ArresterWorks

Arrester Reference Voltage

And Interactive Simulation Tool

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Arrester Reference Voltage and Interactive Simulation Tool

Introduction

From an arrester designer's perspective, the reference voltage of an arrester is perhaps the most important arrester characteristic to understand. Casual users of arrester may not need to understand this characteristic, but arrester specifiers may want to better understand this characteristic because in the near future it will play a bigger role in arrester energy testing. Also anyone interested in doing forensic analysis of arrester should have a good idea what this critical characteristic can reveal. See Companion Interactive Arrester AC Conduction Simulator for an interactive visualization of this characteristic. Also see Annex A of this document for instructions on how to use the interactive simulation tool.

In both the IEC 60099-4 and IEEE C62.11 2013 editions a reference voltage characteristic change from before and after the impulse withstand verification test will be used as a pass/fail criteria.

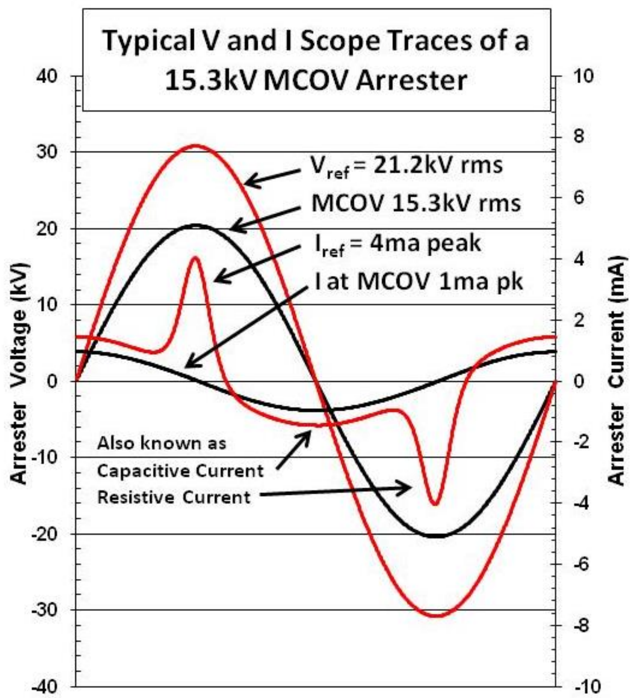


Figure 1: Oscilloscope Traces of an Arresters Voltage and Current

Definitions

The IEC and IEEE definitions are the same.

Reference Voltage (V_{ref}) (U_{ref}):
The lowest peak value independent of polarity of power-frequency voltage, divided by the square root of 2, required to produce a resistive component of current equal to the reference current of the arrester or arrester element. The reference voltage of a multi-unit arrester is the sum of the reference voltages of the series units. The voltage level shall be specified by the manufacturer.

Reference Current (I_{ref}):
The peak value of the resistive component of a power-frequency current high enough to make the effects of stray capacitance of the arrester negligible. This current level shall be specified by the manufacturer.

NOTE—Depending on the arrester design, the reference current will typically be in the range of 0.05 mA to 1.0 mA per square centimeter of disk area.

AC Resistive Current: the current flowing through a varistor that is in phase with the voltage. The dominate current above the knee of on the VI curve.

AC Capacitive Current: the current flowing through the varistor with a peak amplitude 90 deg from the peak voltage. The dominating current below the knee of the VI curve.

Background

It is not clear where the term reference voltage came from, but it appears as early as 1991 in the first IEC MOV Arrester Standard. In the 1976 Transient Voltage Suppression Manual by GE, a term V_x and I_x are discussed and have essentially the same definition as V_{ref} and I_{ref}. Another term that is similar to Vref is V_{1ma}. V1ma is the voltage developed across the terminals of a varistor when 1ma/cm^2 DC is forced through an arrester.

In all cases, the purpose of this voltage measurement is the same, too quantifying the point on the varistor's VI curve where significant conduction begins in earnest with no effect of capacitance or leakage currents. The term reference voltage is very appropriate, because this voltage measurement can be used to determine all other voltage-current characteristics of an arrester.

The Arrester VI Curve

A varistor is a variable resistor with its resistance controlled by the voltage stress impressed across the device. The varistor and arrester Voltage-Current Characteristic Curve (VI Curve) is the fundamental and simple way of showing how the resistance changes as a function of the voltage. This characteristic curve is used in many ways, and is heavily relied upon to understand and predict the performance of an arrester. Figure 2 is a typical VI curve for a 15kV MCOV arrester. Once a VI curve is determined for a varistor disk, the data can be used to predict the full arrester's characteristics.

VI Curves often show only one polarity of the conduction curve of a varistor as does the one in Figure 2. Varistors are bidirectional devices, and the characteristic curve in the negative direction is identical for new non-impulsed varistors.

It is also important to understand that the curve represents the absolute voltage and current characteristic, essentially frequency independent. If a DC voltage is applied to the varistor with this characteristic curve, the resulting current will be the same as if it were an impulse with a peak voltage equal to the DC voltage. The test signals used to create this curve are generally 50 or 60 hz below an amp and impulse above an amp.

Some important points on the VI curve are called out in Figure 2. These points are described in more detail here:

1. **Operating Range:** This is the region of a varistors VI characteristic where the varistor spends its entire life. The conduction in this region is very close to zero with only minimal leakage current flowing through the device. This region is temperature sensitive and as the temperature of the device increases, the conduction increases at the same voltage. In other words, the resistance decreases in this region as the temperature of the device increases.

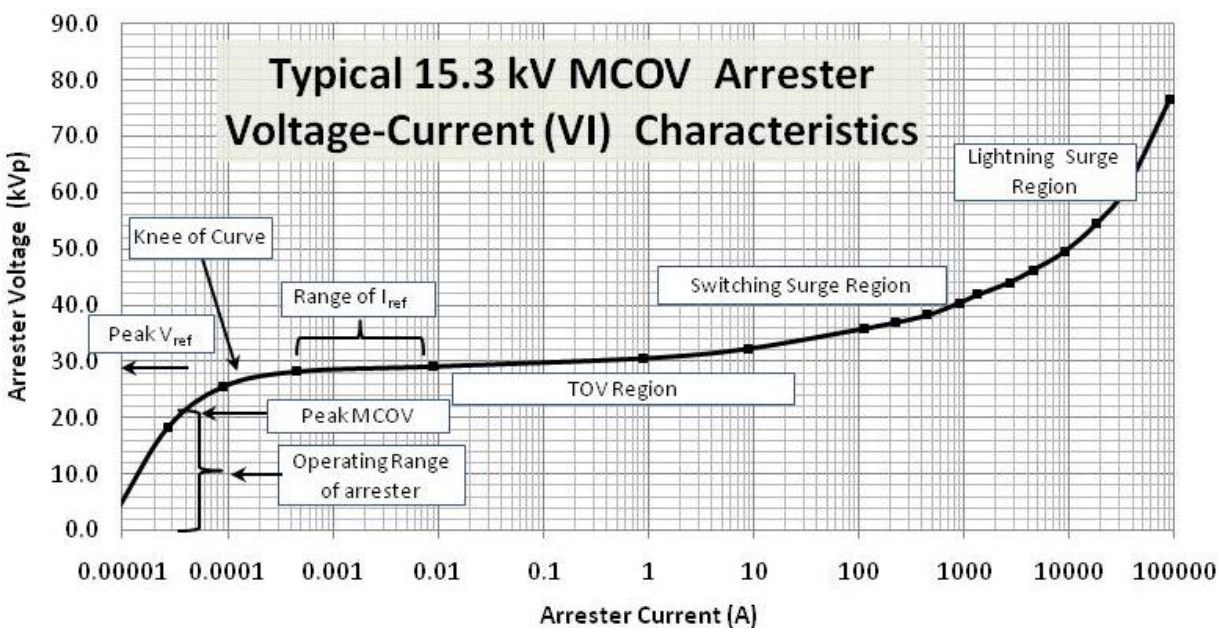


Figure 2: Typical Voltage Current Characteristic Curve

2. **Peak MCOV:** This point shows the maximum voltage stress reached during normal operations. MCOV is typically specified in RMS terms, which is a meaningless value on a VI curve since the varistor reacts to absolute voltage only. The peak MCOV level of an arrester is in the range of 70-85% of the Vref of the arrester.
3. **Knee of the Curve:** This is a loosely used term that roughly describes the voltage stress region where the conduction paths through the varistor rapidly change from the operating or leakage region to the conduction region. On a log-linear scale as shown in Figure 2, it appears as a knee on the curve. At this point
4. **Vref-Iref :** The Vref region is found just above the knee of the curve. This is also the region of conduction where there is more current flow through the zinc oxide grains and junctions than through the leakage current conduction paths. In this region the resistive current dominates the current flow and the capacitive current flow is not dominating. See Figure 1 for a better view of resistive and capacitive current. This region is not set at a specific current level, to allow manufactures to pick the current level that best fits their design. The voltage in this region changes very little with large changes in current. This is where the non-linear behavior of the varistor becomes very apparent. In this region of the VI curve, the varistor is dissipating considerable power and is not considered a long term operation.
5. **TOV:** The Temporary Overvoltage section starts just above the knee of the curve and in fact includes the Vref point. It can extend up to 10s of amps. There is no generally defined upper end of this region. During a TOV event such as a voltage rise on an unfaulted phase of a power system, the voltage level is often high enough in amplitude to cause these levels of current to flow. During conduction in this region, the varistor is rapidly heating since there is considerable energy dissipation taking place that is beyond the normal state.
6. **Switching Surge and Lightning Surge:** For both of these regions, the varistor is in major conduction. This type conduction occurs in impulse form only and the duration of the surges are from the low milliseconds at the switching surge end, to a few microseconds at the higher current regions. The VI characteristic is very temperature insensitive in this region. There does appear to be a slight frequency effect in this region of the curve.

Measuring Methods

Precise Measurement

A Vref measurement is usually carried out in a few seconds. If the measurement takes too long, the temperature of the device can reach damaging levels for the varistor material. If a Vref measurement took 10 minutes, the test equipment would surely not be able to sustain the voltage level and the varistor would certainly be in a failure mode.

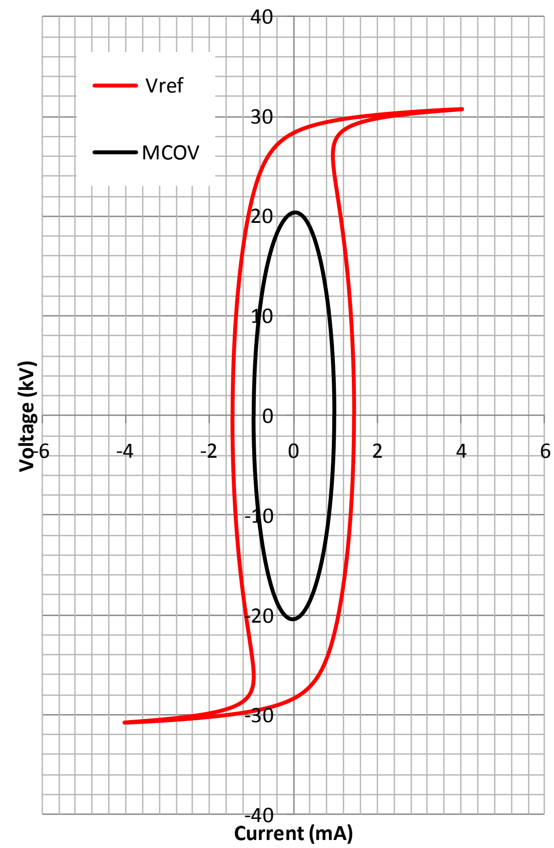


Figure 3: Measuring V_{ref} using a lissajous readout of 15.3kV MCOV arrester current and Voltage

The most common means of measuring Vref, is to apply an AC voltage across the varistor while monitoring the current. The AC rms voltage across the sample that results in a peak current conduction through the sample equal to desired Iref, is then taken as Vref. This procedure can be done by hand while monitoring a scope or fast responding digital meter. It can be done automatically by properly calibrated and set up equipment. In either case, the voltage and current are simultaneously measured to achieve the measurement.

For optimum test results, the power source should be strong enough to produce 5-10ma without significant distortion of the voltage waveshape.

When measuring Vref, the waveshapes should be similar to those found in Figure 1 and 3. The readout as shown in Figure 3 has the advantage of clearly showing the peak reference current when measuring Vref.

It is important that the resistive current is at least visible and measureable and not dominated by the capacitive current as it is at MCOV.

Non-precise measurements

When a stiff or strong AC source is not available for a Vref measurement, a weak source can also provide good results. An example of a weak source would be a typical AC High-Pot tester. These devices have currents available in the range of 1-10 mA maximum but with significant wave distortion at that level. These devices however do have excellent current trip sensors along with built in voltage and current meters. If the current tip sensor is set for about 1ma,

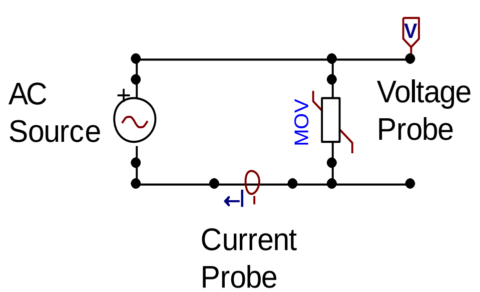


Figure 4: Typical Reference Voltage Measurement Circuit

it can be used to detect when the arrester voltage has reached Vref by tripping out just as it reaches conduction.

Production Tester Considerations

Per IEC 60099-4, routine tests for arrester must include the measurement of Vref. The actual verbiage is as follows.

> "The reference voltage of each arrester shall be measured by the manufacturer at the reference current selected by the manufacturer. The minimum reference voltage of the arrester at the reference current used for routine tests shall be specified and published in the manufacturer's data"

It goes on to also specify that:

> "measurement of reference voltage (*U*ref). The measured values shall be within a range specified by the manufacturer"

If the range as specified by the manufacturer is stated as "15.5kV and up", then the routine test need only detect the minimum reference voltage. However if the range is stated as "15.5 to 17.9kV", then a precise measurement must be made detecting both minimum and maximum levels of Vref. Since the standard indicates that only a minimum Vref need be published, the routine tests for arresters generally is a min value test, leaving the maximum unspecified.

If the reference voltage of two different models are being compared, it is important to know what reference current was used for the Vref test otherwise the comparison may be invalid.

Using Reference Voltage Tests to Predict Residual Voltage

Per 60099-4 Ed 3.0, section 8.3.1.paragraph 3:.

> For arresters with rated voltages below 36 kV (see item b) of 9.1), the manufacturer may choose to check only the reference voltage by routine test. The maximum reference voltage shall then be specified. The measured residual voltages of the test sections are multiplied by the ratio of this maximum arrester reference voltage to the measured reference voltage of the test sections to obtain maximum residual voltages for all specified currents and wave shapes.

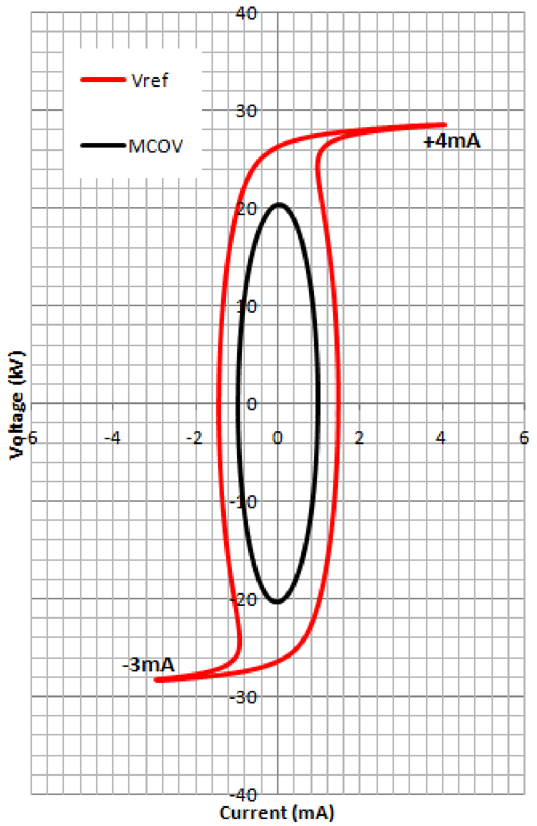


Figure 5: Vref measurement of an impulse degraded 15.3kV MCOV Arrester. Note Lower and asymmetrical V_{ref} lissajous indicates conduction difference between pos and neg polarities

If a maximum reference voltage is specified, and a ratio between max Vref and V10kA is clearly formulated, then the residual voltage tests can be waived and the Vref tests used instead.

Reference Voltage as an indicator of Surge Degradation

It is a well known fact that varistors can experience a change in conduction after a high current impulse. The level of damage is a strong function of the manufacturer of the device and the magnitude of the surge. It is not clear what actually happens at the junction level of the varistor material, but the conductivity change can be accurately measured using Vref measurements. Figure 5 shows that what impulse degraded scope trace indicates. If the arrester has experienced impulse degradation, when it reaches the same reference current in the damaged direction, it will be at a lower voltage and the conduction in the opposite direction will be lower. This is referred to as asymmetrical conduction.

Using Vref in New Energy Tests

Because of the fact that impulse degradation is a universal effect of excessive impulse current, it has been chosen to be an early indicator maximum energy handling capability. In the current edition of both IEC 60099-4 and IEEE C62.11 new impulse withstand tests are specified and as part of the pass/fail criteria, a change in Vref is required. A change of up to 5% is acceptable before to after the test. This is the first time that Vref is used to evaluate performance of an arrester.

Using V_{ref} in Arrester Forensic Analysis

If an arrester has experienced an end-of-life event, it is possible to determine if a high current surge was part of that event by measuring the Vref of the disks that remain. It is however extremely important to make sure all of the arcing products are removed from the disks before the measurement is made. Even if the original Vref level is not known, the asymmetry as shown in Figure 5 will be present if a high current surge was involved.

Reference Voltage and TOV

It is not obvious, but if a closer look is take at the VI trace in Figure 2, it can be seen that Vref level and TOV level are very close together. This relationship is fairly constant across all arrester designs. In other

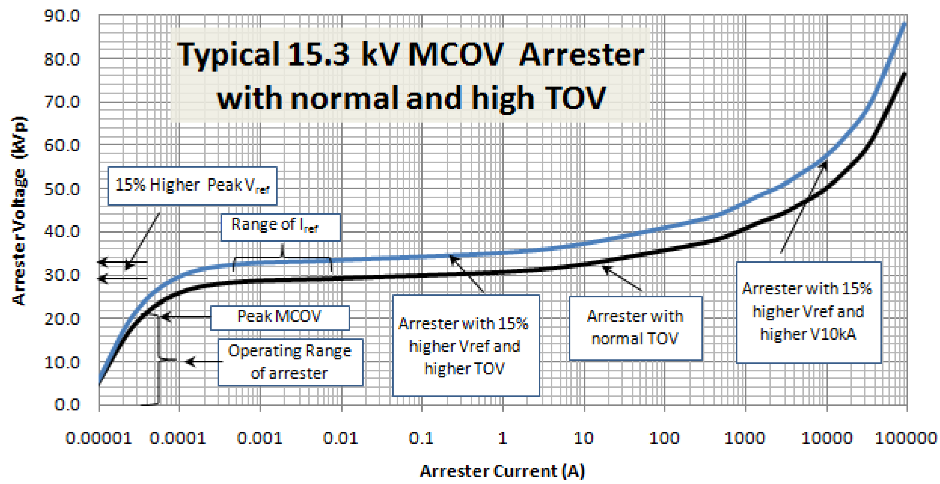
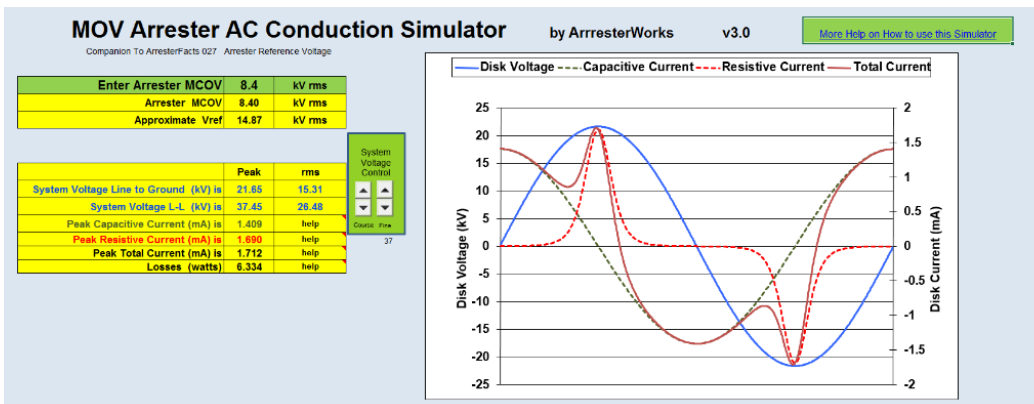


Figure 6: 15.3kV MCOV Arrester with two different Reference Voltages and different TOV withstand

words, by design, Vref and VTOV will be close. However, the ratio between Vref and MCOV is completely at the discretion of the arrester designer. If it is desirable for an arrester to have a better TOV withstand capability, the arrester can be de-rated so that there is more distance from MCOV peak and Vref. This is easily done by adding more disks to an arrester design. However, as it can be seen in Figure 6, it also increases the discharge voltage at 10kA which is not usually desirable.



Using a DC Source for Reference Voltage Tests

Since the initial development of Zinc Oxide Varistors, DC has been used to evaluate the low current region of this semiconductor. To this day many Japanese and Chinese suppliers of disks and arresters use the 1mA DC test to evaluate the turn-on point of their products. At ArresterWorks we routinely use DC tests to determine if the low current region of the varistor VI curve has changed or has experienced impulse damage. The use of DC instead of AC is actually easier and the effect of capacitance is not part of the equation. Without a doubt the use of DC is an effective and accurate means of evaluating arrester VI characteristics.

AC Conduction Simulator

The AC Conduction Simulator is a stand alone Excel based tool for demonstrating AC current conduction through an MOV. It is available on the ArresterWorks ArresterFacts Page.

Annex A of this ArresterFacts offers the instructions on how to use the AC Conduction Simulation Tool. This interactive tool demonstrates how the capacitive and resistive currents are related to the total current through an arrester. It also shows how to determine the proper Iref and how to run a Vref Test.

Summary

The reference voltage of an arrester is a very important characteristic and related to many other arrester characteristics. Understanding it is essential to running effective tests and performing accurate comparative analysis.

About ArresterFacts

Thanks for using ArresterWorks as your source of Arrester and Surge Understanding.

If you ever have any questions about this or other arrester issues, contact Jonathan Woodworth at jonathan.woodworth@arresterworks.com

Visit www.arresterworks.com for all you surge protection needs.

Annex A
Interactive AC Conduction Simulator Overview
AC Current Conduction Thorough an MOV Arrester

Because an MOV arrester is a lossy capacitor at normal system voltages, and a very low impedance at higher voltages it is a complex system that is not easily visualized. This AC Conduction Simulator is a visualization of the various currents. Indeed, there is only one current flowing through the arrester, but it has a distinct capacitive component and a distinct resistive component that sum to the total current. This simulator is a companion to Arrester Facts 027. Arrester Reference Voltage

This simulator is a demonstration model only and not specific to any arrester brand or model. Its purpose is to:

1. Visually Demonstrate AC current conduction through an MOV at various voltages.
2. Visually Demonstrate how to determine the proper Reference current for an arrester.
3. Visually Demonstrate how to conduct a Reference Voltage Test.

This simulation tool is for anyone interested in learning more about MOV Type arresters. It can be copied, modified, improved and used by anyone. Kindly give ArresterWorks credit when appropriate.

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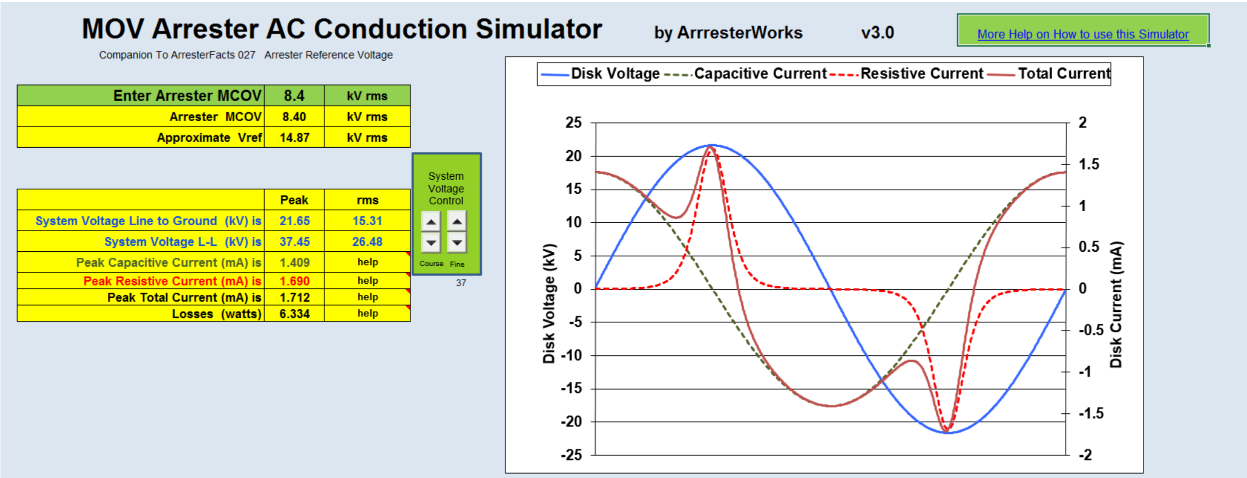
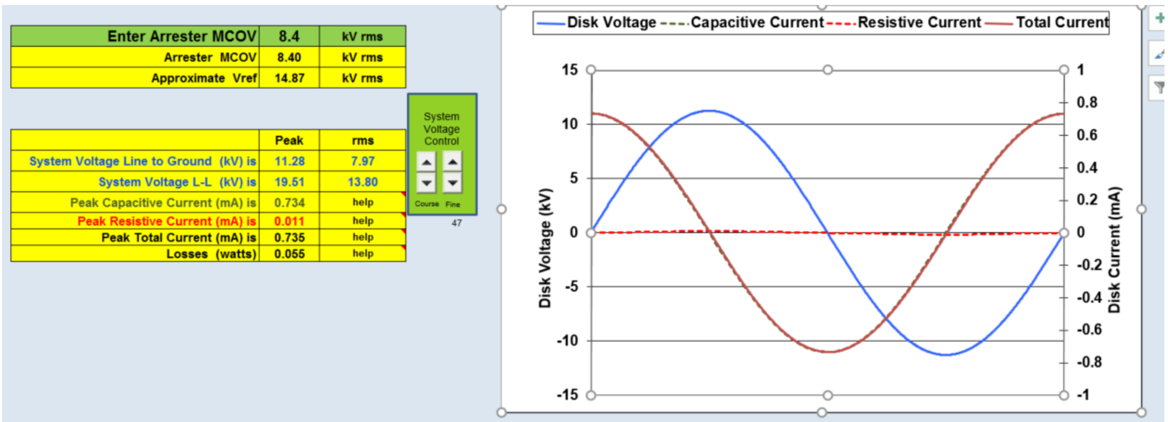


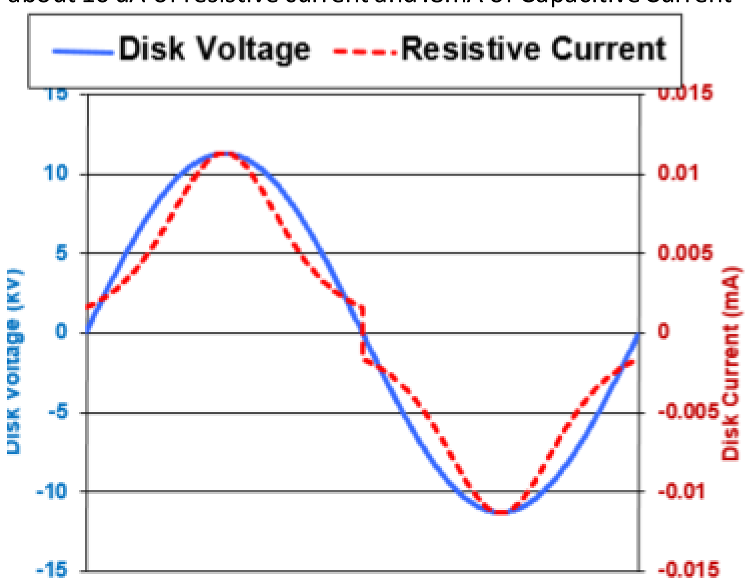
To Visually Demonstrate AC Current Conduction at Normal Operating Voltage

1. Set the arrester MCOV rating to what ever you choose.
2. Adjust the system voltage using the course and fine controls.

At normal system voltage, it should look like this with very little resistive current flowing.



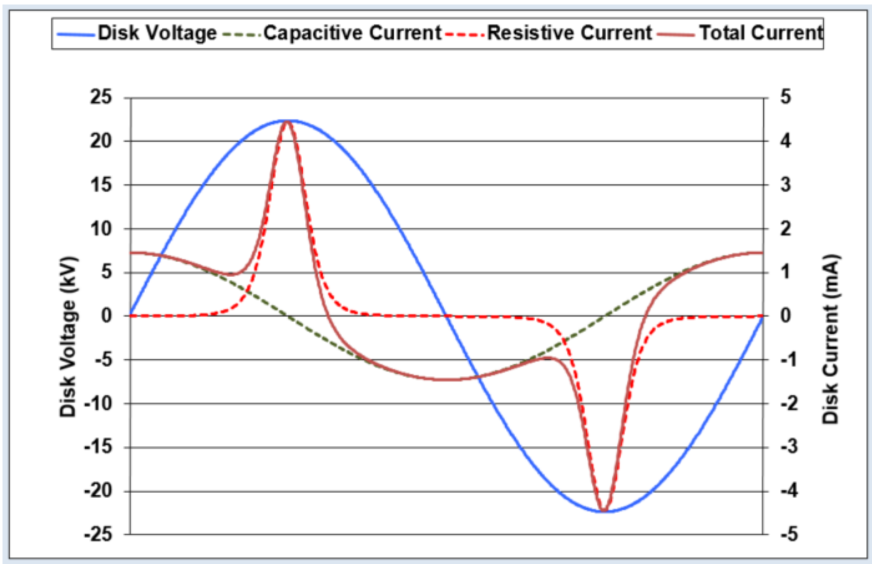
about 10 uA of resistive current and .8mA of Capacitive Current



To Visually Demonstrate AC Current Conduction During a Temporary Overvoltage of 2.0 PU of L-G Voltage

1. Set the arrester MCOV rating to whatever you choose.
2. Adjust the system voltage using the course and fine controls to 2.0 x Line-Gnd voltage during normal operation. If a 13.2kV system issued, the L-G voltage is 7.93. 2X is 15.8kV rms.

At 15.8kV, an 8.4kV MCOV arrester will be in conduction as shown here.



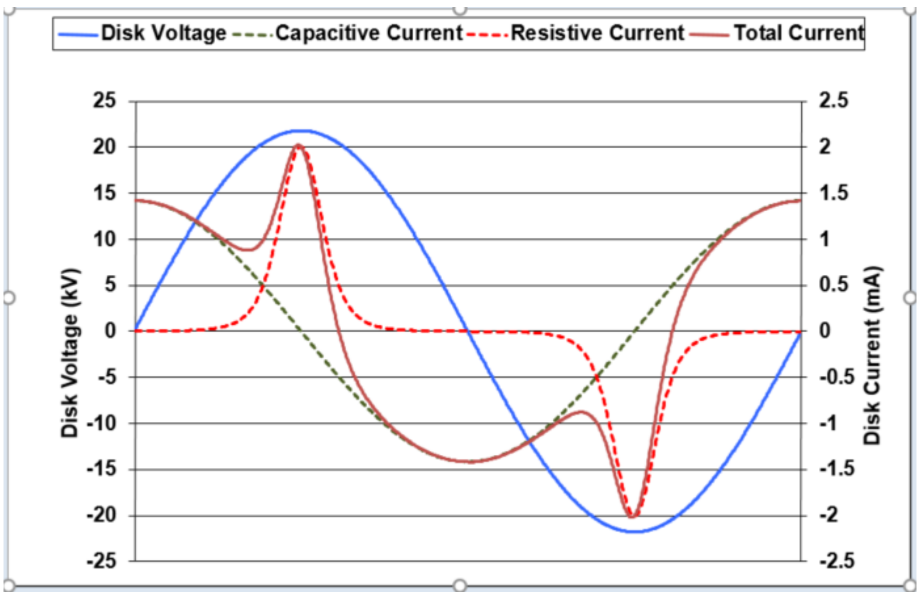
The resistive current has increased to 4.5 ma peak and the capacitive current has increased to 1.5mA peak.

How to determine appropriate I_{ref} for Reference Voltage Test

The definition of a Reference Voltage Test is a measure of the voltage across an arrester in kV rms when a peak current of Iref between 1 and 10mA is conducted through the device.

The definition of Reference Current is any current where the resistive component is the dominant conduction mode and the capacitive current is not a significant factor.

Example: In this model, for an 8.4kV MCOV arrester, a reference current of 2mA peak is necessary to fully eliminate the effect of capacitance. See below



The manufacturer has the option of choosing 2mA peak as the reference current, but could also choose a higher one or one as low as 1.6mA.

For example, we choose 2mA.

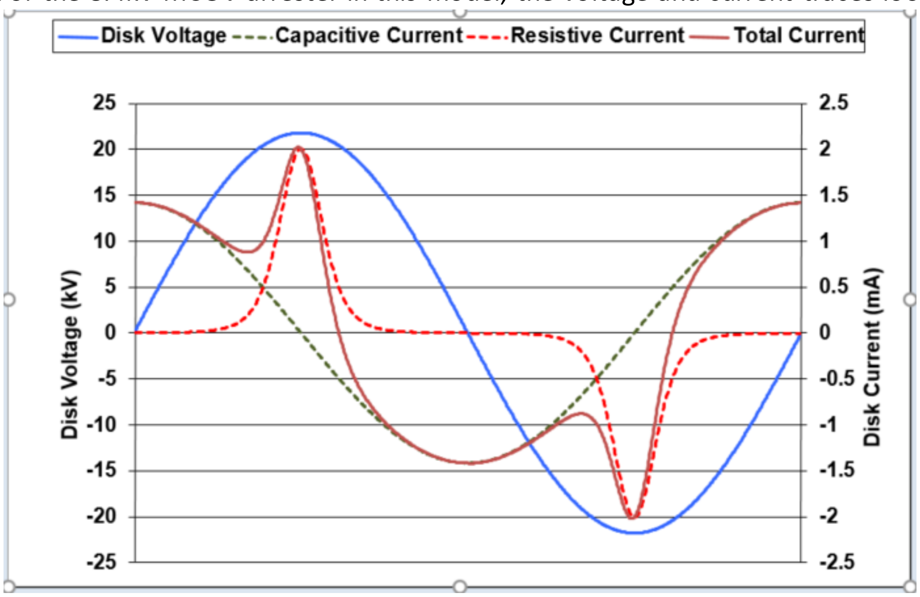
Example Reference Voltage Test at Iref of 2mA peak

The objective of a Reference Voltage test is to check the turn on point of an arrester. The reference voltage is usually at a conduction level where temperature is not so important. It can also be used to predict the 10kA residual voltage.

Conducting a Reference Voltage Test

1. Choose Iref (we chose 2ma based on previous example)
2. Adjust the voltage across the arrester and monitor the current through it until it is equal to Iref.

For the 8.4kV MCOV arrester in this model, the voltage and current traces look as follows:



	Peak	rms
System Voltage Line to Ground (kV) is	21.78	15.40
System Voltage L-L (kV) is	37.68	26.64
Peak Capacitive Current (mA) is	1.417	help
Peak Resistive Current (mA) is	1.990	help
Peak Total Current (mA) is	2.008	help
Losses (watts)	7.310	help

The Reference Voltage for this arrester at 2mA peak is 15.5kV rms.