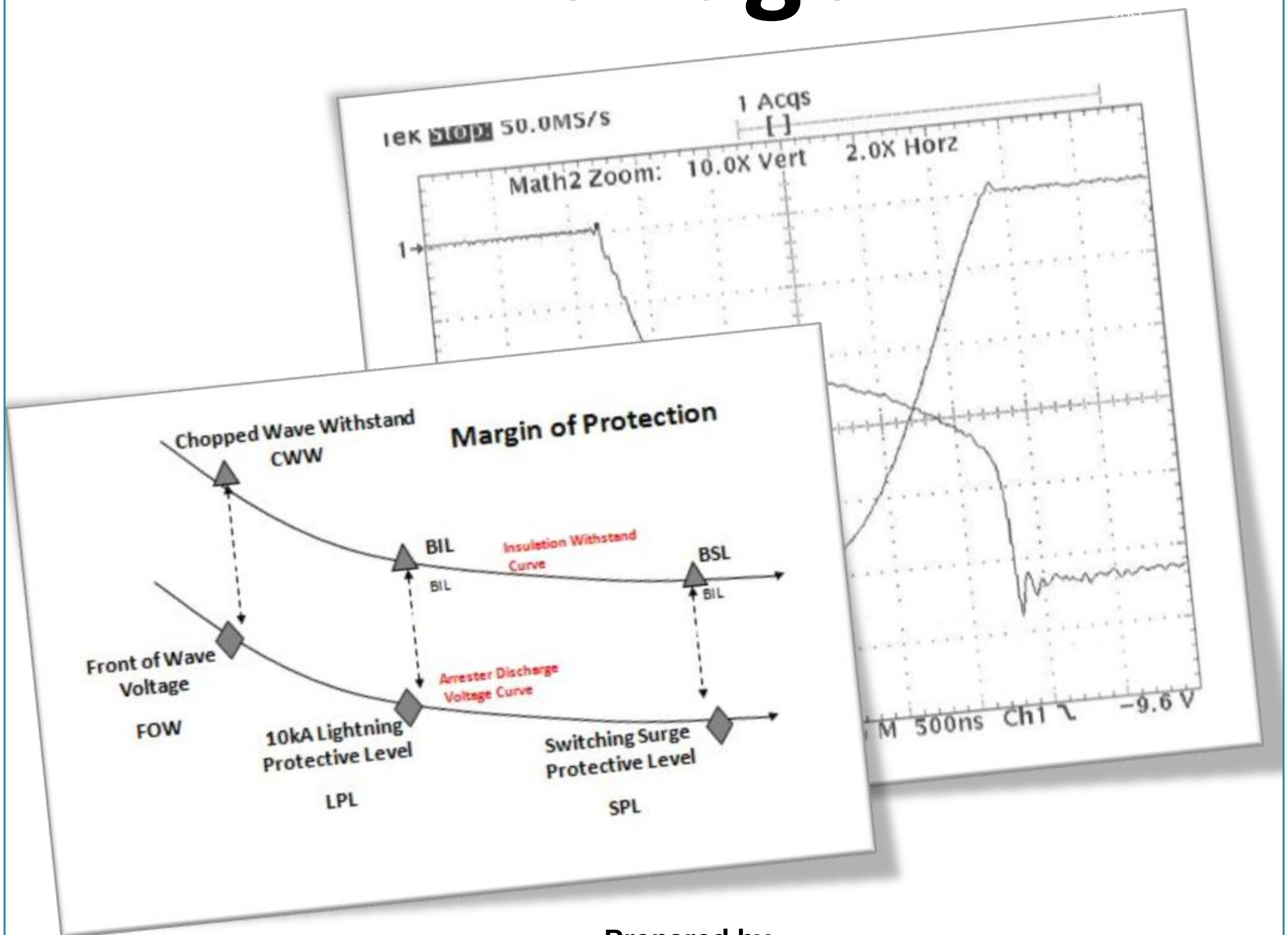
ArresterFacts 013

ArresterWorks

Understanding Arrester Discharge Voltage



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Contents

Introduction

All arresters provide protection to equipment by limiting the voltage across the equipment terminals in the presence of a surge on the system. This voltage limiting characteristic of arresters is the primary feature of an arrester in most cases, and the reason for its existence. The voltage limiting characteristic has several names and has even changed over the years. The term Discharge Voltage is commonly used in the US market while Residual Voltage is used in most other locations around the world. A somewhat obsolete term that describes this characteristic in electrical terms is IR Drop which refers to the voltage across the arrester when a current I passes through the resistance of the arrester R.

In both the IEC and IEEE applications, the term Protective Level is often used in place of discharge voltage. Clamping Voltage is another term sometimes used for discharge voltage. The term Clamping Voltage is more often used when describing low voltage SPD's characteristics. For this document the term discharge voltage will be used and is meant to represent all the other terms used for this voltage limiting characteristic of an arrester.

Definitions

The definition of discharge voltage as published in section 3 of IEEE C62.11 is

3.25 discharge voltage: The voltage that appears across the terminals of an arrester during passage of discharge current.
3.23 discharge current: The surge current that flows through an arrester.

The IEC definition also in section 3 of IEC 60099-4 is
3.36 residual voltage of an arrester ***U*****res**
peak value of voltage that appears between the terminals of an arrester during the passage of discharge current
3.29 discharge current of an arrester
impulse current which flows through the arrester

From the above definitions, it can be seen that the voltage across an arrester during a surge event constitutes discharge voltage. During steady state operation of an arrester, there is generally leakage current passing through the arrester however since it is not surge current, the voltage at steady state is not a discharge voltage. During a switching surge, lightning surge and even high current TOV events, the voltage appearing across the arrester can be considered a discharge voltage.

Application of Discharge Voltage Characteristic

There are three discharge voltage characteristics that together make up the protective level of the arrester.

1. **Front-of-Wave Protective Level (FOW PL)** is the discharge voltage with a rise time of approximately

.5µs. The IEC equivalent to this is the steep current impulse protective level and is the residual voltage across the arrester resulting from a discharge current cresting in 1 µs.

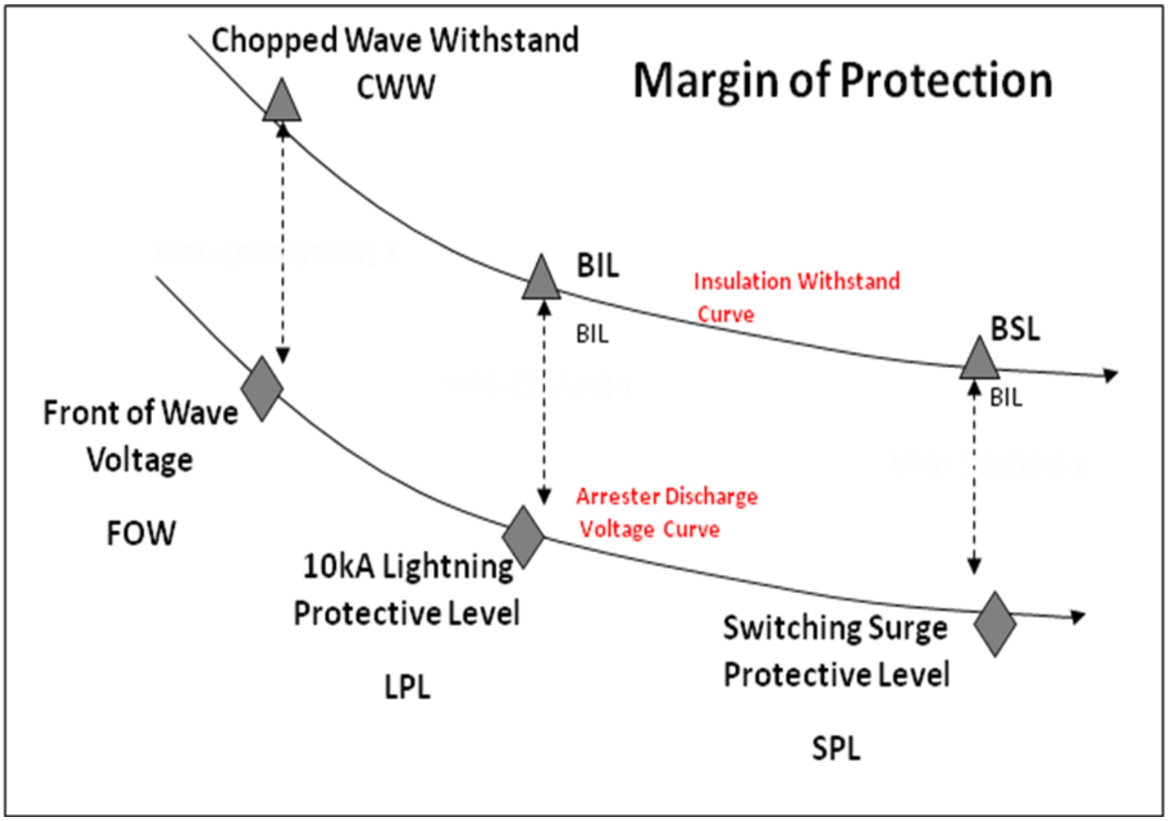


Figure 1: Graphic Overview of Margin of Protection Calculations

2. **Lightning Protective Level (LPL)** is the discharge voltage resulting from a discharge current with an 8-10µs rise time. The IEC term for this is Lightning Impulse Protective Level (LIPL).

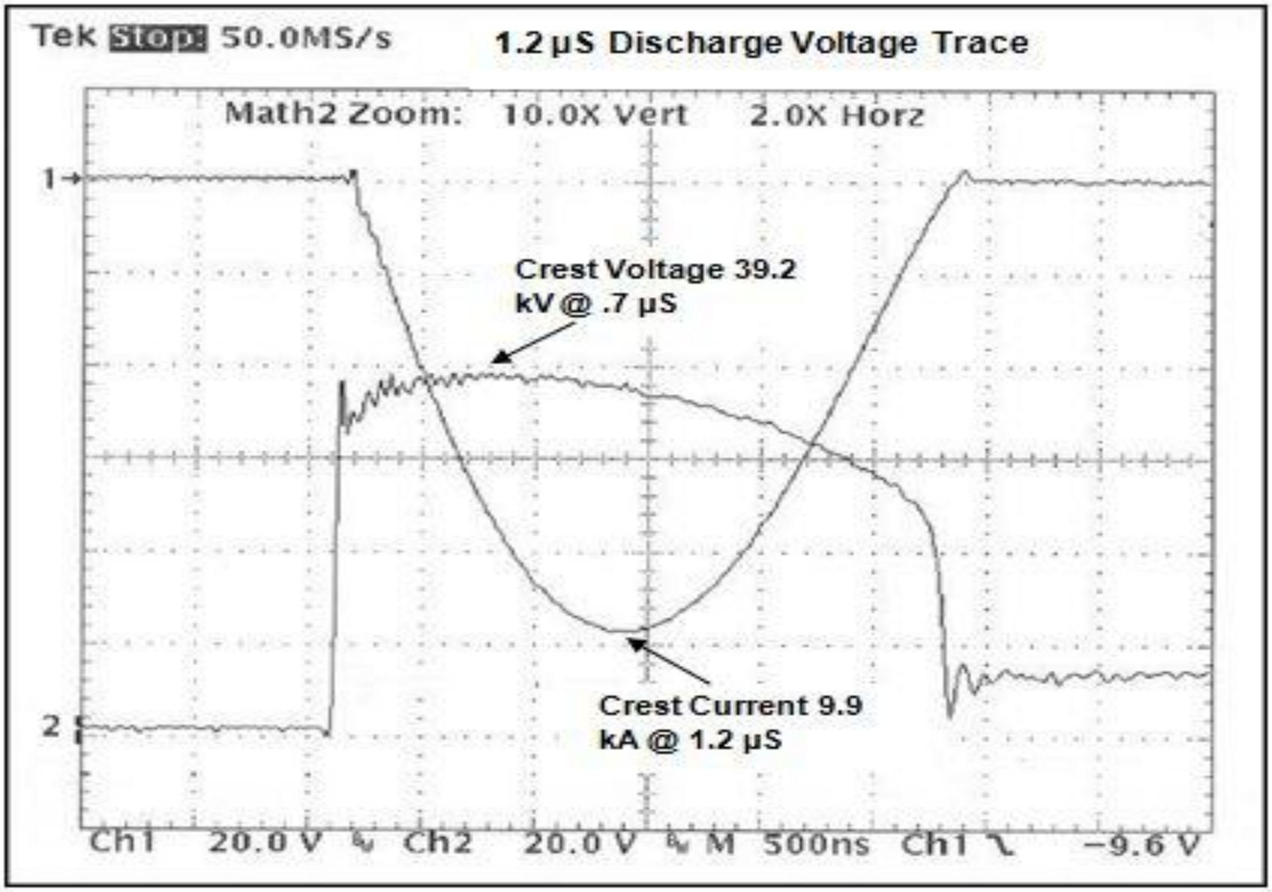
3. **Switching Protective Level (SPL)** is the discharge voltage resulting from a discharge current cresting in 45-60µs. The IEC term for this is Switching Impulse Protective Level (SIPL)

These three discharge voltages are used to determine how well an arrester is protecting nearby equipment. Specifically they are used to calculate the margin of protection. A typical margin of protection exercise is outlined in Figure 1. Margin of protection calculations suggest that the insulation curve should be more than 115% of the arrester discharge voltage curve at a minimum.

Measurement and testing

The measurement of discharge voltage can be very onerous especially in the FOW region of the characteristic. Important considerations when measuring this voltage are:

1. Frequency response of the equipment. Digital oscilloscopes are necessary and the device most often used. Impulse capable current sensors and impulse capable voltage dividers are required.
2. Solid and well connected grounding systems.



3. I

Figure 2: 1.2 µS Discharge Voltage and Current Trace

I

nductance capacitors and wave shaping resistors.

4. Signal filters that provide a real representation of the output of the measuring equipment.
5. Reference samples with very well known characteristics should always be tested before any calibration can be considered complete. Insidious nearly invisible errors can occur with this type of testing and these samples give double assurance that calibration is correct.

A typical output from the test equipment is found in Figure 2.

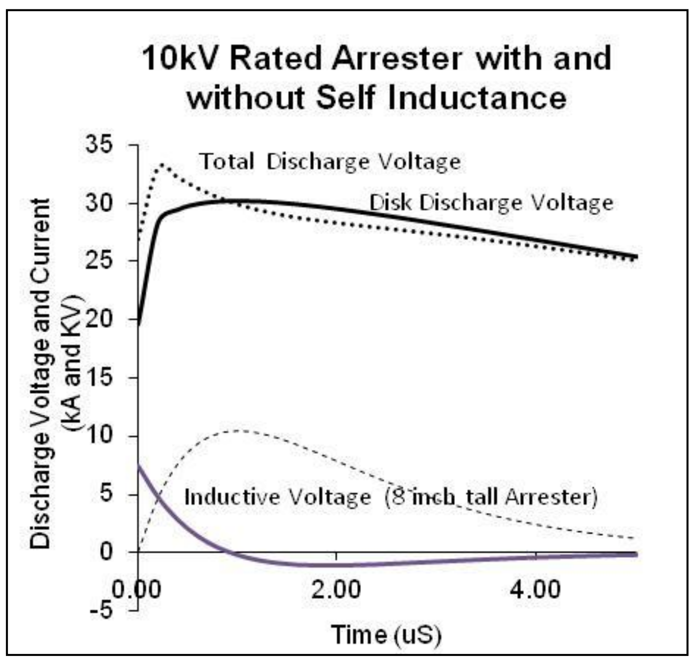


Figure 3: Arrester with and without Inherent Inductive voltage

Inductive and Temporal Behavior

All conductors that have any appreciable length also have inherent inductance and arresters are no exception. Their inductance can become a significant part of the units discharge voltage when the arrester is long. This inductive effect is part of the reason the discharge voltage crests before the discharge current crests as seen in Figure 2.

When measuring discharge voltages using discharge currents cresting in less than 2 µs, on arrester samples shorter than the arrester, it is importance to add conductor to the sample that makes it inductively equivalent to the complete arrester if equivalence is desired. In C62.11 and IEC 60099-4 methods of assembling a realistic prorated section of an arrester are outlined in detail. In 60099-4 a method of measuring the inherent inductance of a MOV disk as also outlined in detail.

Besides the inherent inductance in an MOV arrester, the discharge voltage is influenced by what is known as the temporal transition behavior of a semiconductor. This behavior also appears as inductive behavior, but is a function of the MOV N-Type semiconductor transitioning from a non-conductive state to a conductive state. This effect can be seen at all impulse frequencies, not only the faster rising surges.

Discharge Current Waveshapes

The discharge current waveshapes used for discharge voltage tests were not chosen arbitrarily. The first waveshape used for this type of test more than 50 years ago was the 8/20 current impulse. The story has it that when this type of current wave shape was forced through a Silicon Carbide arrester of that era, the discharge voltage closely resembled a lightning voltage waveshape.

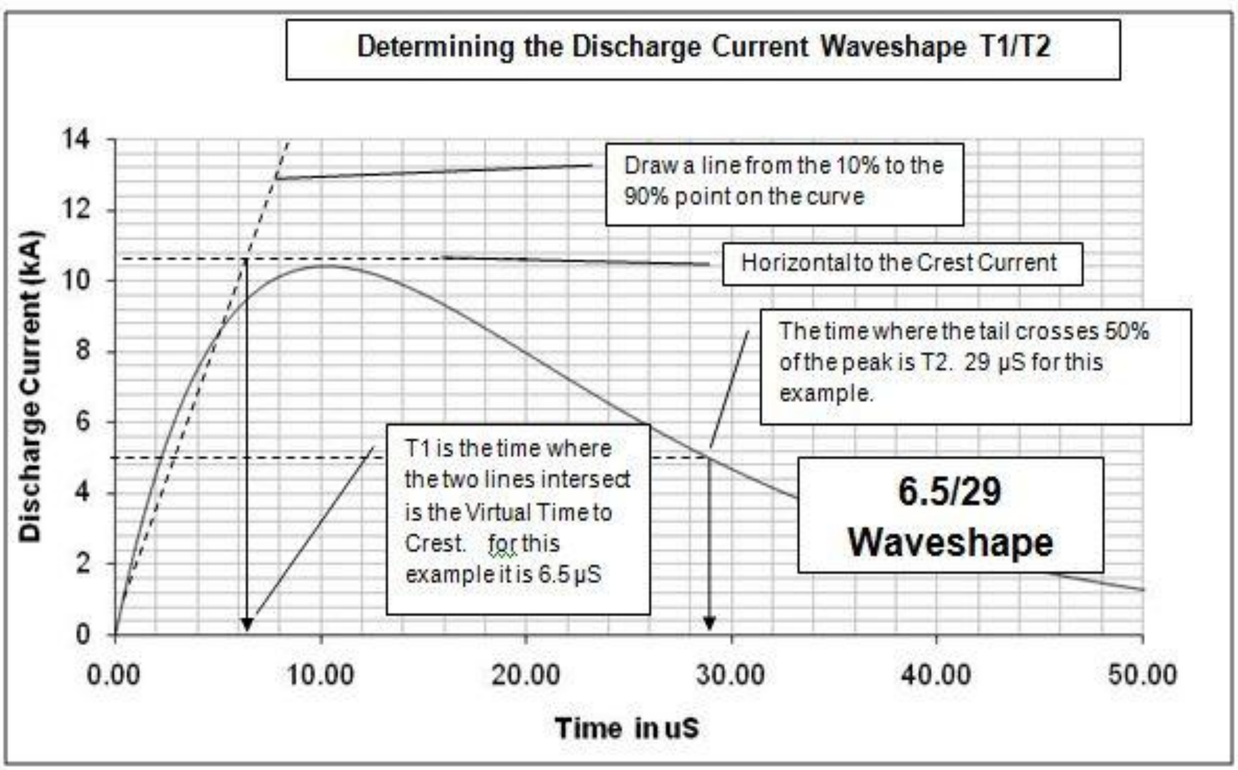


Figure 4: Determining Discharge Current Waveshape

Whether true or not,

the 8/20 waveshape was chosen those many years ago and has remained the standard discharge current waveshape even though it is known not to simulate all lightning current waveshapes. As the understanding of lightning current waveshapes evolved, faster waveshape tests were introduced. To simulate the discharge current of a switching surge on a power line, the slow front and long tail waveshape was adopted.

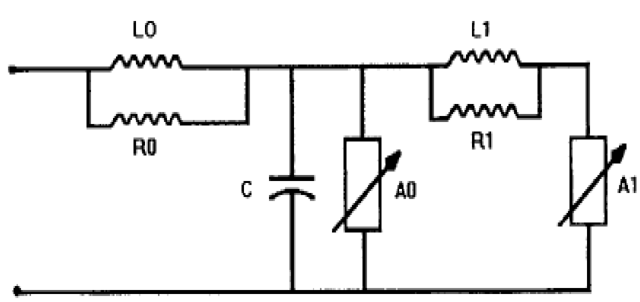
In the course of testing arresters according to C62.11 or IEC 60099-4, the following discharge current waveshapes are used:

1 µs to crest tail is not relevant
2 µs to crest tail is not relevant
8 µs to crest tail is not relevant
4/10 µs
8/20 µs
30 µs to crest tail is not relevant
150 µs to crest tail is not relevant
1000 µs to crest tail is not relevant

The method of measuring the waveshape is accepted worldwide as shown in Figure 4.

Modeling

Modeling the discharge voltage characteristic of MOV arresters has been the topic of many technical papers. Since the characteristic is a combination of non-linear resistance, inductance and transition



behavior of a semiconductor the task has been substantial. A frequency dependent model was developed by a working group of the IEEE Surge Protective Devices Committee in the 90s. It is a practical and accurate model for circuit modeling in most applications.

Where
L1 = 15 d/n
R1 = 65 d/n
d = height of arrester in meters
n = number of parallel columns
L0 = .2 d/n µh
R0 – 100 d/n Ω
C = 100 n/d pF

A0 and A1 can be estimated from the following table

kA	V-I characteristics of AØ	V-I characteristics of A1
	V(p.u.)[a]	V (p.u.)[a]
0.01	1.40	—
0.1	1.54	1.23
1	1.68	1.36
2	1.74	1.43
4	1.80	1.48
6	1.82	1.50
8	1.87	1.53
10	1.90	1.55
12	1.93	1.56
14	1.97	1.58
16	2.00	1.59
18	2.05	1.60
20	2.10	1.61

[a] pu is based on a model element that had a 1.6 kV IR at 10 kA. (See Durbak [B34] for greater detail).

Several other models are explored in a 2003 paper titled "Simulation of Metal Oxide Surge Arrester Dynamic behavior Under Fast Transients" by Bayadi, Harid, Zehar and Belkhiat.

Predicting Peak Discharge Voltage

Predicting discharge voltage at different currents than available in data on hand is often necessary. For this task Equation 1 is a simple and effective model for calculation of discharge voltage if other current/voltage pairs are known.

$e = k*I^n$ Equation 1

Where
e = the discharge voltage
k = constant
I = discharge current
n = nonlinear exponent

If two current-voltage pairs of discharge voltage and current for an arrester are known, the values of n and k for that arrester can be determined with equations 2 and 3.

$n = \ln(E_2/E_1)/\ln(I_2/I_1)$ Equation 2
$k = E_1/I_1^n$ Equation 3

E_1 and I_1 = first voltage current pair
E_2 and I_2 = second voltage current pair

Presentation and Catalog Data

Most arrester catalog sections contain considerable discharge voltage information. Since discharge voltage is a competitive characteristic and does not have a mandated upper or lower limit, the goal of most manufacturers is to have the best possible values to offer. The discharge voltage is often listed for switching surge, lightning surges and fast front surges. It is clearly stated in IEEE C62.11 and IEC 60099-4 as to what the reported value

Station class									
Steady state operation: system voltage and arrester ratings				Protective levels: range of industry maxima per unit of MCOV			Durability characteristics: IEEE Std C62.11-1993		
Max system voltage L-L kV-rms[a]	Max system voltage L-G kV-rms[a]	Min MCOV rating kV-rms	Duty cycle ratings kV-rms	0.5 µs FOW protective level[b]	8/20 µs protective level [b]	Switching surge protective level[c]	High current withstand crest amperes	Trans. line discharge miles	Pressure relief kA rms (symmetrical)[d]
4.37	2.52	2.55	3	2.32–2.48	2.10–2.20	1.70–1.85	65 000	150	40–80
8.73	5.04	5.1	6–9	2.33–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
13.1	7.56	7.65	9–12	2.33–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
13.9	8.00	8.4	10–15	2.33–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
14.5	8.37	8.4	10–15	2.33–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
26.2	15.1	15.3	18–27	2.33–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
36.2	20.9	22	27–36	2.43–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
48.3	27.8	29	36–48	2.43–2.48	1.97–2.23	1.70–1.85	65 000	150	40–80
72.5	41.8	42	54–72	2.19–2.40	1.97–2.18	1.64–1.84	65 000	150	40–80
121	69.8	70	90–120	2.19–2.40	1.97–2.18	1.64–1.84	65 000	150	40–80
145	83.7	84	108–144	2.19–2.39	1.97–2.17	1.64–1.84	65 000	150	40–80
169	97.5	98	120–172	2.19–2.39	1.97–2.17	1.64–1.84	65 000	175	40–80
242	139	140	172–240	2.19–2.36	1.97–2.15	1.64–1.84	65 000	175	40–80
362	209	209	258–312	2.19–2.36	1.97–2.15	1.71–1.85	65 000	200	40–80
550	317	318	396–564	2.01–2.47	2.01–2.25	1.71–1.85	65 000	200	40–80
800	461	462	576–612	2.01–2.47	2.01–2.25	1.71–1.85	65 000	200	40–80
Intermediate class									
4.37–145	2.52–83.72	2.8–84	3–144	2.38–2.85	2.28–2.55	1.71–1.85	65 000	100	16.1[d]

[a]Voltage range A, ANSI C84.1-1989

[b]Equivalent front-of-wave protective level producing a voltage wave cresting in 0.5 µs. Protective level is maximum discharge voltage (DV) for 10 kA impulse current wave on arrester duty cycle rating through 312 kV, 15 kA for duty cycle ratings 396–564 kV and 20 kA for duty cycle ratings 576–612 kV, per IEEE Std C62.11-1993.

[c]Switching surge characteristics based on maximum switching surge classifying current (based on an impulse current wave with a time to actual crest of 45 µs to 60 µs) of 500 A on arrester duty cycle ratings 3-108 kV, 1000 A on duty cycle ratings 120–240 kV, and 2000 A on duty cycle ratings above 240 kV, per IEEE Std C62.11-1993.

[d]Test values for arresters with porcelain tops have not been standardized. Pressure relief classification is in 5 kA steps.

should represent. It is generally understood that values listed in catalog literature should represent the complete discharge voltage which includes the inductive voltage of the arrester and the as well as the native discharge voltage. If the arrester is significantly longer than the MOV disk stack, then the inductive voltage of the inserted spacers also needs to be accounted for and should be contained in the published values.

This short thesis on arrester discharge voltage can get a student of the topic started, but studying high voltage test methods, running the test when possible, and studying IEEE C62.11 and IEC 60099-4 will take you much deeper. Enjoy.

Jonathan Woodworth 12-14-08

Other ArresterFacts Available