ArresterWorks

Arrester Forensics

How to determine the cause of an arrester's last overload

9-13-23 R5

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Contents

Introduction

The purpose of this ArresterFacts is to offer better understanding on the subject of arrester forensics to the engineer, technician or any stakeholder reporting on why an arrester has failed or been overloaded. Forensics in this case means the evaluation of an arrester or arrester components to determine the reason why it or its companion arrester has become inoperative. Arresters are surge diverters for lightning and switching surges that can at times be overloaded; resulting in their end of useful life. This ArresterFacts gives clear reasoning behind the tests and techniques used in the search for the root cause of an arrester's terminal overload.

Definitions

A **terminal overload** is an event where the arrester is stressed beyond its capability to the point of rendering it un-useable. The arrester may or may not be in one piece after the event. The arrester may electrically be an open circuit or a short circuit. The terminal overload may be a failure but this is not always the case. If an arrester is terminally overloaded after a very long service life and during an overvoltage event where it successfully protected a much higher valued asset to which it was meant to protect, then this terminal overload can hardly be called an arrester failure. In fact, the scenario just mentioned should be termed an arrester success and not an arrester failure as it is often called. However if an arrester becomes inoperative within days of its first energization, with no surge events occurring, then it is quite possible that it is an **arrester failure**.

Figure 1 Porcelain Station Arresters with internal core that has experienced a fault current event

Purpose of a Forensic Analysis

It is the responsibility of the arrester forensic analyst to determine if the terminal overload was an arrester failure or an arrester success. Often times the underlying reason for an analysis is that several arresters of similar style have experienced a terminal overload and the organization requesting the analysis needs to know if the problem is isolated or system wide. If it is a system wide issue and is indeed a failure issue, then perhaps a different mitigation strategy would be used than if it was an isolated event. Sometimes the purpose of an analysis is to determine if there is a power system issue that is not related to the arresters, but since the arresters are overvoltage protectors, they result in a terminal overload. The cost of a misdiagnosis can be very expensive. If the cause of the overload is incorrectly identified as a system issue, literally millions of dollars can be spent trying to correct the wrong thing.

Companion Arresters

The importance of companion arresters in a forensic analysis cannot be stressed enough. A companion arrester is one of similar vintage and type that may be on the same phase near the overloaded arrester or on a separate phase in a nearby location. It is preferred that the companion arrester not be overloaded or blown. Unfortunately an arrester that has experienced the terminal overload has much of the forensic evidence damaged or completely covered by the power frequency fault current damage. The power frequency fault current most often flows off the system along the arrester to earth during the terminal event and raises the temperature of the arrester components past their melting point leaving them nearly unrecognizable.

Trick of the Trade: If at all possible, obtain a companion arrester and it will be well worth the extra effort when looking for the overload root cause.

Relevant System Data

Collecting relevant system data is often the most difficult part of a forensic analysis of arresters. The data that can be beneficial to the analysis are as follows:

1. System voltage
2. Neutral configuration of the source transformer. Grounded, floating, impedance grounded.
3. Magnitude of available fault current.
4. Location of the arrester relative to other equipment
5. Other equipment that may be on the same phase in the same substation or on the same line. Capacitors, switches, breakers, transformers, inductors.
6. Status of other equipment during and after the event. Question if they had experienced an overload or failure recently.
7. History of the overload location. Question if there had been other overloads in the past few years.
8. Switching or lightning activity on the day of the event or in prior weeks.
9. Performance history of the arrester vintage and type on the same system.
10. The existence of any other forensic analysis data that may offer clues to the root cause.

Trick of the Trade: Beware of irrelevant data. Often times the dates and locations, of events surrounding the overload are incorrect or inaccurate. Double check the data with multiple sources.

A 15 Step Analysis Procedure

Of course each analysis will be different from the previous ones, but there are some routines that will make the analysis much more effective.

1. Gather as much system data as possible, from as many sources as possible.
2. ***Trick of the Trade:*** If at all possible, perform the analysis with a group. The group can be novice to expert in experience; everyone will have something useful to offer.

Figure 3 A Group Analyses can be highly beneficial. Even the most novice observer can often shed light on the issue

3. Inspect the subject arresters initially and record as much data as possible from the tags, shipping tags, and name plates.
4. If possible, collect original catalog literature on the subject arrester from old catalogs or from online sites.
5. Start a comprehensive set of photographs of the received parts.
6. If a complete arrester (overloaded or companion) is available, perform electrical tests on the complete sample including Vref, watts loss, PD, and leakage.
7. ***Trick of the Trade:*** If any of the arresters are sealed with an internal air volume, a gas analysis may be quite revealing. If this is desired, then before the arrester is disassembled, a gas sample should be drawn and analyzed. See Figure 2
8. Carefully and meticulously disassemble the arrester with the camera constantly in play. Make sure the camera is capable of very close up photos with very high resolution images if possible. Discuss the parts with the group as they are removed, invariably someone will see something you overlook.

Figure 2 Taking a gas sample of an unvented companion arrester can be very useful in the analysis

9. Label the parts as they are removed from the arrester. Clear close-up photos of the labels will make review of the photos easier. It is not possible to take too many photos. The photos will reveal aspects you did not see the first time through the inspection.

10. If the parts are not too damaged, run more electrical tests on the parts.
11. Run through the check list of clues to look for and constantly consider what the clues are revealing.
12. Once the testing and physical examination is complete, let the parts sit exactly in place for at least a day or at least until you have reviewed the photos.
13. Review the photos on a big screen if possible. Examine close up photos with as high a magnification as possible.
14. Write your report as you examine the photos.
15. Run through the list of potential root causes and determine which root causes are not possible. Eliminate the realistic potential root causes one by one until as few are left as possible.

Figure 4 Example of Non-fragmenting nature of polymer housed arresters upon overload or failure

Figure 5 All too often Overload or Failure mode of Porcelain Station Arresters

Top Causes and Indicators of Terminal Overloads and Failures

Moisture Ingress of Porcelain Housed and Hollow Core Type Arresters

Moisture ingress is a leading cause of arrester failures worldwide. For porcelain housed arresters and hollow core polymer housed arresters, moisture ingress is either through the metal diaphragms, which are part of the venting system, or around the rubber seals. For polymer housed arresters, water vapor can migrate directly through the rubber over time or be pumped around end seals. Excess moisture ingress will result in arrester failure over time.

Causes: Manufacturing defects, rough handling during transportation. External flashover that damages the seal.

Failure mechanism: This is a long term failure mechanism. A common mechanism is for moisture to be drawn past an aged seal, crack, or otherwise poor seal into the internal volume due to a difference in pressure between the internal and external volumes of the arrester. (See Figure 7) When the seal is sufficiently ineffective, this seal pumping mechanism draws moist air in during the evening when the internal pressure is lower than the atmosphere. As moist air is exchanged between the internal volume and the external atmosphere, the relative humidity on the inside reaches the same level as the outside. At some point the moist internal volume temperature drops below the dew point and moisture condenses along the electrically stressed components of the arrester. When moisture condenses, it then leads to dry band arcing and dielectric tracking along the wetted surfaces. This tracking will result in eventual short circuit of the arrester.

(**Continued on page 8**)

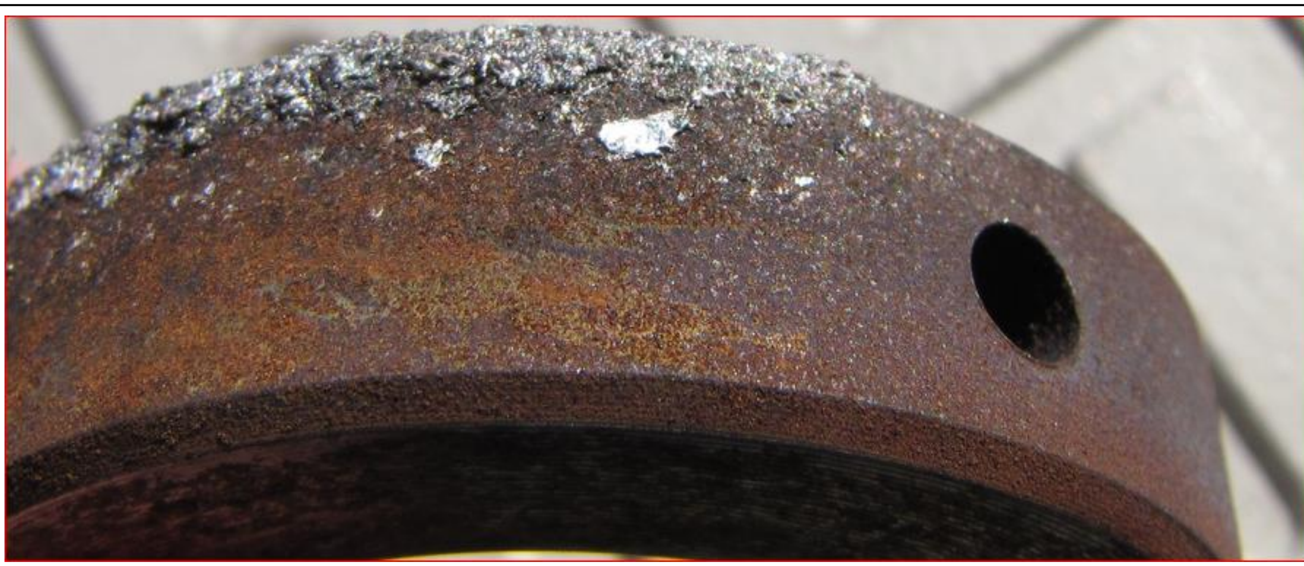
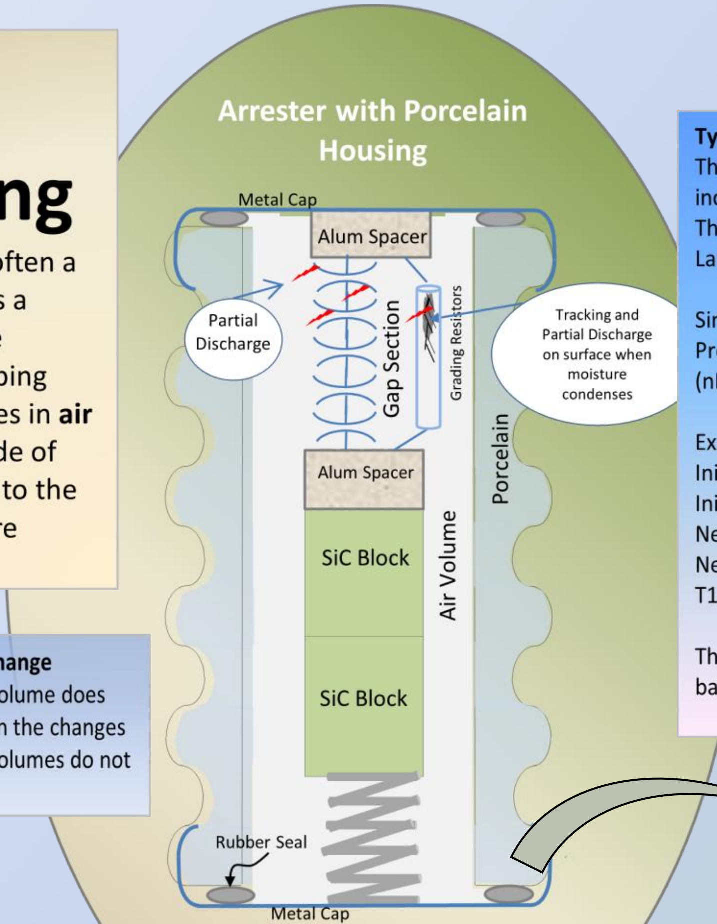


Figure 6 An internal steel component of a porcelain housed arrester that shows old and new rust along with molten metal over the old rust

Seal Pumping

Moisture ingress is often a result of leaks across a **rubber seal** with the assistance of a pumping action due to changes in **air** pressure on the inside of the arrester relative to the atmospheric pressure



Typical Pressure Swings
The internal pressure rises with a temperature increase and falls with a temperature drop. This is in exact correlation with the Ideal Gas Laws. PV = nrT

Since V, n, and r are all constant
Pressure (P)= Temperature (T) x a constant (nR/V)

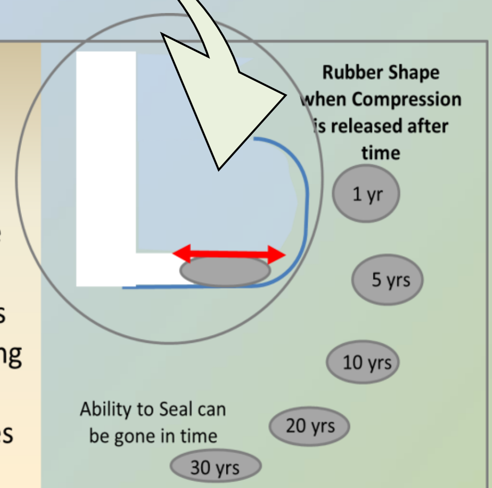
Example
Initial pressure of 1 atm
Initial Temp 23C or 296K
New Temp of 15C or 288K
New Pressure is
T1/T2 = P1/P2 1/(296/288) = .9729 atm

The internal pressure change on a per degree C basis it is .0034 atm/°C

Volume Effect on Pressure Change
Note that since the internal volume does not change, it has no effect on the changes in pressure. Larger internal volumes do not result in higher ΔP

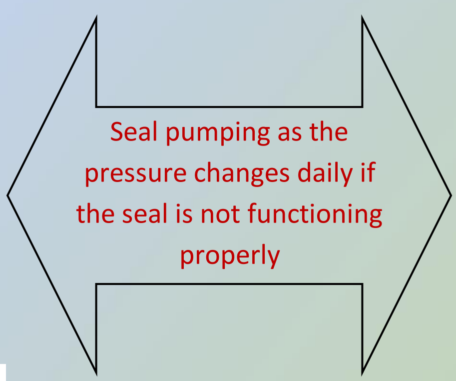
Why Aged Rubber Seals Can Leak

Some rubbers under compression will loose their ability to return to their original shape when the compression is released. This loss of elasticity is called taking a set. After a long enough time, the rubber can looses all its elasticity and its ability to provide the forces necessary to act as a seal



Initial Internal Air Pressure
The initial pressure in an arrester with an internal air space is the air pressure at the point of manufacturing. If an arrester was assembled at an elevation of 1000 meters, it would have an internal pressure lower than one assembled at 500 meters.

Daily Pressure Cycles
From that moment on, internal pressure is then a function of the initial pressure and present temperature. As the temperature of the arrester rises and falls with the cycle of the sun on a daily basis, the pressure rises and falls.



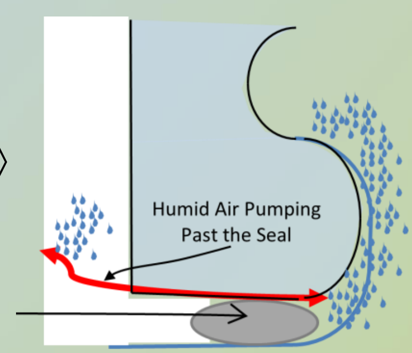


Figure 7 Seal Pumping - What is it?

Indicators: When moisture ingress is part of the failure mechanism, it is indicated by brown rust on metal parts, white rust on aluminum parts, increased watts loss at operating voltage, dull copper and often times tracking along the disks.

Trick of the Trade: Old rust covered by carbon arc products indicate the rust was prior to the failure. See Figure 6

Cautions: Often times the fault current resulting from a moisture initiated failure can look similar to a temporary voltage overload. Often, partial discharge within an arrester for long periods of time will result in the creation of enough ozone to oxidize parts similar to moisture ingress.

Figure 8 Shinny copper shunt implies no moisture ingress or excess partial discharge

Figure 9 Red Die penetrating fluid can be very useful in locating cracks or pinholes in metal diaphragms

Moisture Ingress of Polymer Housed Airless Designs

Although the polymer housed arrester has a reputation of having the ultimate moisture seal, this feature has not proven to be true. Polymer housed arresters with very low internal air volume are susceptible to moisture ingress at points on the arrester where metal terminals exit the unit. It is also a fact that Silicone rubber, EPD rubber and other rubber materials transmit water vapor at various rates, and over time, they can allow the relative humidity throughout the arrester to rise to the same level as the ambient atmosphere. The moisture vapor transmission phenomenon has resulted in the development of arrester designs that are water insensitive. This means even if the rubber transmits water vapor, the vapor is not allowed to condense on internal parts or gather in capillaries, or in any way condense in a form that is detrimental to the arrester performance.

Causes: Manufacturing defects, external flashover that damages the seal, mechanical damage.

Failure mechanism: This is a long term failure mechanism. If water vapor transmission is the cause, the vapor is collected in a small void at the rubber/disk interfaces and condenses during cool temperatures resulting in dielectric failure along the interface. Another potential failure mechanism is for water to somehow penetrate a pressure assisted seal and be transmitted along the fiber glass filled components in capillaries. If the capillaries are electrically stressed, it can lead to dielectric failure and complete failure at times.

Indicators: All the same indicators as described in porcelain housed arresters.

Cautions: Same cautions as in the porcelain housed arresters.

Figure 10 Evidence of Moisture in a solid core polymer housed arrester. Oxidized aluminum

External Flashover

The occurance of this type of event is more common in short arresters between 2.5kV MCOV (Uc) and 25kV MCOV (Uc) because animals are the primary cause. Because of the arrester's inherent characteristic to clamp voltage it is nearly impossible for an arrester to flashover externally without external assistance. Further since the arrester housings is a self-restoring insulator, the flashover may or may not be detected. This is generally a 50 or 60 Hz event and not a lightning event.

Causes: Animals, severe contamination in conjunction with fog or high humidity.

Failure mechanism: If the flashover is animal assisted, the animal is electrocute, and an external arc is created over the outside of the arrester. The fault created from the flashover will be interrupted by an over current device on the system. It is possible that the arrester is 100% unaffected if the ground fault current is limited. The system can generally be re-energized after the event.

Figure 11 Arrester where external flashover did not fail the arrester, but damaged the seal

Indicators: Arc marks on the high voltage side of the arrester, sometimes on the ground end, mild to severe arc marks on the housing. It is possible for the arc and heat to damage the seal of the arrester and may lead to a failure in the future.

Cautions: An arrester that has experienced an external flashover can continue to operate indefinitely. However it should be considered a potential problem in the future since seal damage can be hidden.

Figure 12 Top cap with clear arc marks from an external flashover. The seal may still be good in this arrester

Excessive Partial Discharge

It is generally accepted that some partial discharge will occur within an arrester during short periods of its life. This usually occurs during rain or precipitation when there is significant radial stress due to different voltage levels on the outside surface of the arrester as compared to the voltage levels on the dry inside surfaces. If partial discharge is excessively present, it can lead to degradation of the disk and arrester dielectrics that in turn may lead to complete failure. This failure mode primarily occurs in arresters with significant internal air spaces such as porcelain housed and hollow core polymer housed arresters. This failure mode is a very long term process and may never cause the arrester to fail if the level of partial discharge is low.

Causes: Manufacturing defects, moisture ingress, rough handling, excessive contamination and moisture on the external surfaces.

Failure mechanism: The partial discharge starts small and grows away from the initial point. After long exposures, the dielectrics in the area near the discharge degrade and can lead to flashover of the electrically stressed parts. Partial discharge may also reduce the oxygen content of the air around the disks and in some cases can change the disk characteristics.

Indicators: During electrical tests high frequency spikes can be observed on the power frequency trace, high partial discharge reading with RIV or PD equipment, discoloration of components near edges, corners, and contact points. Multi colored growths on rubber components.

Cautions: Low levels of partial discharge over long periods can corrode and oxidize metal parts similar to moisture ingress.

High Current Lightning

Lightning strokes above the design limits of arresters can cause terminal overload of the arrester's internal dielectrics. If an arrester experiences a direct strike the resulting overload can be immediate; however the loss of function can also be delayed if the damage during the surge was minimal. Minor damage due to a lightning surge can lead to partial discharge that in turn leads to tracking and full electrical failure at a later date.

Causes: Excessive single current surge , successive strokes to the same arrester, TOV following a surge caused by a fault on the circuit that exceeds the arrester capability.

Failure Mechanism: If the arrester capability is exceeded by a lightning stroke, the MOV disk will initially take the surge, heat up dramatically, perhaps crack and then flashover. This leads to a full power frequency flashover and fault current that can cover up all evidence. If the surge just damages the dielectrics of the arrester it may fail later by the same means as above.

Indicators: If the arrester was subjected to a significant surge, it is likely that the MOV material is polarized. This polarization is seen as conductivity in one polarity 5-20% different from conductivity in the opposite polarity. If the surge only damaged the arrester dielectric that lead to a long term dielectric failure there is no real method of determining this scenario. If the fault current available to the arrester is low on polymer housed arresters the rubber may not show any failure. Electrical tests of the arrester will likely show it as shorted or nearly shorted.

Cautions: If the fault current is of sufficient magnitude, it may cover up all the evidence of a lightning induced overload.

Trick of the Trade: AC testing of an MOV disk can show polarization. If the disk was subjected to a significant surge, the disk will show the polarization quite dramatically.

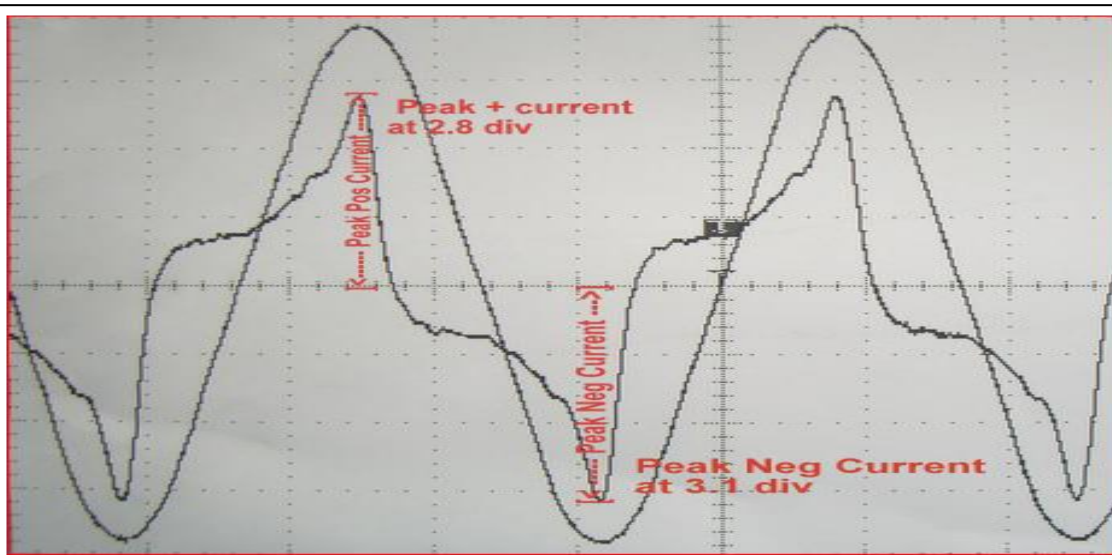
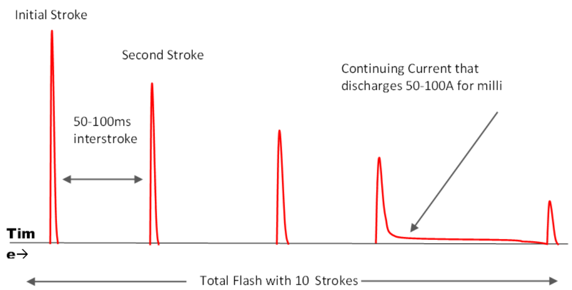


Figure 14 Example of Asymmetric Current through a surge degraded disk

Mulit Stroke Lightning

Lightning strokes very often consist of several strokes withing the flash. They are depicted by the following graphic.



Since the peak current seldom exceeds a few 10s of kA, it does not have the same effect on the arresters as a high current stroke. The charge carried by the stroke can easily exceed 10coulombs (IEEE 1410). With this stroke charge, the standard heavy duty arrester is immediately pushed beyond its 1 coulomb thermal rating. Although never recorded in the field, it is only logical that this failure mode occurs almost as often as multi-stroke lightning does. .

Causes: Multi stroke surge, that exceeds the arrester capability.

Failure Mechanism: If the arrester capability is exceeded by a lightning stroke, the MOV disk will initially take the surge, heat up dramatically, perhaps crack and then flashover. This leads to a full power frequency flashover and fault current that can cover up all evidence. If the surge just damages the dielectrics of the arrester it may fail later by the same means as above.

Indicators

No known indicator of this failure mode except that it looks like a TOV but there was no TOV on the system and a lightning storm recently went through the area**.** A lack of an asymmetrical VI characteristic curve and all the symptoms of a high current failure as described above is also an indicator.

Cautions: If the fault current is of sufficient magnitude, it may cover up all the evidence of a lightning induced overload.

Temporary Overvoltage

A terminal overload caused by a fundamental power frequency voltage beyond the capability of the arrester is a common issue. Arresters are designed to ride through overvoltages and if properly dimensioned when installed, they should not overload in this way. However sometimes circuit configurations change, or breakers hang up or other circuit issues result in elevated voltage beyond the design limit of the arrester.

Causes: Excessive voltage rise in the un-faulted phase of a three phase system, misapplication of the arrester, change in the neutral configuration of the system, ferroresonance, loss of neutral on a system, aging of the disks, and contact of lines with higher system voltage.

Failure Mechanism: During a TOV overload, the voltage across the arrester rises to a level where the disks conduct significant power frequency current. The conduction causes the disk to heat significantly which in turn lowers the resistance of the disk leading to more conduction and ultimate overload. If the TOV overload is only a few percent high, then the heating may take place over a long period.

Indicators: Change in the disk voltage-current characteristics in both polarities, cracking of just a few disks in the stack, flashover of the disks, hole blown in side of polymer housing, vents opened in porcelain housed arrester equipped with vents.

Cautions: Minimal damage to an arrester during a lightning stroke, disk aging, or switching surges, can lead to an overload mode that looks exactly like a TOV overload.

Trick of the Trade: Removal of the faulted section of the disk and AC testing of the chipped parts can reveal TOV overload.

Figure 15 Section of disk chipped out for testing without influence of faulted section

Switching Surge

This overload mode can occur if the arresters are subjected to surges generated from switching cap banks, switching or energizing long lines, switching high voltage lines, and other sources that exceed the design limits of the arrester. This overload condition can only occur on systems above 220kV or on lower voltage systems with extremely high cap banks installed.

Causes: Restrike or prestrike of breakers, re or pre strike of capacitor switches.

Failure Mechanism: See lightning mechanisms.

Indicators: Numerous small holes in the aluminum electrode of the disks. Generally found around the circumference of the disk electrode. Polarization of the disk at low levels can occur.

Cautions: Fault current damage after the initial overload can disguise the cause.

Disk Aging

Since the initial introduction of the MOV arrester, it has been accepted that metal oxide disks can experience a long term change in their characteristics. This change in characteristics is referred to as aging. If the change in characteristics results in more losses at normal operating voltage, then it can lead to an arrester failure.

Causes: Improper manufacturing of the disk.

Failure Mechanism: At normal operating voltages, the losses gradually increase leading to internal heating. When the generated heat exceeds the ability of the arrester to dissipate the heat into the environment, it will lead to dielectric failure and a fault on the system.

Indicators: Hot arrester at operating temperature, excessive electrical losses at operating voltage, some disks much different in losses than others in the same column of disks, nonlinearity of the disk reduced as shown on VI trace, common change in many arresters from the same vintage, type and manufacturer.

Cautions: This failure mechanism can look exactly like a TOV overload.

Less common causes of Arrester Failure and Overload

External Contamination: This type of overload can lead to external flashover of porcelain housings or excessive internal partial discharge.

Improper MCOV or TOV Rating: The installation of arresters with an MCOV lower than the steady state system voltage can result in arrester overload for what would appear to be a minor TOV. For example, if the system has neutral impedance installed, it requires a higher MCOV arrester than a grounded neutral, a fault on the system can lead to arrester overload on the un-faulted phase.

Unbalanced Electric Field: This is a failure mode that can occur on an arrester if the arrester is mounted to close to a ground plane of another phase. This miss-installation condition can lead to partial discharge in the internal volume of the arrester that can lead to failure. This condition may also lead to overheating of the disks due to a voltage imbalance. This failure may also be caused by the use of improper grading rings on the arrester.

Misalignment of Disk Column: In an optimal arrester design, a single disk column within a porcelain housed arrester should be centered along the length of the porcelain housing. If the disks are misaligned during transportation or arrester installation steady state partial discharge above the acceptable level may result. If the column is misaligned during transportation, it may also result in physical damage to the edges of the disks that may also result in partial discharge or internal flashover of the disk during a lightning event.

Improper Spring Pressure: (For designs that require high spring pressure only.) If the spring in an arrester is not of high enough pressure, the disk column may become misaligned during transportation or arrester installation. This type of defect or mishandling can lead to a misalignment issue as discussed above. Also if the pressure of the spring is too low, partial discharge or disk damage may occur during a surge event.

Figure 16 Always take great caution when handling fractured porcelain, the edges are razor sharp

Mechanical Stress: If an arrester is mounted in such a way that it has excessive mechanical stress on the unit, it can fail over long periods of time. This misapplication generally leads to failure of the seals which in turn will lead to dielectric failure of internal components.

Burrs: If a high voltage arrester is assembled with conductive parts that have sharp points or edges, partial discharge can result inside the arrester. This design or manufacturing defect can lead to dielectric failure of the arrester.

Insufficient Dielectric Strength: If any of the materials on the inside of the arrester have either internal or surface dielectric strength inadequate for steady state or impulse states, they can track or flashover. This manufacturing defect can be exacerbated by surge events.

Disassembly Considerations

The dissection of an arrester and its components can be much more difficult if the internal components are not familiar. It is recommended that if at all possible; retain a drawing or sketch of the internal components before disassembly. If the arrester is a porcelain housed unit and cannot be disassembled with bolts, then simply crack the assembly with a hammer. The internal spring pressure is not sufficient to discharge the porcelain more than a few centimeters. Cover the arrester with a blanket or cardboard box to contain the parts.

Cautions: If broken porcelain is involved, it is highly recommended that thick leather gloves be used at all times while handling the broken parts. Shards of porcelain can cause a serious wound to the hand if touched in the slightest manner. When dissecting a polymer housed arrester, a razor knife is most effective.

Also take care not to destroy evidence by over handling parts. This may be an issue with a team evaluation and everyone's excitement to solve the mystery.

Conclusion

Arrester Forensics is a science that should be carried out with a plan. If at all possible have a person on the investigation team with some arrester experience. Improper conclusions can cost more than proper ones at times. The suggestions above should help you make that plan. If you find you are stuck and without a conclusion, let it sit for a day and look at it with new eyes later. This time delay can be quite useful.
Good luck... and don't hesitate to contact Arresterworks with questions in this area.

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

About the author:

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

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