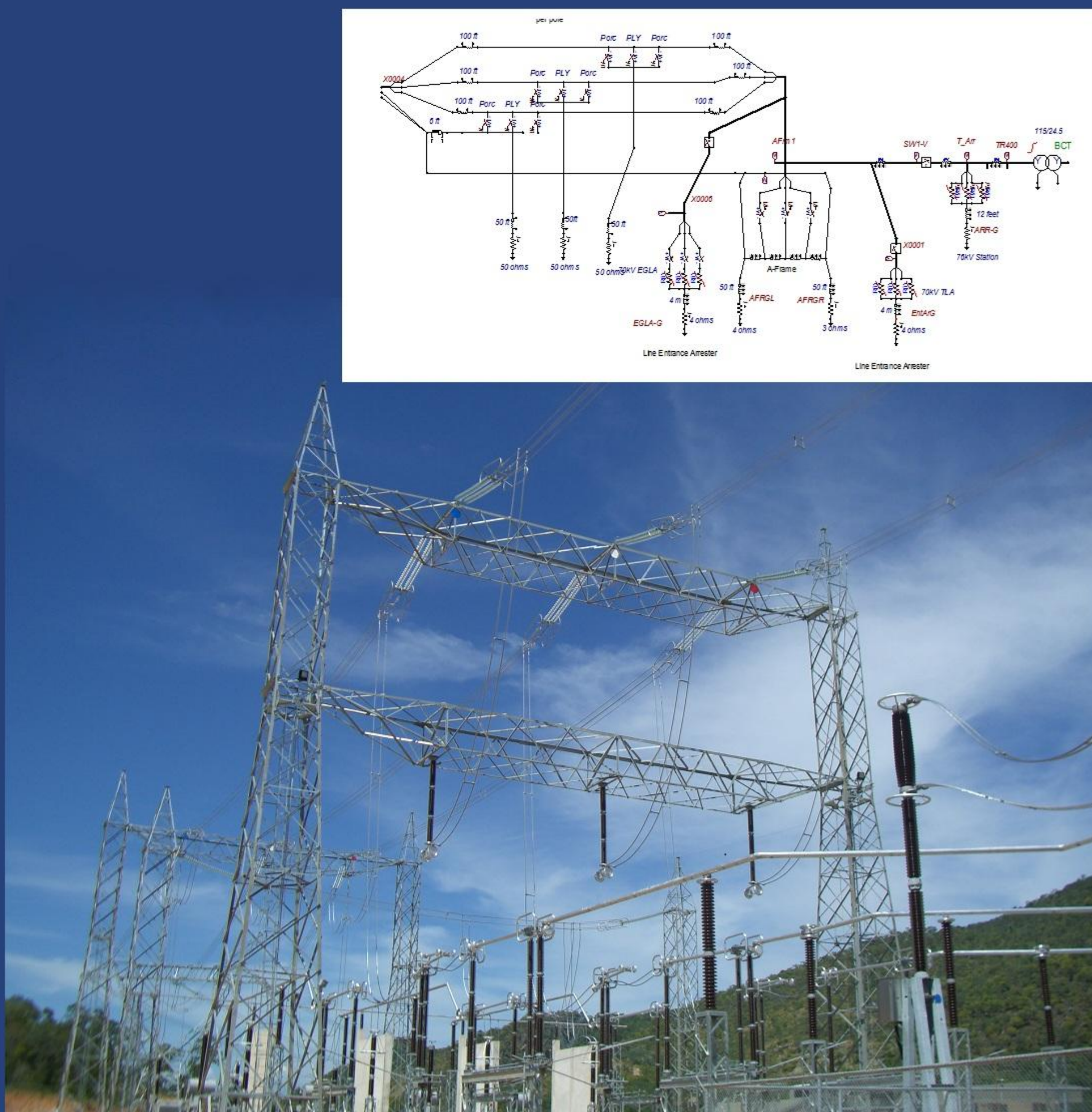
ArresterWorks

Insulation Coordination Fundamentals

Where Arrester and Insulator Characteristics Meet



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Insulation Coordination Fundamentals

Transient overvoltages are a fact of life on power systems. Arresters can be used to effectively control the most frequent type, which are caused by switching operations. Transients caused by lightning are somewhat more difficult to mitigate, but those too can be successfully handled with a judicious effort. How one protects the insulation on a power system is very often an economic decision. It would certainly not be reasonable to insulate only for the operating voltage and allow all transients to cause insulation failure. It is equally unreasonable to insulate for all transient events, if it were even possible. Therefore, a solution that makes a reasonable investment in insulation and protective equipment is the compromise most often taken. This carefully designed combination of insulators and arresters is called insulation coordination.

> **Insulation co-ordination**
> Selection of the dielectric strength of equipment in relation to the operating voltages and overvoltages which can appear on the system for which the equipment is intended and taking into account the service environment and the characteristics of the available preventing and protective devices.

Insulation coordination has become a well developed engineering practice. This practice is where the characteristics of the system, insulation of all forms, and arresters of all forms cross paths. The task of coordinating the insulation withstand levels with the desired performance levels of the system can be significantly different if arresters are applied verses if they are not applied. This coordinating task and arrester selection/locating task can be quite simple at times, and at others very complex. In the most complex forms, computer simulations are highly recommended; however, for a good first approximation, system performance can be modeled using simple formula presented in IEC 60071-1, 60071-2 and 60071-4. These three standards are very well written, very understandable, and easy to use. They cover 99% of what a person needs to know to perform a lightning or switching surge insulation coordination study. IEEE 1313.1 and 1313.2 are another excellent source for better understanding this engineering practice. A third and highly acclaimed reference is "Insulation Coordination of Power Systems" by Andrew Hileman. This 1999 publication is invaluable for the student that would like to understand some of the most complex concepts in insulation coordination.

> **Self-restoring Insulation**
> Insulation which, after a short time, completely recovers its insulating properties after a disruptive discharge during test
> **Non self-restoring insulation (60071-1)**
> Insulation which loses its insulating properties, or does not recover them completely, after a

This ArresterFacts is not meant to be a comprehensive treatise on the subject, but instead a basic coverage of the fundamentals of insulation coordination to help the power engineer understand when a study needs to be done and what might be the benefits of such a study.

Insulation Characteristics

All insulation has its limits of withstand capability.

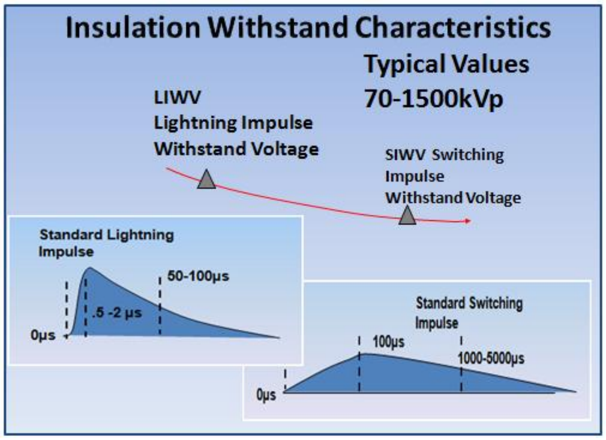

Figure 1 – Insulation Withstand

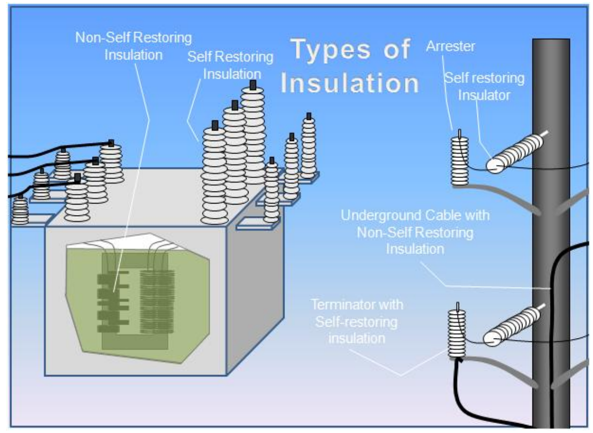

Figure 2 – Types of Insulation

Because it is impossible to insulate high enough to withstand lightning surges, all insulators are designed and tested to determine the level to which it flashes over. Insulation has two fundamental withstand characteristics: lightning impulse withstand and switching impulse withstand. These two characteristics are graphically shown in Figure 1 lightning impulse withstand voltage (LIWV) and switching impulse withstand voltage (SIWV). The LIWV characteristic of external self-restoring insulation is universally tested and verified under dry conditions. The physical straight line length between the insulator terminals is the most significant factor in determining these fast impulse characteristics. The SIWV of external self-restoring insulation is universally tested under wet conditions because this withstand characteristic is a function of the insulation's creepage or leakage distance when wet. The creepage distance is the distance between the two terminals along the surface of the sheds.

Substations Insulation Coordination for Lightning Surges

Substations are subjected to two types of overvoltages that can and do stress the insulation throughout the station. Even if the station is well shielded, lightning surges can enter the station indirectly. All stations need connection to the rest of the system via incoming and outgoing overhead conductors. The only exception to this would be GIS or underground station, therefore all the following pertains to overhead, air insulated substations only. If lighting strikes either incoming or outgoing lines within a span or two of the station, a surge is likely to enter the stations on the conductors.

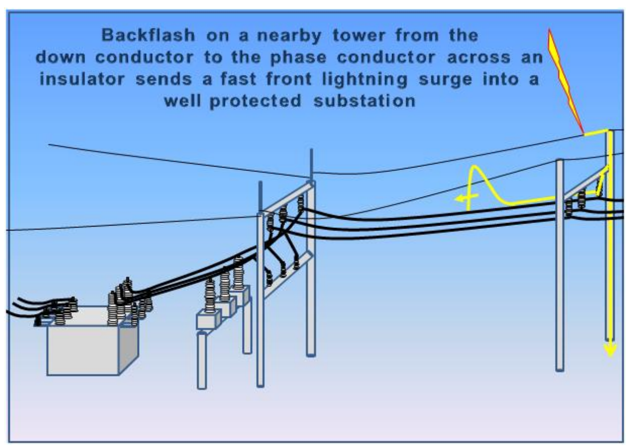

Figure 3 – Backflash into Protected Substation

Even well shielded transmission lines can allow a very fast rising surge to enter a nearby station if there is a backflash to the conductor during a switching or lightning surge (Figure 3);

however, owing to the high insulation withstand on systems above 245kV, back-flashovers are less probable then on systems below 245kv and are rare on systems at 500 kV and above.

Fast rising surges on an incoming conductor have a high probability of flashing over insulation in the substation if there are no arresters. The amplitude of the incoming surge will be approximately equal to the flashover level of the backflashed insulator. If the only mitigation is an arrester at the transformer, it will protect the transformer if properly coordinated with the transformer insulation. The arrester may protect equipment on the surge side to some extent. In this coordination scenario, the probability of its occurrence is quite low over the expected life of the transformer, which is probably 30-40 years; however, if the proper arrester is not located near the transformer, it only takes one occurrence to cause a failure of the expensive asset in the circuit.

Another important part of this coordination scenario is the state of the circuit breaker. If the breaker is in the open position, it will become an endpoint on the circuit. Because endpoints represent a significant change in impedance to the circuit, the voltage will be reflected and cause a doubling effect at the breaker. This voltage doubling effect (see traveling wave theory) will cause the breaker insulator to flashover causing yet another path for power current to flow to ground. This voltage doubling effect can also occur if the breaker is momentarily open and a second lightning surge arrives along the original surge path to find the breaker open. Due to these two potential open breaker scenarios, it is advisable to apply arresters at the line entrance of the station to eliminate the voltage doubling at the breaker and certain breaker bushing flashover.

Yet another variable to consider in substation coordination for lightning is the number of incoming lines to the station. Fortunately, in this case, more lines make it harder to flashover insulators in the substation, but at the same time more lines also increase to probability of an incoming surge. Both these factors are used in the formulas used to determine proper coordination.

Separation Distance

Separation distance is a very important consideration in the protection of substations and insulation coordination of substations. Arresters will limit or clamp a fast rising surge according to their own clamping characteristics immediately in the vicinity of the arrester; however, as the protected insulation is moved away from the arrester, it is less and less protected from fast rising surges as described in scenario 1 above (note there are no separation distance issues for slow rising surges from switching sources). This reduced protection is due again to the effects of traveling waves and reflections. For this reason, the location and distance between critical insulation points in the substation need to be well known before a proper insulation coordination study can be completed.

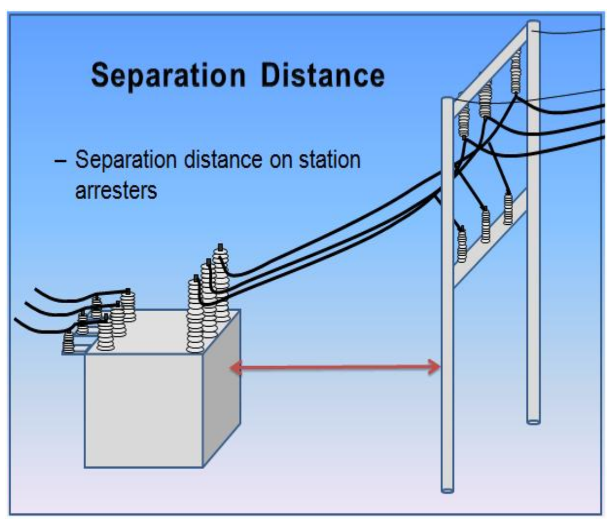

Figure 4 – Separation Distance

Of course, the non-selfrestoring insulation of the transformer is generally the insulation of highest consideration for separation distance issues. The formula for determining the farthest distance between an arrester and the transformer is found in the stated references above as well as in IEC 60099-5. As it turns out, the higher the system voltage, the shorter the allowable separation distances become because the ratio of the transformer withstand voltage and system voltages is reduced.

Substation Insulation Coordination for Switching Surges

Switching surges are of concern only on systems 245kV and above. The magnitudes of switching surges for systems below 245kV generally do not exceed 1.5pu of the system phase to ground voltage. This is due to the fact that the line capacitance, length, and voltage are not of high enough values to result in challenging surges. There are numerous sources of slow front switching surges in substations. Circuit breakers or switching devices are involved in all forms of this surge. Fault and fault clearing overvoltages are generated in the unfaulted phase when the fault is first initiated and when the voltage is re-established.

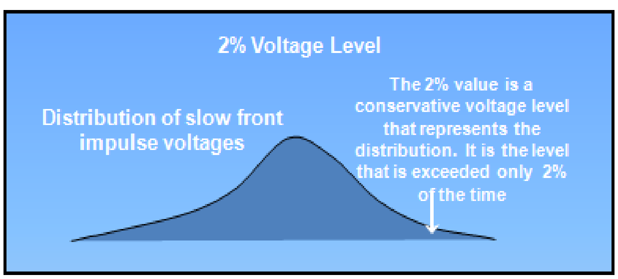

Figure 5 – 2% Switching Surge Statistical Level

Switching surge statistical level is known as the 2% voltage (see figure 5) and range from 1-2 per unit of the crest phase to ground voltage if they are mitigated with pre-insertion resistors or arresters; however, if they are not mitigated, their levels can easily exceed 2.0pu. When energization and re-energization surges are mitigated, load rejection surges need attention. Switching inductive and capacitive currents need particular attention when the associated breakers experience pre-strike or restrike. In this case, the range of 2% voltages is 2-2.5pu.

There are two coordination methods used in the practice of insulation coordination. The deterministic method is used exclusively when applied to non-selfrestoring insulation. When coordinating self-restoring insulation, statistical (also known as probabilistic) methods are almost universally used. The basic difference between these two methods is that in the deterministic method, absolute maximum and minimum values are coordinated. For example, the maximum residual voltage of an arrester for a slow front surge is coordinated and compared to the minimum withstand level of transformer switching impulse withstand level. When using the statistical method in determining the flashover rate of the 25 self-restoring post insulators in the substation the probability of flashover, occurrence and magnitude of the surge are used in the calculation. The results are a probability distribution representing the overall switching surge flashover rate

Arrester Characteristics and Substation Insulation Coordination

Arresters are a fundamental part of insulation coordination in the substation. They are used universally to protect the non-selfrestoring insulation of power transformers. As stated above, the coordination of non-selfrestoring insulation is accomplished using the deterministic method. This is because there are no acceptable test methods that can determine the probability of disruptive discharge in oil/paper insulation systems. Therefore, the only option is to accept the deterministic approach.

Arresters applied in substations characterized by three voltages relative to insulation coordination: the arrester operating voltage (Uc or MCOV), lightning impulse protective level (LIPL) and switching impulse protective level (SIPL). They are shown in Figure 6.

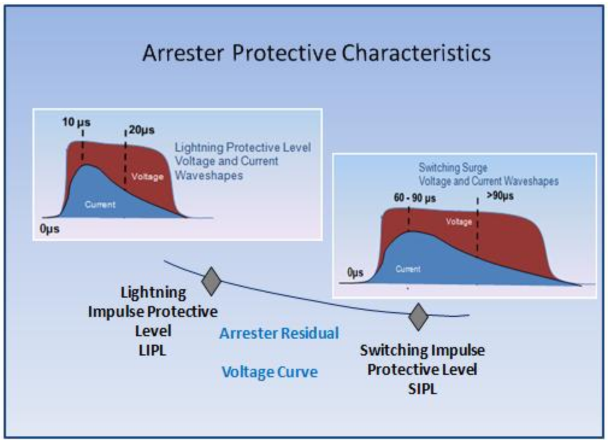

Figure 6 – Arrester Protective Characteristics

For non-self restoring insulation, a deterministic comparison is completed. After the insulation and arrester characteristics are determined, they are then coordinated to insure that there is ample safety margin between them. The comparative graph is shown in Figure 7 and is referred to as the Margin of Protection.

Environmental Effects on Insulation Coordination

Flashover voltages for air gaps depend on the moisture content and density of the air. Insulation strength increases with absolute humidity up to the point where condensation forms on the insulator surfaces. Because insulation strength decreases with decreasing air density, longer strike distance is required to attain the same flashover voltage at 2000m elevation than at 100 meters above sea level. A detailed description of the effects of air density and absolute humidity are given in IEC 60-1 or IEEE Std 4 for different types of voltage stresses. When determining the co-ordination withstand voltage, it should be kept in mind that most adverse conditions from a strength point of view (i.e. low absolute humidity, low air pressure and high temperature) do not usually occur simultaneously. In addition, at a given site, the corrections applicable for humidity and ambient temperature variations cancel each other for all intents and purposes. Therefore, the estimation of the strength can usually be based on the average ambient conditions at the location.

When contamination from salt or industrial pollution is present, the response of external insulation to power-frequency voltages becomes

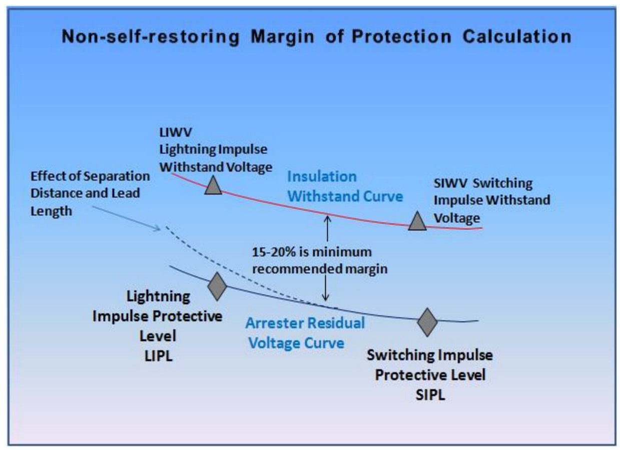

Figure 7 – Non-Self Restoring Margin

important and may dictate longer creepage or leakage distances. This type of contamination does not adversely affect lightning and fast front withstand levels. Flashover of insulation generally occurs when the surface is contaminated and becomes wet due to light rain, snow, dew or fog without a significant washing effect.

Transmission Line Insulation Coordination

Transmission line insulation coordination is also separated into two categories; lightning and switching. The performance assessment methods are based on expected lightning and switching overvoltages and their corresponding insulation levels. Since line insulation is self-recovering, their performances are usually determined by the statistical method.

The practices outlined in substation insulation coordination also apply to line coordination.

The sum of the back flashover rate (BFR) and shielding failure rate (SFR) determine the flashover rate (FOR) which is expressed in flashovers/100km/year. The back flashover rate is the most significant cause of outage on transmission lines.

The fast rising surge associated with a back flashover seldom makes it to the substation due to corona effects; however, fault current and breaker operation resulting from the back flashover is felt over the entire length of the system. Often times, a switching surge is experienced immediately following a lightning caused flashover.

Shielding Failure Rate (SFR)

The shielding failure rate is the number of strikes that terminate on the phase conductors. If the voltage produced by a strike to the phase conductors exceeds the line CFO (critical flashover voltage), flashover occurs.

Another significant variable often involved in lightning flashover coordination is the system elevations. The critical flashover voltage (CFO) of a line insulator can be reduced by as much as 20% at higher elevations. Since transmission lines often traverse high elevations, this factor must be considered. For higher elevations, the insulators may be lengthened or arrester may be applied. Both are excellent means of mitigation.

Back Flashover Rate (BFR)

The back flashover rate is the number of lightning strikes that terminate on towers or shield wires and result in insulator flashover The current impulse raises the tower voltage, in turn this generates a voltage across the line insulation. If the voltage across the line insulators exceeds the insulation strength, a back flashover can be expected from the tower onto the phase conductor.

Switching impulse studies need only be considered for lines exceeding 245kV. For lines below this level, the switching surge magnitudes do not overstress normal insulation configurations. For levels above 245kV, the stresses can be significant.

The Switching Surge Flashover Rate (SSFOR) is determined by numerical integration of the stress-strength relationship. The stress in this case is the switching impulse voltage or switching overvoltage (SOV) quantified by a probability distribution. Strength is the switching impulse withstand voltage (CFO). IEC 60071-2 and IEEE 1313.2 define this process in detail.

If arresters are used to mitigate the SSFOR, the evaluation method is modified to accommodate the change in the SOV since it will no longer be a normal distribution but instead truncated distribution.

Distribution Systems Insulation Coordination

The practice of distribution system insulation coordination is very limited; however, there are some very specific deterministic practices that are quite important. The margin of protection calculations for some system configurations can determine when to and when not to use arresters. For instance, on underground circuits where voltage doubling is common, a margin of protection calculation can reveal that applying an arrester only at the riser pole for systems above 25kV can be a problem. When this is the case, an open point arrester is recommended to provide a lower risk of cable failure.

On ineffectively grounded or delta distribution systems, a close check of the margin of protection can often show that there is little margin compared to well grounded systems. This is due to the fact that higher rated arresters are applied to these circuits to give them ample overvoltage withstand capability. By raising the operating voltage of the arrester, the clamping voltage is also increased and the margin between the transformer's withstand curve and arrester's clamping curve is decreased.

Another factor that can have major impact on insulation coordination on distribution systems is long lead lengths on arresters. Long leads can effectively render an arrester unable to protect non-self-restoring insulation of distribution equipment.

Conclusion

In this brief overview of insulation coordination fundamentals, it can be seen that the many variables involved in this engineering exercise can make this task quite complicated. However, using this method to optimize the use of arresters can result in significant insulation savings on all systems.

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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