ArresterWorks

Separation Distance for Substations

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Separation Distance for Substations

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A common question asked by those responsible for the protection of transformers in substations is: "How far from my transformer can I locate my arrester and still provide adequate protection?" The answer, of course, is never simple and is one that generally takes a few diagrams and charts. Because the value of the power transformers is so substantial, this question cannot be taken lightly. The general rule of thumb is: "Locate the arrester as close as possible to the bushings of the transformer". This rule is one I suggest whenever possible; however, it is not always possible, especially at higher system voltages.

One example of extended separation is in substations at 400kV and above, the arresters become larger than what can be easily supported by the transformer body. In these cases, the arresters are often mounted on separate pedestals. Another example of extended separation distance is when the transformers need to be accessible for fast removal or repair. To accommodate removal, access ways are built between the arrester and transformer, resulting in a separation between the arrester and transformer of up to 30 meters (100 ft) or more. Herein lies the problem; this separation distance (or protective zone, as it is known) can result in reduced protection when there is a fast rising surge entering the station from a lightning induced insulator backflash.

The reason for the reduced protection is that surges travel into a station at nearly the speed of light on an overhead line. When a surge hits an arrester, the voltage is indeed reduced, but not to zero. The voltage at the arrester, at best, is reduced to the discharge voltage of the arrester. The resulting surge that travels past the arrester is reflected at the transformer which

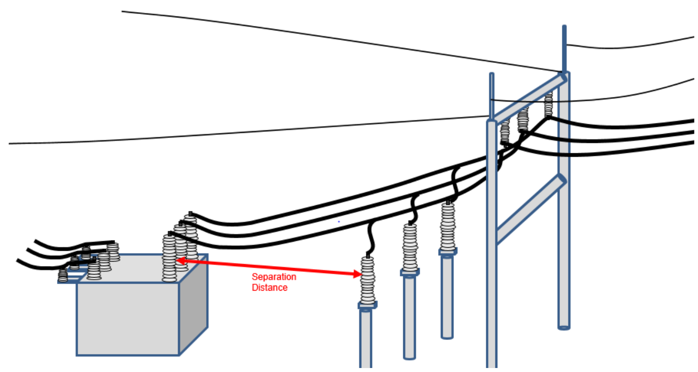

Figure 1 Separation Distance Overview

can result in voltage doubling if the separation distance is long enough. In most cases the reflected voltage only adds a few percent to the incoming surge. It is this traveling wave phenomena and its associated reflection that create the separate distance issue.

Help for Users

Fortunately for arrester users, there are several tools available that offer help. One of these is IEEE Application Guide on Arresters C62.22. Additionally a few words of advice are found in IEC 60099-5.

In C62.22 Annex C, a formula is offered that can be used to determine the maximum distance at which an arrester can be mounted and still achieve a margin of protection of 15%. This simplified method of calculating the separation distance was developed by Bob Hileman in the 1980's and is still valid today.

ArresterFacts 024 is a tutorial on the subject of separation distance and how to calculate the maximum distance while still achieving a well protected transformer.

Simplified Equation (C62.22)

This simplified formula is applicable to surges rising faster than 2us to crest.

$$D = \left(\frac{.385\ x\ C\ x\ Vsa}{S}\right)\ x\ \frac{(.957\ x\ (BIL - Vsa))}{(.292\ x\ Vsa) - (.957\ x\ BIL)}$$

Where

D Maximum Separation Distance (ft) where the voltage at the transformer is 85% of the BIL

C Speed of surge on line 984 ft/sec in overhead lines

S Steepness of incoming surge (kV/us) This Assumes worst case of 1100 for systems below 230kV and 2000 for systems 230kV and up

BIL BIL of transformer (kV)

Vsa Voltage at Junction J (Bus to Gnd) (kV)

Vsa = *Va* + L x (*di/dt*)

Where

Va Fast Front Discharge voltage of the arrester (kV)

L Inductance of the line

L = d1 + d2 x .4uh/ft (d1 and d2 in feet) (see Figure 2)

di/dt Rate of rise of the current surge

di/dt = 2 x *S/Z*

Where

Z surge impedance of the line

System V	Typical Surge Impedance Z
<150kV	450 ohms
161 kV	400 ohms
230 kV	400 ohms
345 kV	350 ohms
500 kV	325 ohms
760 kV	300 ohms

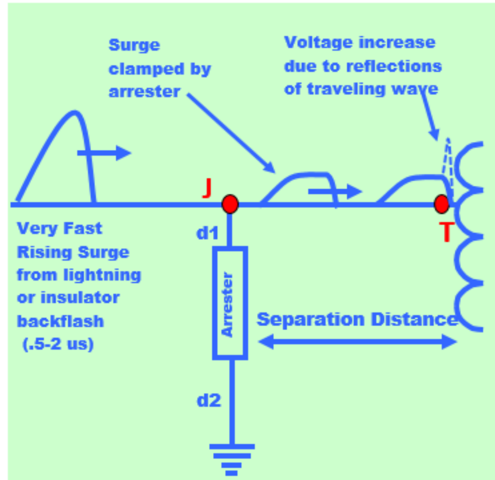

Figure 2 Separation Distance Calculator Circuit

Separation Distance Calculator
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Input Data		
System V	500	(kV) Nominal Line to Line System voltage
MCOV	335	(kV rms) as chosen by the user
BIL	1550	(kV peak) as chosen by the user
d1	3	(ft) height from top of arrester to the bus
d2	15	(ft) distance from the bottom of the arrester to ground
Auto Calculated Data		
Va	1107	= (kV peak) EFOW of the arrester
		(Based on Table 1 of C62.22-1997: Range of industry ratings for EFOW)
S	2000	= (kV/us) Assumes worst case of 1100 for systems below 230kV and 2000 for systems 230kV and up
Z	325	= (Ohms) line surge impedance
C	984	= (ft/usec) speed of propigation
di/dt	12.31	= 2*S/Z
L	7.2	= (d1+d2)*.4uH/ft
Vsa	1196	= Va+L(di/dt) Total voltage at the arrester (EFOW + line drops)

Results
Maximum distance the arreter can be located and maintain a 15% margin of protection
D = (.385*C*Vsa)/S * (.957*BIL-Vsa) / ((2.92*Vsa)-(.957*BIL))

Maximum Separation Distance = 32 feet or 9.9 meters

Voltage at J from Arr + lead inductance = 1196 kV
Voltage at T due to reflections = 1348 kV

Figure 3 Separation Distance Calculator Input and Output (Based on C62.22 Annex C)

Simple Separation Distance Calculator

An interactive Excel based calculator based on the above equation is available. Figure 2 shows the basic circuit and Figure 3 shows the inputs and outputs of the calculator. The inputs are in Green boxes and the output is at the bottom showing the maximum separation distance in feet or meters.

This calculator is downloadable from Arresterworks.com and instructions on how to use this calculator can be found in Annex A of this ArresterFacts.

Graphic Example of Voltage at Terminals

To demonstrate the increase in voltage at the transformer due to separation distance in graphic terms, a simple substation model was created in ATP and the distance between the arrester and transformer were varied. The same parameters were used in the ATP simulation as used in the calculator above. The results are very comparable. The circuit modeled in ATP is shown in Figure 4.

The simulation results of a substation with the arresters located 5 meter from the bushing of a 500kV transformer are shown in Figure 5. Figure 6 shows a separation distance of 15 meters and Figure 7 shows a separation distance of 30 meters. All other parameters of the location were kept the same. The arresters are mounted on a pedestal that results in 5 meters from earth ground to the base of the arrester with the top of the arrester one meter from the incoming line.

In Figure 5, the voltage at the arrester and the transformer are identical as they should be. In this case, the voltage peaks out at 1326kV. This leaves a margin of protection for a 1550kV BIL transformer of only 16%, which is already at the minimum for margin according to IEC and IEEE recommendations. For a separation distance of 15 meters, as shown in Figure 6 the margin of protection is reduced to 8%, which is less than recommended, but still not above the transformer BIL of 1550kV.

As you can see in Figure 7, it is clear that a 30 m separation distance would result in the voltage at the transformer exceeding the withstand level (BIL) of the transformer. This shows that a fast rising surge

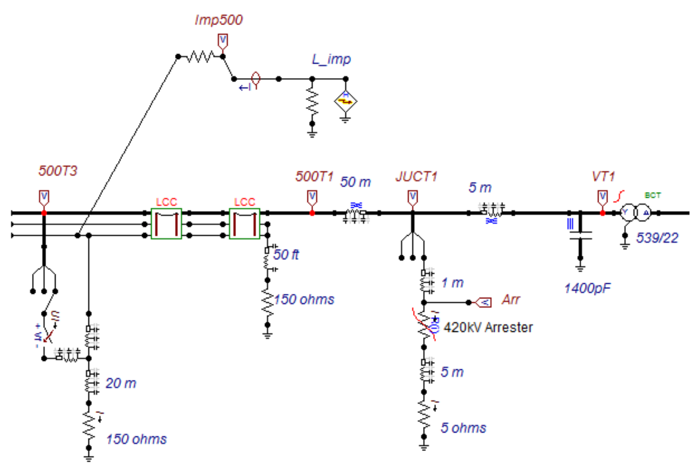

Figure 4 Circuit Modeled in ATP

entering the station with a 30 m separation could damage the transformer and would therefore not be recommended.

This example shows the significance of separation distance between the transformer and arrester. In reality, if it was necessary for the arrester to be located 30 meters from the transformer, a transformer with a higher withstand BIL would have to be selected.

Separation distance is a consideration needed with any equipment in the substation. If a CCVT, CVT, PT or breaker is at an end point on a short line, it would experience the same excessive transient voltage as the transformer above. In this case, an arrester should also be installed for protection near this other equipment.

Transient protection of the high valued transformer within a substation is an important part of the station design. As you can see from this discussion, having the arresters at the proper location is critical to the success of this design. Separation distance should always be evaluated to ensure adequate protection.

Arrester after Transformer

Another configuration that is sometimes used in station design is shown in Figure 8a. In this case the separation distance is measured after the connection to the transformer. Since an arrester protects in both directions the results are the same as it would be in Figure 8b. Annex B covers this scenario in more detail.

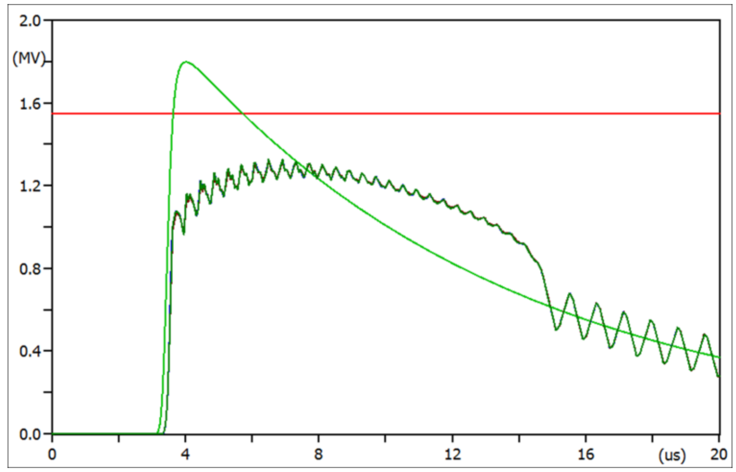

Figure 5 Transient Voltages in the Substation with 5 meters Separation Distance

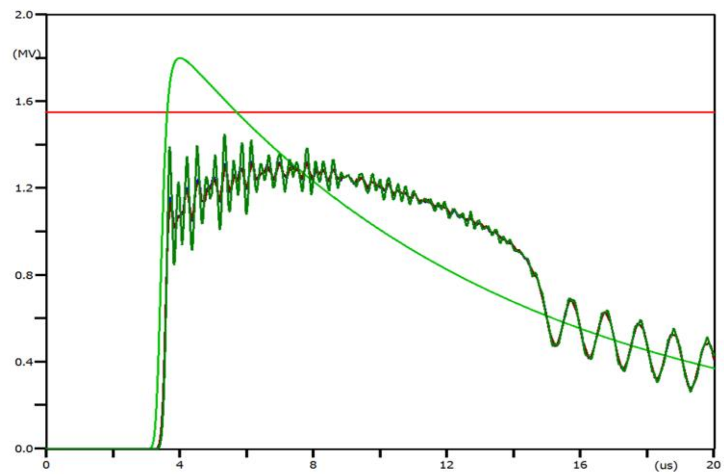

Figure 6 Transient Voltages in the Substation with 15m Separation Distance

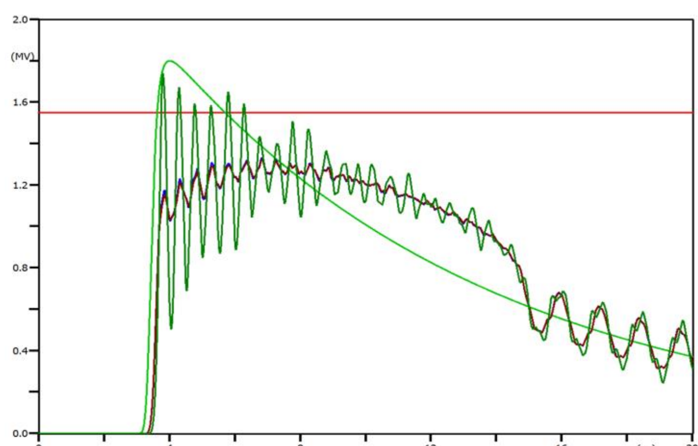

Figure 7 Transient Voltages in the Substation with 30m Separation Distance

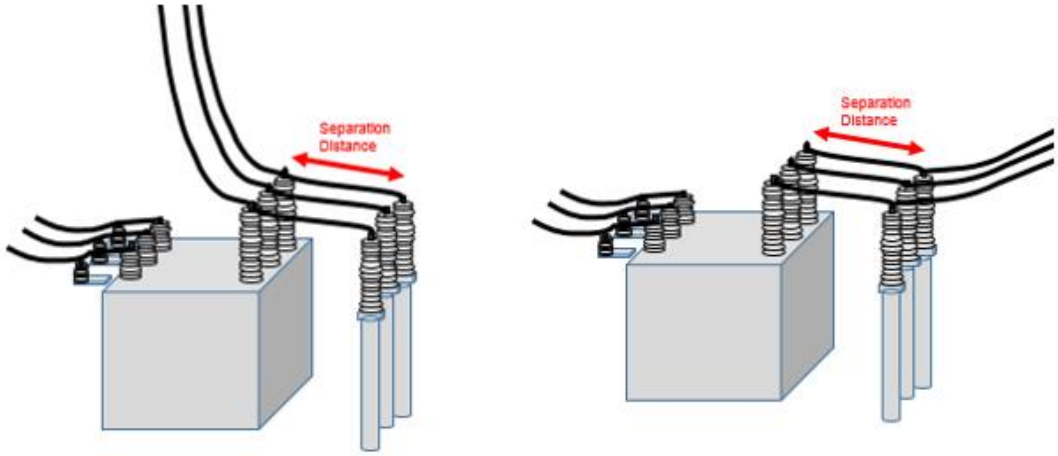

Figure 8 Configurations that are electrically the same and have the same effect on the Transformer Voltage

Arrester after Transformer

Another configuration that is sometimes used in station design is shown in Figure 8a. In this case the separation distance is measured after the connection to the transformer. Since an arrester protects in both directions the results are the same as it would be in Figure 8b. Annex B covers this scenario in more detail.

Based on what can be learned using either the online calculator or a transient program, it is clear that the rule of thumb that states closer is better holds true. However, if close is not an option, then you do have some latitude and you can determine your limits.

With ArresterFacts 024 you can down load

1. Separation Distance Calculator (excel)
2. ATPDraw model for 5,15,30 meter example
3. ATPDraw model for Arrester after Transformer example

Per IEEE C62.22 this formula applies to systems 69kV and higher. However the calculator includes distribution system voltages for your exploration.

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Annex A

Separation Distance Calculator

Background

A great many of us hold Andrew Hileman in very high regard when it comes to insulation coordination. He was an active member of the IEEE Surge Protective Devices Committee for many years. One of his many contributions to these committees was the section in the IEEE C62.22 Arrester Application Guide that provides simple mathematical formulas for calculating complex concepts. Hileman was the main author for Annex C: "Calculations for Surge Arrester Separation Distances." This annex remains, for the most part, unchanged from the 1980s and is still valid and useable.

The calculator discussed here is based on the formula found in Annex C of C62.22. It also incorporates tables from typical arrester characteristics. The limitations of this calculator are

1. Applies to single line and not multiple line systems.
2. Applies to fast rising surges from .5 to 2uS to crest of the voltage.

To use this calculator Microsoft Excel must be installed on your computer. Any version should work, though not all have been tested. Upon starting the spreadsheet, the following screen (Figure A2) should appear.

The white drop down box and bright green boxes are all that require inputting. Once these are entered, the

> **Note:** This calculator determines the Maximum distance the arrester can be from the transformer and still provide a 15% margin of protection.

Results will change in the yellow section at the bottom.

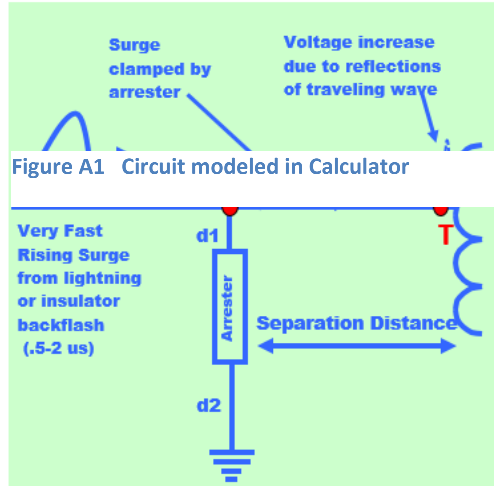

Figure A1 Circuit modeled in Calculator

Figure A1 Circuit modeled in Calculator

No other files are needed to run this program. The Arrester Characteristics are chosen based on the MCOV entered. This value can be changed in the Auto Calculated area if desired. The calculator will use the entered system voltage to determine the steepness of the surge and the surge impedance of the line. Additionally, the calculator will use the entered MCOV, d1 and d2 to calculate Vsa.

The distance from the top of the arrester up to the bus is considered d1. The distance from the bottom of the arrester to ground is d2.

Separation Distance Calculator

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Input Data

System V	500	(kV) Nominal Line to Line System voltage
MCOV	335	(kV rms) as chosen by the user
BIL	1550	(kV peak) as chosen by the user
d1	3	(ft) height from top of arrester to the bus
d2	15	(ft) distance from the bottom of the arrester to ground

Auto Calculated Data

Va	1107	= (kV peak) EFOW of the arrester
		(Based on Table 1 of C62.22-1997: Range of industry ratings for EFOW)
S	2000	= (kV/us) Assumes worst case of 1100 for systems below 230kV and 2000 for systems 230kV and up
Z	325	= (Ohms) line surge impedance
C	984	= (ft/usec) speed of propigation
di/dt	12.31	= 2*S/Z
L	7.2	= (d1+d2)*.4uH/ft
Vsa	1196	= Va+L(di/dt) Total voltage at the arrester (EFOW + line drops)

Results

Maximum distance the arreter can be located and maintain a 15% margin of protection

D = (.385*C*Vsa)/S * (.957*BIL-Vsa) / ((2.92*Vsa)-(.957*BIL))

Maximum Separation Distance = 32 feet or 9.9 meters

Voltage at J from Arr + lead inductance = 1196 kV

Voltage at T due to reflections = 1348 kV

Figure A2 Calculator Input and output Screen (parameters the same as used in the ATP model)

This calculator can be used for distribution systems as well as HV substations.

Separation Distance Calculator		
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Input Data		
System V	13.8	(kV) Nominal Line to Line System voltage
MCOV	8.4	(kV rms) as chosen by the user
BIL	95	(kV peak) as chosen by the user
d1	2	(ft) height from top of arrester to the bus
d2	3	(ft) distance from the bottom of the arrester to ground
Auto Calculated Data		
Va	38	= (kV peak) EFOW of the arrester
		(Based on Table 1 of C62.22-1997: Range of industry ratings for EFOW)
S	1100	= (kV/us) Assumes worst case of 1100 for systems below 230kV and 2000 for systems 230kV and up
Z	450	= (Ohms) line surge impedance
C	984	= (ft/usec) speed of propigation
di/dt	4.89	= 2*S/Z
L	2	= (d1+d2)*.4uH/ft
Vsa	47	= Va+L(di/dt) Total voltage at the arrester (EFOW + line drops)
Results		
Maximum distance the arreter can be located and maintain a 15% margin of protection		
D = (.385*C*Vsa)/S * (.957*BIL-Vsa) / ((2.92*Vsa)-(.957*BIL))		
Maximum Separation Distance =	15 feet or	4.6 meters
Voltage at J from Arr + lead inductance =	47 kV	
Voltage at T due to reflections =	83 kV	

Figure A3 Distribution System Example

Annex B

Example of Arrester Mounted Beyond the Transformer

This example shows that for short distances, the arrester can be either before or after the transformer with little difference in the protection.

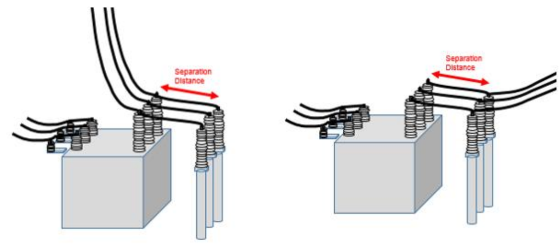

Figure B1   Arrester/Transformer Configurations with arrester before and after transformer

The model used in ATP is as follows.

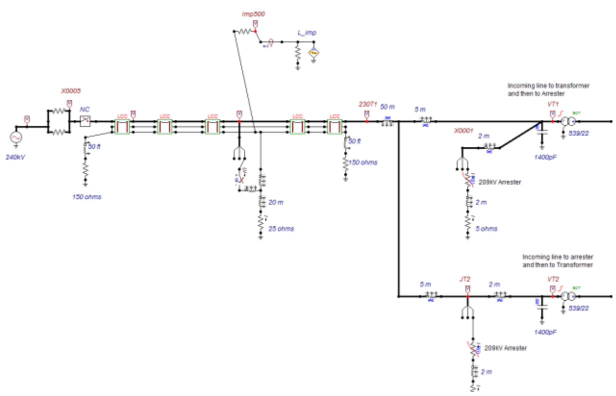

Figure B2   ATP Model Used

The resulting waveshapes from this model in ATP are as follows:

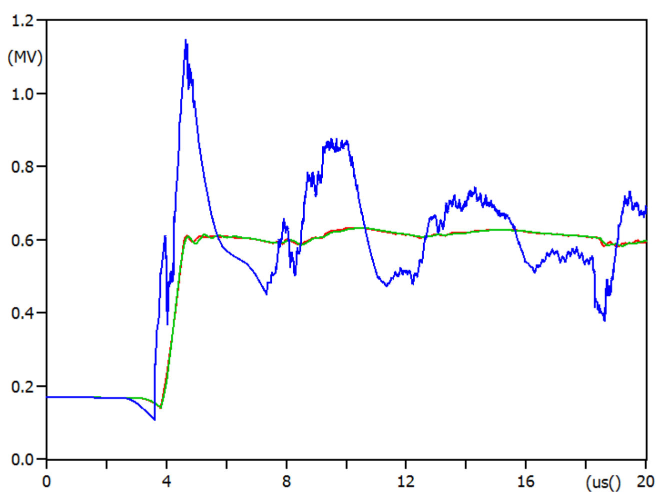

Figure B3   Results of Simulation of arrester before and after transformer

ArresterFacts are a compilation of facts about arresters to assist all stakeholders in the application and understanding of arresters. All ArresterFacts assume a base knowledge of surge protection of power systems; however, we always welcome the opportunity to assist a student in obtaining their goal, so please call if you have any questions. Visit our library of ArresterFacts for more reading on topics of interest to those involved in the protection of power system at:

About the author:

Jonathan started his career after receiving his Bachelor's degree in Electronic Engineering from The Ohio Institute of Technology, at Fermi National Accelerator Laboratory in Batavia, IL. As an Engineering Physicist at Fermi Lab, he was an integral member of the high energy particle physics team in search of the elusive quark. Wishing to return to his home state, he joined the design engineering team at McGraw Edison (later Cooper Power Systems) in Olean, New York. During his tenure at Cooper, he was involved in the design, development, and manufacturing of arresters. He served as Engineering Manager as well as Arrester Marketing Manager during that time. Jonathan has been active for the last 30 years in the IEEE and IEC standard associations. Jonathan is inventor/co-inventor on five US patents. Jonathan received his MBA from St. Bonaventure University.

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