AC and DC – electrical hazards

The electric shock hazard from both ac and dc power systems has been well documented and understood for decades thanks to the research of people like Charles Dalziel. Jim Phillips, PE, explains

Even our understanding of the arc flash hazard has greatly improved thanks to years of research by many individuals and also the introduction of IEEE 1584 - IEEE Guide for Arc Flash Hazard Calculations in 2002. However, when performing arc flash calculations, IEEE 1584 only addresses alternating current (ac) arc flash hazards.

At the present time, there are no standards for calculating the arc flash hazard for direct current (dc) power systems. Even though dc power systems and equipment are not as prevalent as ac, dc systems are found everywhere and include rectifiers, traction power systems, adjustable frequency drives, photovoltaic systems, battery banks and much more. In fact, dc arc flash is the proverbial "elephant in the room".

DC ARC FLASH CALCULATIONS – A WORK IN PROGRESS

Two landmark technical papers were published that began to change the understanding of dc arc flash. The first paper helped elevate the discussion of dc arc flash calculations and is titled: "Arc Flash Calculations for Exposures to DC Systems" by D. R. Doan. It was published in IEEE Transactions on Industry Applications, Vol. 46, No. 6. This paper provides a theoretical approach to dc incident energy calculations based on the concept that the maximum possible power in a dc arc flash occurs when the arcing voltage is 50% of the system voltage. The equations from this paper were ultimately included in the informative annex of the 2012 Edition of NFPA 70E and remain in Annex D of the 2015 edition

A subsequent paper titled: "DC-Arc Models and Incident-Energy Calculations" by R. F. Ammerman, T. Gammon, P.K. Sen and J. P. Nelson (referred hereafter as "DC Arc Models") provides a comparison study of the existing body of research into dc arcs and arc flash modeling that has been conducted over the years. It also provides a series of calculation methods for determining the incident energy from a dc arc flash in open air as well as in a box. The DC Arc Models paper is the basis for dc arc flash calculations that are currently used by many in the industry, including several arc flash software packages.

Calculating the incident energy for a dc arc flash begins with a simple application of Ohm's law which states: $I = V/R$

Where:

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

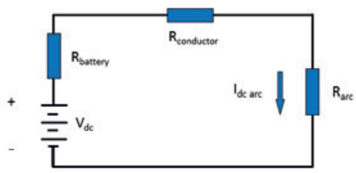

FIGURE 1. Ohm's Law and dc Arc Flash Calculations

By including the dc arc resistance as part of the dc circuit model illustrated in Figure 1, 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, Idc arc can be calculated by:

$$I_{dc\ arc} = V_{dc} / (R_{battery} + R_{conductor} + R_{arc})$$

The DC Arc Models paper also refers to another important document titled "Electric Arcs in Open Air" published in the Journal of Physics D: Applied Physics in 1991 by A. D. Stokes and W. T. Oppenlander. The research included in this document led to the development of the following equation for arc resistance:

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

Where:

R_{arc} = resistance of the arc in ohms
G = 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 G 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. This creates an interesting dilemma since the arcing current is needed to calculate the arc resistance and the arc resistance is needed to calculate the arcing current.

To solve this problem, an iterative solution can be used. This requires making an initial assumption of the dc arcing current. A reasonable 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 be used to re-calculate the dc arc resistance. This process continues until the dc resistance and dc arcing current values no longer change significantly and converge to a final answer.

DC ARC RESISTANCE AND DC ARCING CURRENT CALCULATIONS - ITERATIVE SOLUTION

Figure 2 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 (Vdc) and dividing by the known impedances of the conductor and battery string.

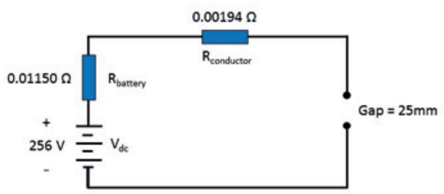

FIGURE 2. DC Arc Flash Example

Begin by solving for the bolted dc short circuit current using the values Figure 2. For the bolted case, Rarc and the conductor gap distance are ignored and only the resistance of the battery string and conductor are used.

$$I_{dc\ bolted} = V_{dc} / (R_{battery} + R_{conductor})$$
$$I_{dc\ bolted} = 256V / (0.01150\Omega + 0.00194\Omega) = 19{,}048 \text{ Amps}$$

As a first approximation of the dc arcing current, $I_{dc\ arc}$:

$$I_{dc\ arc} = 0.5 \times I_{dc\ bolted}$$

Therefore:

$$I_{dc\ arc} = 0.5 \times 19{,}048 \text{ Amps}$$
$$I_{dc\ arc} = 9524 \text{ Amps}$$

DC ARC RESISTANCE WORKSHEET

There are so many calculation steps to keep track of that I developed a series of worksheets in 2010 for my arc flash training program that can be used to simplify the calculations process. These worksheets as well as the examples that follow are from the book "Complete Guide to Arc Flash Hazard Calculation Studies" by J. Phillips, published by Brainfiller, Inc. 2010. ISBN Number 978-0-615-48691-8.

The dc arc resistance worksheet shown as Figure 3, is used for calculating the dc arc resistance of this example. It provides a step by step method for calculating the dc arc resistance based on the Stokes/Oppenlander equation. To use the worksheet, the following data is required:

- Conductor gap distance in millimeters (mm)
- DC arcing current

DC Arc Resistance Work Sheet			
R_{arc} = dc arc resistance in ohms		G = gap in mm	$I_{dc\ arc}$ = dc arcing current
Step 1	G x 0.534	(25) x 0.534	13.3500
Step 2	Step 1 + 20	(13.3500) + 20	33.3500
Step 3	$I_{dc\ arc}^{0.88}$	$(9524)^{0.88}$	3172.2036
Step 4	R_{arc} = Step 2 / Step 3	(33.3500) / (3172.2036)	0.01051

FIGURE 3. DC Arc Resistance Worksheet

Step One: Enter the conductor gap distance G in millimeters (mm) and multiply by 0.534. The gap distance must be defined by the user. IEEE 1584 provides a table of "typical" gap distances.
Step Two: Add the constant 20 to the result found in Step One
Step Three: Enter the arcing short circuit current, Idc arc and raise it to the power of 0.88. Since the arcing short circuit current is not usually known, a typical first approximation is to assume that Idc arc = 50% of Idc bolted.
Step Four: To obtain the dc arc resistance in ohms, divide Step Two by Step Three. The following example illustrates how to calculate the value of the dc arc resistance based on the initial assumption of the dc arcing short circuit current. After the dc arc resistance has been calculated, iterative solutions can be used.

For this example, an arc gap of 25 mm was used which is one of the "typical" values given in IEEE 1584. Using the first approximation of 9524 A which was calculated previously for the arcing short circuit current, the arc resistance Rarc is calculated as 0.01051 Ω as shown in Figure 3.

The next step in this process requires a series of iterations. The calculated value of Rarc can now be added to the original circuit and the dc short circuit current can be re-calculated as follows:

$$I_{dc\ arc} = V_{dc} / (R_{battery} + R_{conductor} + R_{arc})$$
$$I_{dcarc} = 256V / (0.01150\Omega + 0.00194\Omega + R_{arc})$$
$$I_{dc\ arc} = 256 \text{ V} / (0.01150\ \Omega + 0.00194\ \Omega + 0.01051\ \Omega)$$
$$I_{dc\ arc} = 10{,}688.9 \text{ Amps}$$

Once the new value of Idc arc has been calculated, it can be substituted back into the dc arc resistance worksheet and a new value of Rarc can be calculated. The iteration process continues until the values of Idc arc and Rarc do not change significantly from the previous values and converge to the final answers of 11,433.7 A for Idc arc and 0.00895 for Rarc as illustrated in Table 1 and Figure 4. ▶

Iteration Step	$I_{dc\ arc}$	R_{arc}
1	9,524.0	0.01051
2	10,688.9	0.00950
3	11,160.5	0.00914
4	11,335.5	0.00902
•	•	•
•	•	•
•	•	•
Final Step	11,433.7	0.00895

TABLE 1. Iterative Solution for Example Problem

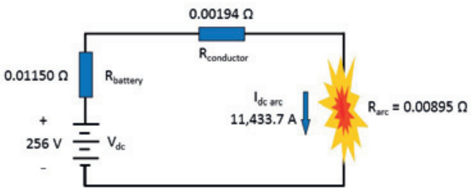

FIGURE 4. Results from Example Problem

POWER AND ENERGY IN THE ARC

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

$P_{arc} = I_{dc\ arc}^2 \times R_{arc}$

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:

$E_{arc} = P_{arc} \times t_{arc}$

Where:

E_{arc} = arc energy in watt·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.

DC INCIDENT ENERGY CALCULATIONS - 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 the DC Arc Models paper, the incident energy for an arc flash in open air at a specific distance can be calculated based on the following equation:

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

A worksheet that is based on this equation and used to solve the arc flash in open air example problem is shown as Figure 5. It breaks the calculation process down into individual steps. A final step is added which converts the units from J/mm2 to the more commonly used units of calories/centimeter2 (cal/cm2).

To use this worksheet, the following data is required:

- DC arcing current in amperes, Idc arc
- Arc resistance on ohms, Rarc
- Arc duration in seconds, tarc
- Distance from the arc in mm, d

Step One: Enter $I_{dc\ arc}$, R_{arc} and t_{arc} obtained from the previous iterative calculations. Square the $I_{dc\ arc}$ value and multiply by R_{arc} and t_{arc} to determine the energy in the arc, E_{arc} in terms of watts-seconds or Joules.

Step Two: Enter the distance from the arc (working distance) in mm. Multiply d by 4 x π or 12.56637

Step Three: Calculate $E_{i\ air}$ by dividing Step 1 by Step 2. The result will be in J/mm^2

Step Four: Convert the answer obtained in Step 3 from J/mm2 to cal/cm2 by multiplying by 23.9

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.

DC Incident Energy Worksheet - Arc Flash in Open Air			
$E_{i\ air}$ = incident energy E_{arc} = energy in arc	R_{arc} = arc resistance in ohms $I_{dc\ arc}$ = dc arcing current		d = distance from arc in mm t_{arc} = time in seconds
Step 1	$E_{arc} = I_{dc\ arc}^2 \times R_{arc} \times t_{arc}$	(11,433.7)² x (0.00895) x (0.3)	351,008.70
Step 2	$4 \times \pi \times d^2$	12.56637 x (457)²	2,624,473.81
Step 3	$E_{i\ air}$ = Step 1 / Step 2	(351,008.70) / (2,624,473.81)	0.1337
Step 4	cal/cm² = J/mm² x 23.9	(0.1337) x 23.9	3.20

FIGURE 5. DC Incident Energy Worksheet - Arc Flash in Open Air

Where:

E_{arc} = arc energy in watt-seconds or Joules (J)

$E_{i\ air}$ = incident energy from an open air arc at distance d in (J/mm^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 paper refers to another technical paper titled "Simple Improved Equations for Arc Flash Hazard Analysis," IEEE Electrical Safety Forum, August 30, 2004 by R. Wilkins.

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

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

Where:

$E_{i\,box}$ = incident energy from an arc flash in a box at distance d in J/mm²

E_{arc} = arc energy in watt·seconds or Joules

d = distance from the arc source in mm

a and k are obtained from optimal values defined in the Wilkins paper and listed in Table 2.

Optimal Values of a and k		
Enclosure Type	a (mm)	k
Panelboard	100	0.127
LV Switchgear	400	0.312
MV Switchgear	950	0.416

TABLE 2 - Optimum Values of “a” and “k” From Wilkins Paper

A worksheet was developed for calculating the dc incident energy for an arc flash in an enclosure/box.

This worksheet is based on the box equation and reduces the calculation into a series of simple steps.

To use this worksheet, the following data is required:

- DC arcing current in amperes, Idc arc
- Arc resistance in ohms, Rarc
- Arc duration in seconds, tarc
- aandkfromTable2
- Distance from the arc in mm, d

Step One: Enter $I_{dc\,arc}$, R_{arc} and t_{arc} obtained from the previous iterative calculations. Square the $I_{dc\,arc}$ value and multiply by R_{arc} and t_{arc} to determine the energy in the arc in terms of watt-seconds or Joules.

Step Two: The value of a must be obtained from Table 2. The value of the distance from the arc (working distance), d in mm must also be defined. Enter each value in the appropriate space in Step Two. Square each value and add the two terms together.

Step Three: Look up the value of k from Table 2 Multiply k and E_{arc} from Step One

Step Four: Divide Step Three by Step Two. The result will be the incident energy in terms of J/mm² at working distance d.

Step Five: To convert the units from J/mm² to the more commonly used units of cal/cm², multiply the answer obtained in Step Four by 23.9

Using values that were previously calculated for Idc arc and Rarc, 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.

To begin this problem, the values of a and k must be determined. Obtaining these values from Table 2 for a panelboard indicates the value of a is 100 and k is 0.127. The previous calculations indicate that $I_{dc\,arc}$ = 11,433 Amps and R_{arc} = 0.00895Ω. The working distance, d is 457 mm and the duration, t_{arc} is 0.3 seconds. These values can be used with the dc arc flash worksheet for calculating the incident energy in an enclosure as illustrated in Figure 6. The result for this calculation is 4.9 cal/cm².

DC Incident Energy Worksheet - Arc Flash in an Enclosure / Box			
$E_{i\,box}$ = incident energy E_{arc} = energy in arc		R_{arc} = arc resistance in ohms $I_{dc\,arc}$ = arcing current	d = distance from arc in mm t_{arc} = time in seconds
Step 1	$E_{arc} = I_{dc\,arc}^2 \times R_{arc} \times t_{arc}$	$(11,433.7)^2 \times (0.00895) \times (0.3)$	351,008.70
Step 2	$a^2 + d^2$	$(100)^2 + (457)^2$	218,849.00
Step 3	$k \times E_{arc}$	(0.127) x (351,008.70)	44578.10
Step 4	$E_{i\,box}$ = Step 3 / Step 2	(44,578.1) / (218,849.0)	0.2037
Step 5	cal/cm² = J//mm² x 23.9	(0.2037) x 23.9	4.9

FIGURE 6. Incident Energy Worksheet – Arc Flash in an Enclosure / Box

DC ARC FLASH CALCULATIONS AND STANDARDS

Except for two technical papers that are referenced in the Annex of NFPA 70E, dc arc flash equations and calculation methods are not part of any standard - Yet! As research regarding dc arc flash and dc source modelling continues, dc arc flash calculation methods will likely become part of a standard someday.

Until then, since no standard presently exists for dc arc flash calculations, why would anyone perform them? You don’t have to look too far back in the history of arc flash to find the answer. Even though IEEE 1584 was first published in 2002, some people were performing arc flash studies and calculations for ac systems long before then. How could that be? By using the best-known methods and equations that were available at the time - and the same thing is happening once again today with dc arc flash. Funny thing about history, it often repeats itself.

Note: As with any analytical calculations or engineering study, only qualified persons should perform them.

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