DC Arc Flash Analysis

By,

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Innovation
Automation
Collaboration

Agenda

- Why conduct DC Arc Flash Analysis?
- Characteristics of an Arc
- DC Short Circuit calculations
- Maximum Power Method
- Stokes and Oppenlander Method
- Paukert Method
- Box / open configurations energy equations
- Discussion Items
- Changes to NFPA 70E 2015

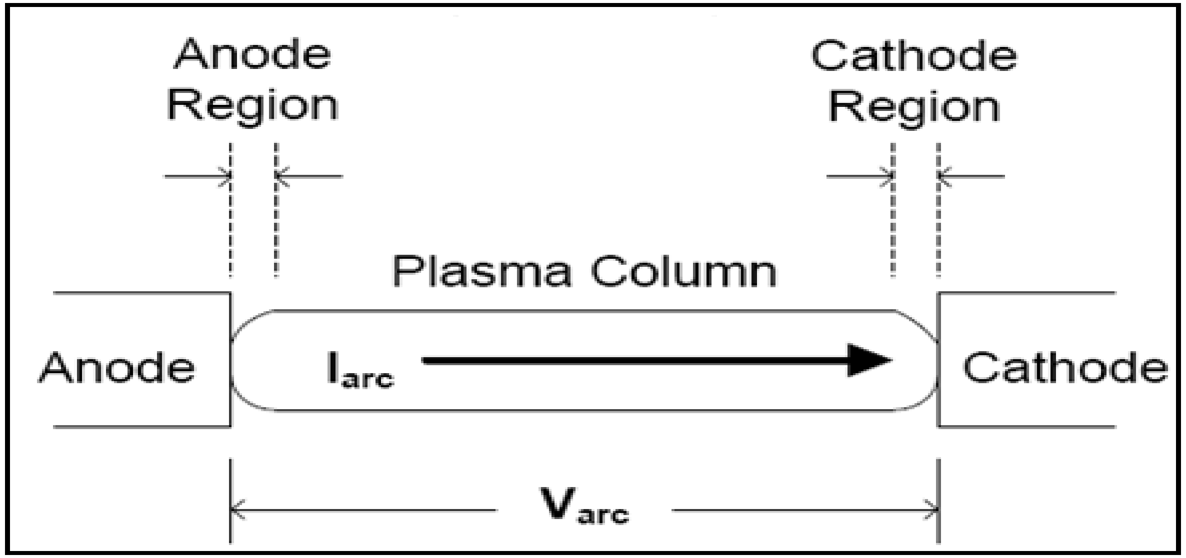
Why conduct DC Arc Flash Analysis?

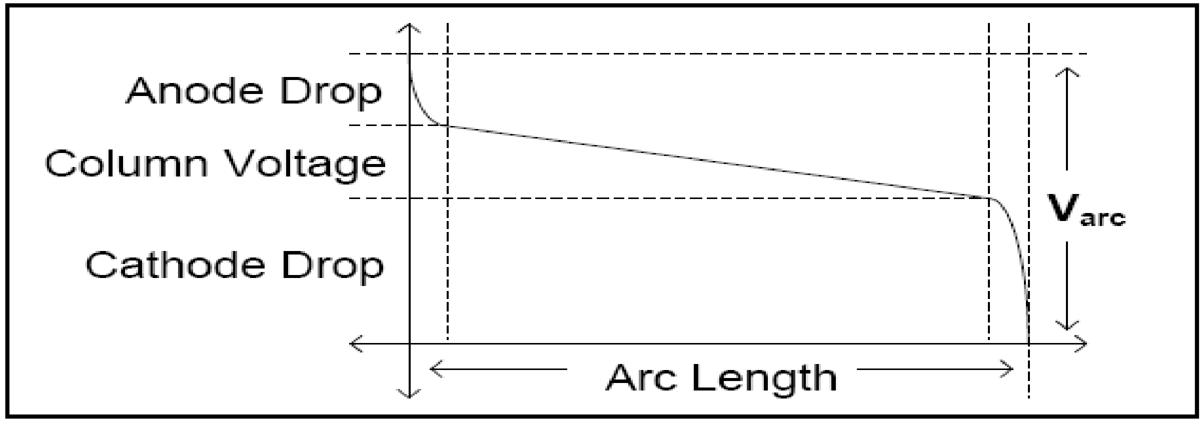
- Several papers have surfaced regarding studies being conducted dc systems
- Many industrial applications of dc power systems
- Hazards can be found:
  - Large uninterruptible power supply cabinets with battery banks
  - Electrical room station battery sets
  - Drive cabinets with dc buses
  - Special process equipment using DC buses such as a salt cell processing

Characteristics of an Arc

- An arc consists of three regions:
  1) Anode region
  2) Cathode region
  3) Plasma column

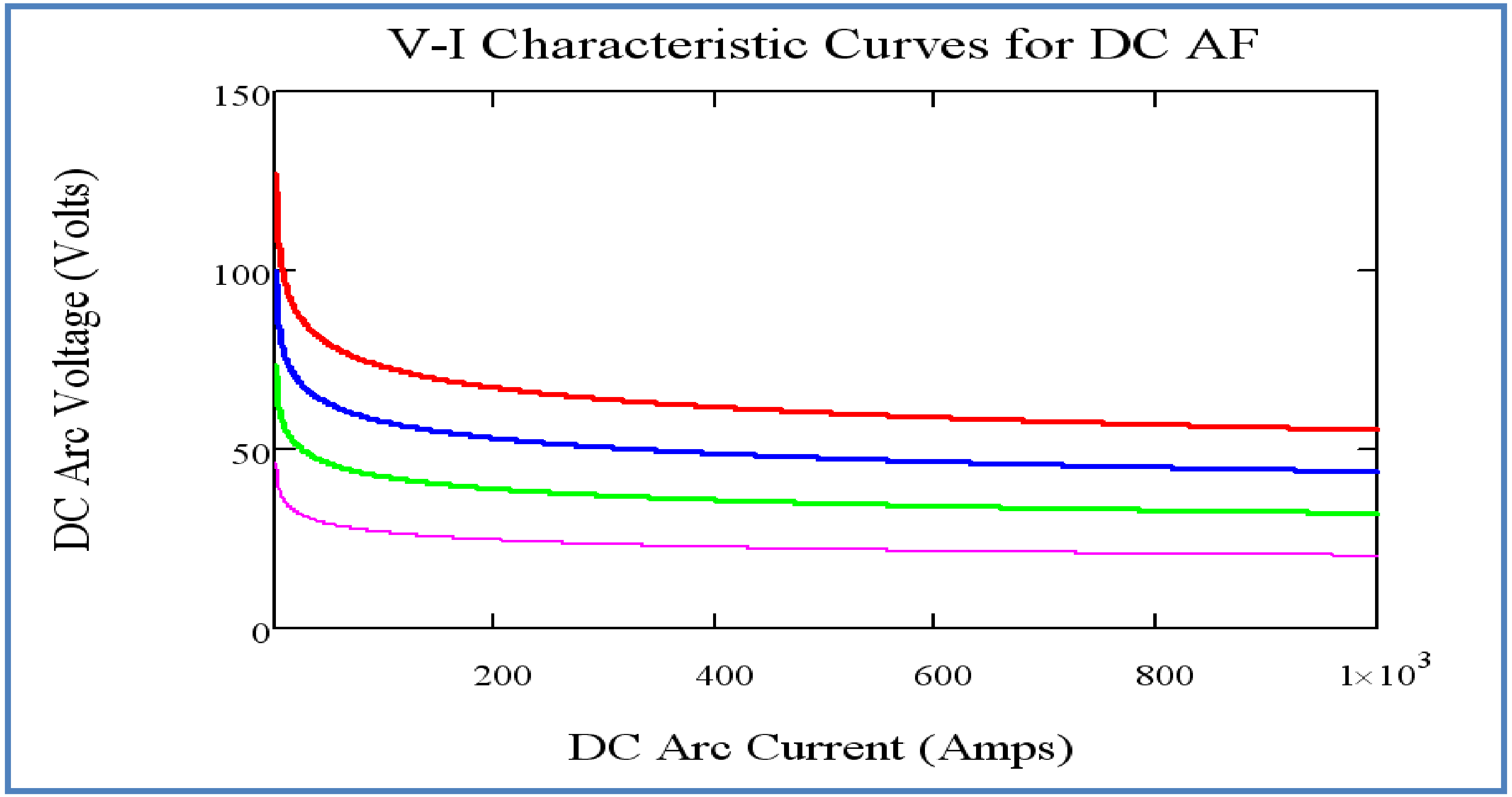
- The voltage gradient across the arc plasma depends on the actual arc length; the arc may deviate from the gap width between the electrodes.





V-I Characteristic Curves

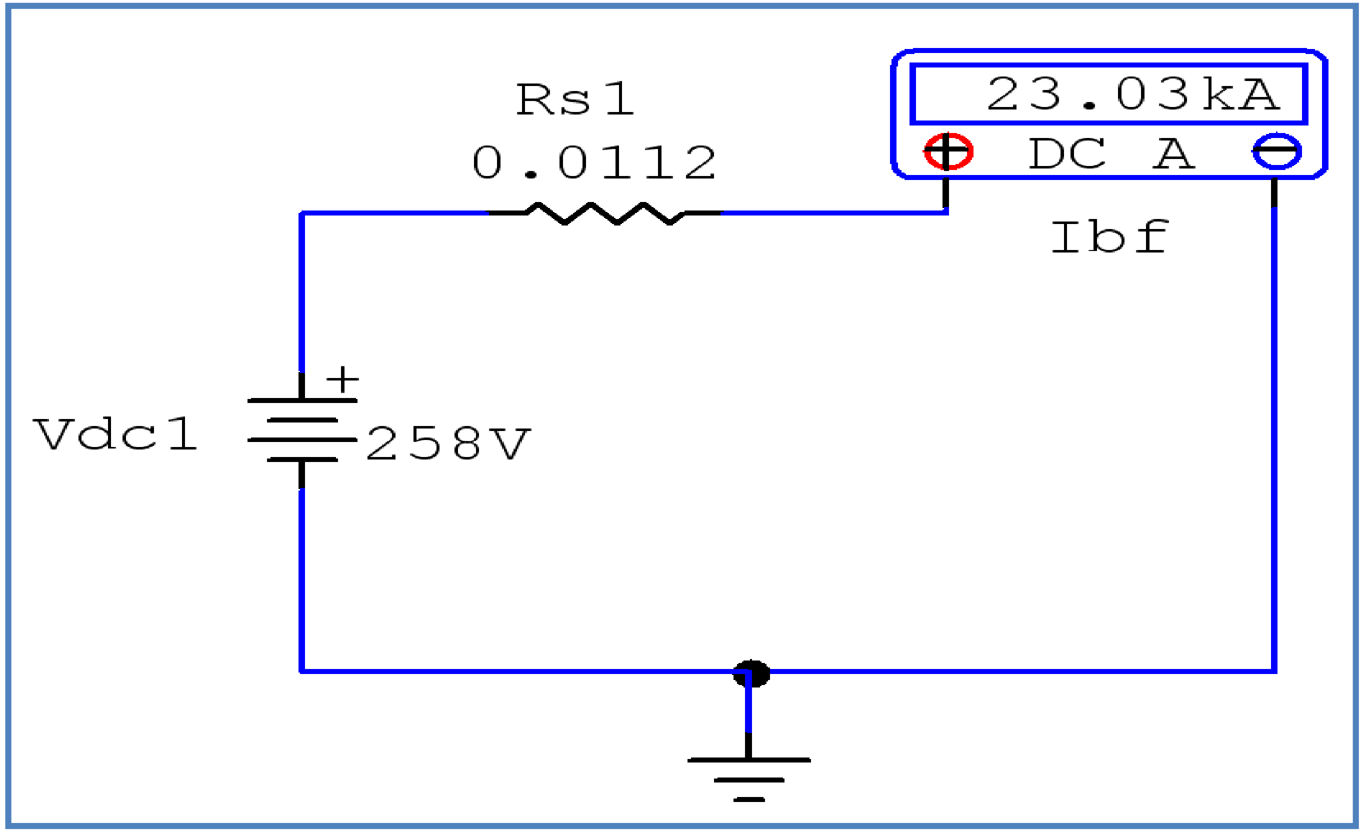
As arc current increases, arc voltage decreases.



DC Short Circuit

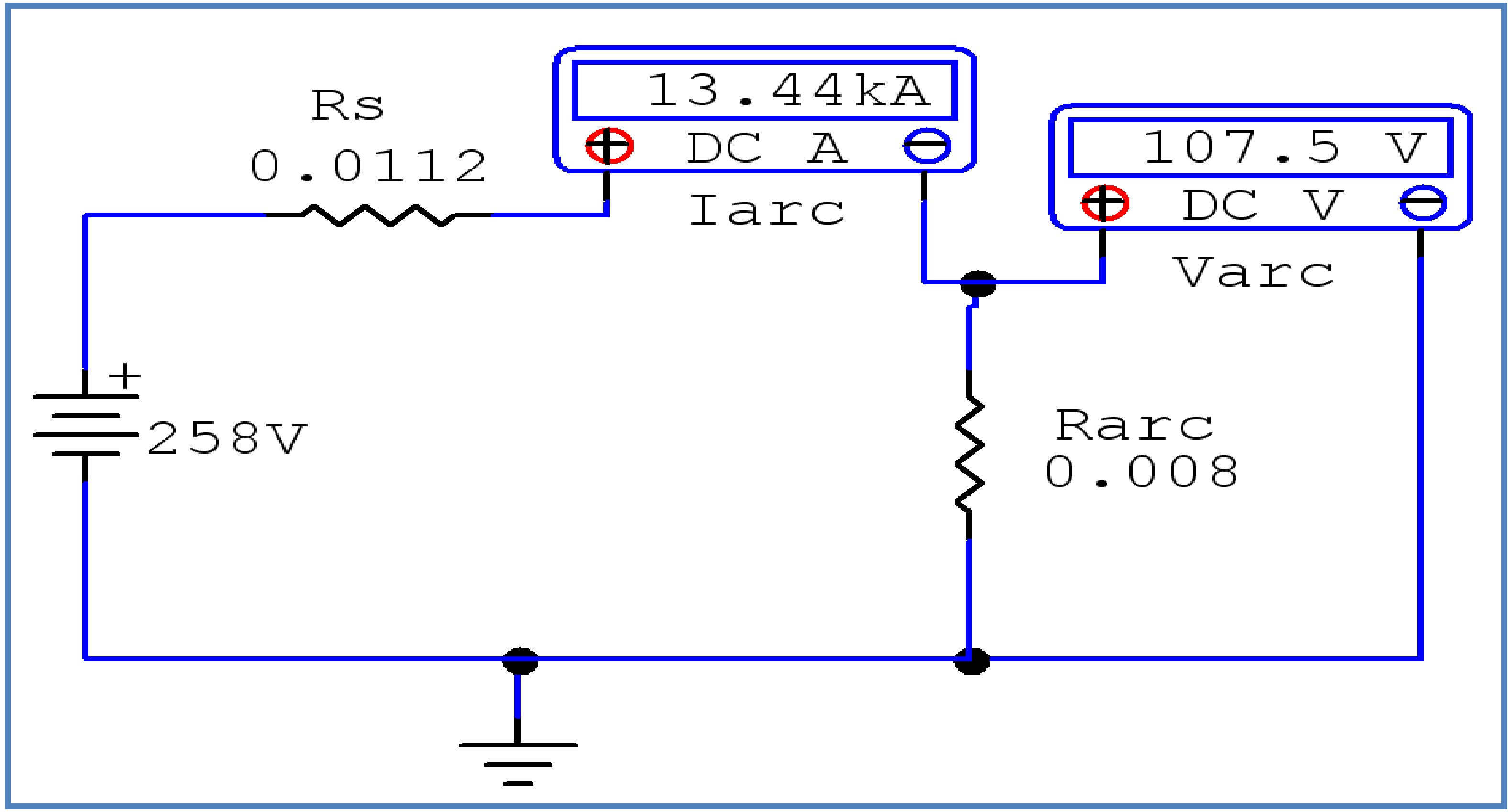
- Battery, Charger, and UPS Sources can be modeled as:
  - Constant Current
  - Voltage behind an impedance

- Thevenin Equivalent of System R is found to calculated the short circuit current.



Methodology for DC Arc Flash

- DC Arc Flash Basic Concepts



3 Methods for DC Arc Flash

- Maximum Power Method
- Stokes and Oppenlander Method
- Paukert Method

Maximum Power Method

- Maximum Power Method was introduced in 2007 in the ESW by Daniel R. Doan.
- Based on the concept that the maximum power possible in a DC arc will occur when the arcing voltage is one-half of the system voltage.

$$I_{arc} = 0.5 \times I_{bf}$$

$$R_{arc} = 0.5 \times \frac{V_{source}}{I_{bf}}$$

Maximum Power Method

Energy equations for Arc in a box and Open Air

$$IE_{open} = 0.01 \times V_{sys} \times I_{arc} \times \frac{T_{arc}}{D^2}$$

$$IE_{box} = 3 \times 0.01 \times V_{sys} \times I_{arc} \times \frac{T_{arc}}{D^2}$$

D.8.1 Direct-Current Arc Flash Calculations.

D.8.1.1 Maximum Power Method. The method of estimating dc arc flash incident energy that follows was presented at the 2007 IEEE Electrical Safety Workshop *(see reference 2, which follows)*. This method is based on the concept that the maximum power possible in a dc arc will occur when the arcing voltage is one-half of the system voltage. Testing completed for Bruce Power *(see reference 3, which follows)* has shown that this calculation is conservatively high in estimating the arc flash value. This method applies to dc systems rated up to 1000 Vdc.

$$I_{arc} = 0.5 \times I_{bf}$$
$$IE_m = 0.01 \times V_{sys} \times I_{arc} \times T_{arc} / D^2$$

where:

I_{arc} = arcing current, amperes
I_{bf} = system bolted fault current, amperes
IE_m = estimated dc arc flash incident energy at the maximum power point, cal/cm^2
V_{sys} = system voltage, volts
T_{arc} = arcing time, sec
D = working distance, cm

For exposures where the arc is in a box or enclosure, it would be prudent to use a multiplying factor of 3 for the resulting incident energy value.

D.8.1.2 Detailed Arcing Current and Energy Calculations Method. A thorough theoretical review of dc arcing current and energy was presented at the 2009 IEEE PCIC Conference. Readers are advised to refer to that paper *(see reference 1)* for those detailed calculations.

References:

1. "DC arc models and incident energy calculations," Ammerman, R.F.; Gammon, T.; Sen, P.K.; Nelson, J.P.; Petroleum and Chemical Industry Conference, 2009, Record of Conference Papers,14–16 September 2009.

2. "Arc Flash Calculations for Exposures to DC Systems," Doan, D.R., IEEE IAS Electrical Safety Workshop, 2007, Record of Conference Papers, March 2007.

3. DC Arc Hazard Assessment Phase II Copyright Material Kinectrics Inc. Report No. K-012623-RA-0002-R00.

Maximum Power Method

Pros: Always giving you arcing current results. Simplicity of calculations (no iterations or complex non linear equations). Most conservative of all methods.

Cons: Could be too conservative because of the arcing current is calculated higher than real life situations. (Ex.- If it falls off the instantaneous pick up, time might be longer.)

Calculations limitations: Cannot predict if an arc can be generated (can occur). This method applies to dc systems rated up to 1000 VDC.

Stokes and Oppenlander

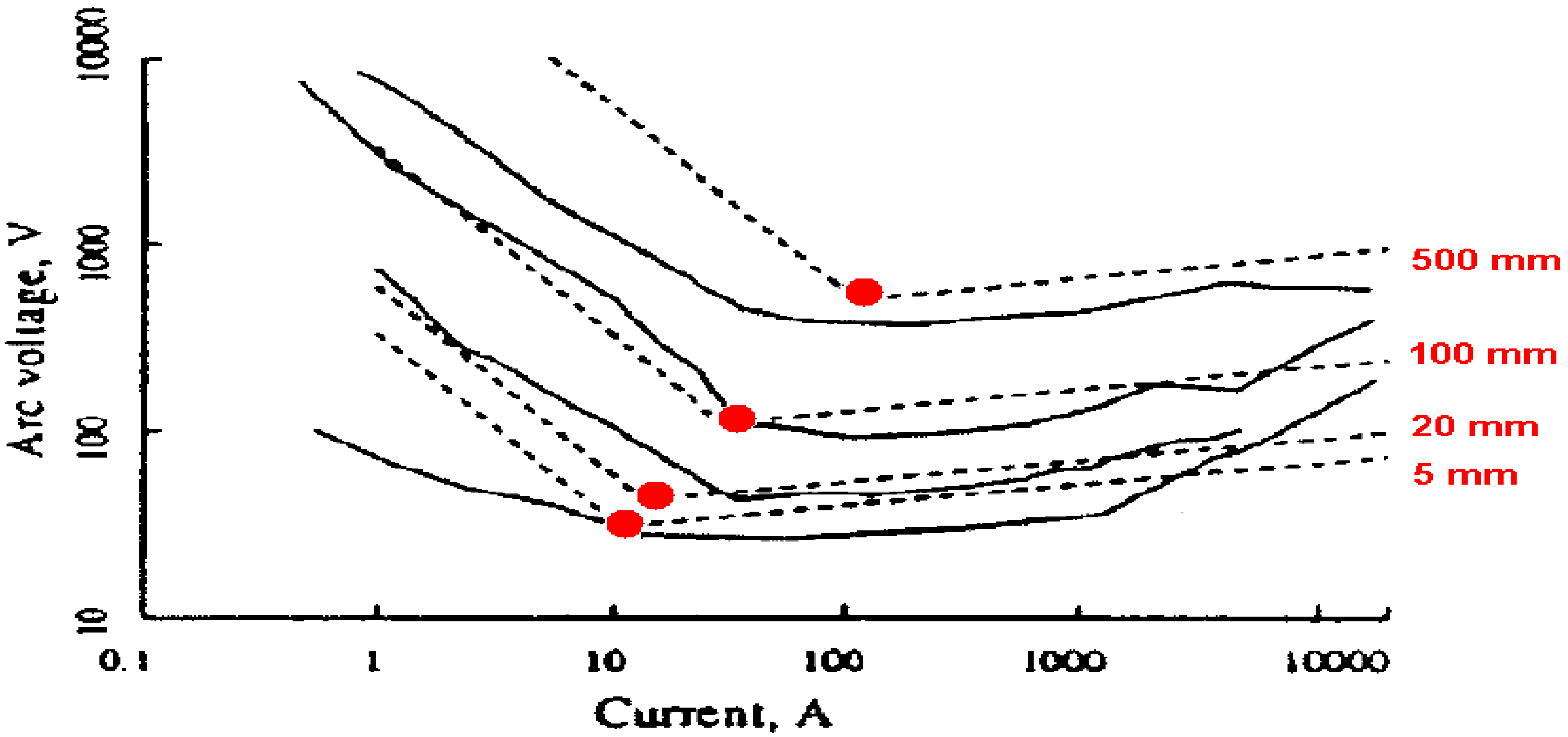
- Performed a study of free-burning vertical and horizontal arcs between series electrodes in open air.
- Based on the extensive study, Stokes and Oppenlander created empirical equations based on test results.
- As a result, to maintain the minimum voltage of an arc, depends on current magnitude, gap width and orientation of electrodes.

Stokes and Oppenlander

Horizontal Arc in Open Air with Copper Electrodes

Continuous Lines – Measured Results

Dotted Lines – Calculated Results

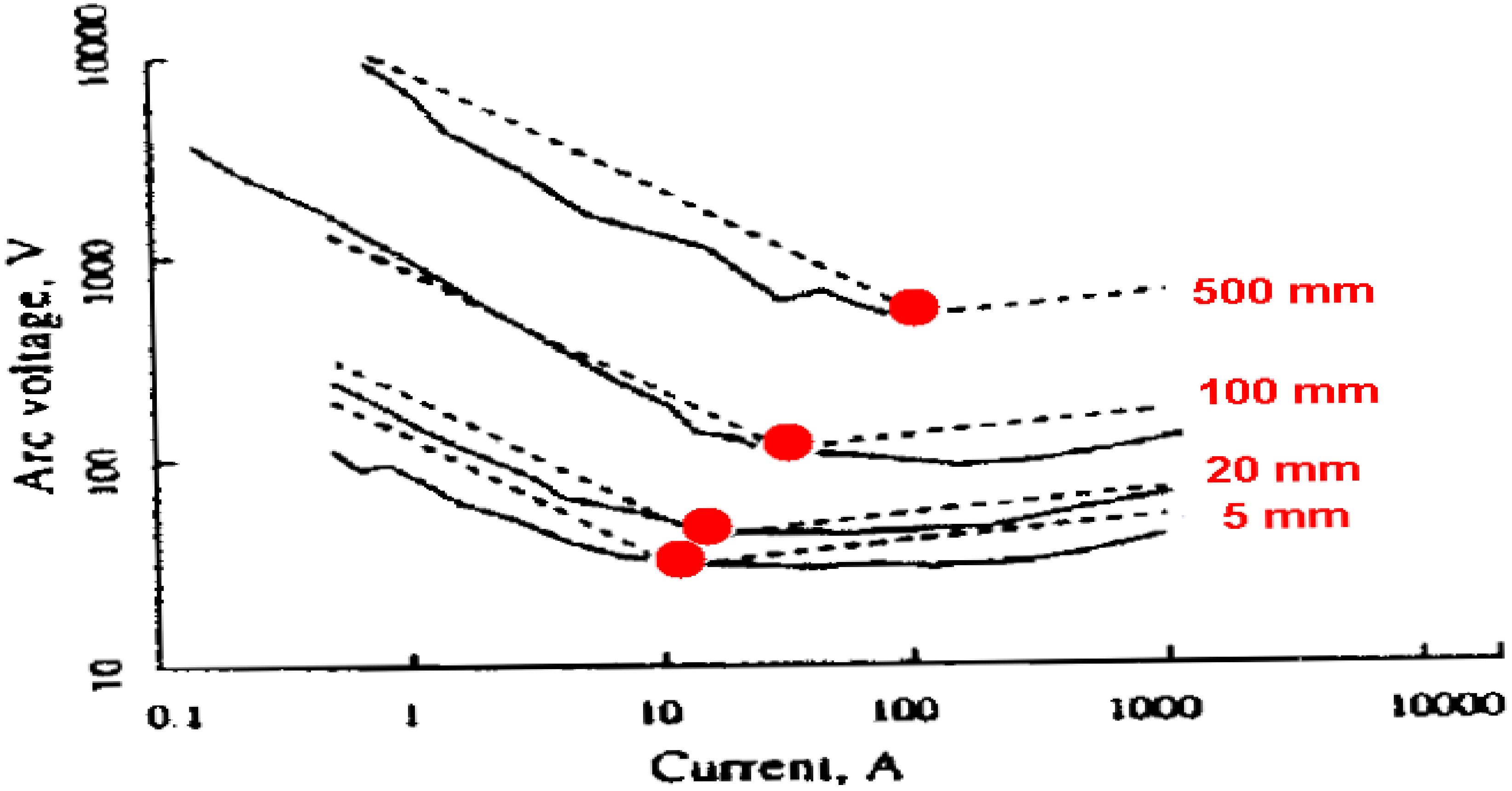


Stokes and Oppenlander

Vertical Arc in Open Air with Aluminum Electrodes

Continuous Lines – Measured Results

Dotted Lines – Calculated Results



Stokes and Oppenlander

Requires iterative solutions by first establishing initial guess and iteratively solve for Rs (fixed) and Rarc (changes).

Zg = Gap between Electrodes (mm)

$$I_t = 10 + 0.2 z_g$$

$$V_{arc} = (20 \times 0.534 \times z_g) \times I_{arc}^{0.12}$$

$$R_{arc} = \frac{(20 \times 0.534 \times z_g)}{I_{arc}^{0.88}}$$

Stokes and Oppenlander

Pros: If the gap, voltage and system impedance are within the limits of the equations, the model can predict if the arc is sustained. If the gap is too long, cannot find an solution (Iarc too low). FCT is more accurate. Energy is more accurate rather than over conservative.

Cons: It requires iterative solutions and not easy to solve.

Calculations limitations: If arcing current is below transition point, a solution cannot be solved.

Paukert

- Paukert compiled published arcing fault data from seven researches who conducted a wide of arc tests.
- Some were AC and some were DC with both vertical and horizontal configurations. Arcing currents ranged from 0.3A to 100kA with electrode gaps from 1 to 200mm.
- Based on the collected data, Paukert formulated arc voltage and arc resistance equations with electrode gap widths.

Paukert

TABLE II
EMPIRICAL ARC FORMULAE FOR $I_{arc} < 100$ A [18]

Electrode Gap (mm)	Arc Voltage (V)	Arc Resistance (Ω)
1	$36.32\ I_{arc}^{-0.124}$	$36.32\ I_{arc}^{-1.124}$
5	$71.39\ I_{arc}^{-0.186}$	$71.39\ I_{arc}^{-1.186}$
10	$105.25\ I_{arc}^{-0.239}$	$105.25\ I_{arc}^{-1.239}$
20	$153.63\ I_{arc}^{-0.278}$	$153.63\ I_{arc}^{-1.278}$
50	$262.02\ I_{arc}^{-0.310}$	$262.02\ I_{arc}^{-1.310}$
100	$481.20\ I_{arc}^{-0.350}$	$481.20\ I_{arc}^{-1.350}$
200	$662.34\ I_{arc}^{-0.283}$	$662.34\ I_{arc}^{-1.283}$

TABLE III
EMPIRICAL ARC FORMULAE FOR 100 A < I_{arc} < 100 kA [18]

Electrode Gap (mm)	Arc Voltage (V)	Arc Resistance (Ω)
1	$13.04\ I_{arc}^{0.098}$	$13.04\ I_{arc}^{-0.902}$
5	$14.13\ I_{arc}^{0.211}$	$14.13\ I_{arc}^{-0.789}$
10	$16.68\ I_{arc}^{0.163}$	$16.68\ I_{arc}^{-0.837}$
20	$20.11\ I_{arc}^{0.190}$	$20.11\ I_{arc}^{-0.810}$
50	$28.35\ I_{arc}^{0.194}$	$28.35\ I_{arc}^{-0.806}$
100	$34.18\ I_{arc}^{0.241}$	$34.18\ I_{arc}^{-0.759}$
200	$52.63\ I_{arc}^{0.264}$	$52.63\ I_{arc}^{-0.736}$

Paukert

Pros: Same as Stokes and Oppenlander. If the gap, voltage and system impedance are within the limits of the equations, the model can predict if the arc is sustained. Energy is more accurate rather than over conservative.

Cons: Requires iterative solutions not easy to solve. Its not applicable and should not be used for electrode gaps more than 200 mm.

Calculations limitations: Current cannot be more than 100kA .

Deriving Energy Equations

$$Power = V_{dc} \times I_{dc}$$

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

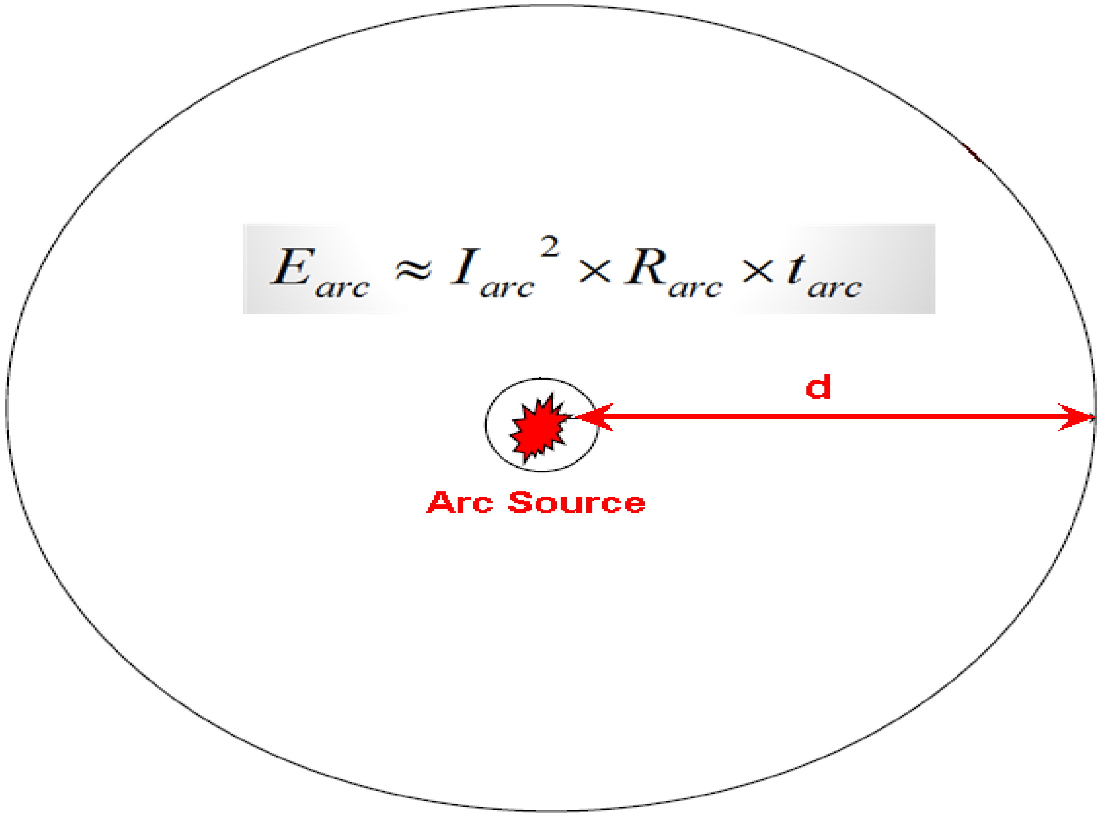
$$E_{arc} \approx I_{arc}{}^{2} \times R_{arc} \times t_{arc}$$

Energy Equations

Energy Equations for Open Air and Enclosed Configurations

$$E_s = \frac{E_{arc}}{4\pi d^2}$$

$$E_1 = k \times \frac{E_{arc}}{a^2 + d^2}$$



Reflectivity Coefficients

Enclosed DC Arc Fault values a and k

Enclosure	Width (mm)	Height (mm)	Depth (mm)	a (mm)	k
Panelboard	305	356	191	100	0.127
LV Switchgear	508	508	508	400	0.312
MV Switchgear	1143	762	762	950	0.416

Comparison of the Stokes and Oppenlander vs. Paukert

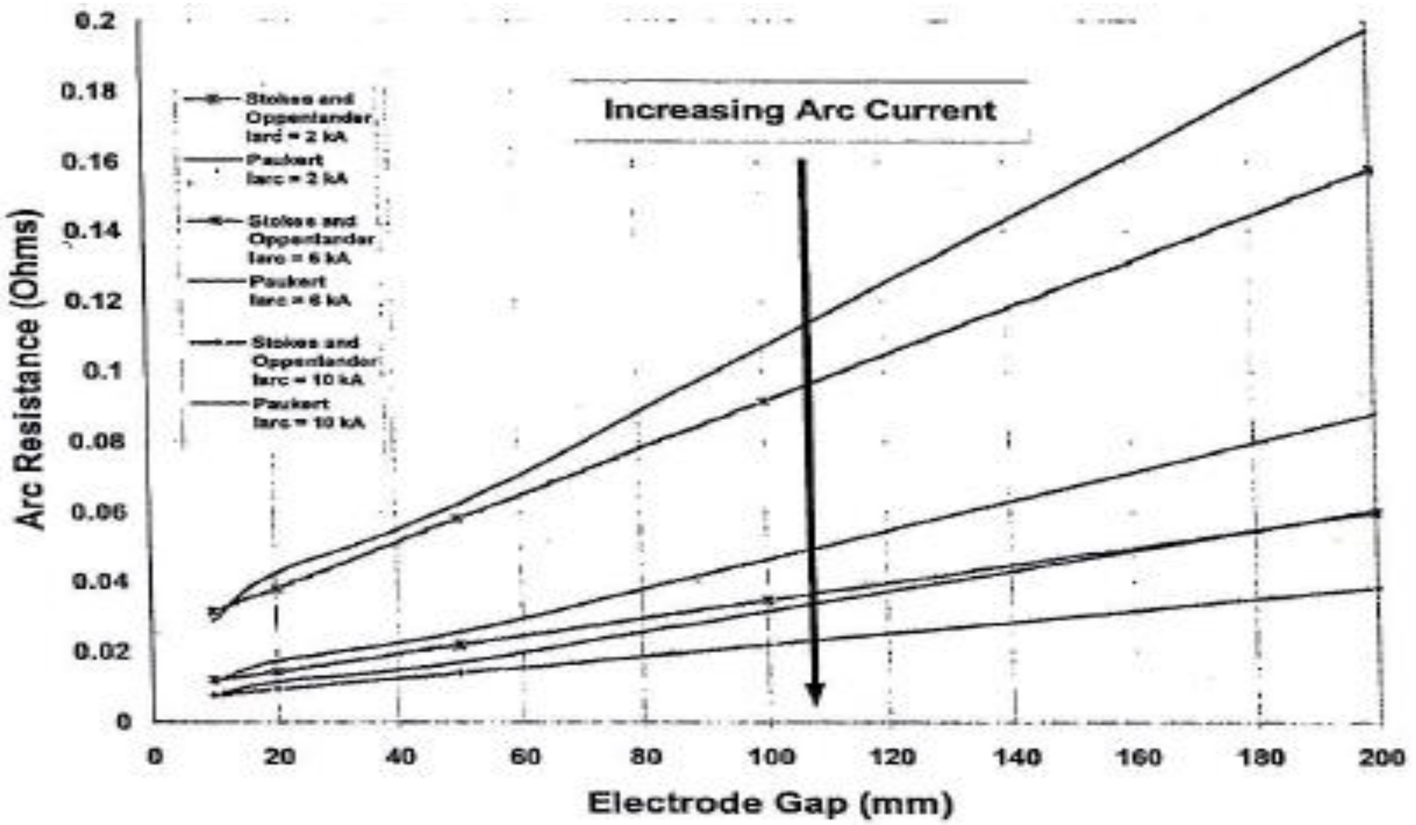


Fig. 15 DC Arc Resistance Comparative Study
(Stokes and Oppenlander / Paukert Formula Comparison)

Comparison of the Stokes and Oppenlander vs. Paukert

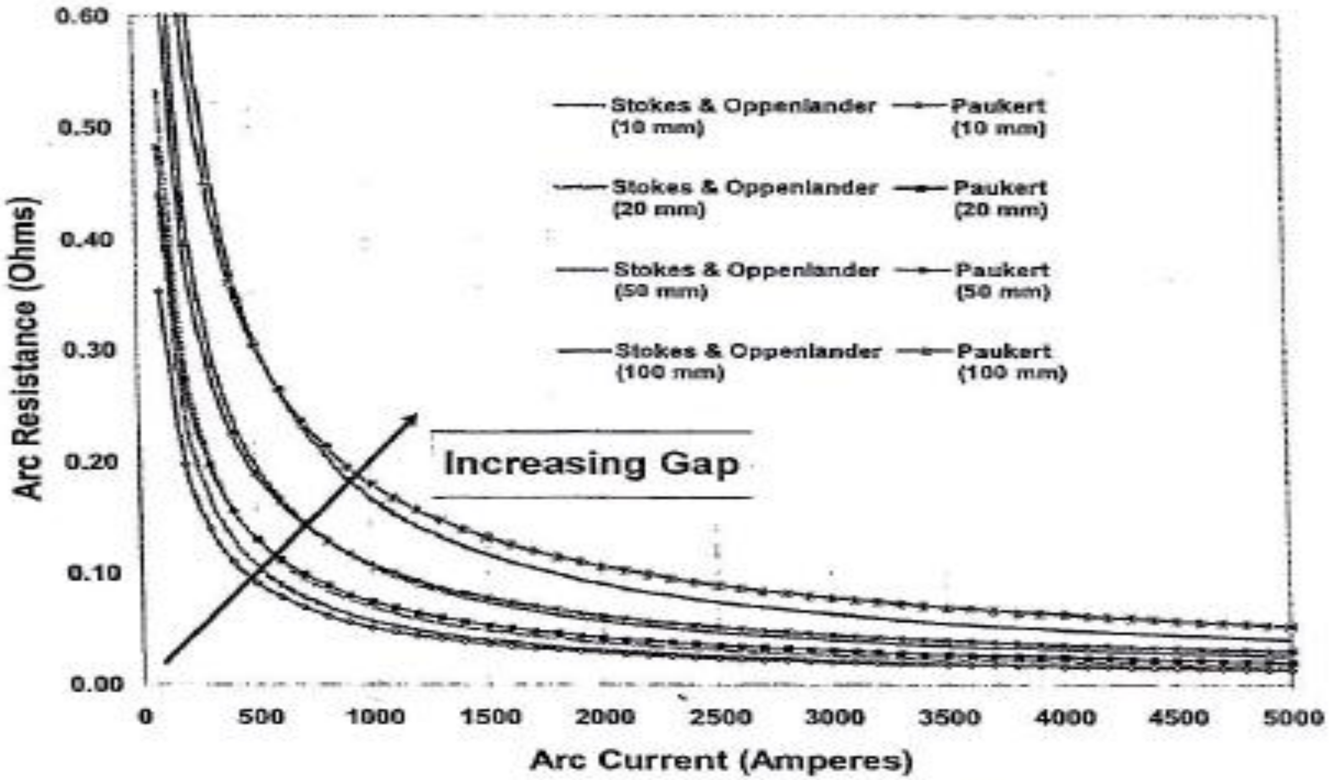


Fig. 14 DC Arc Resistance Comparative Study
(Sensitivity to Electrode Gap)

Comparison of the Stokes and Oppenlander vs. Paukert

Observations based on the Empirical Methods

1) Arc resistance is nonlinear
2) Arc resistance decreases with increasing arc current
3) Arc resistance approaches a constant value at high current magnitudes
4) Arc resistance changes rapidly at low current magnitudes (<1kA).
5) Paukert predicts larger arc resistances than Stokes and Oppenlander predict.
6) For a given arc current, the arc resistance increase linearly with the electrode gap.

Discussion Items

- If only constant current sources are in the systems, cannot find Rarc, Iarc, Varc since R Thevenin is unknown.

- Energy reduction for multiple sources does not subtract current when source is cleared.

- Time constant or rise time of the current is ignored. It is assumed the current has reached its max value. (It is valid for electronic devices, not valid for batteries that have resistances)

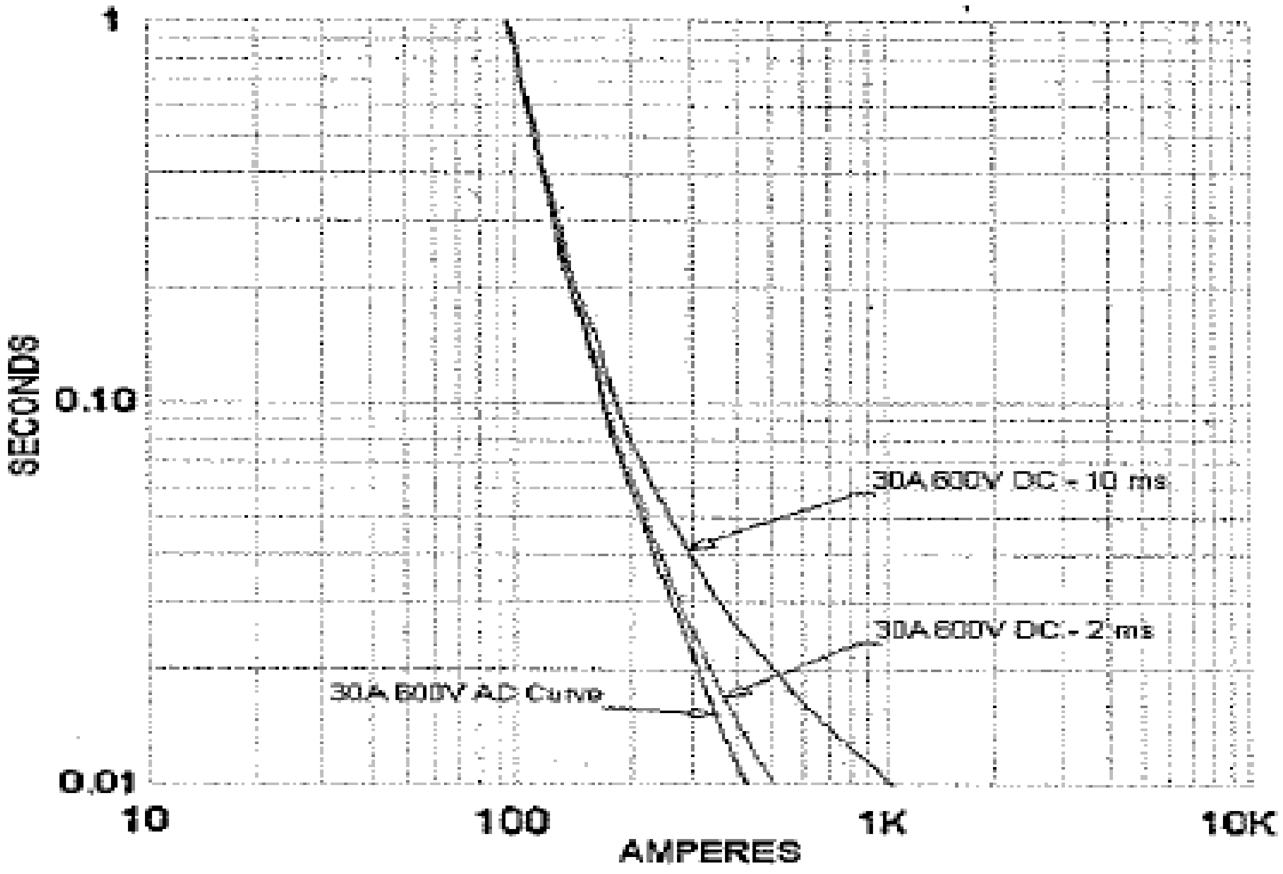


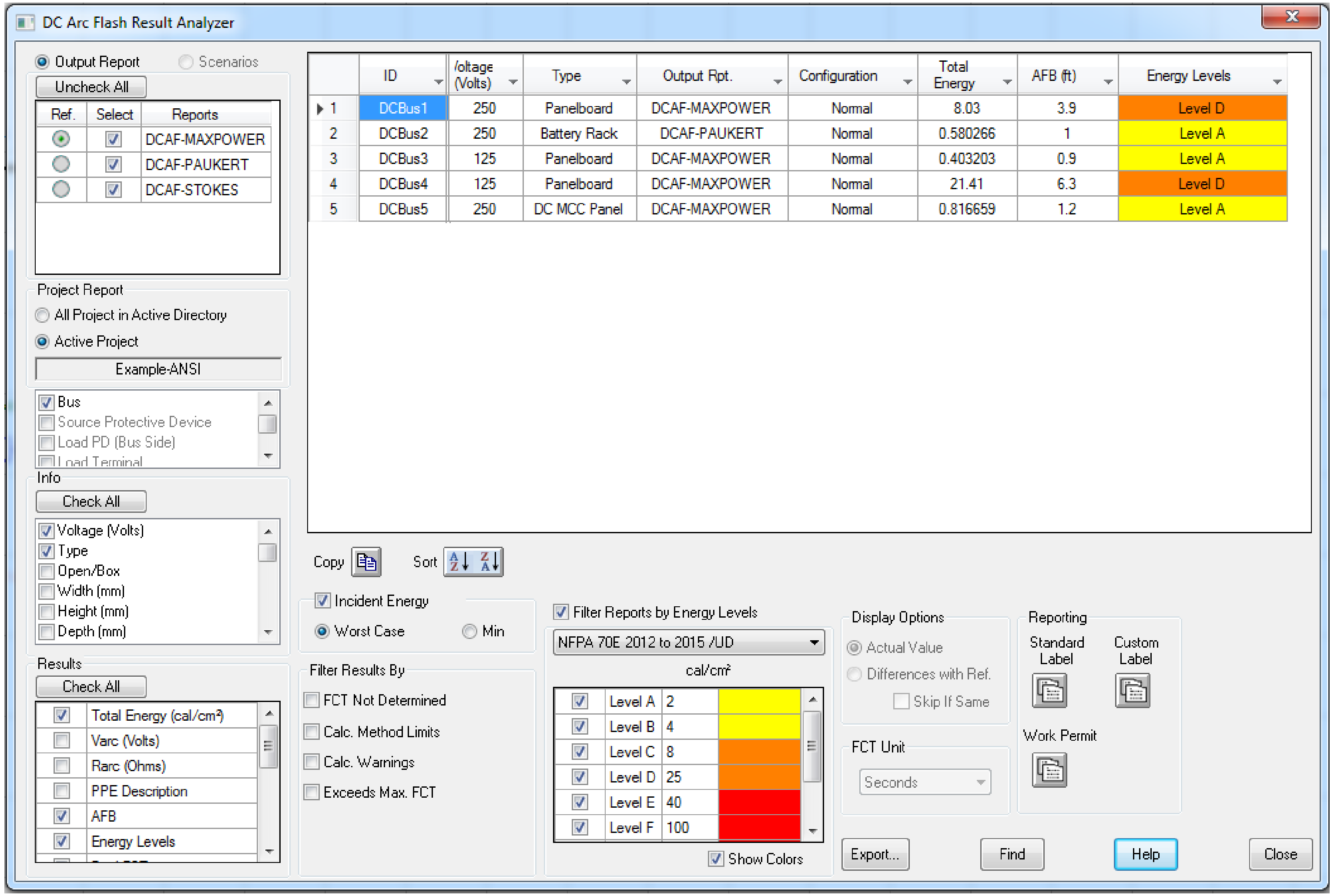
Fig. 3. Effect of L/R on fuse curve.

Comparison of Incident Energy

Bus ID	Voltage (Volts)	MAX POWER	PAUKERT	STOKES
Electrochemical DC Bus	250	7.6	7.2	7
Substation Battery Rack	135	0.9	0.8	0.8
UPS Battery System Bus	350	1.7	1.4	1.2

ETAP Arc Flash Analyzer

Arc flash Analyzer showing multiple sample reports comparing all methods



Updates on NFPA 70 2015

- DC Arc Flash Maximum Power Method
- Removed 125 kVA Exception (An Arc Flash Hazard Analysis may not be necessary for some three-phase systems rated less than 240 Volts
- Added DC Arc Flash Boundaries table. (Table 130.4 (C) b)
- Arc Flash *Protection* Boundary = **Arc Flash Boundary**
- Removed Prohibited Approach Boundary.

References

- NFPA 70E 2015 Standard for Electrical Safety in the Workplace
- J. Paukert, The Arc Voltage and Arc Resistance of LV Fault Arcs", *Proceedings of the 7th International Symposium on Switching Arc Phenomena*, 1993, pp. 49-51.
- A.D. Stokes and W.T. Oppenlander, "Electric Arcs in Open Air", *J. of Physics D: Applied Physics*, 1991, pp. 26-35.
- R. Ammerman, T. Gammon, P.K. Sen, J. Nelson, “Dc Arc Models and Incident Energy Calculations”, Paper No. PCIC-2009-07.
- Daniel R Doan, Arc Flash Calculations for Exposures to DC Systems, IEEE Transactions on Industry Applications, Vol. 46, NO.6, November/December 2010
- Albert Marroquin, Arc Flash Product Manager, ETAP

Thank you!