Over-Voltages and the Distribution System

IEEE Canada
Northern Canada Section

November 17, 2015

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Discussion Outline - OVERVIEW

- The Origin and Shapes of Distribution System Surges
- Insulation Systems – And How They Go Bad
- Where Surges Matter – And What They Do
  - Overhead Systems
  - Underground Systems
- Distribution Surge Arresters – Design and Application
- Reality Check
- Q & A

NOTE: References are in parenthesis - (xx)

Disclaimer

I will mention many companies during this presentation.

Please keep in mind:

1 – I have NO financial interest or otherwise in any of the companies I mention

2 – I work for ATCO Electric Distribution and that is my only source of income

3 – This presentation is my opinion only and does not necessarily reflect ATCO policy, practices, or standards

4 – I expect that you will use this presentation for illustrative purposes only. Any arrester applications you design shall be based on your own professional judgement

The Origin and Shapes of Distribution System Surges

- Overhead


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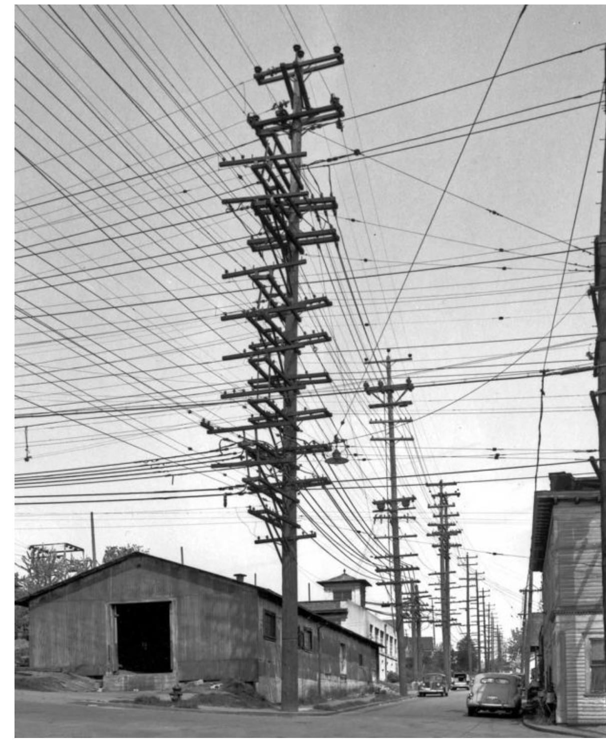
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- Underground – Mostly same as O/H, but with some twists!

What is a Surge?

Surge

- IEEE Std 100: “A transient wave of current, potential, or power in an electric circuit. Note: The use of this term to describe a momentary overvoltage consisting in a mere increase of the mains voltage for several cycles is *deprecated*. See also: swell.”

Temporary Overvoltage (TOV)

- IEEE Std 100: “. An oscillatory overvoltage, associated with switching or faults … and/or nonlinearities … of relatively long duration, which is undamped or slightly damped.”

TOV
It is NOT a Surge!

- Accidental Grounding - Leg of Delta
- Loss of Neutral
- Fault Conditions
- Comingling

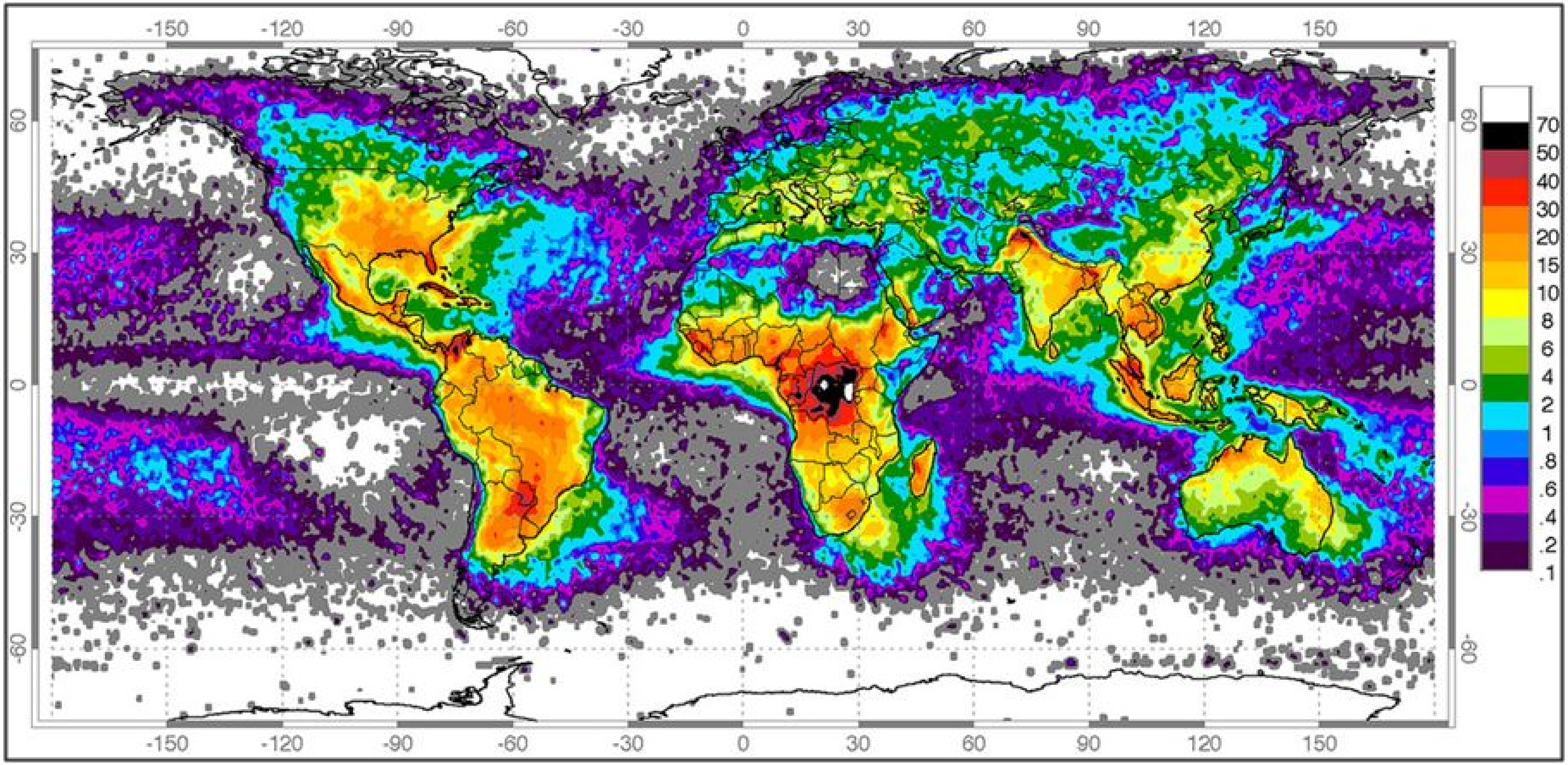
"When Overbuild Meets Underbuild"

Surge arresters provide a simple solution to a complex overvoltage problem

Daniel J. Ward, Dominion Virginia Power

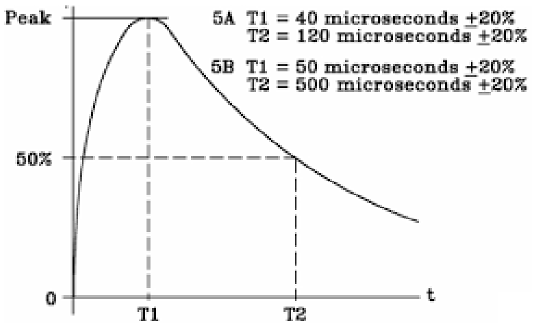
T&D World Magazine - Mar 1, 2011

World Ground Flash Density



www.arresterworks.com/resources/calculator_images/GFD_World.jpg

A Natural Cause - Lightning



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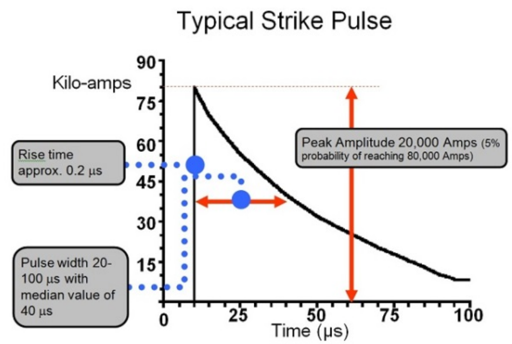

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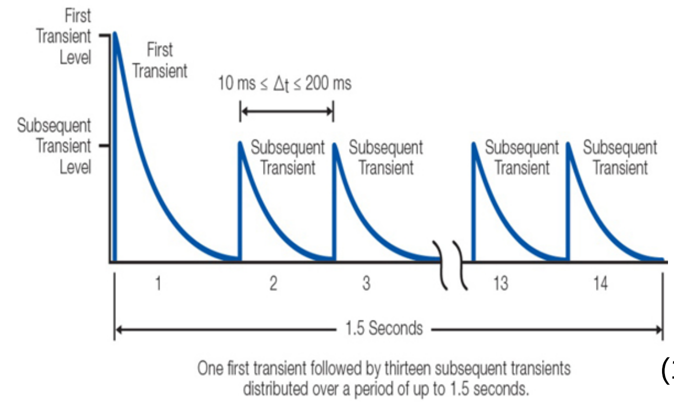

Figure 3. Multiple stroke transient waveform

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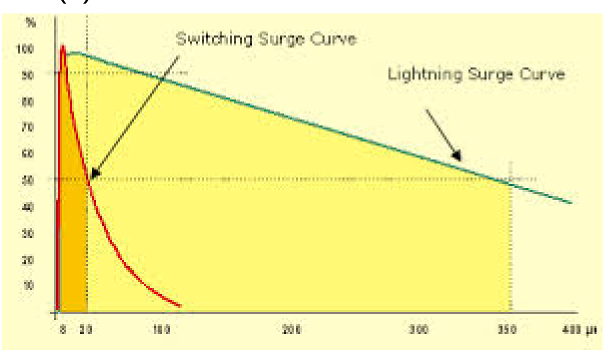
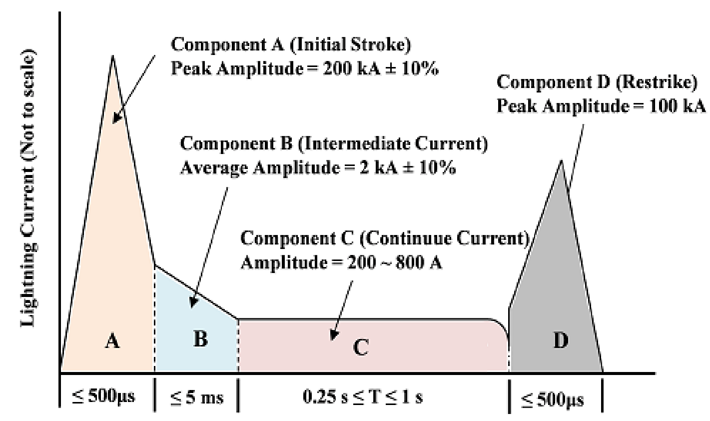




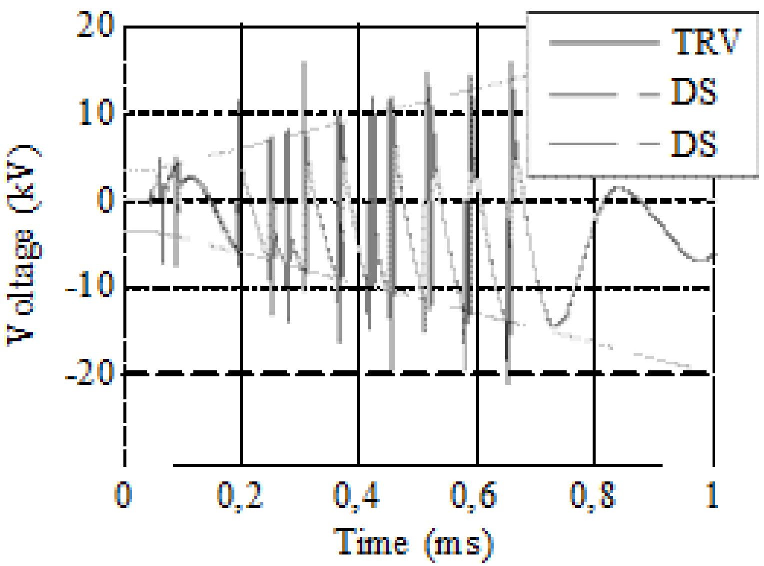
Lightning Current MIL-STD-464

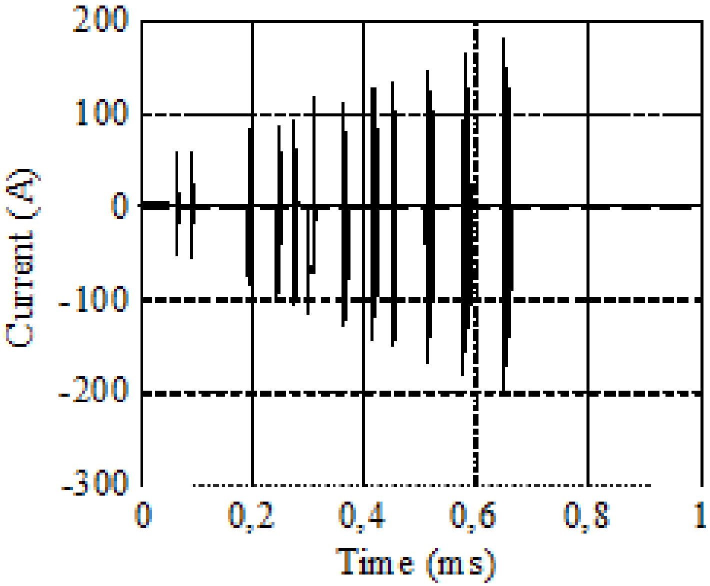
Vacuum Switch TRV Behavior (7)

Simulated TRV Response

Source Voltage: 3.4 kV (6 kV System)

Current at Opening: 4.7 A





Shunt Capacitors

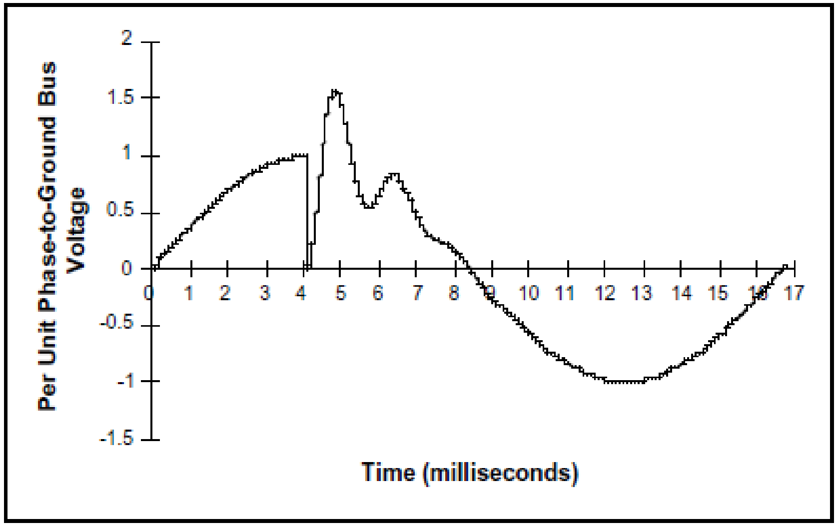
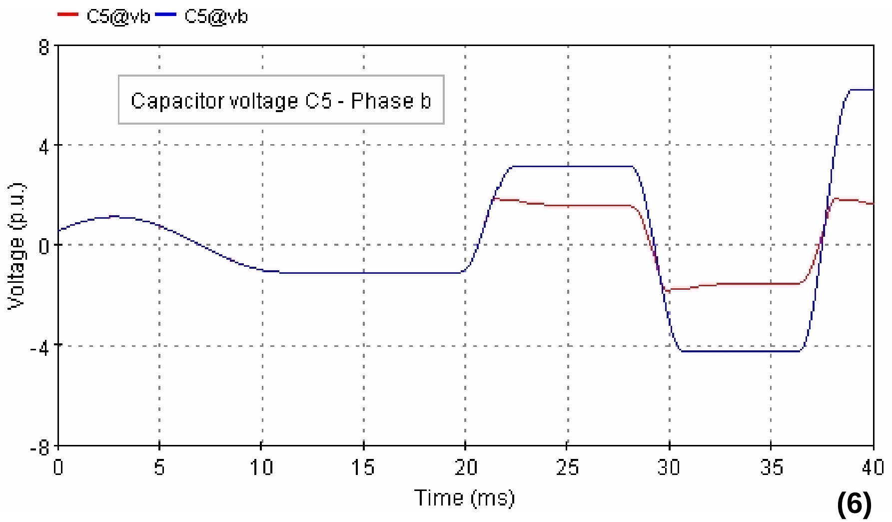


Figure 1. Typical overvoltage transient at the switched capacitor bank bus when energizing a shunt capacitor bank. **(5)**

Effect of switching re-strikes on capacitor voltage



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Current Limiting Fuse Operation

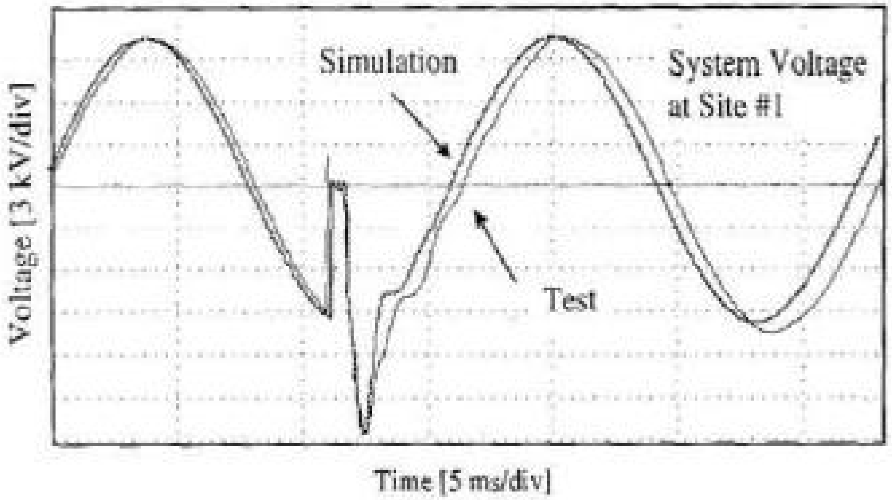


Figure 1. Voltage distortion caused by current-limiting fuse operation (Kojovic*et al*., 1998). **(11)**

Current Limiting Fuse Arc Interruption Voltage

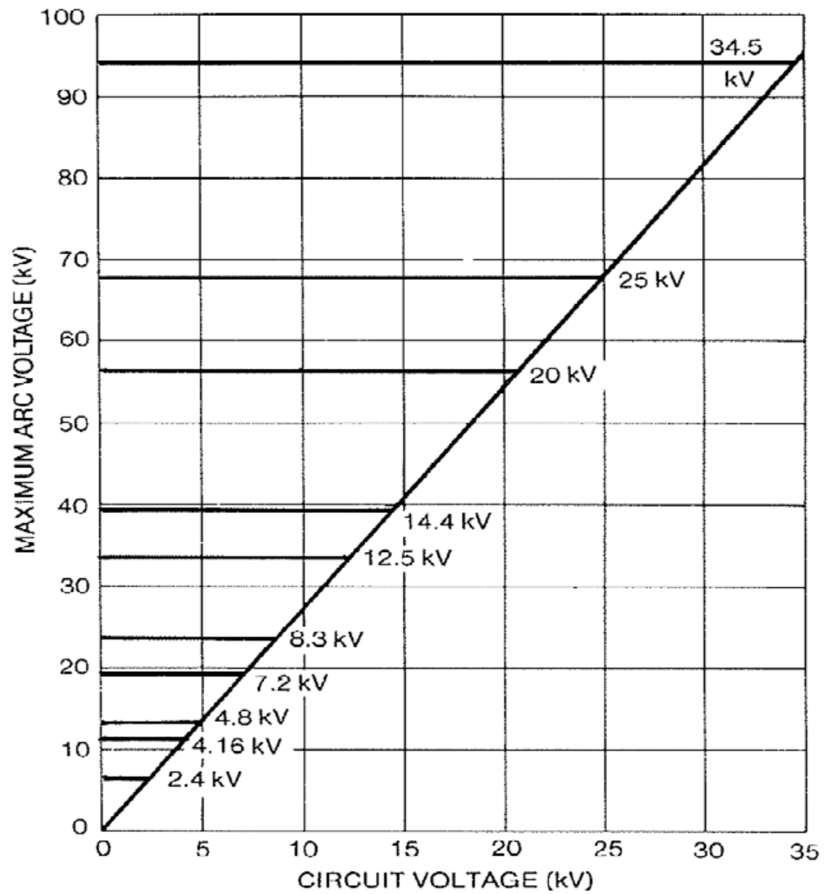


Figure 18B1.
Maximum arc voltage that can be produced by a ribbon-element current-limiting fuse. (34)

Other Surge Waveforms

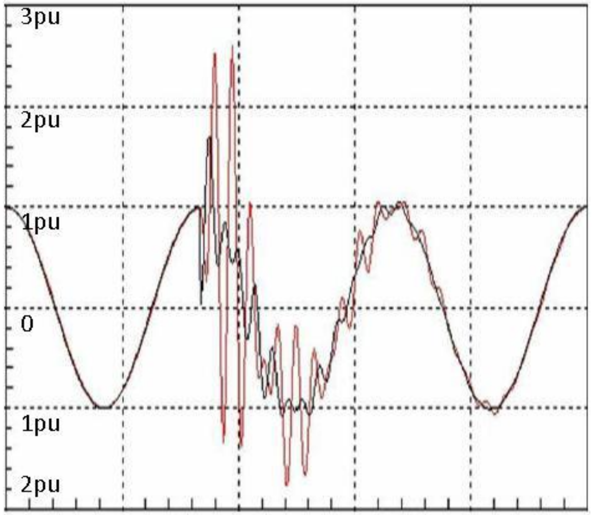
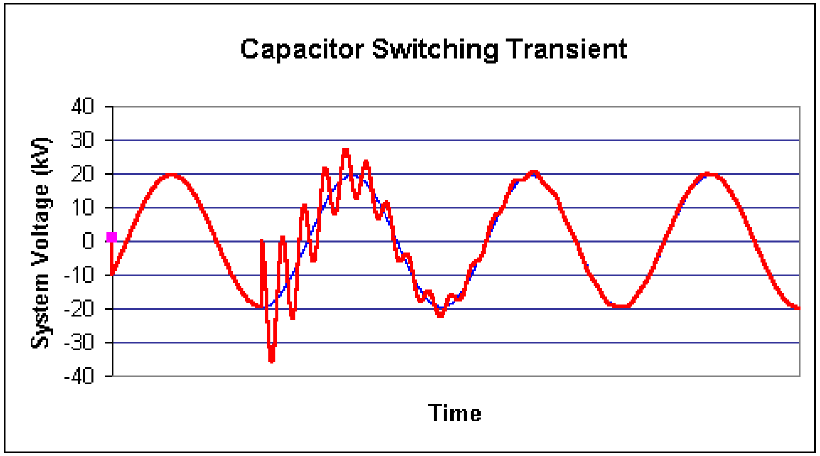


Figure 1 Typical Switching Surge Effect on a Power System

Switching Surge (36)



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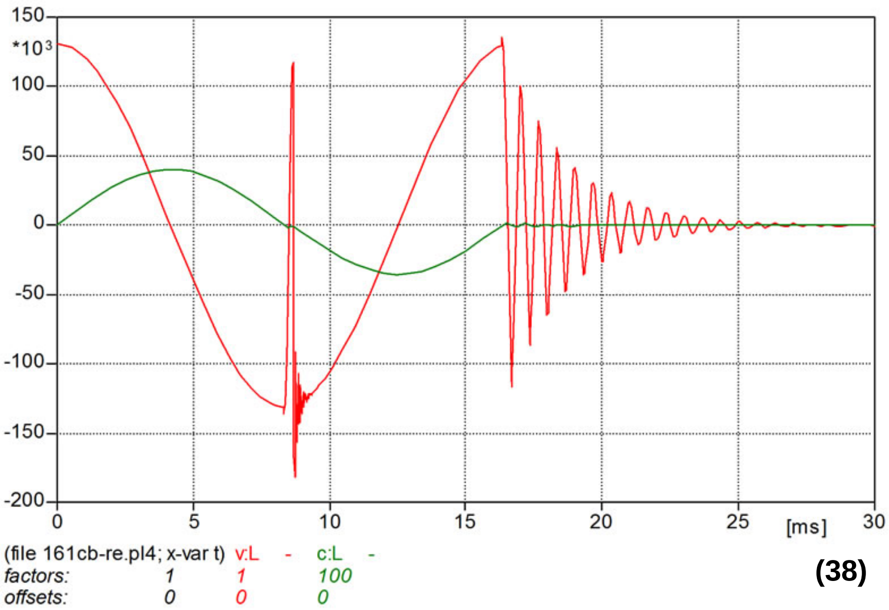

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Surges and Their Waveforms

Just So YOU Know…

Lead Length can ADD up to 1500 Volts/Foot

Lead length is the physical wire distance between the Apparatus and the Line Side of the Surge Arrester

PLUS (+)

The Line Length from the Ground of the Surge Arrester to the Ground of Apparatus

AND for the Love of Goodness,

Please Don't COIL the Leads!!!

Insulation Systems
And How They Go Bad

If we lived in a perfect world, our insulation systems would last forever. But…

We don't.

All Insulation Systems are Doomed from the Start!

- Embedded Manufacturing Defects
- Environmental Contamination
- Shipping and Handling
- "Some" Field Assembly Required

(32)

Insulation Systems– How Do They Fail?

External Sources

- Physical Damage – “Rocks and Rifles”, External Arc
- Contamination – Farming, Exhaust, Salt, etc.

Internal Sources

- Water Ingress
- Arcing under Oil or SF_6
- “Built-In” Defects – Either from Vendor or Customer

Insulation Systems
Contamination and Built-In Defects

Contamination – Surge Arresters Really Won’t Help

- The Failure Mechanisms Associated with Contamination are Active at 60 Hz System Voltage

“Built-In” Defects – Surge Arresters May Help

- If the Failure Mechanism is Triggered by a Surge, then a Surge Arrester will *Delay* the Trouble
- If the “Built-In’ Defect is Active at System Voltage, then a Surge Arrester Won’t Help.

Insulation Systems – Failure Triggers

Contamination

- Dry Band Arcing is the Beginning of the End

"Built-In" Defects

- It is All About Capacitance, Dielectric Constants, and Dielectric Strength
- $C = (k*\varepsilon_0*A)/d$

where k: Air =1, Silicone = 4, EPDM = 2.6

Glass = 6, Polyethylene = 2.25, Porcelain = 6

Which Equals an **Evil** Voltage Divider

Ceramic / Glass

- One Tough Insulation System!
- Can Last a Century or More
- Surges / Flashovers are Generally Benign

Failure Mechanisms

- Slow Clearing Times Crack Ceramic/Glass
- Susceptible to Point Pressures Resulting in Crack Propagation
  - Pin Threads (lead/nylon)
  - Ice Expansion Forms Cracks
- External Contamination / Cleaning

Polymers

Organic/Semi-Organic System

- Manufacturing Process Sensitive

Failure Mechanisms

- Embedded Manufacturing/Material Defect
- If Small Enough, the Defect Lays Dormant Longer
- Surges Reduce PD Inception Levels
- Ultimate Demise of Insulator

(31)

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Dielectric Fluid – Oil (29)

1. **Oxidation:** Oxidation is the most common cause of oil deterioration, which is the reason that transformer manufacturers are careful to seal the transformer from the atmosphere.
2. **Contamination:** Moisture is the main contaminant. Its presence can react with the oil in the presence of heat. It also lowers the dielectric properties of the insulating oil.
3. **Excessively high temperature:** Excessively high heat will cause decomposition of the oil and will increase the rate of oxidation. The best way to avoid excessive heat is to avoid overloading the transformer.
4. **Corona discharges:** Arcing and localized overheating can also break down the oil, producing gases and water, which can lead to the formation of acids and sludge.
5. **Static electricity:** The existence of an insulating fluid flowing past an insulating solid (paper), results in charge separation at the interface of the two materials. Physically, these charges separate at the interface of the oil and paper in any transformer; thus reducing the dielectric strength of the insulating oil. This could also cause internal flashover.
6. **Furans:** Furan derivatives are a measure of degradation of paper insulation. When the paper ages, the long-chain cellulose molecules (polymers) break down in smaller fractions and its physical strength is reduced. The degree of polymerization can be directly related to the concentration of furan derivatives, which are formed in the oil.

SF_6 (28)

Sulfur hexafluoride (SF6) is a relatively nontoxic gas used in a number of applications for its **inert qualities**. The dielectric and other physical and chemical properties related to its **lack of reactivity** have led to the extensive use of SF6 as an insulating medium in switching equipment (e.g., circuit breakers) by electric utilities. While SF6 is inert during normal use, when electrical discharges occur within SF6-filled equipment, toxic byproducts can be produced that pose a threat to health of workers who come into contact with them.

SF6 can decompose into byproducts when exposed to four types of electric discharges (CIGRE1 1997)

- partial corona discharges caused by insulation defects;
- spark discharges that occur at insulation defects or during switching operations;
- switching arcs that occur in load break switches and power circuit breakers; and
- failure arcs that occur due to insulation breakdown or switchgear interruption failure.

Each discharge can result in different mixtures and concentrations of byproducts.

Where Surges Matter ~ *OVERHEAD SYSTEMS* And What They *Do* There

Pin Insulator

Transformer

Regulator

Capacitor

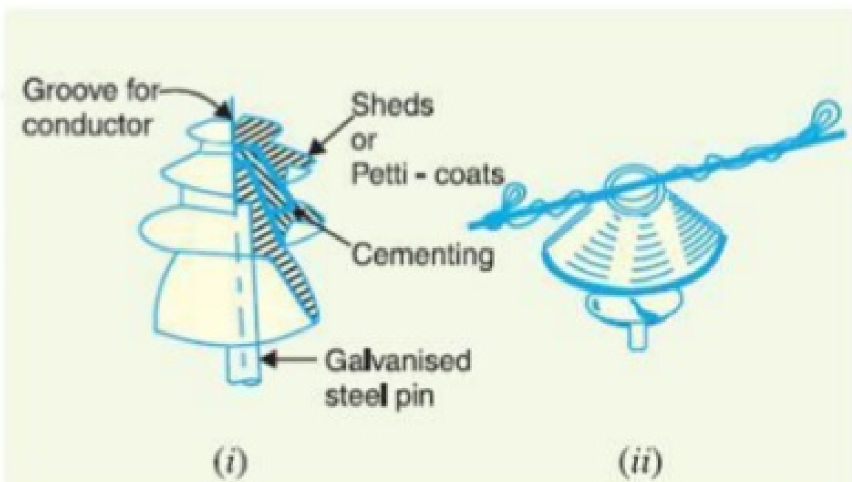
Riser Pole

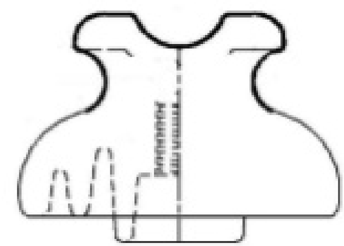
On the Secondary

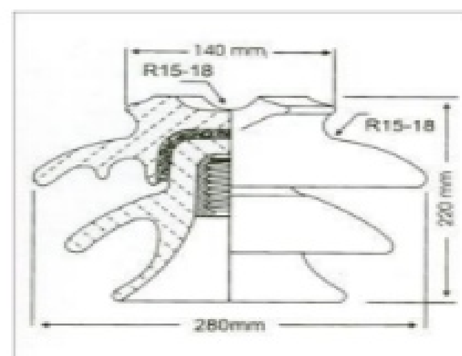
At the Pin Insulator (16)

PIN TYPE INSULATORS

Pin type insulators are used for transmission and distribution of electric power at voltages upto 33 kV. Beyond operating voltage of 33 kV, the pin type insulators become too bulky and hence uneconomical.

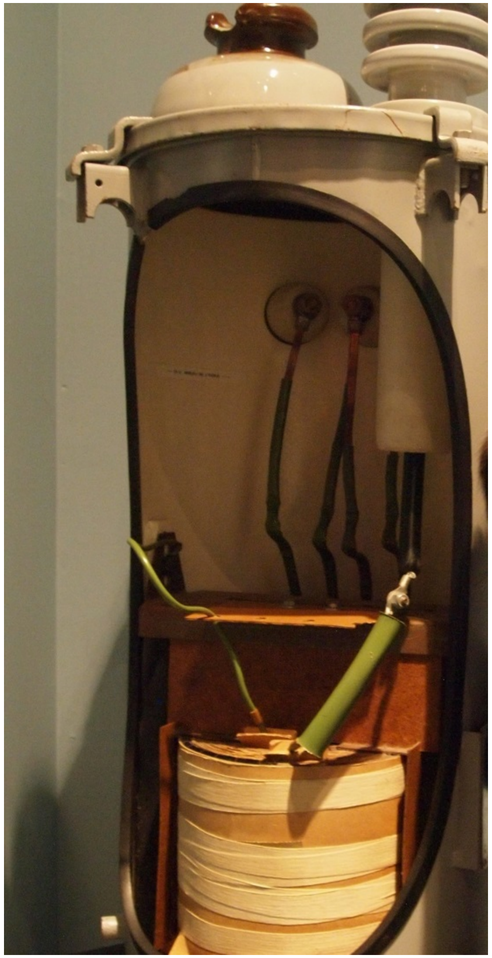






At the Transformer

(9)



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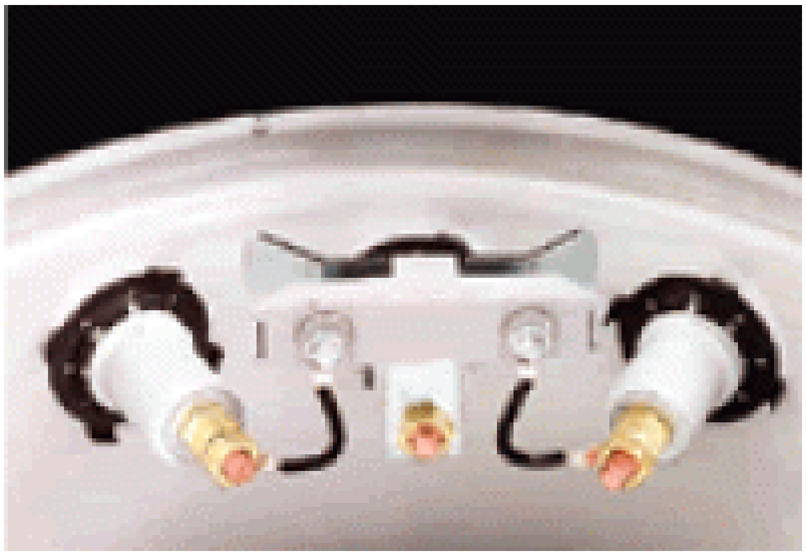
At the Secondary
Transformer Secondary Protection

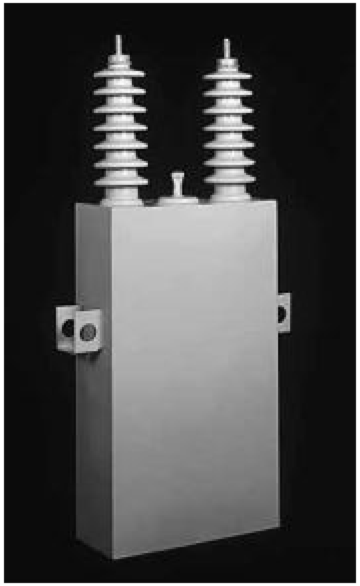
Surge Suppression Inc.



At the secondary bushing – Inside (9)

EATON's Cooper Power Systems

At the Capacitor (17)



(18)

(17)

At the Regulator

(35)

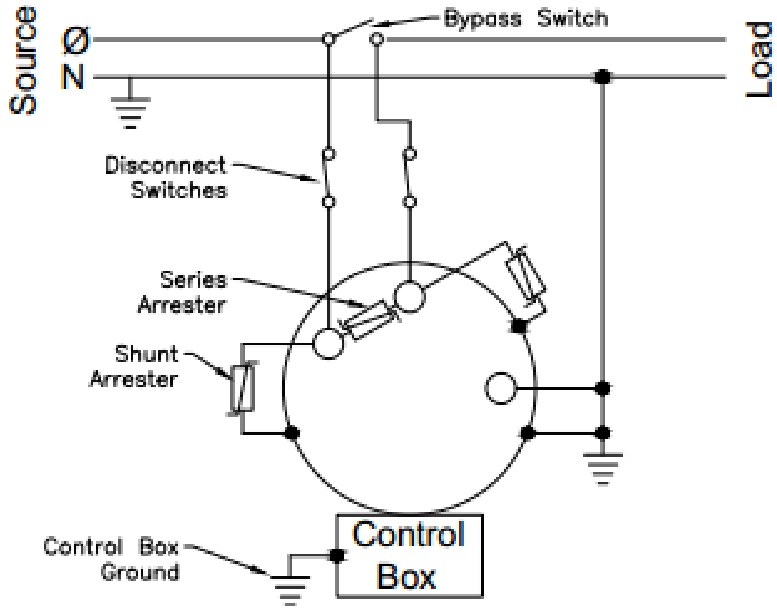
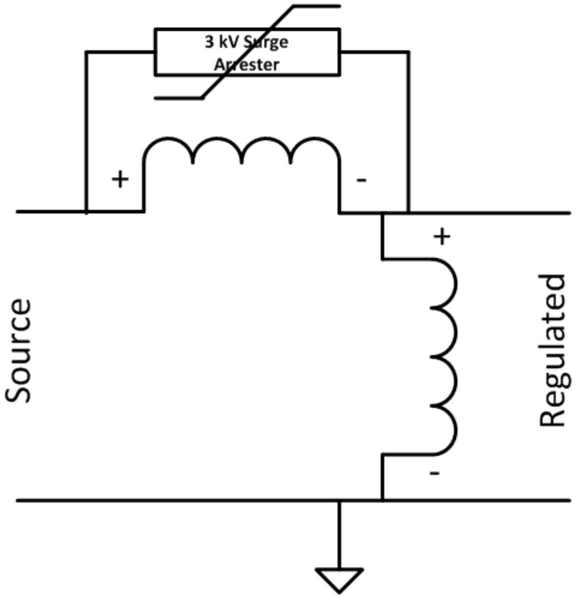


Figure 3. Regulating a single-phase circuit.

(19)

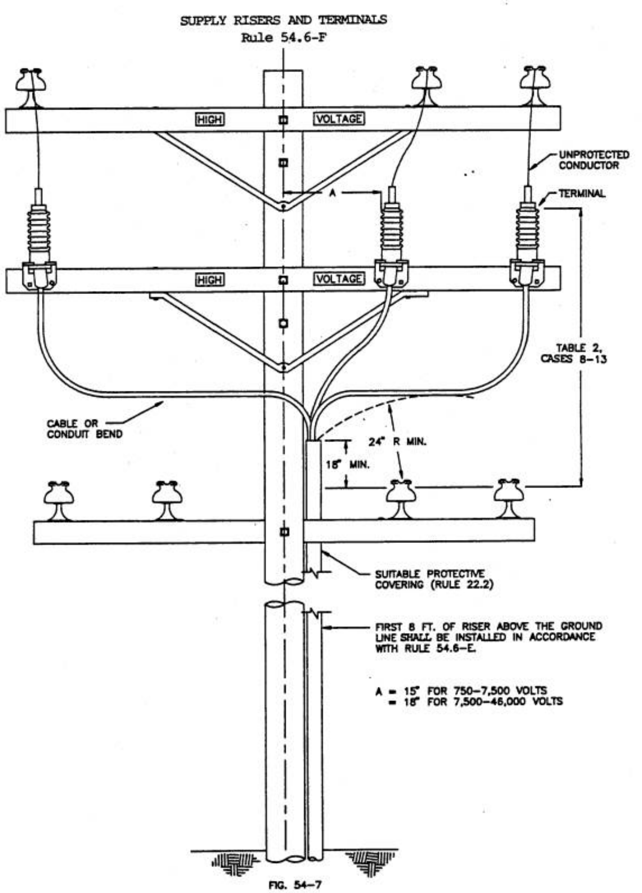


Where Surges Matter ~ *<u>UNDERGROUND</u>* And What They *Do* There

Underground Systems

- Riser Pole
- Cable
- At an “Open Point”

At the Riser Pole



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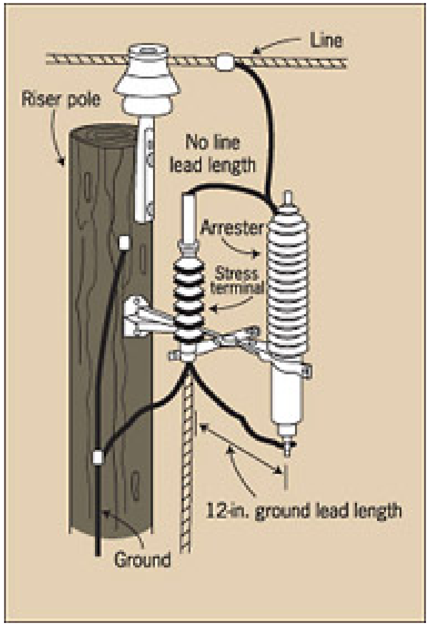

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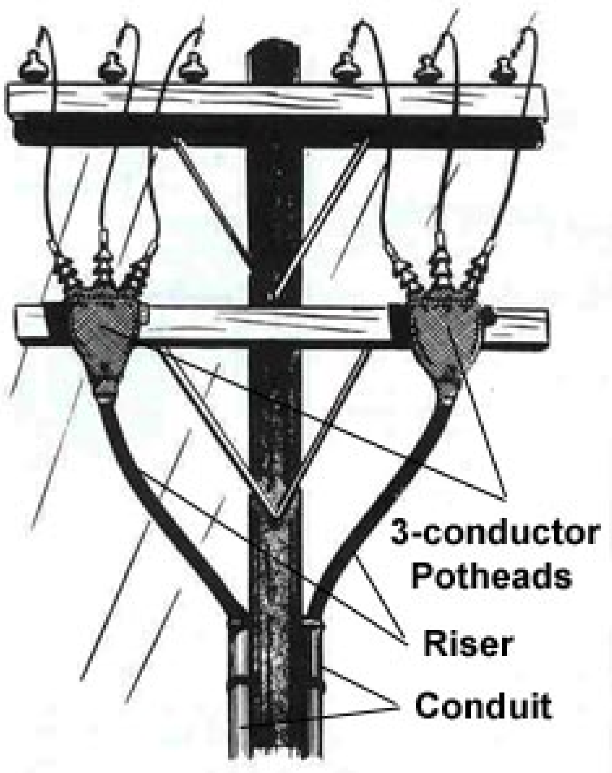

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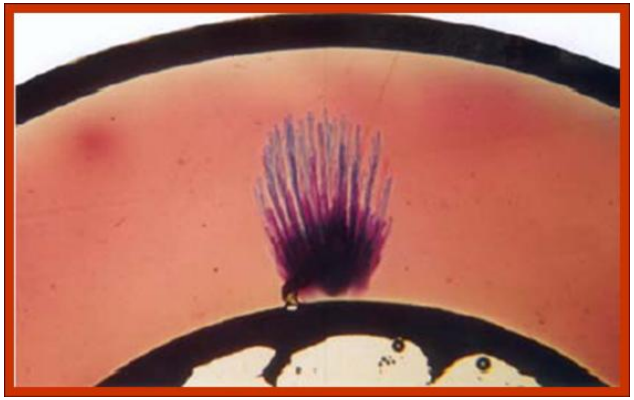
In the Cable

(25)



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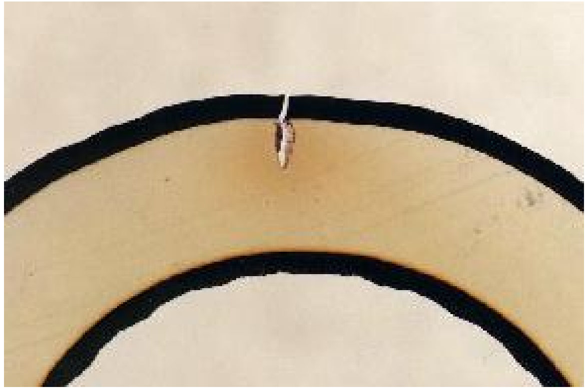

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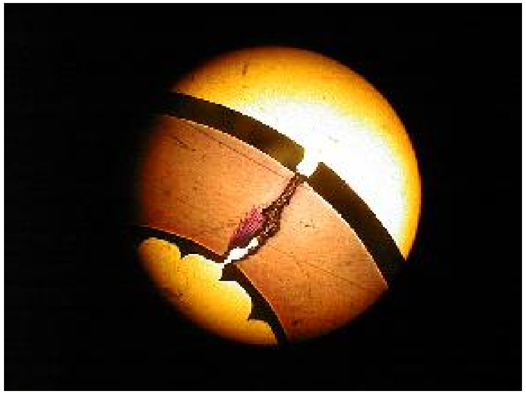

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At an “Open Point”

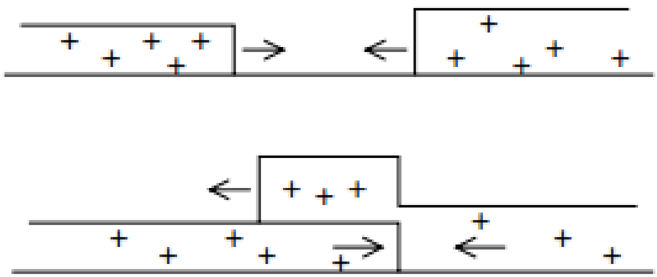

FIGURE 12.7
Forward and backward traveling waves passing each other.

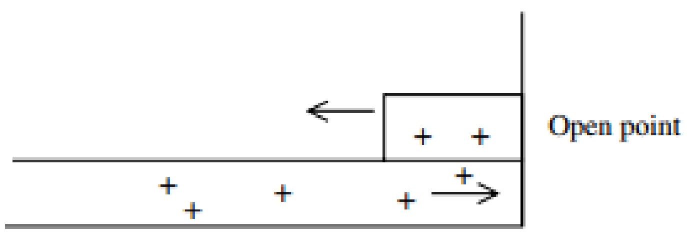

FIGURE 12.8
Traveling wave reflection at an open point.

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At ANY Place on your System

Just So YOU Know…

Lead Length can ADD up to 1500 Volts/Foot

Lead length is the physical wire distance between the Apparatus and the Line Side of the Surge Arrester

PLUS (+)

The Line Length from the Ground of the Surge Arrester to the Ground of Apparatus

AND for the Love of Goodness,

Please Don't COIL the Leads!!!

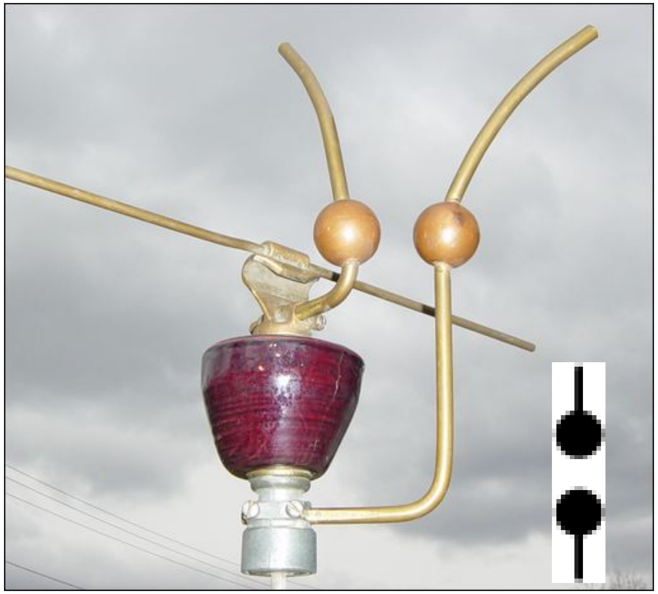
Distribution Surge Arresters
Design and Application

- A Very Brief History of Surge Arrester Evolution
- Explanation of Surge Arrester "Classes"
- Which Class to Use
- How Arresters Eventually Fail

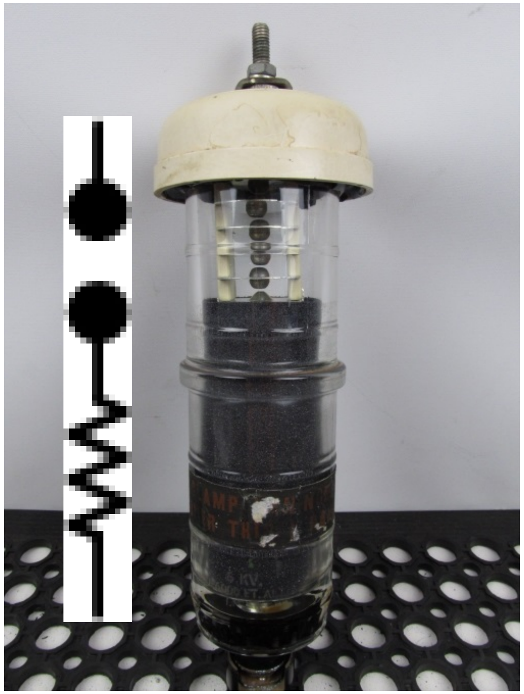
- Surge Arresters have **ONE** Job – Protect Insulation

A Brief History

- Air Gap – Beginning of Time to Now
- Silicon Carbide (SiC) – 1930 to Mid 1980s
- Metal Oxide Varistors (MOV) – 1975+



http://www.arresterworks.com/



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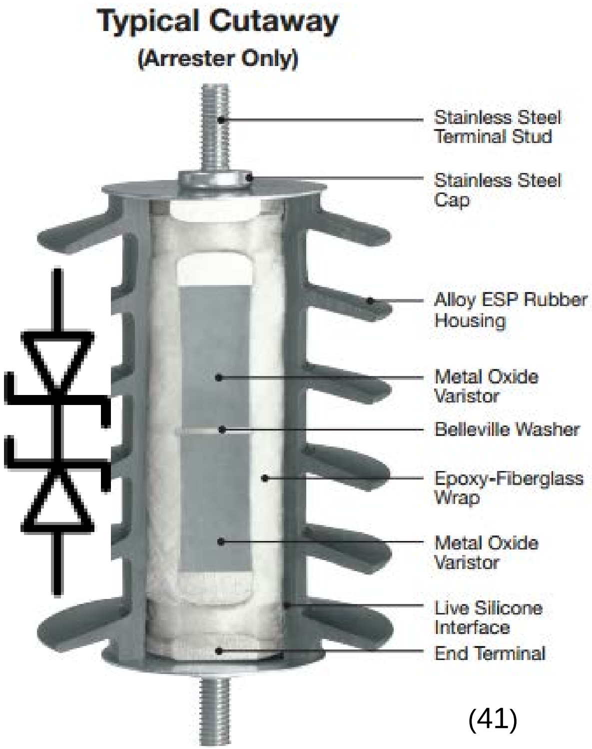

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Differences Between Manufacturers

- None Really
- Arresters are essentially **COMMODITIES**
- Purchase on your preferences such as:
  - Price
  - Vendor Service
  - Availabilities
  - Vendor Preference
  - Etc.
- You will likely be satisfied!
- My Preference???

Surge Arresters – Parameters

<u>Critical Parameters</u> (Minimum Needed)

1. **MCOV** – Maximum Continuous Operating Voltage
2. **TOV** – Temporary Over-Voltage Withstand
3. **EFOW** – Equivalent Front-of-Wave (0.5 μS, Lightning)

<u>Lesser Parameters</u> (May be hard to Coordinate)

4. **Discharge Voltage** – At: 1.5 kA, 5 kA, 10kA, & 20 kA
5. **Switching Surge** – 250 or 500 amps (Class Dependent)
6. **Arrester Class –** ND, HD, RP, Intermediate, Station

Only **6**?!, Really?!

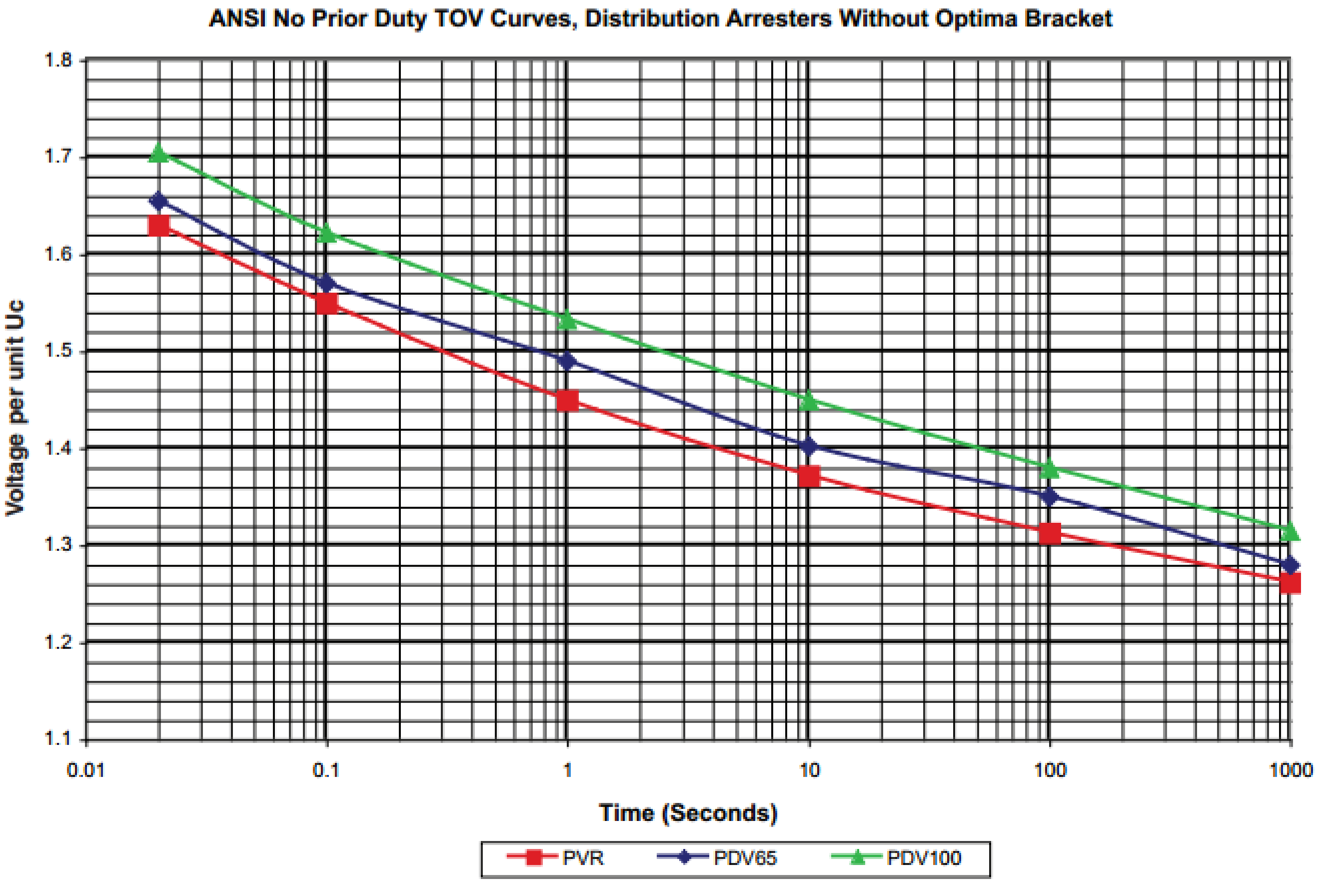
But What is a Surge Arrester RATING?!

Critical Parameter #1 – MCOV

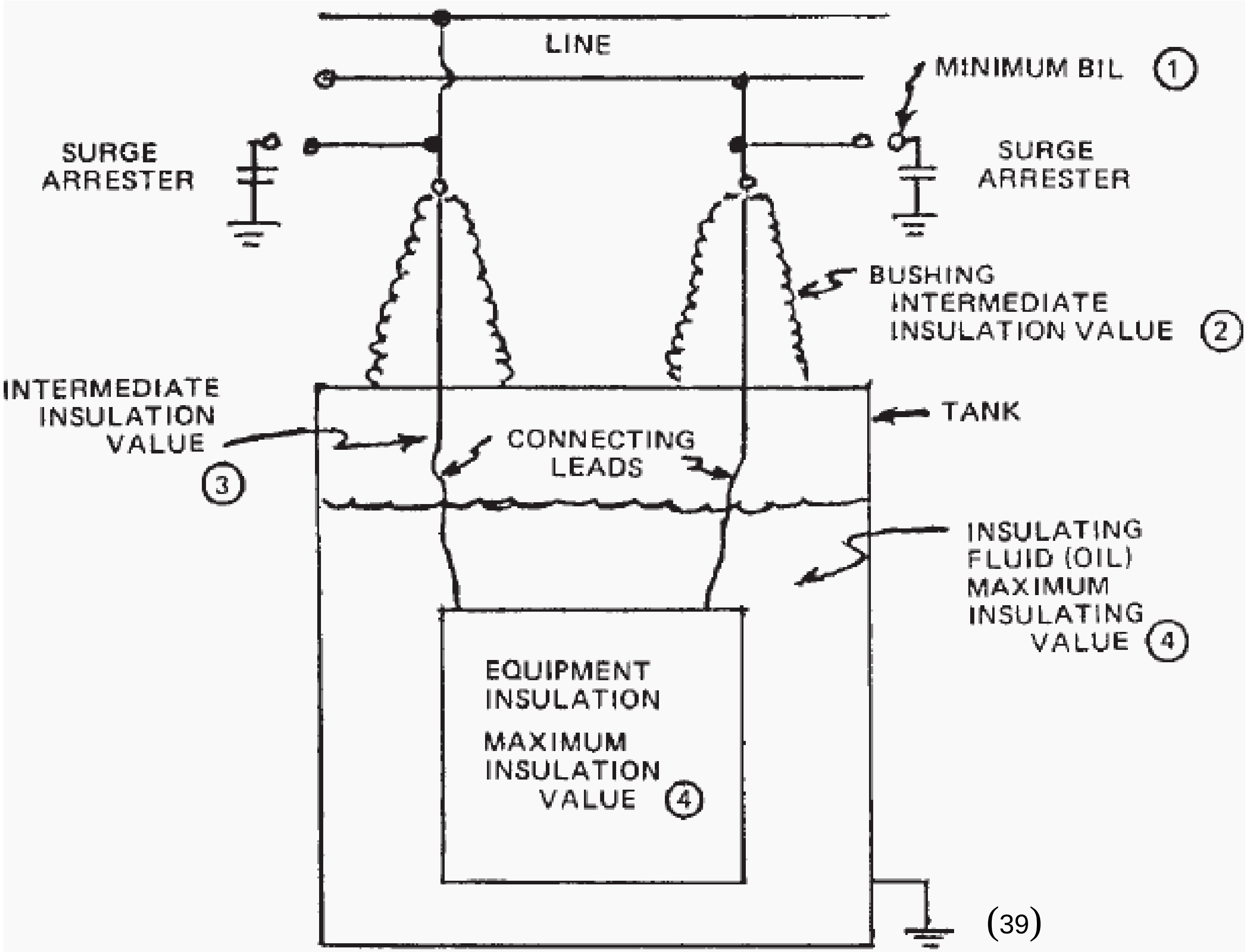
Nominal System L-L Voltage	Maximum L-L Voltage	Maximum Line to GND Voltage		Solid Multi-Grounded Systems (4-Wire)	Uni-Grounded Systems (3-Wire)	Impedance Grounded, Ungrounded, and Delta Systems
kV rms	kV rms	kV rms		MCOV	MCOV	MCOV
4.16	4.37	2.25		2.55	5.1	5.1
4.8	5.04	2.91		--	--	5.1
6.9	7.25	4.19		--	--	7.65
24.9	26.2	15.1		15.3	22	--

Do You See a RATING Here?

Critical Parameter #2 – TOV (41)



Critical Parameter #3 – EFOW (BIL)



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Lesser Parameters 4 & 5

4. **Discharge Voltage** – At: 1.5 kA, 5 kA, 10kA, & 20 kA
5. **Switching Surge** – 250 or 500 amps (Class Dependent)

These two parameters will one used based on the type of equipment you are protecting.

The Discharge Voltage is use at the “End” of Lightning Protective Levels.

Capacitors – Coordinate to Surge Arrester

Schneider Electric – Hong Kong

General Specification for Fixed Capacitor Bank for Electrical Network up to 36kV

According to network rated voltage, the insulation level of equipment is as follows :

Rated Voltage (Vdim)	Insulation Level	Power Frequency Voltage Withstand (kV rms)	Impulse Voltage Withstand (kV peak)
(V)	(kV)		
6600	7,2	20	60
11000	12	28	75
15000	17,5	38	95
22000	24	50	125
33000	36	70	170

Insulators – Coordinate to Surge Arrester

PPC Pin Type Insulators

Catalog Number	Frequency	253-S	261-S	263-S	366-S	380-S	386-ST
ANSI Class		55-2	55-3	n/a	55-4	55-5	55-6
Neck Type		C	C	C	F	F	J
Typical Application (kV)	**60 Hz**	**7.2**	**11.5**	**11.5**	**13.2**	**14.4**	**23**
Dry Flashover Voltage (kV)	**60 Hz**	**45**	**55**	**55**	**65**	**80**	**100**
Wet Flashover Voltage (kV)	**60 Hz**	**25**	**30**	**30**	**35**	**45**	**50**
Puncture Voltage (kV)	**60 Hz**	**70**	**90**	**90**	**95**	**115**	**135**
Impulse Flashover Positive (kV)	**Impulse**	**70**	**90**	**90**	**105**	**130**	**150**
Impulse Flashover Negative (kV)	**Impulse**	**85**	**110**	**110**	**130**	**150**	**170**
Leakage Distance		5"	7"	7"	9"	12"	15"
Dry Arcing Distance		3 3/8"	4 1/2"	4 1/2"	5"	6 1/4"	8"
Cantilever Strength (lbs)		2500	2500	2500	3000	3000	3000
Minimum Pin Height		4"	5"	5"	5"	6"	7 1/2"
Net Weight per 100 (lbs)		183	225	260	390	500	890
Package Weight per 100 (lbs)		191	254	288	400	617	938
Standard Package Quantity		48	24	24	12	12	8

Arrester Class - Parameter #6

- Normal Duty (ND)
- Heavy Duty (HD)
- Riser Pole (RP) (Not a *Real* Class)
- Intermediate Class
- Station Class

Arrester Class size is *Mostly* Determined by the *Diameter* of the MOV Disk

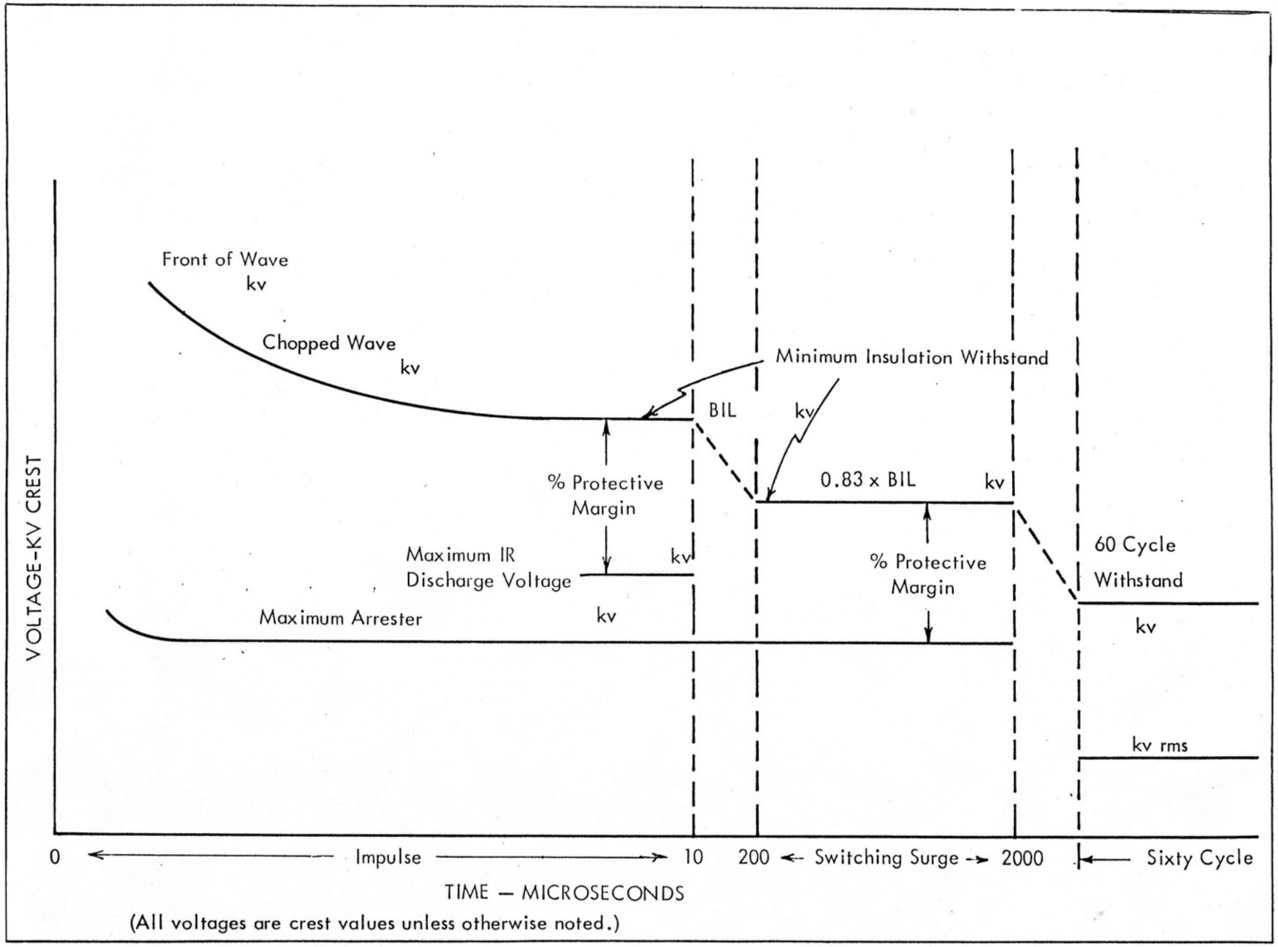
ND = 1”, HD = 2”, RP = 2”, Inter. = 3”, Station = 4”+

Class Comparisons

	Hubbell Product	Rated Voltage kV	MCOV kV	0.5 µsec 10kA EFOW	500 A Switching Surge	8/20 Test Waveform Maximum Discharge Voltage - kV 1.5 kA	3 kA	5 kA	10 kA	20 kA	40 kA	Tempoary Over-Voltage 1 sec kV rms	10 sec kV rms
Normal Duty	PDV65-Optima	18	15.3	62.8	46.4	50.1	53.8	57	63.3	72.6	91.2	22.7	21.7
Heavy Duty	PDV100-Optima	18	15.3	60.6	43.5	45.4	48.4	51.3	56.4	63.5	75.5	23.5	22.2
Riser Pole	PVR-Optima	18	15.3	53.4	35.5	38.9	41.9	44.3	48.9	56.1	66.2	22.2	21.0
Intermediate	PVI-LP	18	15.3	51.6	38.3	40.9	43.2	45.2	48.8	54	60.9	21.4	20.5
Station	EVP	18	15.3	51.6	36.1	38.5	40.4	42.4	45.5	49.1	56.1	21.7	20.8

Protection Level

Protective Margin = ((Insulation Level / Arrester Discharge Voltage) – 1) * 100%



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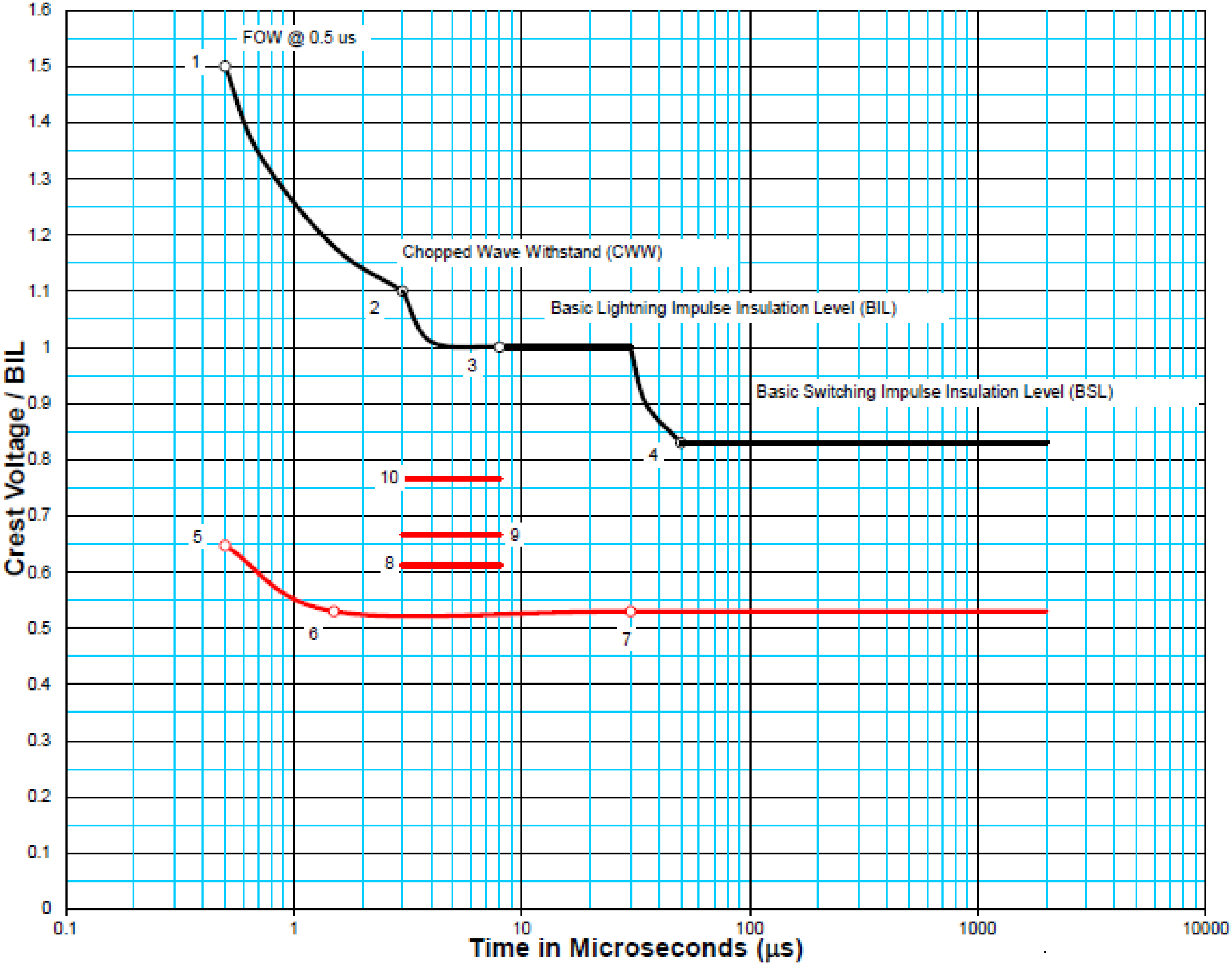
ATCO Electric | Distribution Division



Insulation Withstand Strengths

	Withstand Voltages	Strength (kV)
1	Front-of-Wave @ 0.5µs	225
2	Chopped-Wave @ 3.0µs	165
3	Full-Wave @ 8-30µs	150
4	Switching Surge @ 50-2000µs	124.5

Arrester Protection Levels

	Sparkover Voltages	Strength (kV)
5	Maximum (FOW) @ 0.5µs	97.1
6	1.2x50 Wave @ 1.5µs	79.5
7	Switching Surge @ 30-2000µs	79.5
8	Discharge Voltage @ 5 kA	91.8
9	Discharge Voltage @ 10 kA	100
10	Discharge Voltage @ 20 kA	115

Protection Margins (Note 1)

Chopped Wave PM	70%
Full - Wave PM @ 5 kA	63%
Full - Wave PM @ 10 kA	50%
Full - Wave PM @ 20 kA	30%
Switching Surge PM	57%

Notes

1. Protection margins are based upon ANSI standard C62.2, the minimum protection margin shall be 20% for impulse and 15% for switching surge coordination. The protection margin shall be calculated as follows:

$$\left(\frac{\text{Withstand Strength}}{\text{Protection Level}} - 1\right) \times 100$$

Equipment Data

Location: Wind Farm Undergound Collection System
Protected Device: Transformer (34.5 kV side) BIL: 150
Arrester Manufacturer: Cooper Power Systems
Arrester MCOV Rating: 24.4
Catalog Number: DCEA8S5M30
Date of Manufacturer: 2012
Comments:

Which Arrester Class – What Purpose?

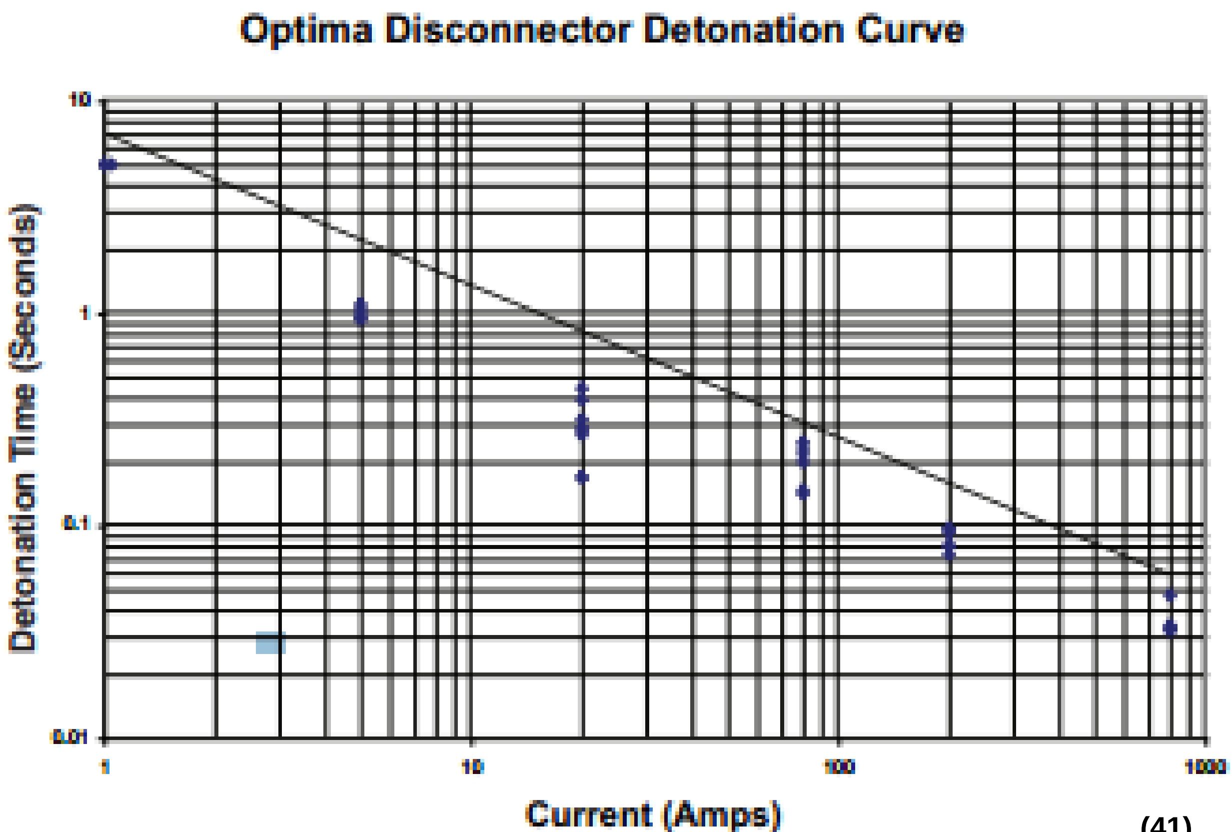
- Your Choice… In Alberta, a low lightning region - Normal Duty is good enough for general purpose protection
- Riser Poles – How important is the circuit?
- Capacitors
  - Normal Duty is OK,
  - Big Banks consider Heavy Duty or Intermediate
- Transformers
  - Normal Duty is OK
  - Big Expensive Transformers… Heavy Duty or Intermediate

Surge Arresters – How Do They Fail?

- TOV is the Number 1 Killer of Surge Arresters in Alberta (As reported on Global National, just kidding…)
  - The Process is Simple: Overvoltage Physically Heats the MOV disk, Heat Lowers the MCOV Which Increases the Heat Generated, Which Lowers the MCOV More, Which Increases th Heat Generated, until BOOM!

- Today's Surge Arresters Rarely Fail Due to a Surge in Alberta. The Quality is Really That Good!

Surge Arresters – Disconnector



(41)

~ Reality Check ~

Should **You** Be Worried about a Surge Armageddon?

(23)

~ Reality Check ~

No, of course not.

Your own historical data is proof!

But, Asset Life would be Extended Significantly with the Proper Application of Surge Arresters!

Where to Focus Your Protection

- Transformer Primaries – **SHORTEST** Lead Length!!!
- Riser Poles – **SHORTEST** Lead Length!!!
- UG Open Points
- Regulators – Primary & By-Pass
- Reclosers – Line AND Load Sides
- Capacitors
- O/H Dead Ends and N/O Switches

Careful There, Electrical Current!

One Last Thing…

Be Careful Where You Place an Arrester

- Fuses – Surge Current Can **Hurt** a Fuse
- Capacitors, Regulators, Reclosers, etc

  There is NO line or load on these devices, at least as surge currents are concerned.

Where to Focus your Protection

Just So YOU Know…

Lead Length can ADD up to 1500 Volts/Foot

Lead length is the physical wire distance between the Apparatus and the Line Side of the Surge Arrester

PLUS (+)

The Line Length from the Ground of the Surge Arrester to the Ground of Apparatus

AND for the Love of Goodness,

Please Don't COIL the Leads!!!

A Shameless Promotion

arresterworks.com

Jonathan Woodworth

Principal Engineer

Jonathan started his career at Fermi National Accelerator Laboratory in Batavia, Illinois, where he was an integral member of the high energy particle physics team in search of the elusive quark. Returning to his home state of NY, he joined the design engineering team at McGraw Edison (later Cooper Power Systems) in Olean. 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. Since 2008 he has been the Principal Engineer for ArresterWorks.

Though his entire career, Jonathan has been active in the IEEE and IEC standard associations. He is past chair of the IEEE SPD Committee, he is past chair of NEMA 8LA Arrester Committee, and presently co-chair of IEC TC37 MT4. He is inventor/co-inventor on five US patents. Jonathan received his Bachelor's degree in Electronic Engineering from The Ohio Institute of Technology and his MBA from St. Bonaventure University.

Contact at 716-307-2431 or Jonathan.Woodworth@ArresterWorks.com

Deborah Limburg

Web and Business Developer

Deborah is a long term veteran in the arrester industry having worked for Cooper Industries for over 25 years. During that time she held a number of positions in the product engineering department, including leader of the Engineering Design Services group. One of her major accomplishments at Cooper was the design and implementation of a virtual product drawing systems for all major product lines. This lead to a considerable reduction in the number of Designers and CAD operators required to maintain the product documentation system. This database system also helped to improve the overall documentation process due to the reduction in human errors.

Additionally she developed the software to handle disk selection process for the tightly matched disk columns required for series capacitor banks and the management of the varistor assembly process. Deborah received her BS in Computer Software from the University of New York State and is a co-inventor on several US patents.

Since 2010 Deborah has been the Web and Business Developer for Arresterworks.

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QUESTIONS?

References

1 – http://www.picturesof.net/pages/090326-134616-923048.html
2 – www.wordy.photos/index.php?keyword=11%20kv%20fuse%20explodes&photo=0XVPcDxoV2g&category=people&title=electric+power+line+explosion
3 – http://www.satcomlimited.com/transparent_over_voltages.html
4 – http://www.hubbellpowersystems.com/cable-accessories/elbow-arresters/description/
5 – http://www.sandc.com/edocs_pdfs/edoc_024494.pdf
6 – "SURGE ARRESTER APPLICATION OF MV-CAPACITOR BANKS TO MITIGATE PROBLEMS OF SWITCHING RESTRIKES"
Lutz GEBHARDT - ABB – Switzerland, lutz.gebhardt@ch.abb.com & Bernhard RICHTER - ABB – Switzerland, bernhard.richter@ch.abb.com
7 – "COMPUTATION OF FAST TRANSIENT VOLTAGE DISTRIBUTION IN TRANSFORMER WINDINGS CAUSED BY VACUUM CIRCUIT BREAKER SWITCHING"
Casimiro Álvarez-Mariño and Xosé M. López-Fernández, Dept. of Electrical Engineering, Universidade de Vigo, EEI, Vigo, Spain, xmlopez@uvigo.es
8 – http://new.abb.com/products/transformers/distribution
9 – http://commons.wikimedia.org/wiki/File:37.5kVA_three_phase_utility_stepdown.jpg
10 – http://uqu.edu.sa/files2/tiny_mce/plugins/filemanager/files/4310333/traveling_wave.pdf
11 – http://revistas.unal.edu.co/index.php/ingeinv/rt/printerFriendly/25218/33722
12 – http://io9.com/photos-from-the-days-when-thousands-of-cables-crowded-t-1629961917
13 – http://www.edn.com/Home/PrintView?contentItemId=4426566
14 –http://www.ecnmag.com/articles/2011/07/advanced-tvs-construction-improves-lightning-protection
15 – http://www.nautel.com/support/technical-resources/tips-n-tricks/04-09-2012/
16 – http:// www.slideshare.net
17 – https://library.e.abb.com/public/a8c42d637aa10aa2c12577ee0055faad/ABB_DPDQPole_Qpole_revB_EN.pdf
18 – http://www.cooperindustries.com/content/dam/public/powersystems/resources/library/230_PowerCapacitors/23012.pdf
19 – http://www.cooperindustries.com/content/dam/public/powersystems/resources/library/225_VoltageRegulators/MN225008EN.pdf
20 – https://www.osha.gov/SLTC/etools/electric_power/illustrated_glossary/substation_equipment/potheads.html
21 – http://ecmweb.com/archive/applying-pole-mounted-overvoltage-protection
22 – http://www.cpuc.ca.gov/gos/Resmajor/SU6/GO95/SU6_GO95_rule_54_6-F.html

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References - continued

23 – http://creepypasta.wikia.com/wiki/File:5178_apocalyptic_destruction.jpg
24 – http://en.wikipedia.org/wiki/Distribution_transformer
25 – http://www.icccable.com/company_product.html?cid=208
26 – http://www.powertechlabs.com/areas-of-focus/power-labs/cable-technologies/condition-assessment-the-whole-picture/
27 – http://www.ee.washington.edu/research/seal/projects/seal_robot/sensors.html
28 – http://www.epa.gov/electricpower-sf6/documents/sf6_byproducts.pdf
29 – http://cdn2.hubspot.net/hub/272197/file-251812186-pdf/white_papers/afi-wp-transoil1.pdf
30 – http://reliabilityweb.com/index.php/print/defects_in_nonceramic_insulators_can_they_be_detected_in_a_timely_manner1
31 – http://www.inmr.com/thermal-inspection-program-finds-failing-dead-end-polymeric-insulators-2/5/
32 – http://en.wikipedia.org/wiki/Fallout_shelter
33 – http://classicconnectors.com/wp-content/uploads/2012/07/Illustration.jpg
34 – "Electrical Distribution System Protection", 3rd Edition, Cooper Power Systems, 1990
35 – http://www.cooperindustries.com/content/public/en/power_systems/products/voltage_regulators/32-step_single-phase.html
36 – https://fisitech.wordpress.com/2010/10/22/practical-issues-switching-surgeac-transcient/
37 – http://nepsi.com/services/power-systems-studies/
38 – http://file.scirp.org/Html/3-9800140_1113.htm
39 – http://electrical-engineering-portal.com/definition-basic-insulation-level-bil
40 – http://www.schneider-electric.com/download/hk/en/details/18865768-General-Specification-for-Fixed-Capacitor-Bank-for-Electrical-Network-up-to-36kV/?reference=Fixed_capacitor_bank_36kV_specENv2
41 – http://www.hubbellpowersystems.com/catalogs/arresters/31_optima.pdf
42 – http://www.coe.montana.edu/ee/seniordesign/archive/SP13/150mwwindfarm/Data_Content/InsulationCoordination.pdf