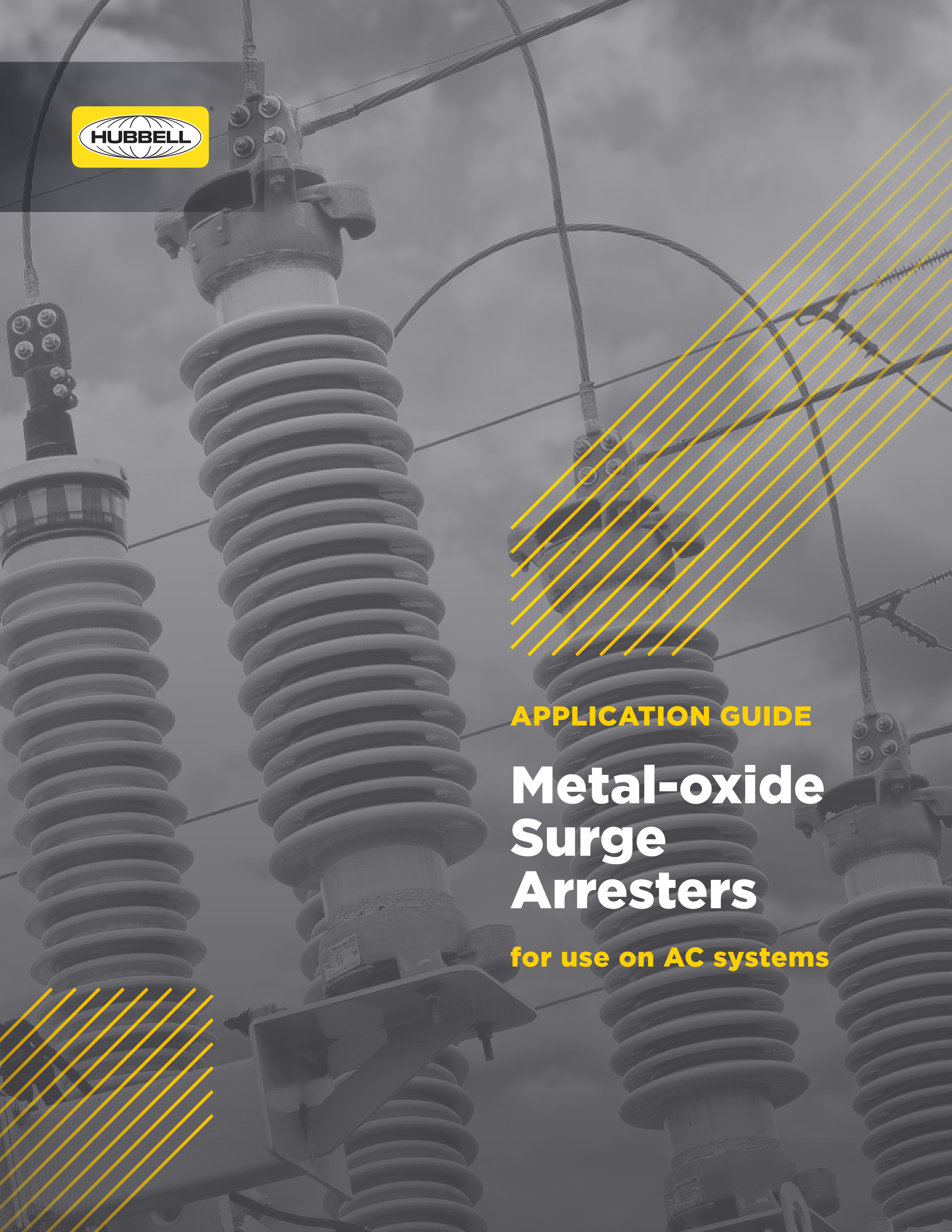

HUBBELL®

APPLICATION GUIDE

Metal-oxide Surge Arresters

for use on AC systems

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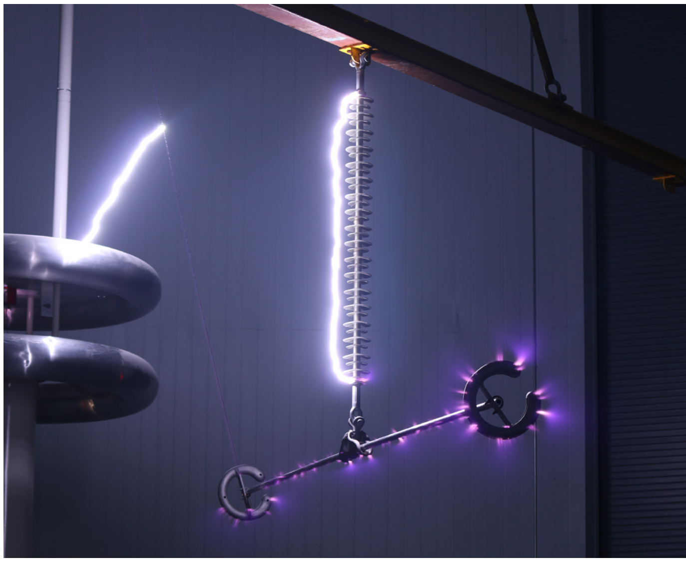
01 Introduction

Power system overvoltages are a common occurrence in the day to day duty for various distribution, substation and transmission equipment. Overvoltages can arise due to normal power frequency voltage fluctuations or due to lightning and switching surges. Surviving system overvoltages is a key facet to ensuring reliable and consistent power quality for your customers.

Next to your people, your power grid infrastructure is your largest and most valuable investment. Every lightning surge, insulator flashover and switching event adds wear and tear to utility equipment, prematurely aging it, and requiring utilities and their customers to shoulder the cost of replacement. Various mitigation methods can be used to protect critical equipment insulation from failure due to high voltage surges.

One such method includes limiting the resulting voltage during a surge, to a level below the critical strength of the insulation. The main objective for any protective measure is to achieve an acceptably low level of service interruptions or equipment failures. The definition of acceptably low will surely vary depending on the application and the implications of such an interruption or equipment failure. Above all, the method of providing this protection must be economically feasible and provide safety to both line crews and the general public.



Insulator flashover during impulse testing

One such method to offer surge protection and limit overvoltages is achieved using Metal-Oxide Varistor (MOV) type surge arresters. The MOV was originally developed in Japan in 1967, which opened a new doorway for modern overvoltage protection. The new technology was adapted for high voltage applications and made its way to the United States of America and other countries around the globe. The first MOV surge arrester was ultimately introduced in 1976. The new design quickly led to the obsoletion of the prior technology, Silicon Carbide (SiC). SiC arresters were introduced in 1930 and were virtually the exclusive choice for equipment protection for over forty years.

02 History

Protection of electrical lines dates back to the early 1800's with the introduction of the telegraph. The earliest method of protection was a simple rod gap. Other predecessors to SiC arresters included the electrolytic, pellet oxide and the oxide film arrester. The introduction, in 1930, of the first SiC arrester marked the beginning of the modern era of lightning arrester design.

The multi-gap silicon-carbide arrester design relied on the series gaps to spark over at a predetermined voltage level and then to interrupt system follow current, which was limited by the silicon-carbide material. A primary disadvantage of this design was the series gaps could not interrupt the flow of follow current until the system voltage made a zero crossing. As system voltages increased and lines lengthened in the 1940's and 1950's, the burden of energy absorption on the SiC blocks in an arrester became quite severe.

The Ohio Brass Company began manufacturing surge arresters in 1950 with the introduction of the Thorex series. Thorex brought several innovations by pioneering the use of a SiC discs in conjunction with a series gap that magnetically drove arcs along runners into a cooling shoot. This advancement eliminated the use of expensive external arrester bracing by drastically reducing the height of surge arresters.

Ohio Brass made a major breakthrough in arrester development in 1957 with the introduction of the current-limiting gap. The new design, dubbed Dynagap, converted surge arresters from a mere lightning protective device to a key member of insulation coordination planning. Because the gap was used to develop a back electromagnetic field during a power follow-current operation, the arrester did not have to wait for a system voltage-zero crossover to interrupt follow current.

The most important contribution of the current-limiting gap to system protection was it permitted a significant reduction in the arrester protective levels. The consequent reduction in system insulation levels in turn saved utilities millions of dollars. This innovation changed the design, manufacture and application of surge arresters for the next 20 years, until the transition to MOV technology.

Ohio Brass began manufacturing MOV discs in 1978. This investment again changed the future of overvoltage protection. This venture led to DynaVar in 1979 which translated modern MOV technology into a superior arrester product. DynaVar offered significant technical advantages, due to the nonlinearity of the MOV element.

The Ohio Brass Company was purchased by Hubbell in 1978 and became the cornerstone for Hubbell Power Systems, Inc. Hubbell has continued to lead the innovation of surge arrester design into both the MOV and polymer era of surge protection.

03 Surge Arrester Function

SiC type arresters were rated by the voltage which they could pass the ANSI duty-cycle test. Selection of a SiC type arrester consisted of choosing an arrester with a rating equal to or greater than the maximum line-to-line system operating voltage times the coefficient of ground at the point of application. Modern MOV type surge arresters still reference the duty-cycle voltage rating, however they are selected and most often referred to by their Maximum Continuous Operating Voltage (MCOV) or Uc for IEC designs. It's important to note the duty-cycle rating is being obsoleted in the IEEE market, while for now it is still very relevant in IEC standards.

Protection

A surge arresters' primary function is to the limit the voltage appearing across the terminals of the equipment being protected to a level below its critical flashover voltage. To ensure a proper margin of protection is achieved users need to understand how voltage can vary under surge conditions.

The maximum voltage imposed on a system varies based on the use and placement of an arrester. The corresponding arrester clamping voltage is referred to as the discharge voltage in IEEE applications and residual voltage in IEC applications. For purposes of this guide the term used here within will be residual voltage. The actual voltage seen by the system can additionally vary depending on whether the arrester is a gapped or gapless design. In the case of gapless arresters, the maximum voltage is the residual voltage across the MOV discs and miscellaneous conducting elements. In the case of gapped arresters, the maximum voltage is the higher of the residual voltage or gap sparkover voltage.

Lightning

The most common duty seen by distribution and transmission surge arresters is due to lightning events. The effect of these strikes is largely localized and the closest structure to the strike will have the highest impact. The time to crest for the voltage wave is very short and typically ranges from 0.5 to 8 µs. The resulting traveling wave can lead to insulator flashover, equipment damage and power quality issues. The duration of a typical lightning stroke is less than 100 µs.

Lightning severity is generally assessed by considering the Ground Flash Density (GFD) for a region. The severity for an area varies drastically when considering different locations, such as California versus Florida in the United States.

Switching

While switching duty is common in all arrester applications it is of most concern for station class arresters. During a switching surge the entire line is charged to the switching surge voltage level. The time to voltage crest is slow, compared to lightning duty and is in the range of 30 to 45 µs. The switching surge can lead to power transformer and equipment failure. The duration of a typical switching surge can be 2,000 µs or longer.

04

Surge Arrester Design

Surge arresters applied on system voltages above 1 kV a.c. are governed by two primary standards, IEEE C62.11 and IEC 60099-4. Other standards exist for more specialized applications including internally and externally gapped arresters, d.c. arresters and gas-insulated arresters.

IEEE

IEEE Standard C62.11-2020 divides surge arresters by their application. Design types include distribution, station and intermediate classes. Distribution subcategories include Light Duty (LD), Normal Duty (ND) and Heavy Duty (HD). While not a distinct type of surge arrester the Riser Pole arrester is commonly specified for its unique application. However, this Riser Pole arrester is in fact a HD type arrester, simply with enhanced (lower) protective characteristics.

IEC

IEC Standard 60099-4 Ed. 3.0 divides surge arresters strictly by distribution and station class types. Arresters are further subcategorized into classification Low, Medium and High. This produces three distinct classes for distribution and three more for station applications. The classes are commonly referred to by their acronym: Distribution Low (DL), Distribution Medium (DM) and Distribution High (DH), as well as Station Low (SL), Station Medium (SM) and Station High (SH).

The prior version of IEC 60099-4 Ed. 2.2 used a class-based system. This system included Class 1-2 which were primarily for distribution or sub-transmission applications, while Class 3-5 were more scoped for substation type applications. The remainder of this application guide will focus on the latest IEC standard, Ed. 3.0.

Future Work

Current IEEE and IEC standards primarily identify distribution and station class arresters. A third type, commonly referred to as transmission line arresters (TLA) or line surge arresters (LSA) is briefly, although not adequately addressed by these existing standards. For purposes of this guide the discussion will refer to this technology as an LSA. LSA's are in wide use across the globe and have been grouped into two categories: 1) Non-gapped line arrester (NGLA) and 2) Externally gapped line arrester (EGLA).

In 2018 a new work item proposal was issued to cover the design and type tests associated with all LSA's. A joint logo IEC/IEEE 60099-11 will be released in accord with the guidelines of Project Team 11. This standard is still in the early development stage and will likely be released in five years.

Arrester Construction

Surge arresters can be characterized by numerous factors, but one of the most common is the insulation material. Porcelain was formerly the dominant material for all applications. A paradigm shift in the design and specification of arresters occurred in 1986 with the introduction of the first polymer housed surge arrester, a distribution design, by the Ohio Brass Company.

At the time all arresters were manufactured using a porcelain housing. Porcelain arresters of this era were notorious for moisture ingress failures. During the end of life event a porcelain arrester could possibly eject particles. This posed a huge safety risk because porcelain distribution arresters can be located outside of homes, restaurants and in other public locations. Once the polymer design was introduced the industry went through a rapid transition afforded by the invention of polymer arresters.

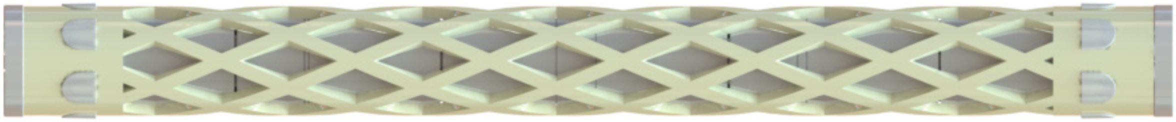
A current vintage polymer housed distribution arrester is displayed in the Figure below. The experience and research pioneered by the Ohio Brass high voltage insulator group was key to leveraging polymer technology for arrester design and application. The technology was later adapted for intermediate applications in 1991 and station class applications in 1993. The introduction of polymers paved the way for two distinct types of arrester construction: hollow core and solid core.

Polymer housed distribution arrester

Hollow Core Versus Solid Core Arresters
The introduction of polymer materials and designs prompted the need for revised test standards. Both IEEE and IEC standards worked towards addressing the new polymer solid type design. While not formally defined in an IEEE or IEC standard, the terms hollow core and solid core are commonly used to characterize the different methods of arrester construction. These two types of arresters are further characterized by their amount of internal gas volume.

Solid core (left) versus polymer hollow core (right) arrester

Solid core arresters are, as the name suggests, a solid type design with virtually zero internal gas volume. The MOV blocks are held together with a fiberglass weave that is composed of fiberglass roving impregnated with a resin. The fiberglass is wound around the MOVs during production. The resulting assembly is typically referred to as a module. A polymer housing is then assembled to this wrapped module. A silicone dielectric grease is used as the live interface between the module and housing. These designs are not equipped with a directional pressure relief device. In the event of arrester short circuit, the polymer housing will tear to vent the resulting pressure buildup.



Arrester module

Hollow core arresters utilize either a ceramic housing or hollow composite insulator with an external polymer insulating material to contain the MOV blocks. The porcelain hollow core design strictly uses a ceramic housing. The polymer hollow core design is a combination of a fiberglass tube and a direct molded polymer housing. This design retains >5% internal air volume, which requires a leakage test be performed during production. These designs are additionally equipped with directional pressure relief devices. Based on the manner of construction hollow core designs typically have a superior cantilever capability when compared to solid core arresters. Polymer hollow core designs are additionally lighter than equivalent porcelain designs and tend to be more forgiving to potential mishandling.

All arresters feature weather sheds constructed from polymer or porcelain. The housing shields the internal MOV elements from the external environment, while the weather sheds add surface area to help disperse surface currents. This feature can be critical in polluted environments.

Polymers

Numerous polymer materials and associated compounds are utilized in the utility industry. Polymer insulating materials for arresters are typically defined by the base material. There are three primary base materials available in the market: ethylene propylene (EP), dimethyl siloxane (silicone), and combinations of both.

All polymer compounds used for electrical apparatus insulation are produced with fillers and additives to enhance the base polymers characteristics. The base material makes up only about one third of the total polymer material. Most of the materials' properties are developed by the additives and fillers that make up the rest of the material. Just because two products use the same base material does not mean they will perform the same in the field.

EP rubbers, Ethylene Propylene Monomer (EPM) and Ethylene Propylene Diene Monomer (EPDM), offer superior resistance to electrical activity. Materials with EPM or EPDM as the base material will typically perform well in corona cutting and tracking tests. The resistance to tracking and erosion allows them to perform well in highly contaminated environments. EPDM materials also offer superior mechanical strength that protects against mishandling or potential damage from wildlife while in service.

Silicone rubbers have a high degree of hydrophobicity. In other words, water beads up on the surface. Only under severe wetting will a continuous sheet of water form on the weather sheds. Without a sheet of water, the electrical activity on the surface is drastically reduced. Although silicone-based materials don't withstand tracking and erosion as well as EPDM, the hydrophobicity limits the electrical activity that causes the tracking and erosion.

ESP™

Combinations of the two materials have been developed to combine the resistance to erosion and tracking of an EP material with the hydrophobicity of a silicone-based material. Hubbell manufactures surge arresters and various other electrical components using a proprietary rubber compound. The material, trade named ESP™, is made with a base material that is a combination of EPDM and low molecular weight silicone oil. This hybrid material is used for Hubbell distribution arresters and solid core station and intermediate arrester housings.

ESP™ was formulated over many years of research beginning in the early 1960's. Ohio Brass began researching polymer materials in 1964. The goal at the time was to produce a polymer that would meet or exceed the capabilities of porcelain. Ohio Brass ultimately introduced polymer transmission insulators in 1976. Many years of research, testing and refinement were required to ensure a good quality and reliable material was being offered to the industry.

Technology and expertise from polymer transmission insulators were leveraged to create the world's first polymer housed distribution surge arrester in 1986. In less than ten years the porcelain housed distribution arrester was no longer manufactured in the US.

The combination of the mechanical and electrical resistance of EPDM with the hydrophobicity of silicone rubber created the best insulating material available. Ohio Brass developed a series of critical tests to ensure the long-term performance and reliability of a polymer. These tests include oxidative stability, ultraviolet exposure, corona cutting, tracking and erosion and salt fog accelerated aging. A superior testing program ensures critical characteristics are verified and lead to the long-term performance of equipment.

- Resistance to tracking and erosion
- Ultra-violet (UV) resistance
- High mechanical strength
- Low moisture permeability
- High mechanical strength
- Short- and long-term hydrophobicity

The ultimate test for any polymer material is field exposure. Utilities have demonstrated the longevity of Hubbell polymer products for over 40 years. A testament to ESP is highlighted by the 35-year history of the PDV arrester line, which culminated with Hubbell shipping its 40 millionth polymer housed distribution surge arrester in 2020.

05

Metal Oxide Varistors (MOV)

Ohio Brass invested in the large-scale manufacture of MOV discs beginning in 1978. This investment marked a turning point for the utility industry and all surge arrester manufacturers. The MOV is the heart of all modern high voltage surge arresters. To ensure superior performance MOV manufacturing requires strict attention to quality control practices. Hubbell continues to manufacture MOV discs in-house in our US facility.

While standards and guides exist for the design, manufacture and application of surge arresters, there is no such reference document for MOV discs. The material composition and method of manufacturing is strictly dependent on the manufacturer. Hubbell considers MOV manufacturing and the associated material science to be a core competency. MOV discs are manufactured in a wide range of heights and diameters, ranging from 29 to 75 mm.

An MOV is a collection of millions of microscopic electronic switches that are basically programmed all to come on at a given signal. The MOV is designed to take excess energy to ground to protect equipment on the other side of the device. MOV's are not only used in arresters, they are used all the way down into the power strips you use in your home.

Range of Hubbell produced MOV blocks

MOV Structure

The internal crystalline structure of the MOV is what gives an MOV its electrical characteristics. Hubbell controls this structure by design. At the microscopic scale, the MOV is predominantly zinc oxide crystals formed during a high temperature sintering process. The boundaries between the crystal grains are where the majority of electrical performance characteristics are established.

The composition of an MOV disc includes approximately 90% Zinc Oxide (ZnO) and 10% additives. The live additives at the crystal grain boundaries provide the switch-like behavior of the MOV. These additives include oxides of other metals such as Bismuth, Antimony, Nickel, and Manganese. The amount of each additive has a critical effect on the varistor characteristics. Additional binders and organics are added to aid with MOV disc processing. Given the complexity of producing high quality MOVs, a long sequence of steps must be tightly followed from start to finish.

Manufacturing Process

The timeline from incoming material to finished MOV electrical testing is twenty-five days. Because of the long duration and complexity of processing, the cost impact of variations must be minimized by a significant number of quality checks throughout production. Even before the first step of production, incoming raw material batches must be tested to match supplier certifications. The purity content, contaminant level, particle size, surface area, and crystal structure are all critical characteristics which must be known before manufacture.

During varistor manufacture the material research laboratory supports the production facility by analyzing raw materials and performing consistent quality assurance checks on in-process materials. Raw materials are checked for particle size and chemical composition before leaving the supplier. The materials are further verified by Hubbell personnel to ensure the composition does not include trace impurities, which might influence the operating characteristics of a finished MOV.

The manufacturing process begins with the assignment of an MOV batch number. The batch number will carry through the entire process and be printed on each MOV disc. This level of traceability allows complete control of the process, including tying back to the raw materials. The process starts with weighing the correct amount of materials. The additives include compounds in powders of 1 to 10 micrometers in diameter. The raw materials are milled to reduce particle size and ensure a uniform mix is achieved.

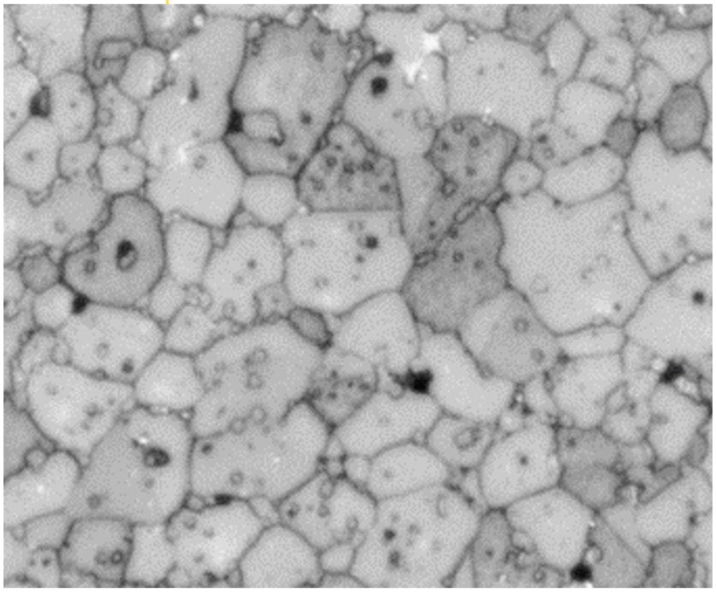
The material continues into a high-heat process known as calcining. The calcined additive aggregate is again milled to further reduce particle size to enhance uniform mixing with the ZnO. The ZnO is weighed and combined with the additives in a dispersion unit that uniformly disperses the additives around the zinc oxide particles. A homogenous mixture with uniform distribution of chemical phases enhances the electrical characteristics of the varistor.

Mixing of the slurry determines chemical uniformity of the final product. The slurry continues into a two-story tall spray dryer which converts the slurry into a free-flowing spherical powder. The particle size and dryness of the powder affect the ability to press the powder into disc shape during the next phase and are analyzed before proceeding.

The spray dried powder is compacted within hydraulic cylinders to a specific density. The hydraulic presses incorporate sensors to ensure each disc is consistent and has no bubbles or uneven stresses. At this point, the newly formed discs are tough enough for light handling even though they are only compacted powder.

Racks of pressed MOVs are loaded into low temperature ovens to remove the organic materials for 24 hours. Once the MOVs cool, they are ready for crystal growth in the high temperature kilns. Each MOV is carefully loaded into a ceramic carrier box for transport through the kiln.

Now a 30-hour sintering operation occurs in a kiln which incorporates 13 control zones 44 thermocouples recording temperature. Sintering takes the 50% of theoretical density achieved in the pressing operation and increases it to 98% of theoretical. This high density eliminates voids that could lead to electrical failure.



Microstructure of an MOV block

During sintering, an insulating layer forms on the outside of the disc. Hubbell augments this layer by adding a very high resistance glass collar that improves and raises the electrical insulation level. The collar is sprayed onto the varistor. This collar provides excellent resistance to moisture and also insulates the varistors to prevent flashover during lightning or switching surge discharges.

Once this collar is baked and hardened, the circular faces of the discs undergo precision grinding to expose a conductive surface of the crystalline MOV. This operation additionally ensures parallelism. The material is then ultrasonically cleaned and inspected in preparation for metalizing application, which provides uniform conductivity between varistors when they are assembled in a final surge arrester.

After the metallizing step, Hubbell qualifies each and every new MOV with a 100% Rated Energy Test. The larger the diameter of the disc, the more energy impulses it must withstand to prove it meets Hubbell standards. This pass or fail test was devised by Hubbell engineers to guarantee there are no flaws in all new MOV discs. Any internal flaws such as pinholes or cracks, and any external flaws like chips, bumps, or other imperfections and the MOV may be violently destroyed.

Once the MOV passes the Rated Energy Test, it is cooled before the Routine Classification Test. The electrical protection, known as residual voltage, must be precisely measured with a lightning impulse at a specific level. The voltage measured during this test is printed directly on the MOV next to its batch identification. The result is used to sort and package discs into groups of similar values.

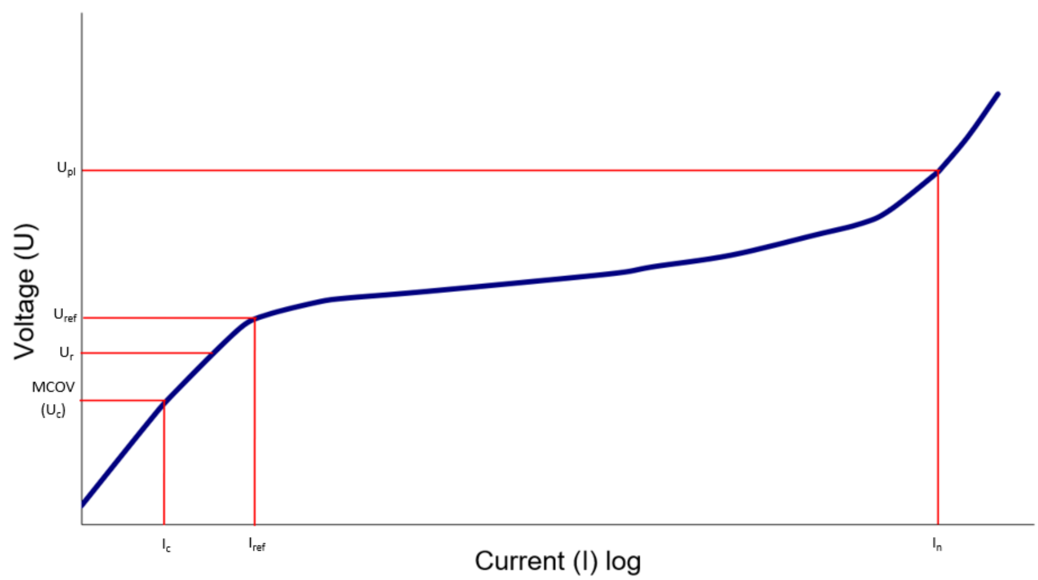
The exact value will be used at the arrester factory to match blocks to specific arrester designs.

Before the discs are released for shipment, the entire batch of sorted MOV discs is set aside for additional testing. Sample discs are selected for Quality Assurance tests to determine the properties of the batch. Because Hubbell engineers devised a sequence of testing that gets more and more difficult, some discs must be sacrificed and are destroyed during testing. The main batch of MOV discs will be released only when Quality Assurance targets are satisfied.

The complex production process is continually supported by numerous functional groups including production operators, process engineers and technicians, plant engineering, facility maintenance and material scientists.

Volt-amp characteristics

Once introduced, the MOV quickly revolutionized the surge protection industry based on its superior nonlinear volt-amp characteristics. An example V-I curve is shown below. The V-I curve is ultimately divided in three distinct regions: power frequency, switching and lightning impulse. In the power frequency region, an arrester is continually energized at U_c (MCOV) at a corresponding current, I_c. An arrester is further characterized by U_r (formerly known as duty-cycle voltage rating in IEEE), which is the voltage at which an arrester must perform during the operating duty test. U_r also correlates to a 10 second temporary overvoltage capability. The turn on point of the arrester, also referred to as the "knee" of the V-I curve, is known as U_{ref} or reference voltage. This is the corresponding voltage at which time the arrester conducts Iref or reference current. I_{ref} is a manufacturer specified value that should be sufficiently high enough to make the effects of stray capacitance negligible.



Typical Volt-Amp curve for an MOV arrester

Above U_{ref} is the highly nonlinear portion of the MOV V-I curve. This region includes a relatively low increase in voltage, with a corresponding large increase in current. This region is dominated by switching activity which typically range from 250 to 3000 Amps. This residual voltage is known as the switching impulse protection level or U_{ps}. Arresters are further characterized by their lightning impulse protection level, also know as U_{pl}. This is the maximum residual voltage of the arrester at the corresponding nominal discharge current. Typical published currents range from 1.5 to 40 kA.

Classifying Current

Surge arresters are classified depending on their typical application and associated voltage. Distribution arresters for example are not designed or intended to handle switching impulses. As such, they are not assigned a corresponding switching classifying current. Station arresters, on the other hand, are exposed to both lightning and switching activity. The magnitude of any such duty is typically related to the system voltage. Tables showing the comparison between IEEE and IEC classifying currents for various arrester classes are shown in the following tables.

IEEE classifying currents

Arrester Class	Typical MCOV Range (kV)	Lightning Impulse Classifying Current (kA)	Switching Impulse Classifying Current (kA)
Light Duty (LD)	2.55 – 39	5	-
Normal Duty (ND)	2.55 – 39	5	-
Heavy Duty (HD)	2.55 – 39	10	-
Intermediate	2.55 – 115	5	0.5
Station	2.55 – 115	10	0.5
Station	116 – 245	10	1.0
Station	246 – 448	15	2.0
Station	>448	20	2.0

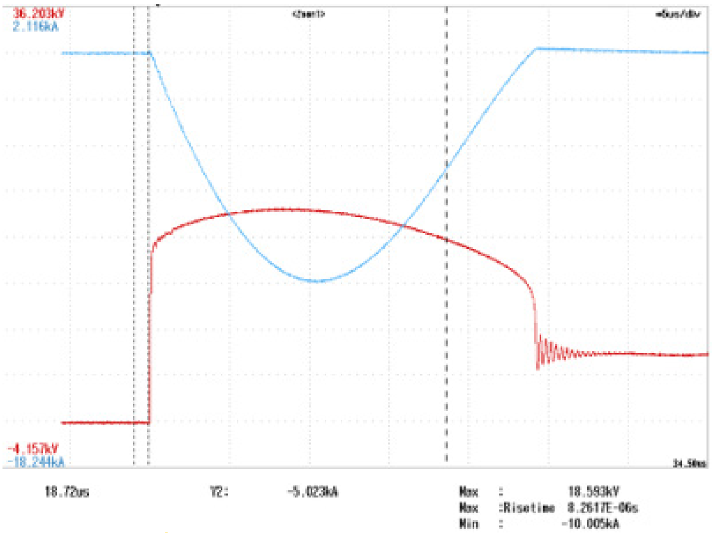
IEC nominal discharge currents

Arrester Class	Nominal Discharge Current (kA)	Switching Impulse Discharge Current (kA)
Distribution Low (DL)	2.5	-
Distribution Medium (DM)	5	-
Distribution High (DH)	10	-
Station Low (SL)	10	-
Station Medium (SM)	10	1
Station High (SH)	20	2

Residual (Discharge) Voltage

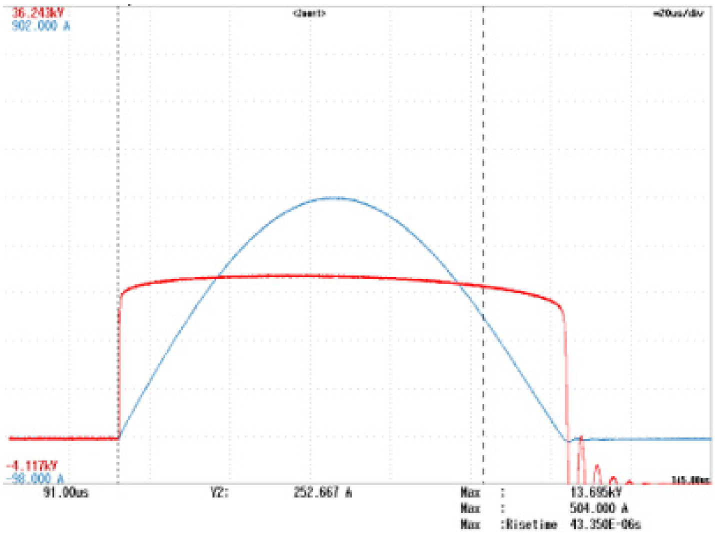
Surge arresters are manufactured using one or more MOV discs connected electrically in series. Manufacturers characterize MOV discs by their residual voltage. Standards detail three distinct impulses at which MOV blocks and ultimately arresters must be characterized by. These impulses are steep current or front-of-wave (FOW), switching and lightning. An example switching and lightning impulse are shown in the following figures.

The rate of rise, duration and magnitude of any transient event may influence the ability of an arrester to survive this duty. The FOW or steep front impulses are particularly fast rising and reach crest voltage in a short time frame. Lightning impulses are slower, but otherwise similar in duration to the FOW impulse. Limitations for these impulses are typically related to the charge or magnitude of the duty. Switching impulses, however are quite long when compared to typical lightning duty. This extended duration in turn contributes significant heating to the MOV blocks which could cause thermal instability.



Example 8/20 μs impulse at 10kA

Example 40/90 μs impulse at 500 A



Steep Current Impulse

The steep current impulse or FOW impulse corresponds to a lightning impulse in which the impulse current crests in 1 µs. The peak voltage is reported at the lightning classifying current of the arrester.

This test is performed for two conditions: 1) the MOV varistors alone and 2) for the complete arrester which accounts for the inductive voltage drop of metal current carrying components. The latter test accounts for the summation of the MOV FOW discharge voltage plus the magnitude of L di/dt.

The magnitude of the inductive voltage drop can be calculated as follows:

$L = 1\ \mu H/m\ (0.3\ \mu H/ft)$

di/dt = Lightning classifying current/µs dependent on the lightning classifying current of the arrester

Switching Impulse

The specified waveshape for switching duty is characterized by discharge current cresting in 45 to 60 µs. Peak voltages are reported at current magnitudes of 0.5, 1 and 2 kA. Additional testing is commonly performed at 0.25 kA, as well as higher and lower current magnitudes for specialized applications.

Lightning Impulse

For laboratory testing the specified waveshape for mimicking lightning impulses is designated as 8/20. This waveshape defines a virtual front time of 8 µs and a time to half-crest of 20 µs. This is a historical carry-over from the IEEE C62.1 standard for gapped SiC arresters. Peak voltages are reported at current magnitudes of 1.5, 3, 5, 10, 20 and 40 kA. Additional testing is performed at the relevant classifying current, e.g. 15 kA for 550 kV applications.

06 Performance

MOV surge arresters are exposed to the rigors of system overvoltages, environmental contamination, damaging UV exposure and various other factors that could ultimately degrade the material. The IEEE and IEC arrester standards have a series of tests that are scoped to overstress arrester designs to ensure their longevity in the field. While the absolute lifetime of MOV arresters is still being analyzed, it is typical to see lifetimes in the range of 20 – 40 years.

Switching Surge Energy Rating

Station and intermediate arresters are commonly subjected to switching surge duty during their lifespan. Understanding and quantifying the amount of energy an arrester can dissipate while in service will help ensure longevity of the product.

Both station and intermediate class arresters are characterized by their switching surge energy rating. The test verifies the multi discharge switching surge capability, which is a thermal claim. The capability is expressed in kJ/kV of MCOV or kJ/kV of Ur dependent on the applicable standard. This rating is not applicable to distribution type arresters.

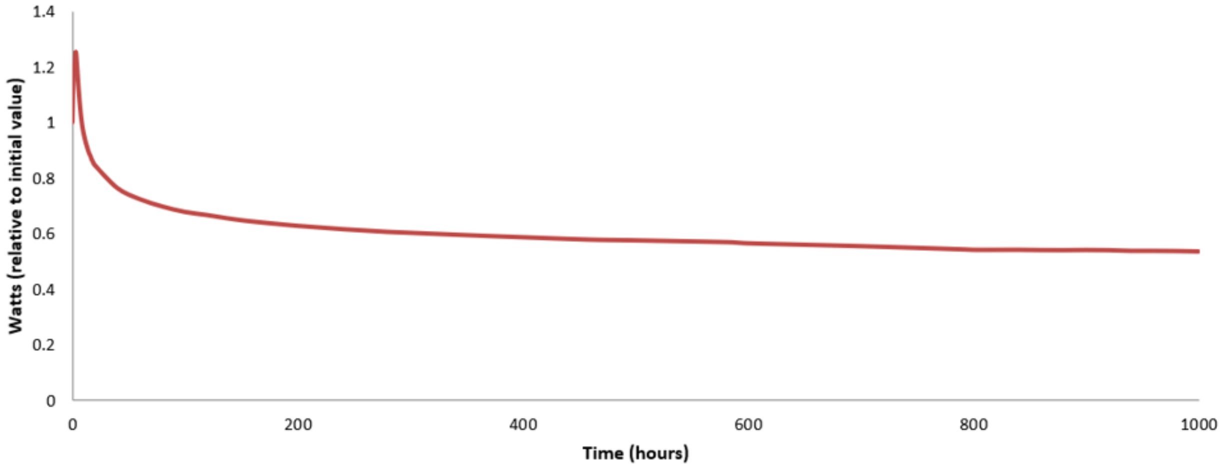
Charge Transfer Rating

Both station and intermediate class arresters are additionally characterized by their impulse withstand capability. This test determines the maximum charge an arrester can transfer in multiple instances without physical damage occurring. The capability is expressed coulombs (C).

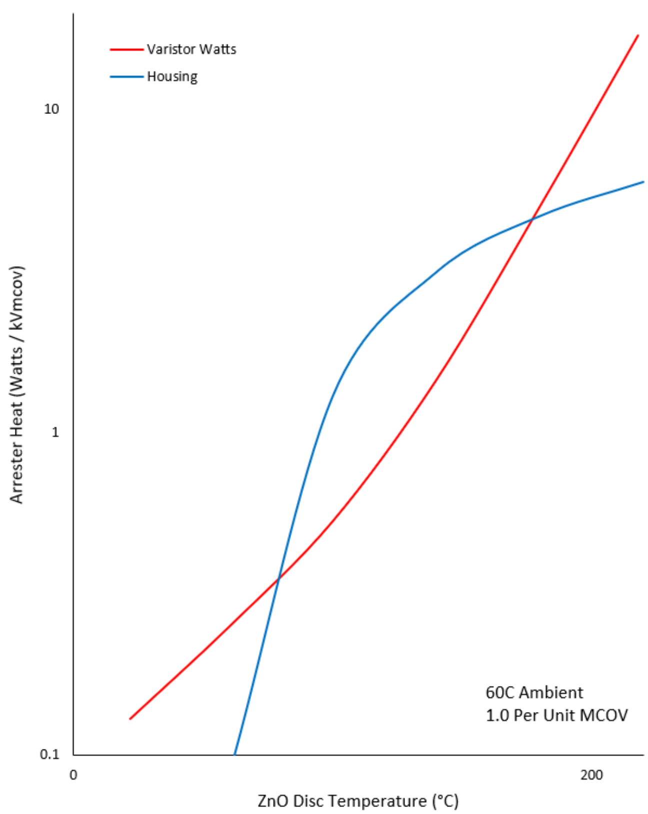
This test distinctly differs from the switching surge energy rating testing because thermal recovery is not required. This ensures the MOV is rated based on its charge conduction capability, without an impact from discharge voltage. This prevents manufacturers from making an arrester with a higher discharge voltage with the same impulse current charge capability, to claim a higher energy dissipating capability. This can easily be misunderstood as better energy capability when in fact it is not.

Long Term Aging

To ensure a long service life the arresters and associated MOV discs must remain stable while in service. A key facet to the longevity of an arrester is the ability for the MOV discs to never increase long-term power dissipation during their lifetime. This trait is demonstrated by the long-term stability under continuous operating voltage type test. Stability is demonstrated by energizing the MOV blocks at an elevated voltage while heated to 115^{0}C for 1000 hours. The relative watts loss must remain stable and/or decrease over time.



Varistor Accelerated Aging Curve



Thermal dissipation

Thermal Stability

The ability for MOV discs to dissipate the heat generated due to power loss will ensure a long service life. The thermal transfer can vary based on the internal components and their associated heat transfer rate. Similarly, solid core or hollow core arresters can have a different rate of dissipating heat generated from the MOV blocks. A balancing act is formed between the ability of the arrester housing to dissipate heat versus the heat generated from MOV disc power loss.

07

Surge Arrester Selection

The most critical function of any surge arrester is insulation protection of applicable apparatus, such as transformers, from damaging overvoltages. To ensure protection, proper selection of a surge arrester is of upmost importance. Each application may require special considerations to reduce the possibility of equipment damage or arrester overload.

MCOV (U_c)

Selecting the proper arrester MCOV relies on understanding the power frequency voltage stresses that will be imparted on an arrester during its life. Most utility equipment is selected and classified according to the maximum line-to-line voltage. Surge arresters are a stark difference, compared to these other devices. The selection criteria begins by considering the maximum continuous line-to-ground voltage. This calculation requires knowledge of the nominal line-to-line voltage, as well as the voltage regulation. Most utilities try to maintain a 5% or less voltage regulation, however it is not uncommon to see applications that increase to 10% or even 15%.

Arresters are largely applied on systems that are either four-wire multigrounded wye or three-wire wye or delta, high or low impedance grounded. The former multigrounded application is the most straightforward. An example calculation is displayed for a nominal 138 kV L-L multi-grounded application with 5% voltage regulation.

$$\text{Line-to-ground voltage (kV)} = \frac{\text{Line-to-line voltage (kV) x Voltage regulation (\%)}}{\sqrt{3}}$$

$$\frac{138 \text{ kV x } 1.05}{\sqrt{3}} = 83.6 \text{ kV}$$

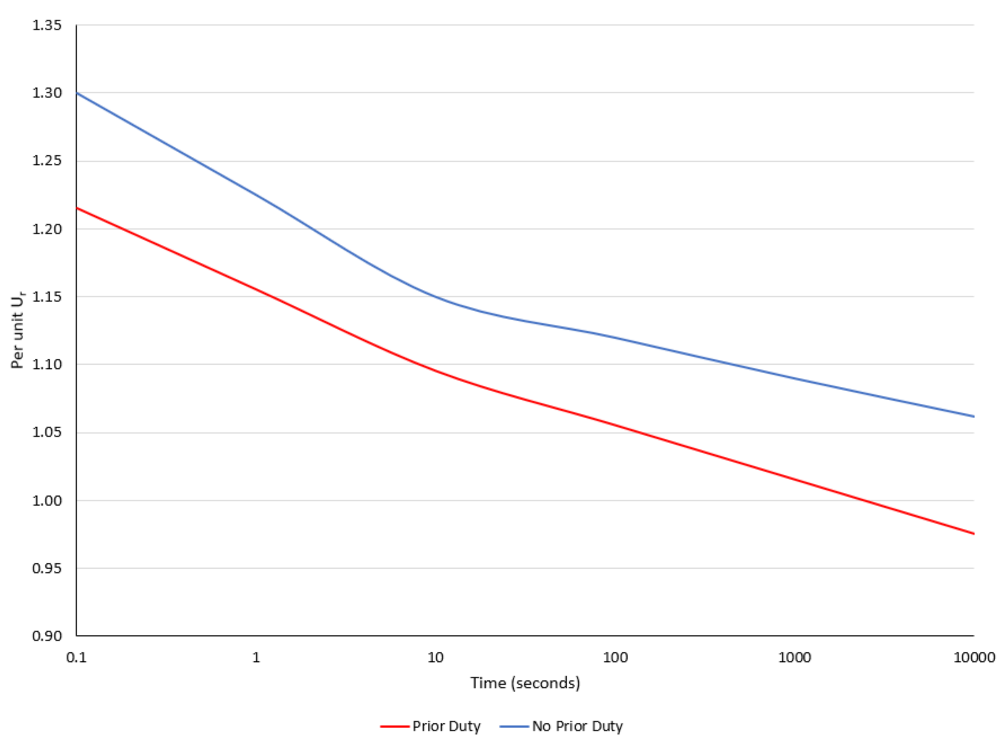
In this application the maximum continuous line-to-ground voltage is calculated to be 83.6 kV. A corresponding minimum recommended arrester MCOV would be 84 kV. A higher rated arrester may be required due to higher voltage regulation, grounding conditions or TOV conditions. The voltage regulation of 5% is generally sufficient, however it is not uncommon to consider a factor of 10% or even 15%.

Additional considerations are required for applications where the system is configured as delta, resistance or impedance grounded, or ungrounded. Sizing an arrester at or above the maximum line-to-line system voltage may be required. Most manufacturers publish a table of recommended arrester MCOV values for typical system voltages. These are merely minimum recommendations and additional analysis is frequently required.

Temporary Overvoltage (TOV)

Because the power grid is imperfect, the quality and control of voltage can impart overvoltages on an arrester. A temporary overvoltage (TOV) also known as power frequency overvoltage is defined as any power frequency voltage that lasts for a duration less than 3600 seconds. This condition may overstress an arrester if care is not taken during selection.

Type tests are defined to evaluate the overvoltage capability of an arrester with and without prior duty. The prior duty test is intended to simulate the effects of a lightning or switching discharge imposed on an arrester. This type of duty would elevate the temperature of the MOV blocks and limit the thermal recovery capability of the arrester. An example TOV curve with and without prior duty is shown below.



Power-frequency voltage versus time capability

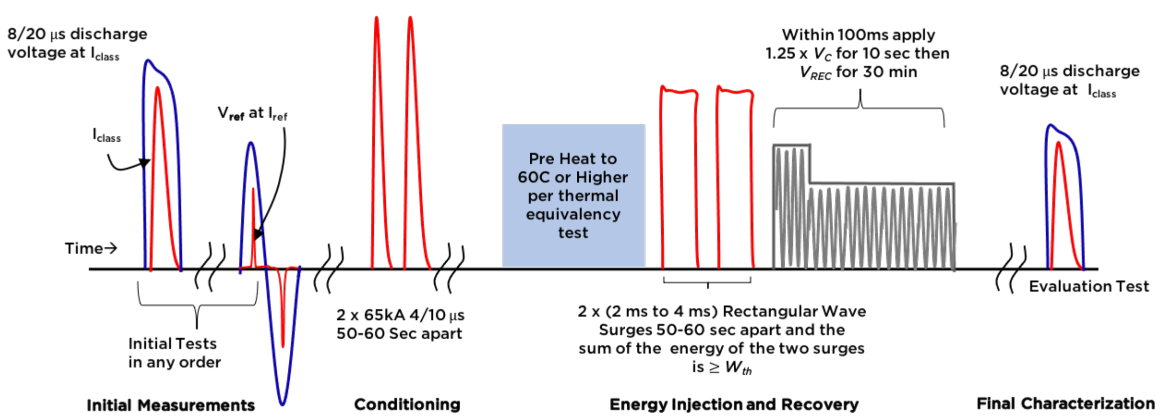
One such cause of an overvoltage is a neutral shift on an ungrounded or impedance grounded system. A neutral shift can occur during a system imbalance, such as a line-to-ground fault. This shift imparts a TOV on the arrester that could cause damage unless the arrester is sized to account for this overvoltage. If the duration and magnitude of a fault is known this can be compared against the TOV capability curve for an arrester.

It's a common misconception that surge arresters are capable of limiting normal power frequency overvoltages. The clamping capability of an arrester is only true for relatively short duration events caused by switching or lightning impulses. It's critical to size an arrester to withstand temporary overvoltages, rather than try to limit the magnitude of such an overvoltage. In some application surge arresters are applied as sacrificial type devices to limit overvoltages that may damage other equipment.

Energy

Substation arresters are more likely to encounter switching surge impulses in their application, as opposed to the lightning duty expected for distribution and line arresters. The energy capability or rating of a surge arrester is the amount of switching surge energy (typically in kilojoules) that the arrester can absorb or dissipate, while remaining thermally stable. This ensures the arrester can dispel the significant heat generated during a long magnitude switching surge.

The following image depicts the switching surge energy rating test. It begins with measuring discharge and reference voltage. Next apply two 4/10 µs current impulses at 65kA magnitude. This is followed by preheating to 60 ^{o}C. Once the sample is sufficiently heated, two square wave impulses are applied within a 1-minute period at a magnitude based on the manufacturer's claim. Within 100 ms, an elevated voltage (1.25 x V_C) is applied for 10 seconds, followed by recovery voltage for 30 minutes. Power loss through the arrester is monitored throughout this process, which in turn demonstrates thermal recovery of the sample. Measurement of the discharge voltage again after the sample cools to ambient and a visual inspection are performed.



Switching surge energy rating

The output of this test is a 2-shot thermal energy rating for a family of arresters. Ultimately, an arrester's energy handling capability is limited by the thermal capability of the design. IEEE and IEC type tests are virtually identical, except in the method of claiming per kV_{MCOV} or per kV_{Ur}, respectively. Comparison tables for IEEE and IEC claimable energy ratings are shown below.

Energy Class	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**J**	**K**	**L**	**M**	**N**
Energy Rating (kJ/kV-MCOV)	3	4.5	6	7.5	9	11	13	15	18	21	24	27	30

Energy Rating (kJ/kV-Ur)	1	1.5	2	2.5	3	3.5	4	4.5	5	6	7	8	9	10
	11	12	13	14	15	16	18	20	22	24	26	28	30	36*

**Additional levels can be claimed above 36 kJ/kV-Ur in steps of 6 kJ/kV-Ur*

Selection of the switching surge energy rating is ideally determined through an EMTP or similar type model. This level of analysis is not always available and simplified analytical approaches can be used. The IEEE C62.22 application guide provides guidance on how to estimate the required energy based on various system parameters.

Energy absorbed by an arrester is given by

$$J = \int E(t) I(t) dt$$

If I (t) is a square wave current of constant magnitude (IA) and duration T, then E (t) will be a square wave discharge voltage of constant magnitude (EA) and duration T.

Then the above integral simplifies to

$$J = E_A I_A T$$

This is same as

$$J = V_A I_A T$$

with:

$T = 2D_L / c$

(time to travel from one end of line to other and back)

The energy discharged by an arrester in kilojoules may be conservatively estimated by the equation:

$$J = 2D_L V_A I_A / c$$

J = Energy discharge by arrester (kJ)

I_A = Switching impulse current (kA)

V_A = Corresponding arrester switching impulse discharge voltage (kV)

D_L = Line length (km)

c = Speed of light (300 km/s)

Determining EA and IA can involve manufacturer data and an iterative process is better to refine the actual values. Using this equation, a conservative estimate can be made to determine the switching requirements for an application. For an example assume a system voltage of 161kV L-L, a line length of 322 km with Z = 400 Ohms. A 98 kV MCOV arrester is used with a 222 kV residual voltage at 300 A.

$$E = 2 \times 322 \times 222{,}000 \times \frac{300}{300{,}000} = 142.9 \text{ kJ}$$

The calculated energy can be rearranged in per unit of MCOV to compare against the chosen arrester design. Thus, 142.9/98 yields an energy requirement of 1.46 kJ/kV MCOV.

This approach generally requires an iterative process to converge on the current generated during a switching event. A simplified or rule of thumb approach can otherwise be used to estimate the energy. This approach is taken from Annex G of the IEEE C62.22 guide.

$$W_{MCOV} = 0.021\, U_{l\text{-}g}\; L / Z$$

W_{MCOV} = Energy discharged into the arrester (kJ/kV of MCOV)
$U_{l\text{-}g}$ = Maximum line-to-ground voltage of the line (kV rms)
L = Line length (km)
Z = Line surge impedance (Ohms)

The line surge impedance can generally be assumed to be between 300 – 450 Ω, although it varies based on system voltage. The other characteristics are application based. A sample calculation is provided for comparison to the iterative method.

Assume the same example with a system voltage of 161kV L-L, a line length of 322 km with Z = 400 Ohms. A 98 kV MCOV arrester is considered for this application.

$$W_{MCOV} = 0.021 \times \frac{161}{\sqrt{3}} \times \frac{322}{400} = 1.57 \text{ kJ/kV MCOV}$$

This conservative approach yields a slightly higher amount of energy discharged through the arrester. Either method can be considered appropriate when more sophisticated calculations are unavailable.

A common station arrester for a 161 kV application has a Class E energy rating. This corresponds to a 2-shot energy handling capability of 9 kJ/kV MCOV (≥4.5 kJ/kV MCOV per shot). The energy discharged through the example is 1.57 kJ/kV MCOV. The selected arrester is considered more than adequate for the application.

Housing Material

Until 1986 all distribution and station class surge arresters were manufactured using a porcelain housing. The development of various rubbers has largely displaced the use of porcelain as the primary insulating material for arresters. Now, both types are offered in various design packages. The use of polymer versus porcelain is primarily a user driven decision. Polymer housed arresters now have 30+ years of demonstrated service and are available in both solid and hollow core design variations. Many users have discovered benefits of switching to polymer housed designs, including:

- Lower mass compared to similar porcelain arresters
- Material is less susceptible to damage during shipping or handling
- Polymer type designs do not experience brittle fracture during pressure relief operation
- Possible to reclose on polymer-housed arresters after a pressure relief operation

Comparable porcelain and polymer hollow core arresters

Porcelain housed station class arresters still fill a niche in the market. Many utilities trust the extensive service performance which has been demonstrated by porcelain housings. Aside from the aforementioned points, polymer and porcelain arresters both adhere to the same requirements.

Pollution Level

The amount of creepage distance or external surface area of the arrester insulating material can influence its long-term performance. An increase in creepage distance may be required if the arrester is installed in areas that subject the external housing to contaminants that may influence or increase the amount of external leakage current flowing across the housing.

The creepage distance or pollution level of the arrester can be selected using standard IEC insulation levels. These levels include low, medium, heavy and very heavy. The creepage distance of the arrester is thus calculated using the system voltage U_m and the specified pollution level.

- Light – 16 mm/kV
- Medium – 20 mm/kV
- Heavy – 25 mm/kV
- Very heavy – 31 mm/kV

Before the 2020 edition of the standard IEEE C62.11 indicated the use of a minimum creepage distance of 1 inch (25.4 mm) for each 1 kV rms of duty-cycle voltage rating. This requirement was removed in the latest edition. In general, most arrester designs include more creepage distance than is required. Arresters to be installed in areas of heavy pollution may require higher creepage values or other special considerations.

Insulation coordination

Equipment protection is the number one job for a surge arrester. A vital step in the selection process is evaluating the margin of protection between the arrester and the equipment its protecting. IEEE C62.22 recommends a minimum of 15% protective margin between the surge arrester and power transformer insulation. A margin of 20% is recommended for most other applications. The arrester discharge voltage and corresponding insulation withstand level are provided below.

- Arrester FOW discharge voltage compared to the chopped wave withstand (CWW) of the equipment being protected
- Arrester 8/20 lightning discharge voltage compared to the basic impulse insulation level (BIL) of the equipment being protected
- Arrester switching surge discharge voltage compared to the basic switching impulse insulation level (BSL)

The margin of protection or protective margin (PM) can be calculated using the following formula.

$$PM = \left(\frac{\text{Insulation level}}{\text{Arrester discharge voltage} + \text{lead length adder}} - 1\right) \times 100$$

The lead length impacts the resulting voltage and adds stress to equipment if it **1)** carries surge current and **2)** is in parallel with the protected equipment. This impact is caused by the inductive voltage drop in the lead. The voltage drop is calculated using the formula V = Ldi/dt. Where:

L = 0.3 μH/ft
di = Current magnitude in kA
dt = Rate of current rise in μs

$$V = L\frac{di}{dt} = 0.3\left(\frac{10}{8}\right) = 375 \text{ V/ft}$$

Additional calculations are required for coordinating the protection of equipment on underground systems, including insulated cables. For both gapless and gapped arresters, compare the doubled sum of discharge voltage at assumed current and connecting lead voltage with transformer and cable BIL. Using a recommended protective margin of 20% the following conditions should be validated (for systems without open point arresters).

Oil insulation: CWW ≥ 1.2 × 2 × FOW
Dry insulation: BIL ≥ 1.2 × 2 × FOW
Both insulations: BIL ≥ 1.2 × 2 × LPL

When an open point arrester is not in use the following calculations hold true.

$$\text{Max voltage stress} = 2 \times \text{FOW}$$

$$PM = \left(\frac{\text{BIL}}{2 \times \text{FOW}} - 1\right) \times 100\text{ft}$$

When an open point arrester is in use the following calculations hold true.

$$\text{Max voltage stress} = \text{FOW} + \frac{1.5 \text{ kA Ures}}{2}$$

$$PM = \left(\frac{\text{BIL}}{\text{FOW+1.5kA Ures/2}} - 1\right) \times 100\text{ft}$$

Pressure Relief

When an arrester reaches end of life, it behaves like a direct short to ground. The arrester in turn conducts the available system fault current. Surge arresters must survive this event without a violent shattering of the housing and internal components. The collapse or thermal fracture of an arrester is acceptable, if it does not eject components outside of a ring of specified diameter and height built around the test sample.

Selecting an arrester with a pressure relief rating greater than the available short-circuit current in the substation will ensure a catastrophic failure does not occur. Typical distribution arrester designs hold a 20 kA rating, while station class designs hold a 63 kA rating. Additional levels, as high as 80 kA, are available for special applications. This higher rating requires specialized testing, which is not realizable at most laboratories.

While an arrester will only short circuit once in its lifetime, the proper selection of the pressure relief rating is a critical consideration. Doing so will ensure the safety of line crews, the general public and equipment.

Seismic

Arresters are qualified for application in seismic zones according to the guidelines of IEEE 693. This standard details test procedures for seismically validating a wide range of products including arresters, switches, bushings, and a multitude of other equipment types. Annex K of IEEE 693 specifically covers requirements for surge arresters.

All surge arresters above 90 kV duty-cycle voltage rating are required to survive a shake table test with no structural damage and remain functional. Functionality is demonstrated by successfully passing routine production tests after shake table testing. IEEE 693 allows seismic qualification based on the concept of “qualifying equipment by group”. This concept permits products of different voltage ratings, but similar physical structure, to be combined into groups for qualification purposes. The most seismically vulnerable piece of equipment of each group shall be analyzed or tested.

Arresters shall be selected for seismic zones according to their qualified zero period acceleration or ZPA level. ZPA is the acceleration level of the high-frequency, non-amplified portion of the response spectrum (e.g., above the cutoff frequency, 33 Hz). This acceleration corresponds to the maximum (peak) acceleration of the time history used to derive the spectrum. The most common levels are 0.5 and 1.0 g ZPA.

Hubbell maintains third party test reports that validate the seismic capability of all substation type arresters. These reports can be provided upon request.

08 Routine Testing

IEEE and IEC arrester standards require 100% of production output be tested to ensure all products meet manufacturer published values. Hubbell manufactures surge arresters in their ISO 9001 and 14001 certified facilities. Critical tests mandated by these standards include verifying residual voltage, reference voltage, partial discharge and power-loss. Other tests may be applicable dependent on the design, such as seal leak rate for hollow core arresters and current distribution for multi-column arresters.

Residual Voltage

The residual voltage of each MOV block is measured at 5 or 10 kA, with an 8/20 waveshape. Fully assembled arresters are characterized by the summation of the individual residual voltages for each MOV block. This test is critical to ensure the arrester yields manufacturer claimed protective levels.

Reference Voltage

This test is performed at the manufacturer declared reference current (I_{ref}) and ensures the turn on voltage of the arrester. This test ensures the arrester is built with a sufficient volume of MOV block to meet manufacturer declared overvoltage and energy claims.

Partial Discharge

This test is performed at 1.05 x MCOV after voltage is raised to 1.25 x MCOV and applied for at least 2 seconds. The internal partial discharge rate is measured and must not exceed 10 pC. It is permissible to shield the external connections.

Power Loss

This test is performed at 1.25 x MCOV for distribution arresters and 1.20 x MCOV for intermediate and station arresters. The test ensures the power loss through an arrester is within a manufacturer specified range. This value can be useful for future inspection and monitoring methods.

Seal Leak Rate

This test is performed on hollow core type arresters that retain at least 10% of their volume in the form of gas. Applicable arresters are tested to ensure the quality of the arrester seal. Hubbell utilizes a helium-mass spectrometer test to validate the arrester's seal is appropriate.

Current Sharing

Arresters that are comprised of two or more parallel columns of MOV blocks shall be tested to confirm the critical current is within tolerances specified by the manufacturer. This test is performed with a switching or lightning impulse. Hubbell mandates all columns within a multi-column arrester have a current sharing tolerance within 5%, unless stricter tolerances are required for the application.

MOV Testing

Additional tests are performed on MOV blocks according to Hubbell internal engineering specifications. These tests are not mandated by any standard but are deemed critical by Hubbell to ensure superior performance. This includes both routine and batch quality assurance testing. Additional details on testing include:

MOV routine tests

- Visual inspection – Verifies no defects are present which are considered unacceptable.
- Rated energy – Each block receives multiple high energy square wave impulses. Each block has a rated energy based on the defined J/cc for the block diameter and height.
- Discharge voltage – 8/20 µs impulse which characterizes every block with a corresponding residual voltage. This measured value is referenced when assembling multiple blocks into complete arresters.
- AC test – Measures V_{ref}, power loss and capacitive current on each block

MOV batch QA tests

- Square wave energy test – Destructive test which subjects the material to high energy discharges. This test characterizes the rated energy of the batch.
- High current test – Subjects MOV blocks to two impulses at the defined high current rating. Residual voltage must be within manufacturer defined limits after testing.
- Life test – Accelerated aging test performed at elevated temperature while power loss is monitored. The final power loss shall be less than or equal to the initial value.
- A.C. test – Verifies various a.c. characteristics are within manufacturing limits.

09 Applications

Each application is considered unique and can require detailed evaluation. An arrester specification is helpful in ensuring the proper product is selected for each application and only high-quality products are selected. Additional analysis can be required for nonstandard or special applications.

Phase-To-Phase Protection

While nonstandard, surge arresters can be applied in a phase-to-phase protection manner. Overvoltages may arise between phases when a transformer or reactor is switched off. If the overvoltage is not mitigated the withstand voltage between phases can be exceeded. The phase-to-phase arresters should be sized similarly to the phase-to-ground arresters, while accounting for system voltage regulation. Other phase-to-phase applications require detailed review of the application to appropriately size the arresters.

Series Compensation Varistor (SCV) Protection

For transmission of moderate amounts of power over moderate distances, transmission lines at nominal voltages of 138 kV or 230 kV are widely used. When there is a need to transmit very large quantities of power over very long distances, it is generally more economical to increase the transmission line voltage to 345 kV, 500 kV or even 765 kV. The same amount of power can be transmitted at lower currents as the line voltage is increased, allowing smaller diameter conductors to be used and a decrease in line loss.

Even with higher transmission voltages, there are limits to how much power can effectively be transmitted. If the power transmission needs exceed these limits, additional lines may need to be built, which is becoming increasingly difficult to accomplish due to the long process involved in acquiring rights-of-way, satisfying environmental concerns, etc. However, in many cases the problem can be eased by use of series capacitors to increase power transmission capability. In addition to providing increased power transfer capability, the use of a series capacitor can also reduce voltage drops and improve overall stability of the transmission system.

Individual power capacitor units are typically available in sizes ranging from 200 – 1,200 kVAR and maximum continuous currents up to about 180 A. Although the capacitor voltage is only a fraction of the line-to-ground voltage of the transmission line, the capacitor is series connected into the line, so the voltage from each capacitor terminal to ground is the line-to-ground voltage of the line at that point. Therefore, the capacitor must be insulated from ground, typically by placing it on a platform supported by station post insulators with tension insulators used for cross bracing. A separate platform is required for each phase of the line. One side of the capacitor would be electrically connected to the platform, while the other side would be connected to the line.

The availability of high voltage metal-oxide arresters in the 1980s resulted in a shift away from the simple power gap protection scheme and its associated transients' problems. The concept is simple – connect a metal oxide arrester across the capacitor, the arrester is designed to start conducting (divert current away from the capacitor) when the capacitor voltage reaches a predetermined level (typically 2.2 – 2.5 per unit of the peak maximum continuous operating voltage of the capacitor). In practice it is a bit more complicated.

A conventional arrester, connected line-to-ground across a transformer for example, may be called upon to conduct very high levels of surge current produced by lightning or switching, but only for very short durations (few µs to a few ms). It may also be exposed to short periods (up to a few hundreds of ms) of power frequency overvoltages of quite modest level, perhaps 1.25 – 1.50 times the peak maximum continuous line-to-ground voltage. On the other hand, an arrester applied across a series capacitor can be exposed to prospective power frequency voltages that are many, many times its normal maximum continuous operating voltage. This occurs when the series compensated line conducts fault current due to a fault somewhere on the line itself or elsewhere in the system.

With this scheme, the voltage across the capacitor is limited by the varistor. The fault current that flows through the line is "commutated" back and forth between the capacitor and the varistor as the voltage across the capacitor goes through its (zero)-(positive peak)-(zero)-(negative peak)-(zero) cycle. When a fault occurs on the system, the amount of fault current that flows in the series capacitor, and therefore the energy that will be deposited into the varistor, will depend to a large extent on the location of the fault. The fault may be on the line that has the series capacitor (termed an "internal" fault) or may be on another line on the system (termed an "external" fault).

In both cases, fault current would flow through the series capacitors and the varistors would limit the voltage across the capacitors. However, the series compensated line could remain in service in the case of an external fault (to clear this fault it would be necessary to open the breakers at each end of the line experiencing the fault). When the fault is cleared, the fault current through the capacitors disappears and the line returns to its normal operating condition. In the case of an internal fault, it would be necessary to open the breakers at both ends of the series compensated line to clear the fault.

Extensive system fault studies are typically performed by or on behalf of the end user to determine the worst-case scenarios for both internal and external faults. Some knowledge of varistor V-I characteristics is required to estimate the energy that will be deposited into the varistors for each fault situation and for the protective level selected.

It is generally the case that internal faults give rise to the highest varistor energy requirements, but, in some cases, the varistor would have to be of enormous size to handle the energy from the worst-case internal fault. In such cases, it may be decided to size the varistor to handle the worst-case external fault and to implement means of protecting the varistor in the event a high level internal fault.

Cubicle Mount

Surge arresters can be installed inside a metal cubicle or cabinet to protect capacitors, switchgear, cables or various other pieces of equipment. Offering protection with conventional surge arresters can be a more economical alternative to replacing equipment. While not required, its advisable to only use polymer housed arresters without a ground lead disconnector in enclosed applications. Operation of a disconnector could cause inadvertent stray arcing that may damage the equipment an arrester is intended to protect. Porcelain top arresters are also available for this application, although polymer designs are more commonly applied.

Cable Sheath Protection

Overvoltages or faults can lead to induced voltages on a cable sheath. If this voltage variance is not controlled, it can cause damage or even cause the cable to fail by exceeding the rated capability. Sheath voltage limiters (SVL) or surge arresters can be applied to mitigate the damaging effect of overvoltages. The MCOV should be sized to exceed the voltage that will appear on the sheath that is induced during power frequency events. The protective margin should also be verified for lightning and switching events. Distribution type arresters are typically adequate for this application.

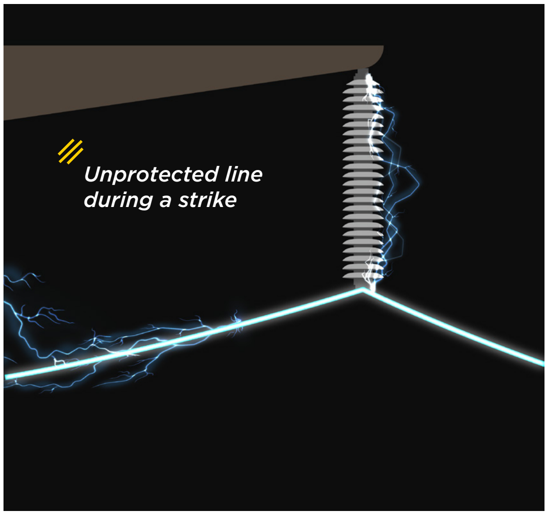
Line Surge Arresters

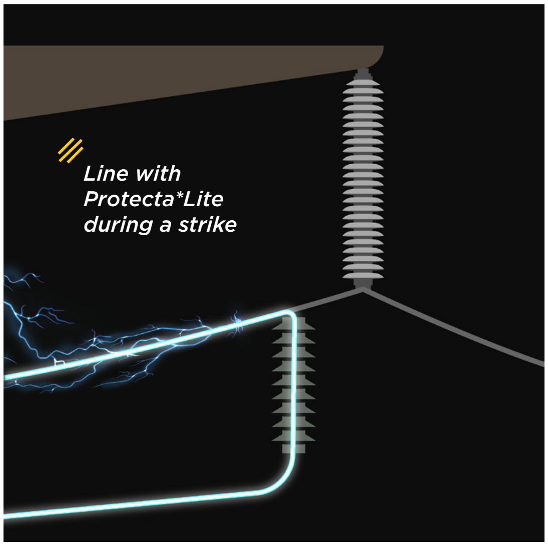
Common applications for surge arresters transverse various distribution and substation applications. Rather than providing equipment protection line surge arresters (LSA's) are reliability-based products that help reduce or eliminate the possibility of momentary interruptions from occurring. Designs can be segmented into NGLA or EGLA offerings.

The severity of a minor interruption can range from an inconvenience to a significant loss in productivity for consumers. The cost of momentary interruptions is known to significantly impact manufacturing facilities by means of lost revenue. Interruptions can cause security and safety risks for hospitals, schools and government entities.

Furthermore, momentary interruptions are now considered intolerable for the average residential consumer.

Until the late 1980's, protective devices used to mitigate lightning induced interruptions were not commonly applied on transmission lines. Hubbell commenced the manufacture of LSA's in 1988. The practice of applying polymer line surge arresters was quickly adopted following the introduction of the first MOV polymer housed distribution arrester in 1987. Since the line surge arrester introduction nearly thirty years ago, millions of line surge arresters have been installed at varying system voltages around the world.





The implementation of polymer housed LSA's is still a relatively new technology compared to more traditional methods for improving transmission line reliability, such as:

- Implementation of an Overhead shield wire (OHSW)
- Upgrading an existing OHSW shield angle
- Increasing line insulation
- Improve ground footing resistance
- Complete line rebuild to incorporate the aforementioned concepts

Traditional NGLAs are highly customizable for various applications. This is critical considering the wide array of designs and standard construction methods. The selection process can also vary from typical distribution and station applications. Four primary points are considered for specifying arresters for line applications: 1) MCOV (Uc), 2) Type (distribution versus station), 3) Mounting configuration and 4) Hardware.
MCOV determination is similar to that for common distribution and station designs. The type selection is more application dependent. Most line applications are below 230 kV Us where the primary duty will be caused by lightning. It is not necessary to specify the use of large station class arresters for the majority of transmission applications. If the arresters are going to be exposed to both lightning and switching duty, the use of station class design is warranted. Voltages above 230 kV also require this level of protection due to the size and mechanical strain imposed on an arrester.

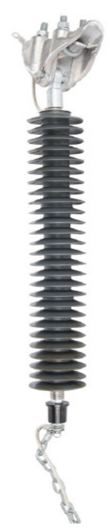
If vibration dampers are installed the mounting position likely needs to be modified to account for the added weight of an LSA. This is especially relevant when an arrester is hung from the phase conductor, due to the added weight on the conductor. Dampers should be adjusting according to the damper manufacturer's specifications.

Liquid Immersed Arresters

Certain applications require the use of an arrester inside of the transformer to mitigate potential voltage rise across the transformer winding. Distribution type under-oil arresters are available for immersion inside distribution type transformers. These arresters can be used where the maximum temperature does not exceed 125 ^{0}C and where the weighted average temperature does not exceed 90 ^{0}C.

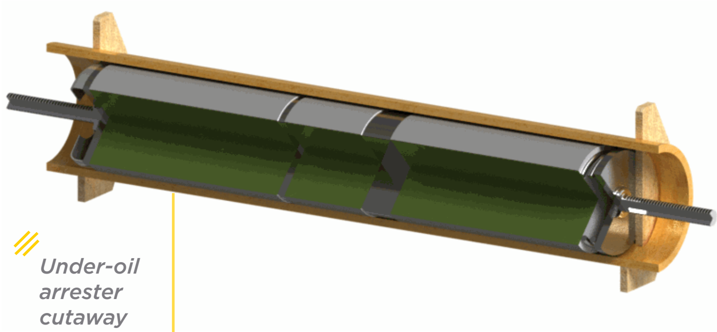
Primary LSA mounting configurations

Tower Mount



Conductor Mount

Insulator Mount



Under-oil arrester cutaway view

Arresters immersed in the oil of a transformer may be preferable due to optimized protection. The impact of separation effects is eliminated due to installation near the transformer winding. Drawbacks include ensuring the arrester is rated for the temperature of the transformer oil and whether the design is fail-open or fail-short type. A fail-open design will allow the system to re-energize after an over current device has cleared the fault, however the equipment is left unprotected.

Underbuilt Distribution Circuits

The restriction of new line construction has promoted the need to combine distribution and transmission lines on the same structure. This can be beneficial due to utilizing the same right-of-way and combining construction schedules. However, additional consequences and impacts can be caused without proper planning.

If an OHSW is being used on the transmission line the distribution circuit can be impacted due to back flashover. A successful shield angle would send a resulting surge down the tower ground. The voltage magnitude is likely to be higher than the distribution circuit insulation. The underbuilt distribution circuits would in turn be impacted by back flashover, unless arrester protection is included in the design.

If arresters are installed on the underbuilt circuit, they can be used as sacrificial devices in the event line is dropped from the overhead transmission circuit. The arresters on the underbuilt circuit would fail quickly due to the substantial overvoltage (consider a 69kV phase-to-ground line falling onto a 13-kV phase-to-ground system). While an arrester failure may seem unattractive it would in turn prevent other more valuable equipment on the system from potential failure. Intermediate or station class arresters installed without a disconnector would be most appropriate in this application. The lack of a disconnector would in turn lock out the line until crews could repair the overhead line and remove the shorted arrester.

Neutral Protection

Unearthed neutrals can be damaged due to lightning and switching overvoltages. The neutral insulation may be overstressed due to asymmetrical faults or switching operations in the power system. The insulation of a transformer neutral is typically less than the phase bushing. In this case it is recommend that a similarly sized arrester to the line-to-ground installation be used. In the event the neutral is fully insulated a reduced voltage arrester may be acceptable. A study of the application may be required for specialized applications.

Six-surge Arrester Protection

Some special applications may require the addition of arresters between phases. This protection is in addition to arresters installed between line-to-ground. The phase arresters should be sized higher than nominal system voltage with the associated voltage regulation. An example application is for arc furnace protection.

Four-legged Arrangement (Neptune)

The Neptune design is a variation of the six-arrester arrangement, which happens to use two fewer arresters. Two arresters are installed in series between phases and earth. The arresters in turn offer protection between phases and phase-to-ground. To offer appropriate protective levels the fourth arrester should be sized to a different rating then the other three arresters. It is important to consider the TOV the arresters need to withstand in the event of a line-to-ground fault.

10 Service Conditions

Surge arrester application and the associated service conditions are vast and wide ranging. Arresters can be exposed to sub-zero temperatures, hurricane force winds, contaminants and the impact of seismic conditions. Confirming the arrester can successfully survive these conditions is key to ensuring longevity of the arrester and your equipment. Standard operating conditions for a.c. surge arresters are identified in IEC 60099-4 and IEEE C62.11, including:

- Nominal power system frequency of 48 to 62 Hz
- Altitude of 1000 m (3281 ft)
- Ambient air temperature in the general vicinity of the arrester between -40 ^{o}C and 40 ^{o}C
- Wind speeds ≤ 34 m/s
- Vertical installation

Exposure to conditions outside of these limits will require special consideration in the design and application of surge arresters.

11

Mixing SiC & MOV Arresters

There are still many SiC arresters installed around the world. These products have a finite life expectancy, although they may still be offering good protection. The SiC arresters will inevitably reach end of life and need to be replaced. If one arrester fails, consideration should be given to replacing all nearby arresters, not just the one that failed. Three main variables should be kept in mind when making this decision: protective levels, pressure relief requirements and the possibility of transferred surges.

Modern MOV arresters offer superior protection and performance when compared to equivalent SiC type designs. Lower residual voltages translate to improved protection for equipment. This becomes more important as transformers and other pieces of equipment age. Typically, insulation strength degrades over time.

Most applications have seen a considerable increase in the available short circuit current since the installation of SiC arresters. If this level of current is not carefully considered it could exceed the SiC rated pressure relief level and result in the violent fragmenting of the arrester in the event of failure.

The third and less considered variable is the possibility of a switching surge being transferred from the high-side to the low-side arrester. This can occur if the high-side arrester is SiC type, while the low-side arrester is an MOV type. The lower impedance device will react or operate to quell the surge coming down the line. In this scenario the high-side SiC arrester will not achieve gap spark over until the low-side MOV arrester is already conducting. This occurrence transfers the surge through the transformer windings for discharging through the low-side arrester.

These issues, along with the unpredictable end of life event can be avoided by replacing SiC vintage arresters with superior MOV technology. It's important for utilities to consider replacing all three phases on both the high and low side in the event of a SiC type arrester failure or replacement program. Additional benefits can be seen by using MOV type LSAs in station entrance applications. This usage will prevent lightning surges near the substation from traveling into the substation.

12 Installation

All surge arresters are subjected to routine testing during production according to applicable IEEE and IEC test requirements, in addition to manufacturer specific tests. Routine testing prior to installation is not required and is typically not capable of reproducing factory or laboratory routine tests.

Anyone installing surge arresters should be familiar with all applicable local, state and federal guidelines. Before proceeding the equipment should be inspected for signs of damage during transport or subsequent handling. Installation instructions are included with all Hubbell surge arresters. The instructions should be reviewed prior to proceeding with arrester installation. The MCOV of the arrester should be verified against the packaging label, arrester nameplate and all associated work instructions. If there is a disagreement with the material, please stop and seek further clarification.

It is recommended to always connect one end of the arrester to ground potential, prior to connecting the arrester to line potential. This ensures the arrester has a direct path to ground in the unlikely event the incorrect arrester is installed.

Grading Rings Versus Corona Rings

A grading ring is sometimes required to ensure a uniform voltage distribution along an MOV type arrester. The ring becomes necessary when the length of an arrester reaches a sufficient distance to cause stray capacitance along the MOV stack. A grading ring redistributes the electrical field of the arrester to ensure the uppermost unit or MOVs are not over stressed. If a grading ring is required it will be shipped with the surge arrester. The ring is to be installed on the line end connection of the arrester and face inward on the design.

(left) 500kV surge arresters during installation with both grading and corona rings

(right) 230kV polymer surge arresters installed with grading rings

Corona rings are traditionally used to shield external hardware to prevent a corona phenomenon from occurring. Continuous or long-term corona exposure can lead to degradation of insulating materials or create interference with electronic communication. The use of a corona ring varies based on the application and hardware being used but may be necessary at voltages as low as 230 kV.

Multi-unit Stacking Order

Some surge arresters require multiple units be stacked together to reach the required MCOV. This is typically necessary at Us ≥ 230 kV. The stacking order for multi-unit arresters is critical to maintain proper electric field distribution. The sequence is listed on the base nameplate of all multi-unit arresters. Unit nameplates are attached to the upper casting of each unit to ensure proper identification. Typically, the highest voltage unit will be applied on the line end and descend towards the ground end. Note, this is not always the top of the assembly since arresters may be installed in a suspended manner.

Mounting Orientation

Most surge arresters can be mounted in an upright, angular or underhung configuration. Depending on the design a special part number may be required to ensure the sheds are not inverted. Horizontal mounting is possible, if the arrester is not subjected to forces outside of its continuous cantilever capability.

Torque

Line and ground terminals, as well as intermittent unit connecting bolts should be installed as indicated on the arrester outline drawing. During assembly please refer to the maximum recommended fastener torque values shown in the following table. Higher or lower torque may be required depending on the grade of hardware being used.

Recommended Tightening Torque

Stud Size (Inches)	Maximum Recommended Tightening Torque ft-lbs (Nm)
3/8	20 (27)
1/2	40 (54)
5/8	90 (122)
3/4	125 (170)

Storage

All Hubbell arresters are designed for outdoor use and may be stored outdoors if suitable precautions are taken to prevent deterioration of the packaging material. The arrester may be covered with a polyethylene or other waterproof covering to keep them dry, clean and free from litter until installed. In climates where outdoor temperature and humidity can rapidly deteriorate the packaging material, it is recommended arresters stored outdoors be removed from their packaging and be vertically bolted to a skid.

Testing

Arresters are 100% routine tested before shipment according to applicable IEEE and IEC standards. Field testing is not required prior to installation. Most field-testing capabilities are insufficient to replicate laboratory routine testing. Low voltage testing can be troublesome, since the voltage is far below the turn on voltage of an arrester.

13

Surge Arrester Accessories

Surge Counters

A surge counter can be installed in conjunction with an arrester to better understand system and arrester performance. This device will include an electro-mechanical cyclometer and can come with an optional leakage current meter. Other design variations are available for distinct applications.

Surge counter with optional leakage current meter

The counter is installed at the base or ground end of an arrester. An insulating base is required when installing a counter. The insulating base acts to isolate the counter and base of the arrester from ground potential, in order to read the leakage current flowing through the device.

Hubbell surge counters are designed to bolt directly to the insulated arrester base. No additional lead connection is required, except to ground. If a lead is used, it is recommended to be insulated and be as short as possible. This will prevent a potential voltage drop.

While a counter can provide useful information about the operating tendencies of an application it is not a good predictor of arrester health. There is not a finite number of operations or surges that can be dissipated during an arresters life. Total leakage current is generally not sensitive enough to detect degradation of a device. Neither leakage current nor the number of surges seen by an arrester are ideal indicators of operating condition.

Ground Lead Disconnector

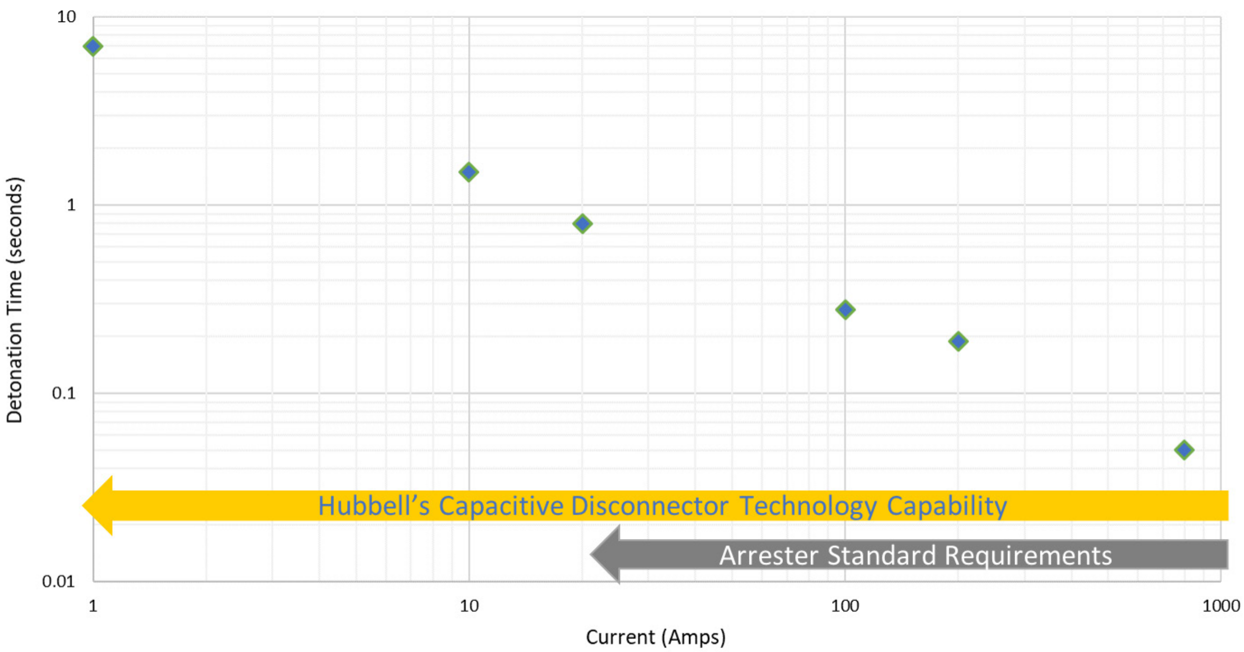
A ground lead disconnector (GLD), also referred to as an isolator, is a critical cog in the application and lifespan of distribution and line arresters. While equipment protection is the number one job of a surge arrester it is equally important to provide safe and reliable power to end users. This requires a component that can physically and electrically disconnect a shorted arrester from a system. The GLD is in turn applied on virtually all distribution and transmission type applications. It is typically avoided in station applications to ensure a much more critical piece of equipment, such as a high voltage power transformer, is never left unprotected.

The electrical circuit of the GLD consists of a grading component connected electrically in parallel with a spark gap. The grading component is typically either of resistive or capacitive nature. This component is the normal path to ground for arrester grading and leakage currents. Other critical components in the assembly include a blank .22 cartridge.

In the event of arrester failure, fault current flows through the shorted arrester and through the GLD grading component. The flow of fault current produces a voltage across the capacitor and parallel spark gap. The voltage necessary to sparkover the gap varies based on the design. If the voltage reaches sufficient magnitude to maintain the arc, heat is transferred to the cartridge. The transfer of heat will ultimately reach an ignition point that results in cartridge detonation. Heated air within the isolator housing is combined with hot gases produced by cartridge detonation pressurizing the GLD chamber and fracturing the GLD housing. The resultant pressure buildup separates the GLD and propels the lead terminal away from the arrester. Physical separation of the lead from the arrester removes the arrester from the circuit so the line is not locked out.

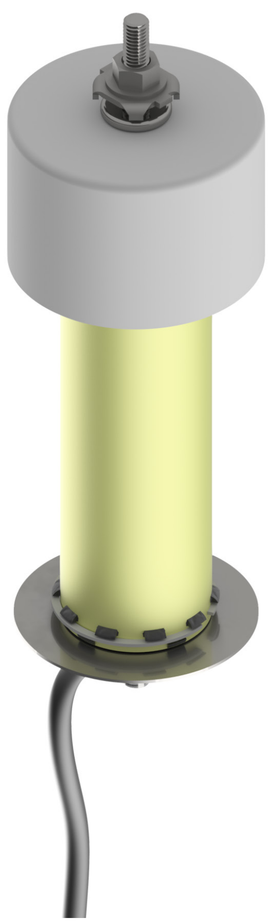
Hubbell utilizes a capacitive graded disconnector design for all distribution type arresters. This capacitor provides a distinct technical advantage for end users. IEEE and IEC standards only require disconnectors operate down to fault currents of 20 A. The Hubbell capacitive graded design operates at current magnitudes down to 1 A. The full capability curve is shown below.

Time versus current disconnector capability



Fire Protection Disconnector (FPD)
The Hubbell FPD is designed to install electrically in series with a non-gapped distribution arrester (in accordance with IEEE C62.11). Unlike a conventional GLD the FPD is designed and tested to remove the possibility of fire-producing sparks being dropped by a surge arrester. This added benefit can be necessary or required in wildfire prone areas.

During normal operation the FPD continuously monitors leakage current flowing through the connected arrester. Similar to a GLD, the Hubbell FPD functions to physically disconnect a compromised arrester from a distribution circuit to prevent line lockout. However, rather than waiting for the arrester to short and draw fault current, the FPD reacts and operates when an arrester begins to degrade.



To perform this function in a controlled, predictable, and rapid manner, the disconnector housing is designed to physically separate. In the event an FPD operates a bright yellow sleeve is displayed. This bright sleeve acts as a visual indicator to field personnel that the assembly (arrester and FPD) needs to be replaced.

Wildlife Protection Devices
Both distribution and station applications run the risk of nuisance outages causes by wildlife interference. Guarding is typically used on distribution type arresters to shield the line connection from inadvertent contact from wildlife. If an animal were to compromise the minimum recommended clearance between the line and ground terminal it could cause an external flashover. This event could damage equipment and the animal associated with the event. Protective devices for these applications should be carefully designed and selected to ensure they can withstand the outdoor conditions and leakage current caused by line voltage. These devices not only offer protection to a utility's valuable electrical assets, but wildlife as well. Similar devices can be used for station class arresters. Hubbell offers a full range of wildlife protection guards through the Reliaguard® brand.

14 Monitoring

Surge arresters do not require routine maintenance to ensure good field performance. No special maintenance work is required because surge arresters are completely sealed and do not contain moving parts that might degrade during their life. A visual inspection is typically adequate to determine if an arrester is in good working condition. Verifying the condition and integrity of ground lead disconnectors, earth connections and grading rings is advised during routine inspection.

Special circumstances and the desire to monitor arresters can arise depending on the application. Arresters installed in locations serving a critical load or customer are a good example. If arresters are installed in an area of heavy pollution the arrester may need to be cleaned periodically or supplemented with an external coating. Light washing with a mild detergent is suitable for cleaning contamination from a porcelain housing. Polymer materials can be damaged during washing or cleaning, so it is critical to verify proper techniques with the manufacturer before cleaning this type of arrester. Recent research has shown no ill effects from algae or other bio elements growing on a polymer housing.

Monitoring Methods

All arresters are required to be tested before shipment according to IEEE and IEC arrester standards. As such, no testing at receipt or during installation of an arrester is required. Common in field test methods are not capable of replicating laboratory or factory tests.

There is no single field test that will indicate the complete operating characteristics of an arrester. If field testing is desired there are several options with varying levels of value and ease of use. Common methods to inspect the condition of installed arresters include measuring power loss, partial discharge, leakage current, resistive current, third harmonic current and temperature.

Power loss – Degradation of an MOV arrester will manifest in the form of increased resistive current or power loss. A voltage reference is required to monitor power loss. This type of monitoring is typically performed with the arrester off line.

Partial discharge (PD) – PD monitoring is a common on-line field test used to analyze the condition of power transformers, cables, rotating machines and various other pieces of equipment. While long exposure to PD can result in dielectric breakdown, it is not a reliable indicator of arrester health. Internal arrester PD testing is included as a routine production test.

Leakage current – Deterioration of an MOV arrester will lead to increased leakage current and associated rise in internal temperature. The leakage current of an arrester can be monitored both on and off line. On-line monitoring includes the use of surge counters with included milliammeters to continuously monitor the leakage current of installed arresters. Off-line measurements can be performed using portable voltage sources. Typically, portable equipment is only capable of a low voltage (5 or 10 kV), which is not a good indicator of arrester health. While measuring leakage current is common in the industry it is not viewed as a reliable indicator of arrester health. Leakage current can also be influenced by external contaminants which lead to an increase in the external surface current.

Resistive current – Unlike total leakage current, the resistive component of leakage conductor is a good indication to changes in an arresters operating characteristics. Most on-line monitoring techniques are not capable of accurately measuring the resistive component of total leakage current. Off-line monitoring in a laboratory setting is thus required.

Third harmonic current – Newer techniques and equipment are now capable of on-line monitoring the third harmonic component of leakage current. Because a voltage reference is not required it makes this technique practical for continuous monitoring with the arrester in service. The third harmonic component of current is based on the resistive current along with the voltage and temperature of the arrester. Harmonics in the voltage can contribute to sizeable error in the third harmonic reading if the total harmonic content is high.

Thermal – Infrared monitoring is the simplest and most efficient field inspection test. Infrared imaging compares arresters that are similar in age and vintage. If significant differences are discovered, increased monitoring may be recommended. During this test, arresters are not taken out of service. Thermal or infrared cameras are relatively inexpensive and minimal training is required for use. Periodic inspection is encouraged to track changes in the operating condition of an arrester over time. The time of day, along with weather and system conditions are known to influence thermal readings.

Consulting with the arrester manufacturer is advised in order to select an appropriate field test method and subsequently analyze results from field testing.

Laboratory Testing

In the event field testing is not adequate additional testing can be performed for further evaluation of an arresters health. Arresters removed from service can be returned to Hubbell for evaluation testing. Repeating routine production tests can indicate if an arrester is still within normal operating guidelines. If an arrester is deemed to be in good condition it can be returned to the user and be placed back in service or storage.

15 Failure Analysis

MOV type surge arresters are a mature technology. Continuous developments over the last 40 years have improved the critical characteristics of MOV blocks. Reputable manufacturers, such as Hubbell, have continually refined their designs and manufacturing procedures. The failure rate of surge arresters is extremely low.

Surge arresters can become electrically compromised due to several reasons. Four main surge arrester failure modes are MOV disc aging, surge duty, system TOV and moisture ingress. These failures modes are commonly caused by exceeding the arrester TOV or energy handling capability, as well as seal pumping. Regardless of the mode of failure the arresters ultimately suffer a form of thermal runaway and dielectric breakdown. In this scenario an arrester acts as a sacrificial type device, to ensure critical assets are not damaged.

In the event of arrester end of life, the unit will need to successfully discharge and relieve system fault current. The pressure relief claim is a one-time rating; however, it is not uncommon for arresters to be reclosed on after the unlikely event of arrester failure. This practice is not directly addressed by IEEE or IEC type standards. However, manufacturers can elect to perform this non-standard test to ensure good field performance. It is not recommended to reclose on a porcelain housed arrester due to the thermal nature and associated brittle fracture of ceramic material. Polymer housed arresters offer a distinct advantage over porcelain in this regard. Both solid core and hollow core type polymer housed arresters are capable of surviving reclosing events.

Investigation of a shorted arrester can be performed either by the manufacturer or other qualified agencies. If an evaluation is desired its critical to understand the circumstances associated with the arrester failure. Available system data, such as voltage traces, switching activity, nearby lightning activity are quite valuable in this scenario. Additionally, the timely removal, storage and proper packaging of the components are equally as important.

Disposal

Care should be taken when removing shorted arresters from service. Arresters which have reached end of life should be disposed of in accordance with local, national and international guidelines. Various components within an arrester can be recycled.

16 Industry Involvement

Hubbell Power Systems has a long tradition of supporting standards and industry development. Areas that we support include IEC standards development through IEC TC37, IEEE standards development through SPDC, CIGRE, National Organizations such as NEMA in the USA and numerous international conferences. These conferences include events such as INMR World Congress, IEEE PES/T&D Expo and the CEATI Grounding and Lightning Conferences.

Hubbell Power Systems is also willing to share its expertise directly with customers. We conduct monthly webcasts on various technical topics, including an in-depth series on surge arrester design, manufacturing and selection. An annual arrester seminar is conducted at our arrester manufacturing facility. Topics covered include MOV microstructure, arrester types, arrester selection, insulation coordination and evolution of surge protection products. Additionally, our field sales force and network of agents can help with individual training as needed.

17 Summary

High voltage surge arresters are a critical element in the protection of a utility's vital assets. Modern MOV type surge arresters have reached a mature state with a tendency for users to specify polymer housed designs. Various arrester designs types are available for protecting distribution systems, power transformers, circuit breakers, generators, and line insulation.

Proactively replacing arresters which have reached a vulnerable state, including SiC type designs, can vastly improve the reliability and protection of a network. The proper selection, handling, installation, monitoring and ultimate replacement of surge arresters is imperative to offer the high level of reliability which is demanded in today's environment.

Acronyms & Common Terms

ANSI – American National Standards Institute

BIL – Basic Impulse Level

Creepage (Leakage) Distance – External surface area of an arrester housing

DL – Distribution Low

DM – Distribution Medium

DH – Distribution High

Duty-cycle Voltage Rating – Historical term that defined the selection and capability of internally gapped SiC arresters according to IEEE C62.1. Term has been removed from IEEE C62.11-2020

EGLA – Externally-gapped line arrester that adheres to IEC 60099-9

Front-of-wave (FOW) Impulse - Fast rising wave shape with a virtual front time of 1 µs

Grading ring - Circular metal component used to modify voltage distribution along an arrester

IEEE – Institute of Electrical and Electronics Engineers

IEC – International Electrotechnical Commission

I_c – Continuous current of an arrester

I_n – Nominal discharge current of an arrester

I_{ref} – Reference current of an arrester

I_s – Rated short-circuit current

MOSA – Metal oxide surge arrester

MOV – Metal Oxide Varistor

MDCL – Maximum Design Cantilever Load. Test according to IEEE C62.11 that demonstrates the maximum permissible cantilever load an arrester can substation without damage.

MCOV – Maximum Continuous Operating Voltage

NGLA – Non-gapped line arrester

PD – Partial discharge

Q_{rs} – Repetitive charge transfer rating

Q_{th} – Thermal charge transfer rating (distribution only)

SL – Station low

SM – Station medium

SH – Station high

SLL – Specified long-term load according to IEC 60099-4 Ed. 3.0

SSL – Specified short-term load according to IEC 60099-4 Ed. 3.0

Strike Distance – Shortest path from line to ground potential

Switching Impulse - Wave shape caused by switching activity with a virtual front greater than 30 μs

SiC – Silicon carbide

TOV – Temporary overvoltage

> **No-prior duty** - Test in which the arrester has not been exposed to W_{th} or Q_{th} impulses
>
> **Prior duty** - Test in which the arrester has been exposed to W_{th} or Q_{th} impulses

U_c – Continuous operating voltage of an arrester

U_{pl} – Lightning impulse protective level (LIPL)

U_{ps} – Switching impulse protective level (SIPL)

U_r – Rated voltage of an arrester

U_{res} – Residual voltage of an arrester

U_{ref} – Referenced voltage of an arrester

U_m – Maximum system voltage

U_s – Nominal system voltage

W_{th} – Thermal energy rating of a station or intermediate arrester given in kJ/kV of Ur (IEC) or kJ/kV of MCOV (IEEE)

References

IEEE C62.11

IEEE C62.22

IEC 60099-4

IEC 60099-5

www.nemaarresters.org

Notes

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hubbellpowersystems.com

For product inquiries, please contact your local sales representative or customer service representative.

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