults. Because of the deterioration of cables, connectors, conductors, and other system components caused

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by long-time weathering and ageing effects, without adequate and proper maintenance, the possibility of DC arc occurrence is expected to increase sharply[1,4].. It should also be stressed that, unlike AC arcing, the absence of current zero-crossing makes DC arcs more sustainable [21], [23], [26], [29], [31].

An example of a PV system and different types of arc faults are shown in Fig.1.

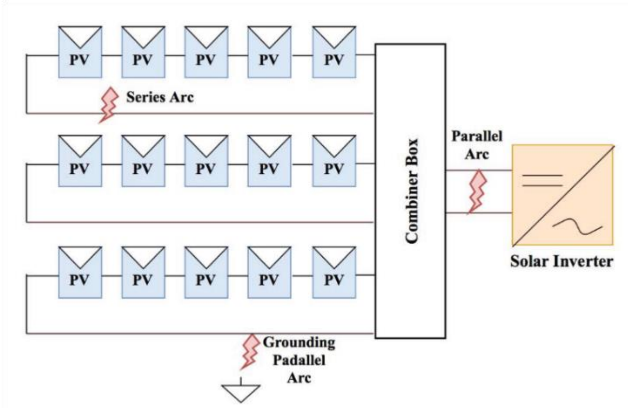

Fig.1. An example of PV systems and arc fault types

DC arcing occurs across small gaps in connections. Bad joints decrease the cross-section's contact area, effectively increasing the resistance and, thus, the heat loss. The higher operating temperature accelerates the deterioration process of the connecting point, which leads to a loose connection [5]. Subsequently, the point of discontinuity forms a tiny gap that the current could keep flowing. When the electric field between two electrodes exceeds about (in normal conditions), air starts to ionize and plasma is developed, which will finally form a series arc [37]. Due to the extra impedance contributed by the arc, the fault current (lower than the standard operating current level) will not be sufficient tomelt the fuse or activate the overcurrent protection devices [6], [7], [38]. Specifically, the series arc fault will not draw an inverse current like a parallel arc fault [8], and the average load current contributes to the total fault current. With the increased impedance injected by arc fault, the current level will go down and thus cannot reach the level to melt the fuse [9], [22], [24], [28], [32].

Furthermore, the current level will return to normal because the inverter operates for maximum Power Point Tracking (MPPT). At the same time, the arcing fault still exists, presenting more challenges to DC arcing fault detection. As a result, the heat energy generated by the arc over a long duration could damage system components severely, seriously threatening system stability and human safety [10], [25], [27], [30].

2. ELECTRIC SHOCK AND ARC FLASH HAZARDS

There is a real danger of electric shock to anyone entering any of the electrical cabinets, such as combiner boxes, disconnect switches, inverters, or transformers, or otherwise coming in contact with voltages over 50 Volts. Another electrical hazard is an arc flash, an energy explosion that can occur in a short circuit situation. This explosive release of energy causes a flash of heat and a shockwave, both of which can cause severe injury or death. Properly trained and equipped technicians and electricians know how to install, test, and repair PV systems safely. However, there is always some risk of injury when hazardous voltages and/or currents are present. Untrained individuals should not attempt to inspect, test, or repair any aspect of a PV system due to the potential for injury or death due to electric shock and arc flash [33], [35], [36].

The possibility of fires resulting from or intensified by PV systems may trigger concern among the general public and firefighters. However, concern over solar fire hazards should be limited because only a tiny portion of materials in the panels are flammable, and those components cannot self-support a significant fire. Flammable components of PV panels include the thin layers of polymer encapsulates surrounding the PV cells, polymer backsheets (framed panels only), plastic junction boxes on the rear of the panel, and insulation on wiring. The rest of the panel comprises non-flammable components, notably including one or two layers of protective glass that comprise over three-quarters of the panel's weight [34].

The heat from a small flame is inadequate to ignite a PV panel, but the heat from a more intense fire or energy from an electrical fault can ignite a PV panel [11]. Improving understanding of the PV-specific risks, safer system designs, and updated fire-related codes and standards will continue to reduce the fire risk caused by PV systems.

3. CHARACTERISTIS OF DC ARC

Understanding and studying the characteristics of an electric arc is very important. DC arc exhibits nonlinear features, and their characteristics vary with arc length, electrode material, electrode geometry, and current level [12]. The quasi-static arcing V-I characteristic with a fixed arc length is shown in Fig. 2. It can be seen that in the lower current region, the smaller the current, the larger the voltage, where the power of the arc ($P_{arc} = V_{arc}I_{arc}$) tends to remain the same; while in the higher current region, with the increasing current, the voltage remains approximately unchanged. The red line identifies Those two regions,vwhich is the so-called current transition point line. Stokes and Oppenlander carried out the most exhaustive experiment that covered a wide range of current levels and arc lengths with series electrodes. The transition current is then defined by (1).

Furthermore, based on the huge data set, the V-I characteristic in the "constant voltage" region is defined in (2) [13].

$$I_{arc} = 10 + 0.2L \tag{1}$$

$$P_{arc} = (20 + 0534L)I_{arc}^{1.12} \tag{2}$$

where L is arc length in mm. It should be noted that the arc gap width is not equal to actual arc length, and the additional impedance injected into the circuit is contributed by arc length.

The current level in the PV string is not high, whereas it is much higher in the combiner box and the DC side of the inverter (the current level at the DC side of the inverter could go up to several thousand amps in large PV utilities).

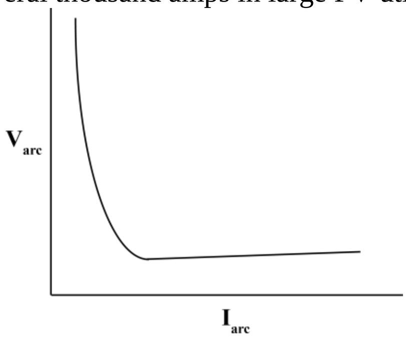

Fig.2. Arcing voltage and current characteristic

Figure 2 shows the quasi-static V –I characteristic for a “fixed” length arc. In the low-current region (identified by the dotted line), the arc voltage drops as the arc current increases; as a result, the arc power (P = V I) tends to remain relatively constant in this region. For “larger” currents, the arc voltage increases slightly with increasing arc current. (A transition current, which defines the boundaries between the low- and high-current regions, is presented later). With wall-stabilized arcs, the arc plasma is only partially ionized in the low-current region, whereas the plasma becomes fully ionized above some threshold current [14]. A similar transition in the level of ionization is observed for free burning arcs.

4. DC ARC FLASH HAZARD CALCULATIONS

At the present time, methods for calculating the DC arc flash hazard are not directly addressed in any standard. IEEE 1584 2018 IEEE Guide for Arc Flash Hazard Calculations [15] only addresses the ac arc flash hazards.

Other few important technical papers were published that began to change the understanding of dc arc flash [16 - 19]. These papers provide a theoretical approach to DC incident energy calculations.

Calculating the incident energy for a dc arc flash begins with application of Ohm’s law:

$$I = \frac{U}{R} \tag{3}$$

Where:

I = Current in amperes
U = Voltage in volts
R = Resistance in ohms

By including the dc arc resistance as part of the dc circuit model illustrated in Figure 3, the arcing current can easily be determined. This circuit diagram is of a battery string and includes the DC voltage, DC battery resistance, conductor resistance and dc arc resistance. As part of the overall process, the DC arc resistance must also be calculated since it is usually not known.

Once all of the resistance values have been determined, the dc arcing current, I dc arc can be calculated by [12]:

$$R_{arc} = [(20 + 0.534 \times L)]/I_{dc\,arc}^{0.88} \quad (4)$$

Where:
R_{arc} = resistance of the arc in ohms
L = conductor gap distance in millimeters
$I_{dc\,arc}$ = dc arcing current

In order to calculate the arc resistance using this equation, the conductor gap distance L and the dc arcing current must be known. The gap distance is specified by the user however, in order to determine the dc arcing current, the arc resistance must already be known. To solve this problem, an iterative solution is used. This requires making an initial assumption of the dc arcing current. A the initial assumption is that the dc arcing short circuit current is 50% of the dc bolted short circuit current.

Once this initial assumption is made, the dc arc resistance can be calculated which is then used to re calculate the dc arcing current. The "new" dc arcing current can then used to re calculate the dc arc resistance. This process continues until the dc resistance and dc arcing current values no longer continues until the dc resistance and dc arcing current values no longer change significantly and converge to a final answer.change significantly and converge to a final answer.

Figure 3 illustrates the circuit that is used as an example for calculating the dc arc resistance and the dc arcing current. The calculation process begins by determining the dc bolted short circuit current first. This requires taking the dc voltage (V_{dc}) and dividing by the known impedances of the conductor and battery string.

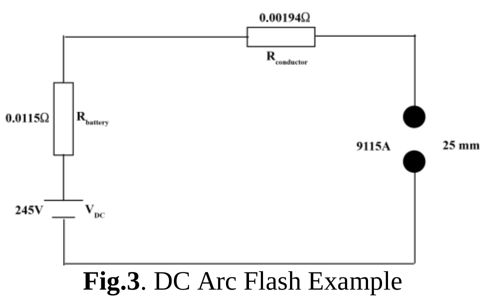

Fig.3. DC Arc Flash Example

First iteration is for the bolted dc short circuit current using the values from Figure 3. For the bolted case, R arc and the conductor gap distance are ignored and only the resistance of the battery string and conductor are used.

$$I_{dc\ bolted} = U_{DC}/(R_{battery} + R_{conductor}) \quad (5)$$

$$I_{dc\ bolted} = 245/(0.0115 + 0.00194) = 18229A \quad (6)$$

$$I_{arc} = 0.5 \times 18229A = 9115A \quad (7)$$

To calculate R_{arc}, equation 4 is used. For the first itteration, R_{arc}= 0.01051
For the next itteration, equation 5 becomes:

$$I_{dc\ arc} = U_{DC}/(R_{battery} + R_{conductor} + R_{arc}) \quad (8)$$

Table 1 shows the results for ten itterations.

Table 1. ***Results of $I_{dc\ arc}$ and R_{arc}***

Iteration	$I_{dc\ arc}$ (A)	R_{arc} (Ω)
1	9115	0,010927667
2	10054	0,010023651
3	10442	0,00969567
4	10590	0,009576304
5	10645	0,009532811
6	10665	0,009516958
7	10672	0,009511178
8	10675	0,00950907
9	10676	0,009508302
10	10676	0,009508022

Figure 4 ilustrates the final results.

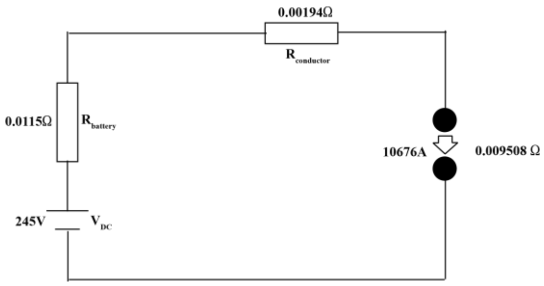

Fig.4. Final resuts of the iteration

Once the dc arcing current and dc arc resistance have been determined, the power in the arc can be calculated by:

$$P_{arc} = I_{dc\,arc}^2 \times R_{arc} \quad (9)$$
$$P_{arc} = 1.084 \text{ kW} \quad (10)$$

Where:
P_{arc} = power in the arc in watts
$I_{dc\,arc}$ = dc arcing circuit current in amperes
R_{arc} = dc arc resistance in ohms

The energy in the arc is a function of power and time. Therefore the energy in the arc can be calculated by:

$$E_{arc} = P_{arc} \times t_{arc} \quad (11)$$

Where:
E_{arc} = arc energy in watt x seconds or Joules
t_{arc} = arc duration in seconds

The duration of the arc flash will either be dependent on the clearing time of an upstream protective device operating or the reaction time of a person jumping away from the hazard. IEEE 1584 presently suggests that a maximum time of 2 seconds may be used based on the reaction time and assuming there are reasonable conditions for a person to escape. Thus, for arc duration of 0.3 s, the arc energy is 325 kJ.

4.1. DC Incident Energy Calculations in open air

Similar to the IEEE 1584 calculation methods, consideration must be given to whether the dc arc flash occurs in open air or in an enclosure/box. If the dc arc flash occurs in open air, the energy will radiate spherically in all directions and the person would be exposed to a smaller portion of the energy. If the event occurs in an enclosure, the incident energy exposure will be greater since it is focused out of the box opening.

According to [12], the incident energy for an arc flash in open air at a specific distance can be calculated based on the following equation:

$$E_{i\,air} = E_{arc}/(4\pi \times d^2) \quad (12)$$

Where d is distance from the arc in mm

Using the dc arcing short circuit current and arc resistance that was previously calculated, the incident energy can be calculated. This requires knowing the working distance from the prospective arcing location to the worker as well as knowing the duration of the arc flash. For this calculation, a maximum arc duration of 0.3 seconds was used. This value would normally be defined by the characteristic of an upstream protective device. A working distance of 18 inches (457 mm) was used which is a "typical" value obtained from IEEE 1584 [19]. In case of open air, the incident energy is 0.1238 J/mm^2 or 2.96 cal/cm^2.

4.2. DC arc flash in an enclosure / box

If the dc arc flash occurs in an equipment enclosure, the energy will be directed out of the open end of the box. For this calculation, the DC arc models defined in [20] are used.

According to this paper, the equation for determining the incident energy from a dc arc flash being focused out of an enclosure is:

$$E_{i\ box} = k \times E_{arc}/(a^2 + d^2) \quad (13)$$

Where:

$E_{i\ box}$ = incident energy from an arc flash in a box at distance d in J/mm^2
E_{arc} = arc energy in Joules
d = distance from the arc source in mm
a and k are obtained from optimal values defined in [20].

For a panel board, a =100 and k = 0.127.

Using values that were previously calculated for I_{dc} arc and R_{arc} , the incident energy will now be calculated based on the arc flash occurring in a box/enclosure. The enclosure is assumed to be a panelboard and the same working distance and arc duration from the earlier example are used.

In case of a panel board, the incident energy is 0.189 J/mm^2 or 4.50 cal/cm^2.

5. CONCLUSION

The models presented in this paper have been based on tests conducted over time by researchers in different countries and under very different protocols. The V –I characteristic is inversely proportional and nonlinear at low current levels. At high arcing-current levels, the analysis in this paper has shown that the arc-resistance voltage drop approaches a constant value. A method has been presented to estimate the incident energy levels possible during an arcing fault to quantify the risks associated with high-current DC systems. Results from a case study demonstrated that the risks associated with high current dc systems may be significant.

Arcing behaviour is highly variable, and the existing DC arc models cannot accurately and reliably assess all the characteristics of DC arcs. Additional arc testing is needed to develop more accurate V –I characteristics and better DC-arc resistance models. Extensive testing in a controlled environment is needed to study the incident energy levels associated with DC arcing faults. A hazard risk assessment is needed to identify where dc arcing faults might be initiated in industrial power systems. The relative severity of the arc flash hazard posed by different types of DC power equipment must be identified.

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