Understanding High Speed Surges/Transients

TVA PQ Group - Transmission

August 1, 2017

High-Speed Transients

Source of Energy	**Discussed or Not Discussed Today**
Lightning	Discussed
Line or cable switching	Discussed
Nuclear Bomb Detonation EM Pulse	Hopefully Not Needed to be Discussed

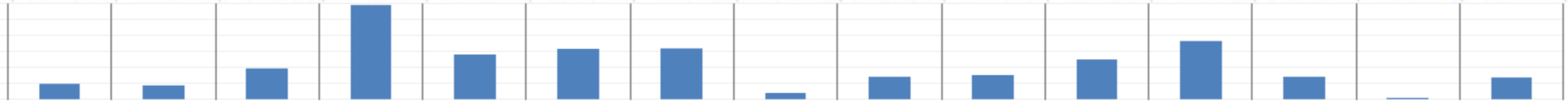
Goals of Presentation

- Present transient concepts hopefully useful to IEEE members
- Only basic EE equations used – no PHD-speak – no LaPlace Transforms
- Lighten-up presentation with 10 Case Studies
- Try to make presentation more applications oriented versus design oriented
- Try to present something useful to all attending

Lightning Surges Section

Tennessee Valley Area
Number of Lightning Flashes – Displayed By Month
For Years 2000 to 2014

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Jan	35730	2804	23192	2670	9524	7289	85227	5235	46466	9234	40987	16584	79136	16068	13569
Feb	86901	60093	2250	42925	22887	81606	20415	49191	104030	58161	13200	51188	45154	34818	44441
Mar	125144	29607	204610	142084	84477	204731	83976	57841	139330	35523	92201	154896	185636	102301	28101
Apr	120101	161367	208389	361152	124266	347492	497721	116269	198312	150380	235200	775059	101600	139976	437970
May	405443	321088	334545	1280579	537536	341318	706497	210205	455852	509998	594615	338249	265925	179528	157794
Jun	315283	553246	381507	512009	615003	436572	507051	561173	502277	733026	796421	882881	189000	483863	692882
Jul	540731	629846	882742	1197988	1055503	928026	539419	483912	819608	571849	648300	754149	974525	517723	426535
Aug	554843	428161	585169	1234092	470586	909646	766155	514467	317320	390376	628727	621872	497032	397711	485198
Sep	211182	118494	112579	101098	86566	96225	310244	72532	54087	233170	64702	170499	266811	124086	204209
Oct	26175	51668	54728	60454	292812	15757	32821	35304	21554	54591	92077	13662	47227	19285	170771
Nov	32628	68528	144784	12316	57457	146685	39537	69399	5199	993	20858	35289	14198	4552	3267
Dec	29296	7450	32170	2067	45382	64899	4647	22202	42009	10786	17416	5759	40376	22658	19757
Tot	2483457	2432352	2966665	4949434	3401999	3580246	3593710	2197730	2706044	2758087	3244704	3820087	2706620	2042569	2684494



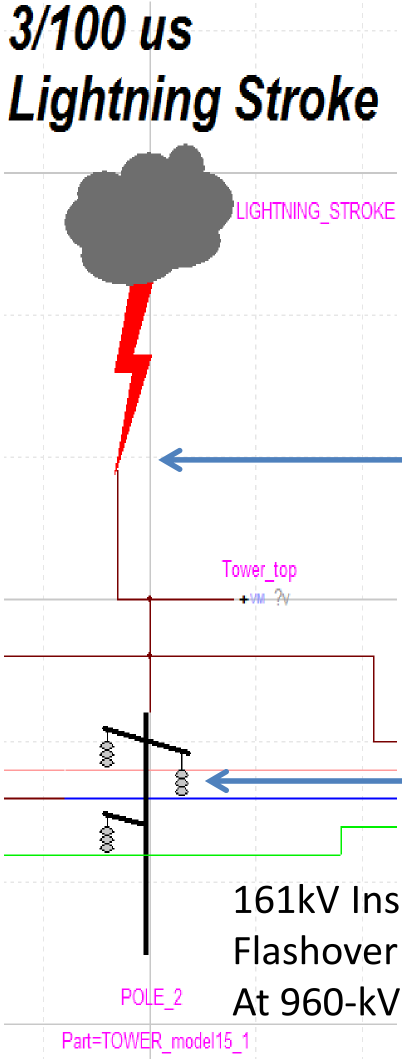
Blue highlighted area shown above indicate peak lightning times are spring and summer

Lightning Strike Simulation Concept - Shown On One Slide

V=L di/dt – Must move di/dt down pole before insulator breakdown

15-kA Simulated

3/100 us Lightning Stroke



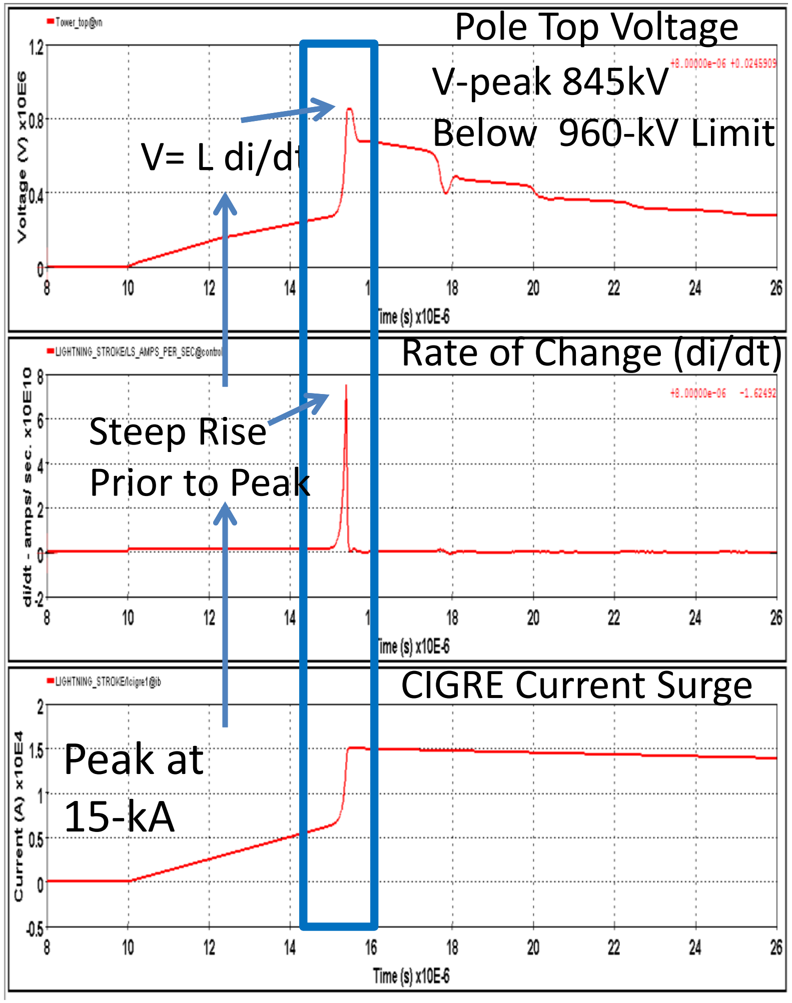
Strike Hits Pole Top

Stroke Goes
Down Pole
Into Ground

Insulators
Subjected to
Voltage Stress

161kV Insulators
Flashover
At 960-kV

Shaded Time Below – Critical Time



Pole Top Voltage

V-peak 845kV
Below 960-kV Limit

V= L di/dt

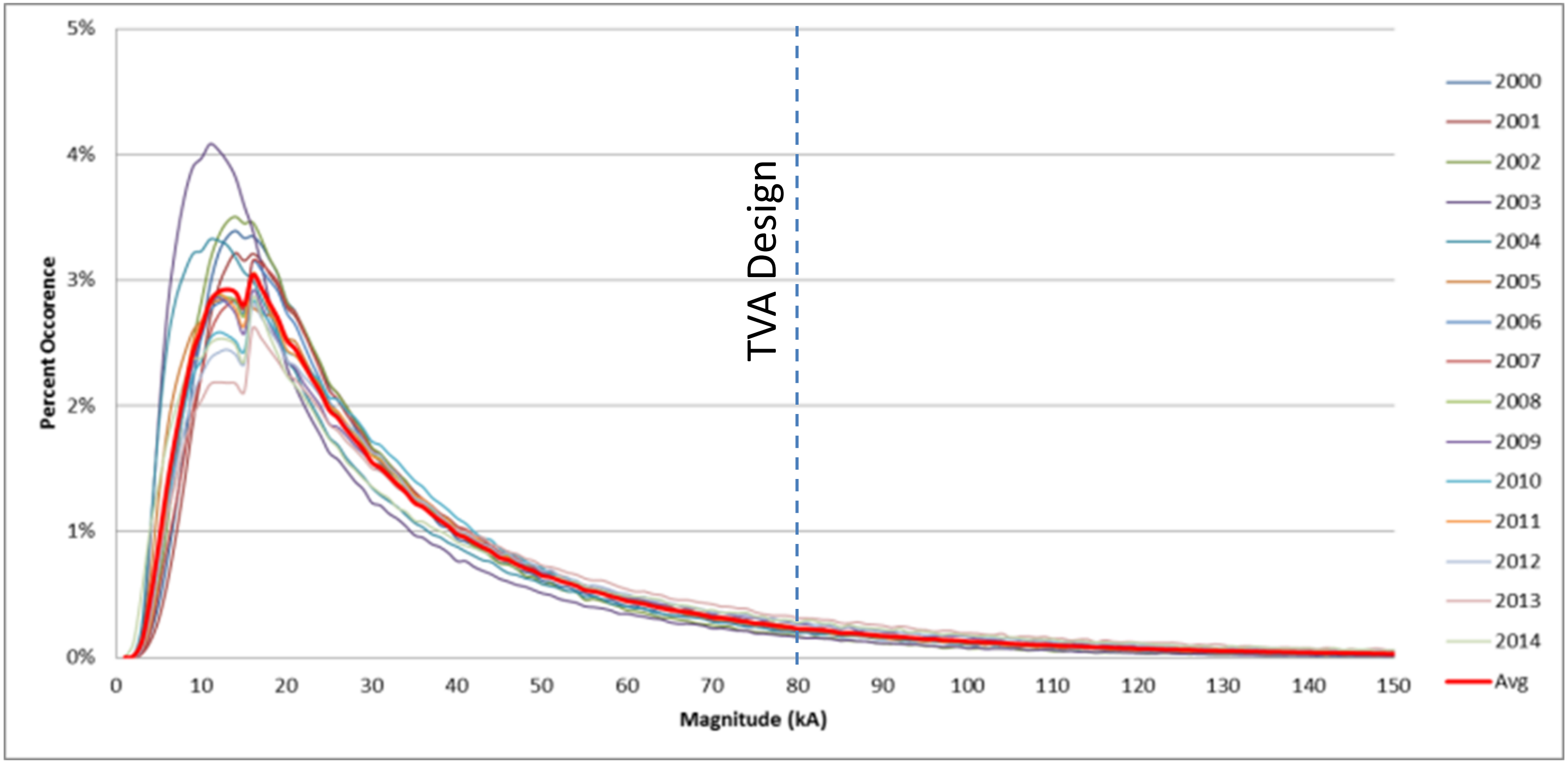
Rate of Change (di/dt)

Steep Rise
Prior to Peak

CIGRE Current Surge

Peak at
15-kA

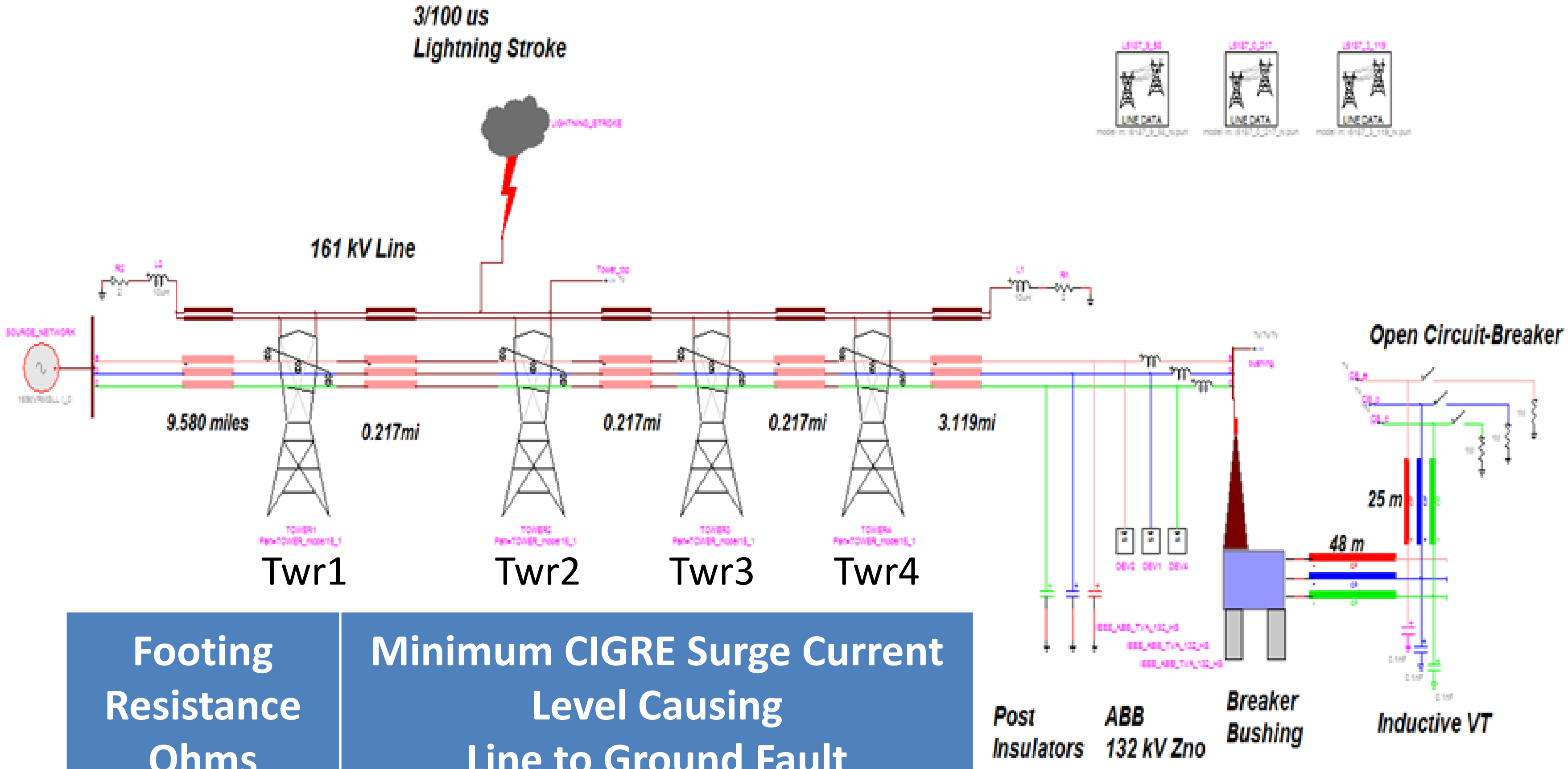
Intensity of Lightning Strike Levels in TVA Area



The previous slide shows the importance of di/dt while TVA's statistics are based on kA magnitude. It is important to recognize this because a low magnitude strike may have a higher di/dt than a larger magnitude strike.

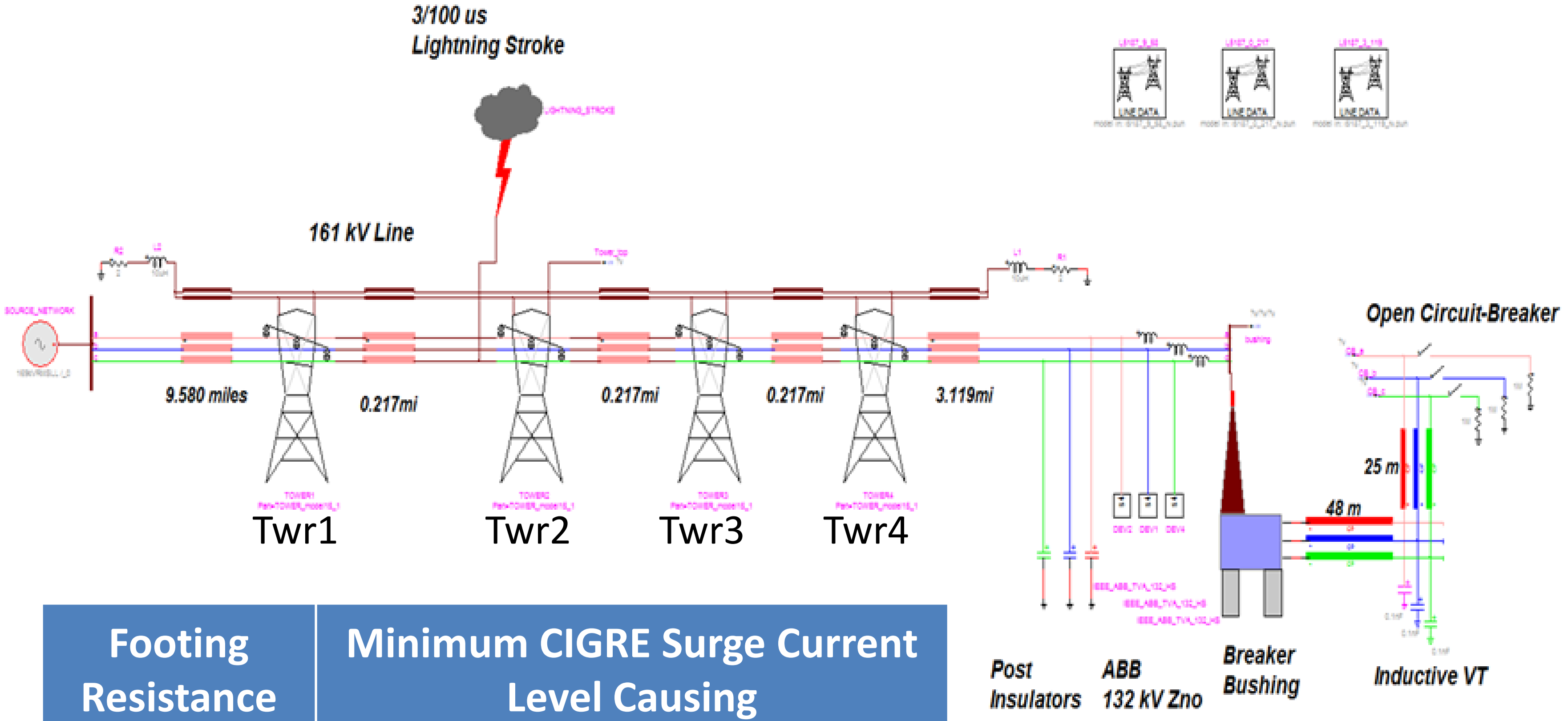
With this said, the TVA staff generally believe that larger magnitude kA strikes are more likely to create insulator flashovers than smaller strikes. Fortunately there are many more smaller strikes (<15-kA) than larger strikes (>80-kA).

161-kV SG-1 Tower
Back-flash Simulation
(Lightning Hits Shield Wire – Top Tower 2)

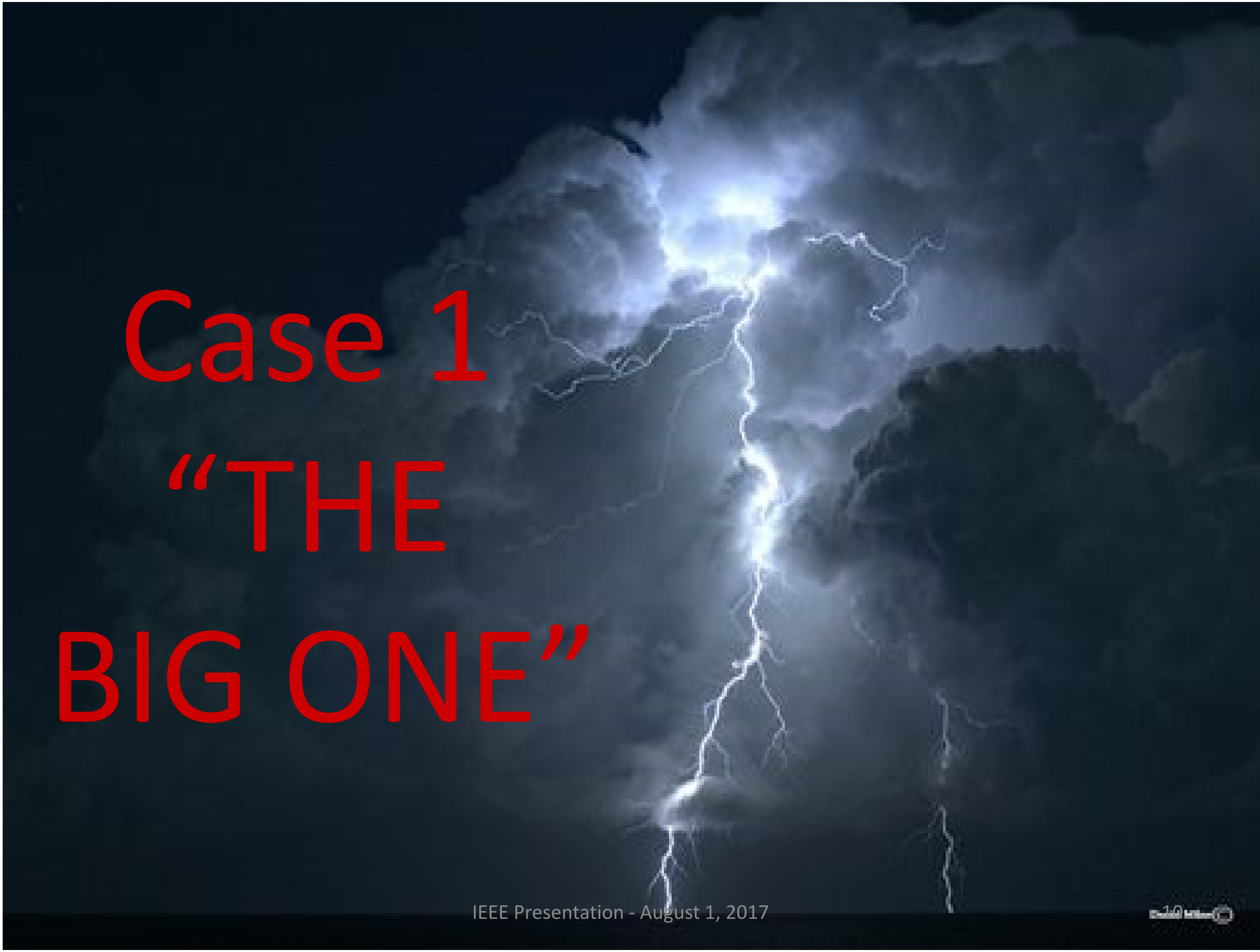


Footing Resistance Ohms	Minimum CIGRE Surge Current Level Causing Line to Ground Fault
20	48-KA – Pole 2 – B Phase
80	21-kA– Pole 2 – C Phase

161-kV SG-1 Tower
Direct Attachment to C-Phase Simulation
(Shield Wire Failure – Top Tower 2)



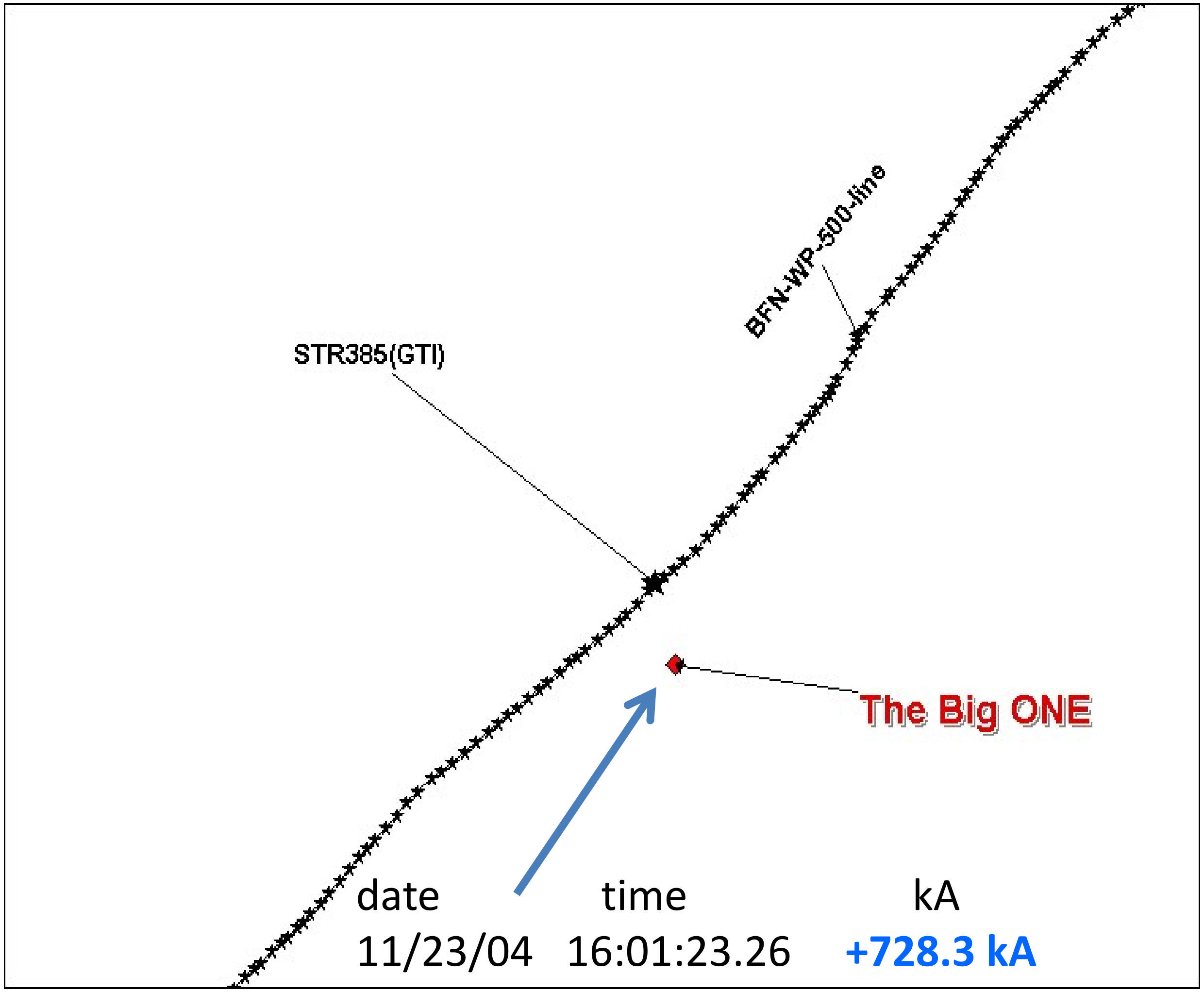
Footing Resistance Ohms	Minimum CIGRE Surge Current Level Causing Line to Ground Fault
20	5-kA
80	5-kA



Case 1 “THE BIG ONE”

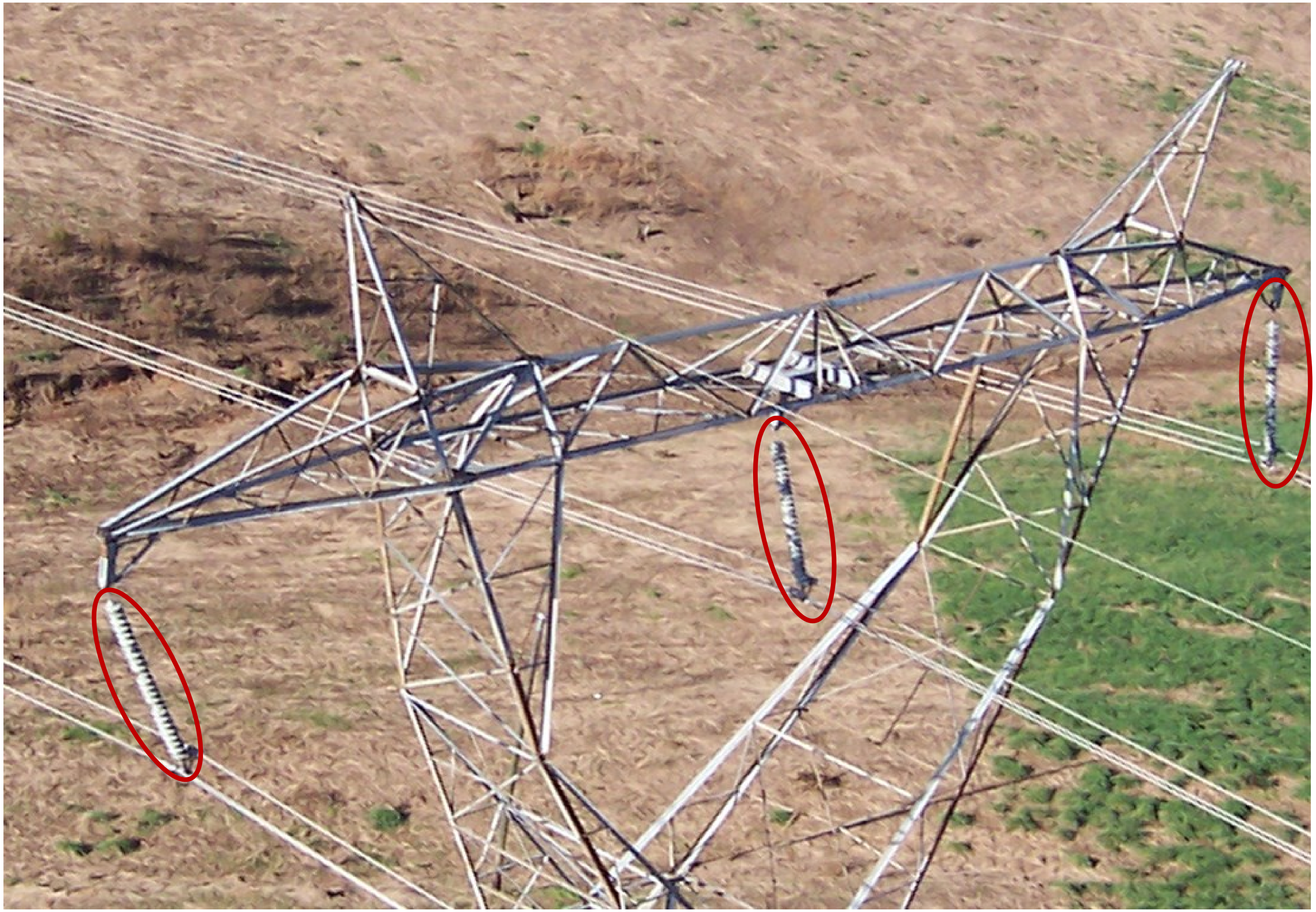
Magnitude of Lightning Strike – 728-kA
Hit 500-kV Line Between BFNP – West Point, MS

…strokes/flashes with estimated peak current above 500kA seem to occur only a few (5-20) times per year, throughout the whole U.S. This would literally mean "less than one in a million."



date	time	kA
11/23/04	16:01:23.26	**+728.3 kA**

728-kA Lightning Strike Hit Tower and the 3-Line Insulators Flashed Over – Insulators Were Damaged But Line Reclosed



Big – One Case Summary Concept

Insulators May Be Looked at as Line Fuses

Sometimes It is Best That They Operate (Flashover)

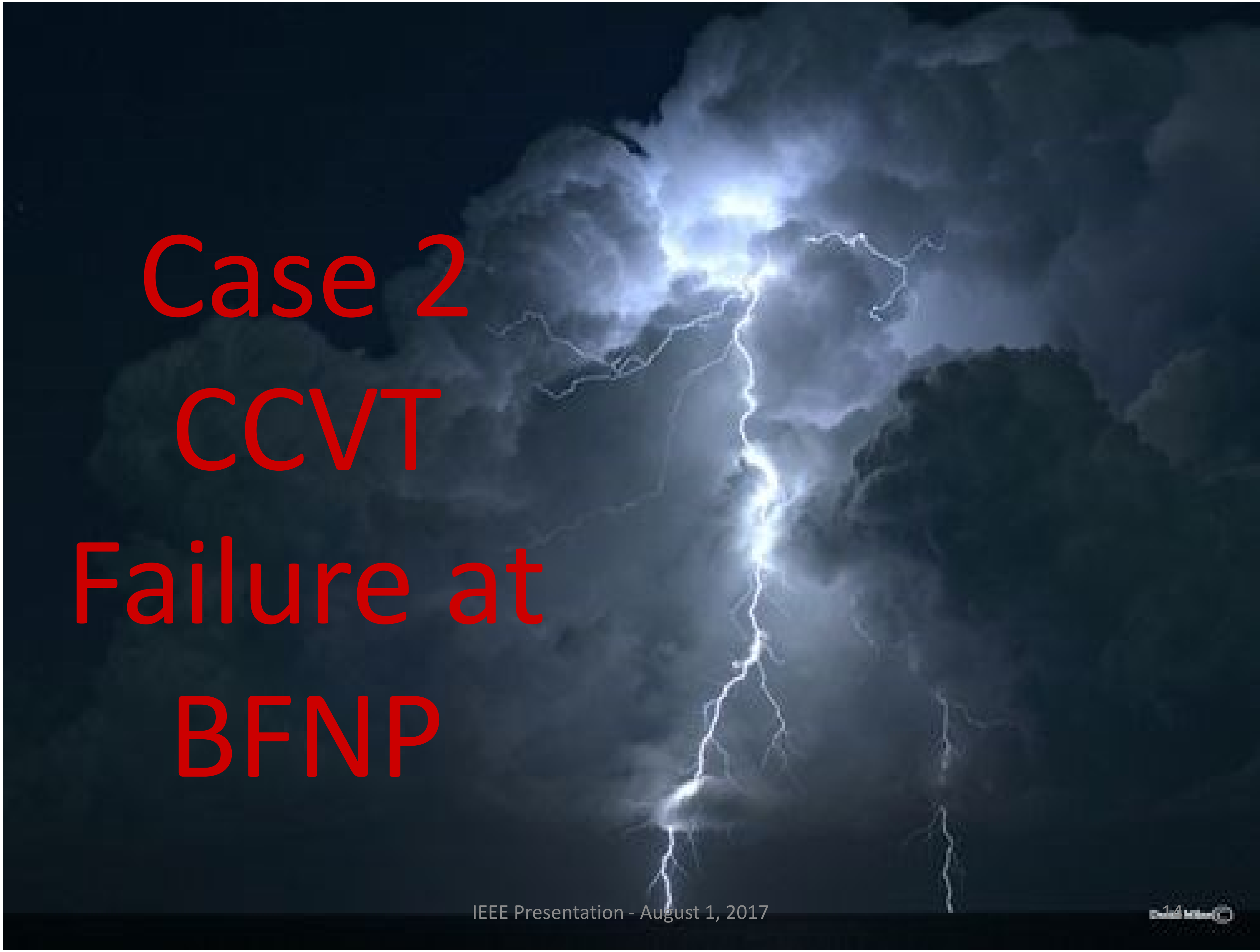
- Insulators are low-cost compared to other equipment. TVA staff were glad this three-phase fault occurred where it did because the massive energy went to ground in a remote field instead of traveling to substation equipment

- Statistical Mid-Band Voltage Flashover Levels for Transmission Insulators are:
  - 500-kV Insulators - 1995-kV
  - 161-kV Insulators - 960-kV

- Hopefully major events flashover remotely to substation.

  Typical BIL levels for substation equipment are:
  - 500-kV Equipment - 1550-kV
  - 161-kV Equipment - 750-kV
  - Unlike insulators – once substation equipment flashover their life is over!

-



Case 2
CCVT
Failure at
BFNP

1999 CCVT Failure at Browns Ferry Nuclear Plant

- One or more lightning strikes damaged a 500-kV class, C-Phase Capacitive Coupling Voltage Transformer – later it exploded!!
- Debris traveled over 300 yards and damaged many bus insulators
- Investigation Team determined lightning was root cause of failure
  - > I= C * dv/dt – for a high frequency transient, the CCVT (primarily three stages of series capacitors) looked like a short to ground
  - > High current from lightning flow drilled holes in series cap packs
  - > Failure occurred much later -- in heat of summer day
- Solution – At 500-kV Line Terminations – Station Class Arresters were installed
  - > If the voltage peaks (and dv/dt) are limited by arrester operation, then the transient current flow through the CCVT will be within design limits – this concept will show up later in this presentation!!

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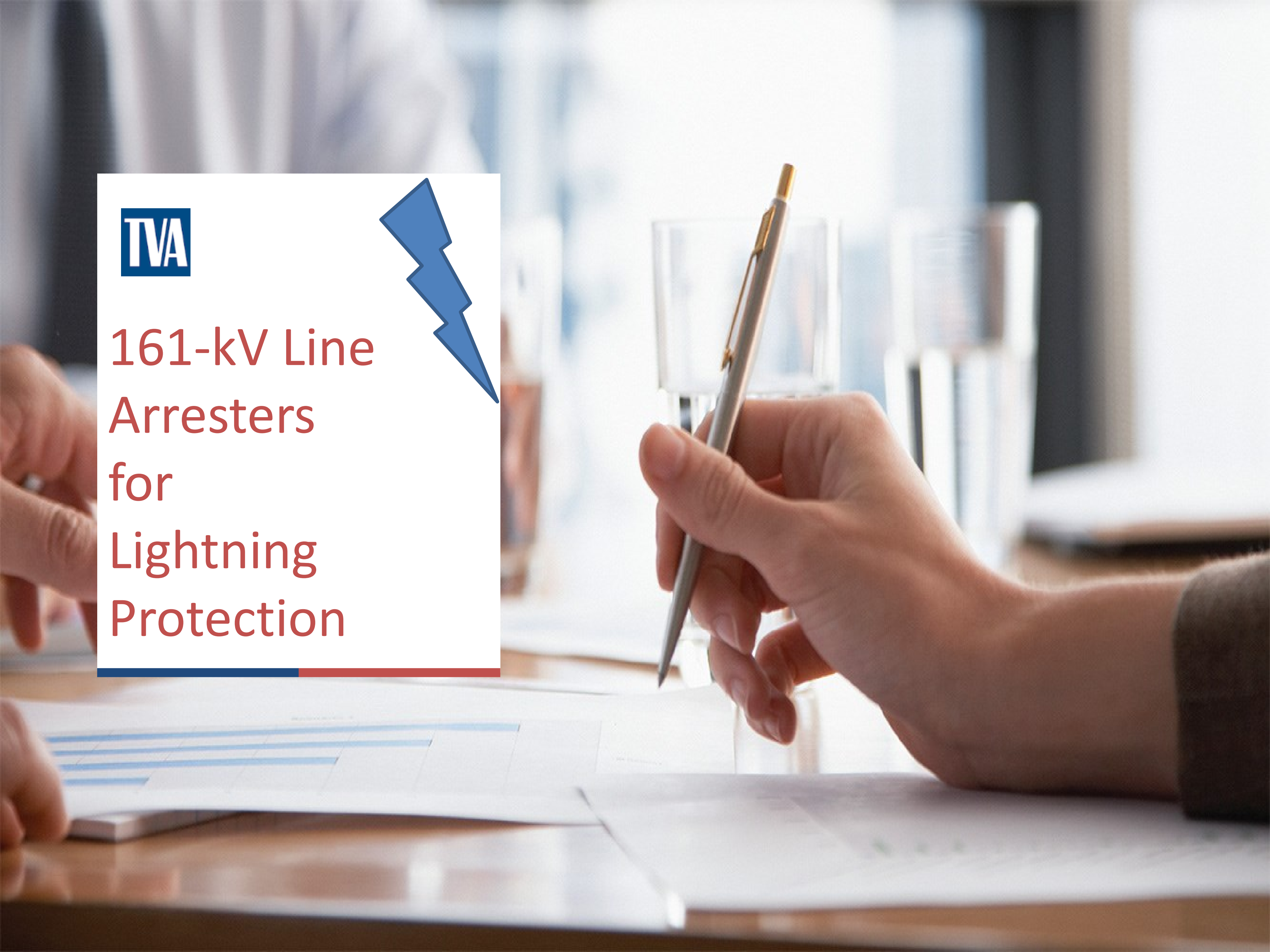
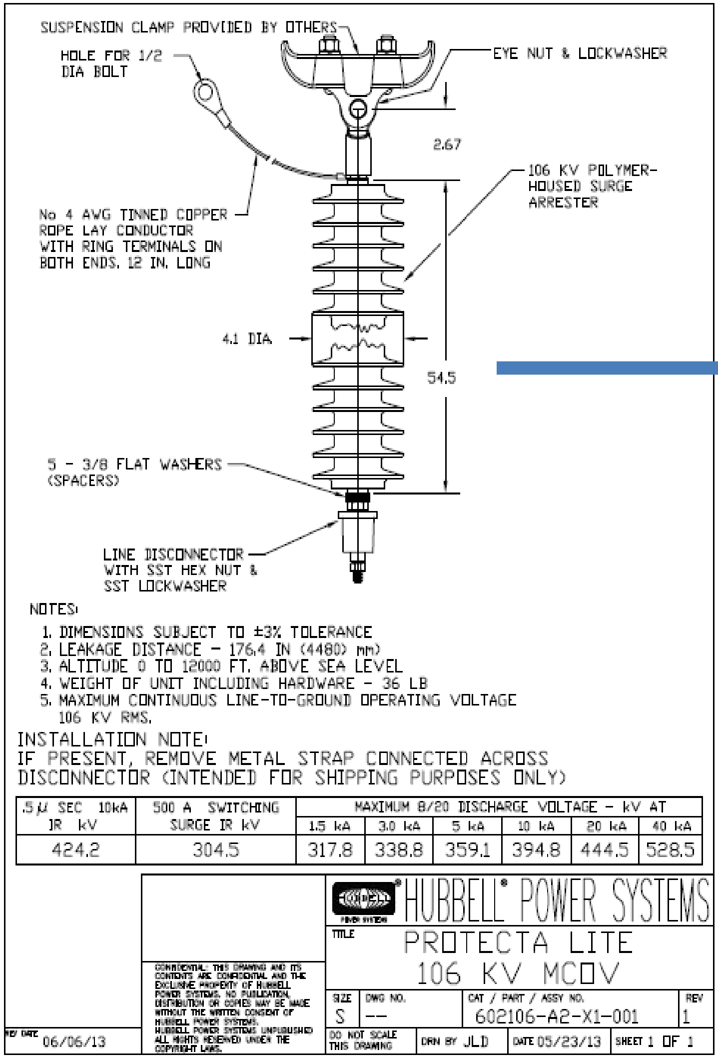


161-kV Line Arresters for Lightning Protection

TVA Uses 161-kV Class Hubbell Protecta Lite Line Arresters

Goal – Handle Tower Strike Without Faulting



NOTES:

1. DIMENSIONS SUBJECT TO ±3% TOLERANCE
2. LEAKAGE DISTANCE - 176.4 IN (4480) mm)
3. ALTITUDE 0 TO 12000 FT. ABOVE SEA LEVEL
4. WEIGHT OF UNIT INCLUDING HARDWARE - 36 LB
5. MAXIMUM CONTINUOUS LINE-TO-GROUND OPERATING VOLTAGE 106 KV RMS.

INSTALLATION NOTE:
IF PRESENT, REMOVE METAL STRAP CONNECTED ACROSS DISCONNECTOR (INTENDED FOR SHIPPING PURPOSES ONLY)

.5 µ SEC 10kA IR kV	500 A SWITCHING SURGE IR kV	MAXIMUM 8/20 DISCHARGE VOLTAGE - kV AT					
		1.5 kA	3.0 kA	5 kA	10 kA	20 kA	40 kA
424.2	304.5	317.8	338.8	359.1	394.8	444.5	528.5

HUBBELL® POWER SYSTEMS

TITLE PROTECTA LITE
106 KV MCOV

SIZE S
DWG NO. --
CAT / PART / ASSY NO. 602106-A2-X1-001
REV 1

REV DATE 06/06/13

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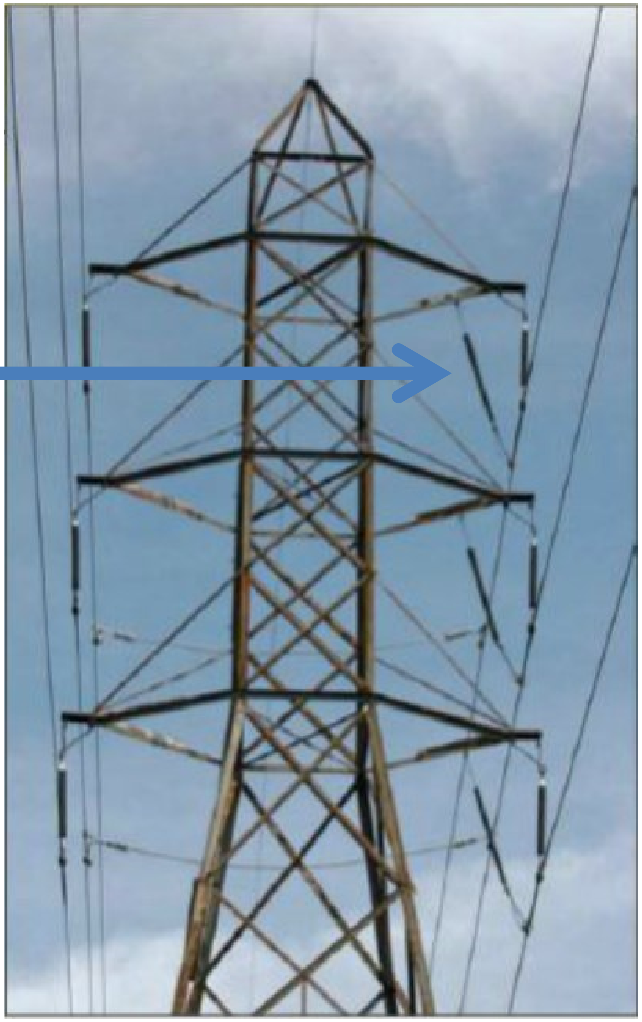
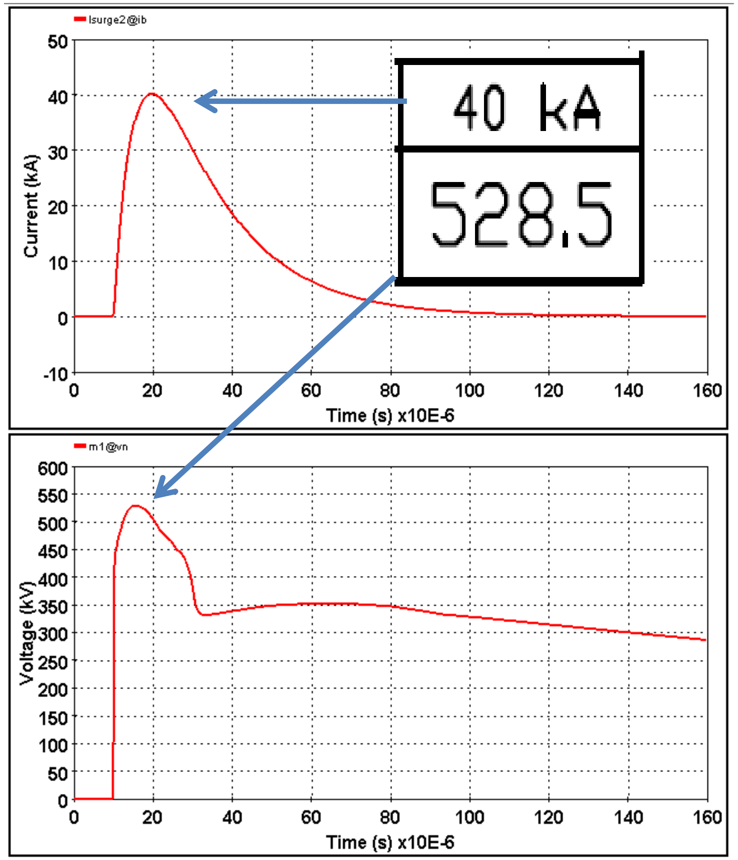
DATE 05/23/13
SHEET 1 OF 1



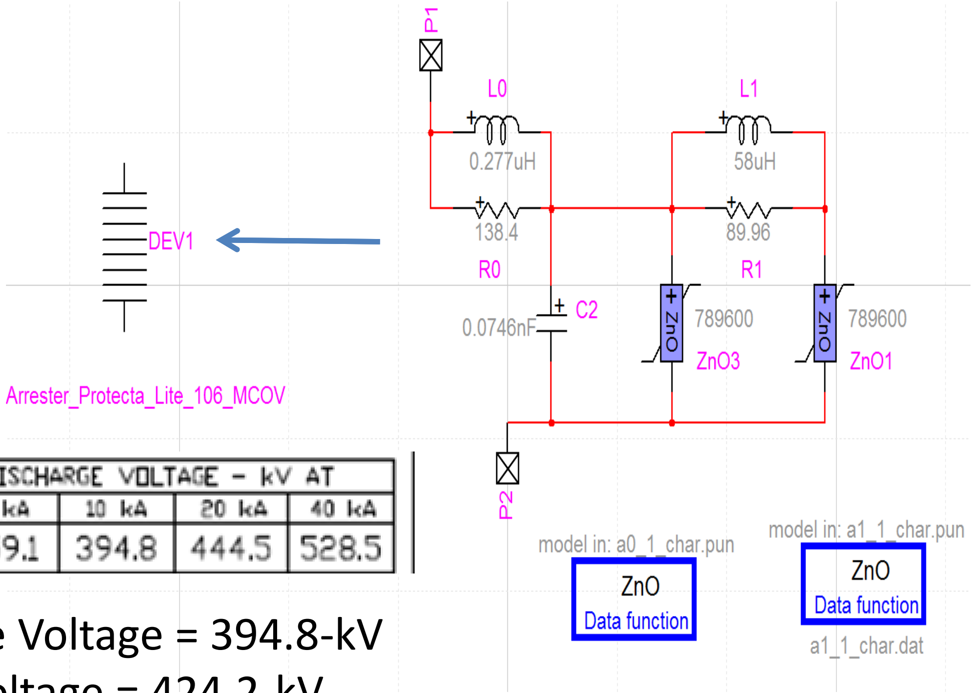
IEEE High Speed Model in EMTP-RV for 106-kV MCOV Protecta Lite Arresters

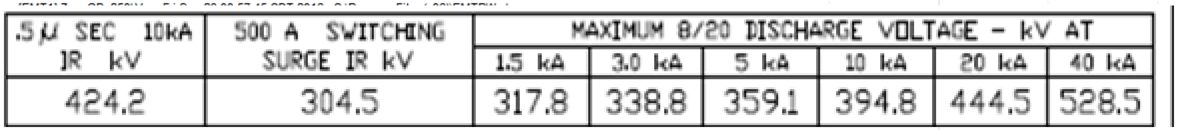


IEEE High Speed Model for Hubbell Protecta Lite 106-kV – Voltage Clamp - 528-kV at 40-kA

Quick Part Simulation

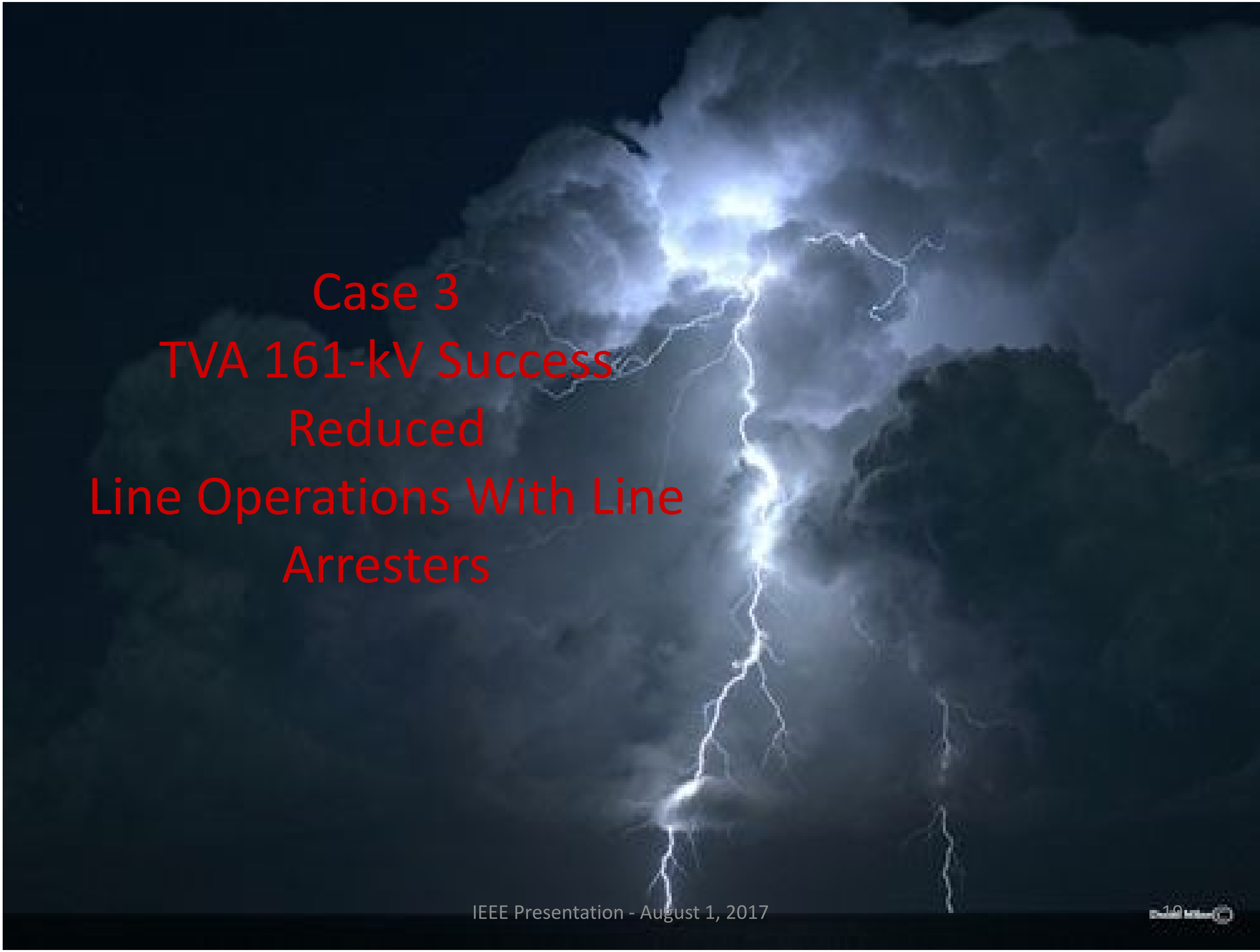
Slower Part Simulation





.5 µ SEC 10kA IR kV	500 A SWITCHING SURGE IR kV	MAXIMUM 8/20 DISCHARGE VOLTAGE - kV AT					
		1.5 kA	3.0 kA	5 kA	10 kA	20 kA	40 kA
424.2	304.5	317.8	338.8	359.1	394.8	444.5	528.5

Note at 10-kA, 8/20us: Max Discharge Voltage = 394.8-kV
But at 10-kA, 0.5us: Max Discharge Voltage = 424.2-kV
For High-Speed Transients, Arresters Aren't As Effective



Case 3

TVA 161-kV Success
Reduced
Line Operations With Line
Arresters

Type SG-1 Back-flash Simulation - Arrester on Poles As Listed (Lightning Hits Shield Wire – Top Pole 2)

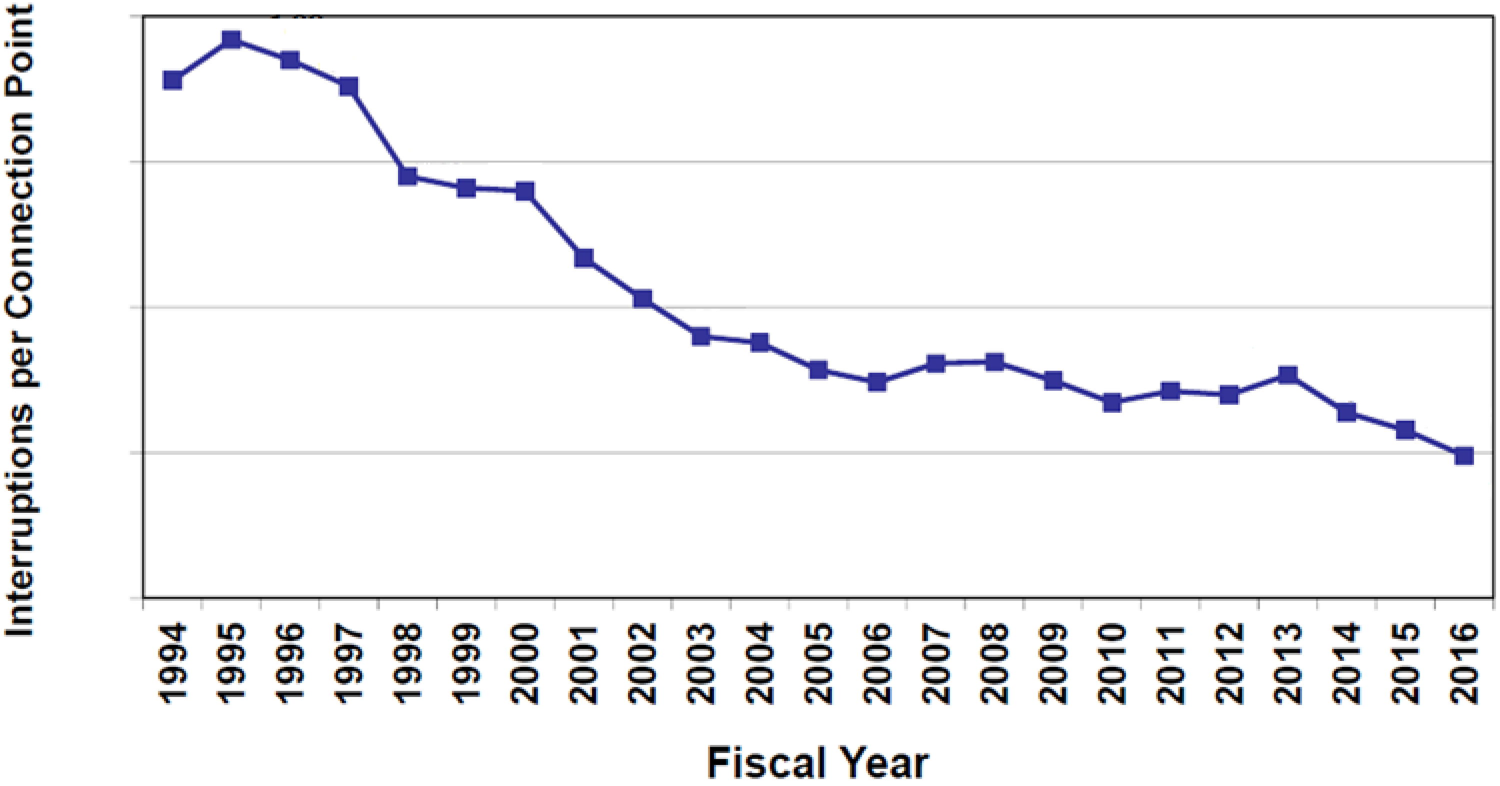
	Arresters on Tower 2 Only Lightning Strikes Tower 2 Shield Wire	Arresters on Towers 1 & 3 Only Lightning Strikes Tower 2 Shield Wire
Footing Resistance All Towers - Ohms	Minimum CIGRE Surge Current Level Causing 1st Phase to Flash to Ground Line to Ground Fault	Minimum CIGRE Surge Current Level Causing 1st Phase to Flash to Ground Line to Ground Fault
20	300+kA– Tower 3 – C Phase	48-KA – Tower 2 – B Phase
80	66-kA– Tower 3 – C Phase	21-kA– Tower 2 – C Phase

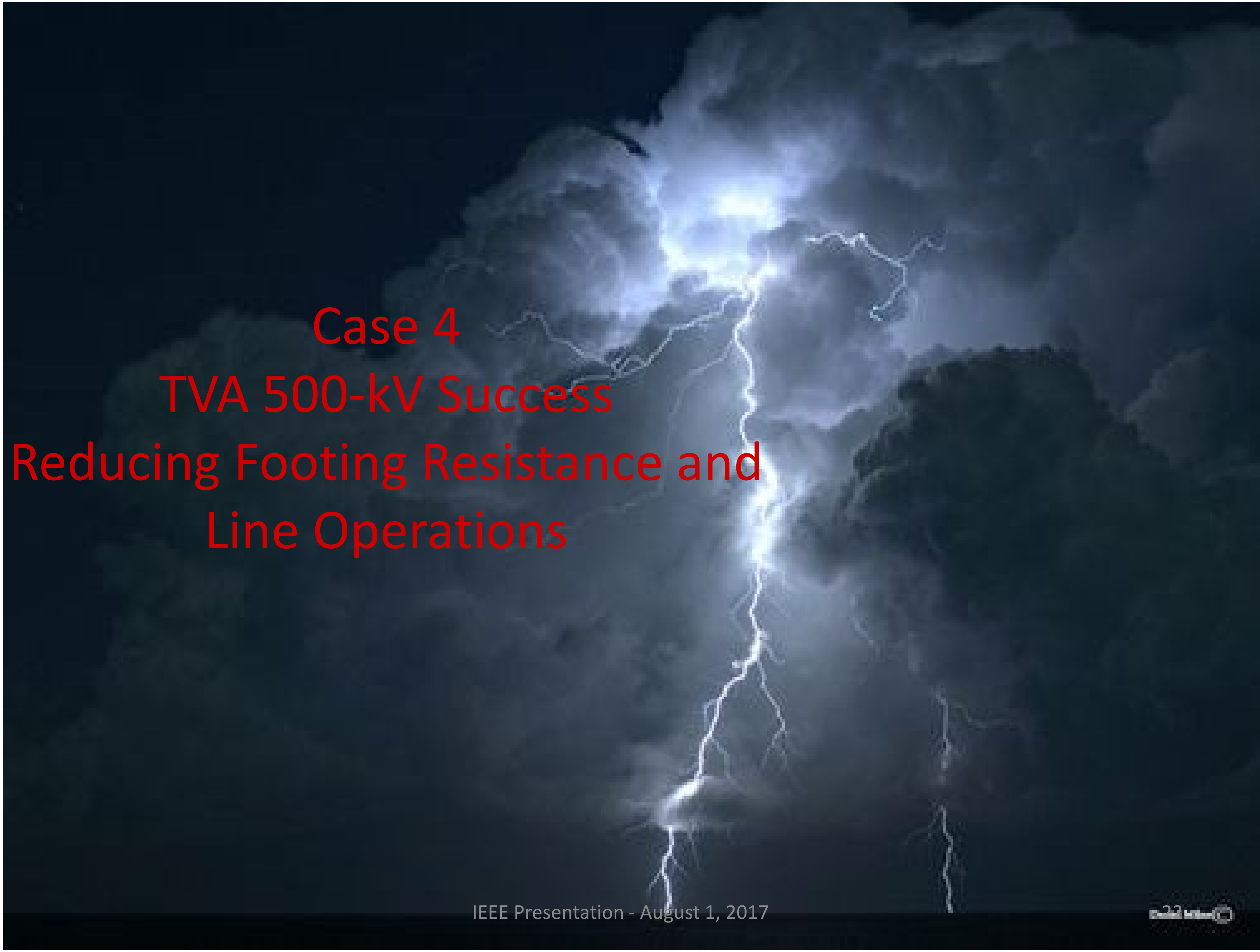
Towers 1/3 Arresters Don't Help Tower 2 Strike – Same Back-Flash Numbers as Before!!

Key Concept – If you want to protect towers – arresters must be on towers where lightning strikes – one tower away does not work. Arresters need to be on all three phases.

Related Concept for Substation Equipment – for this reason arresters are normally mounted on transformers to insure optimum protection or on (or close to) terminals of smaller equipment, i.e. VTs, CCVTs, breakers

Connection Point Interruption Frequency (CPI)





Case 4
TVA 500-kV Success
Reducing Footing Resistance and Line Operations

500-kV Line Lightning Protection Improvements

500-kV Back-flash Simulation - (Lightning Hits Shield Wire – Top Tower 2)

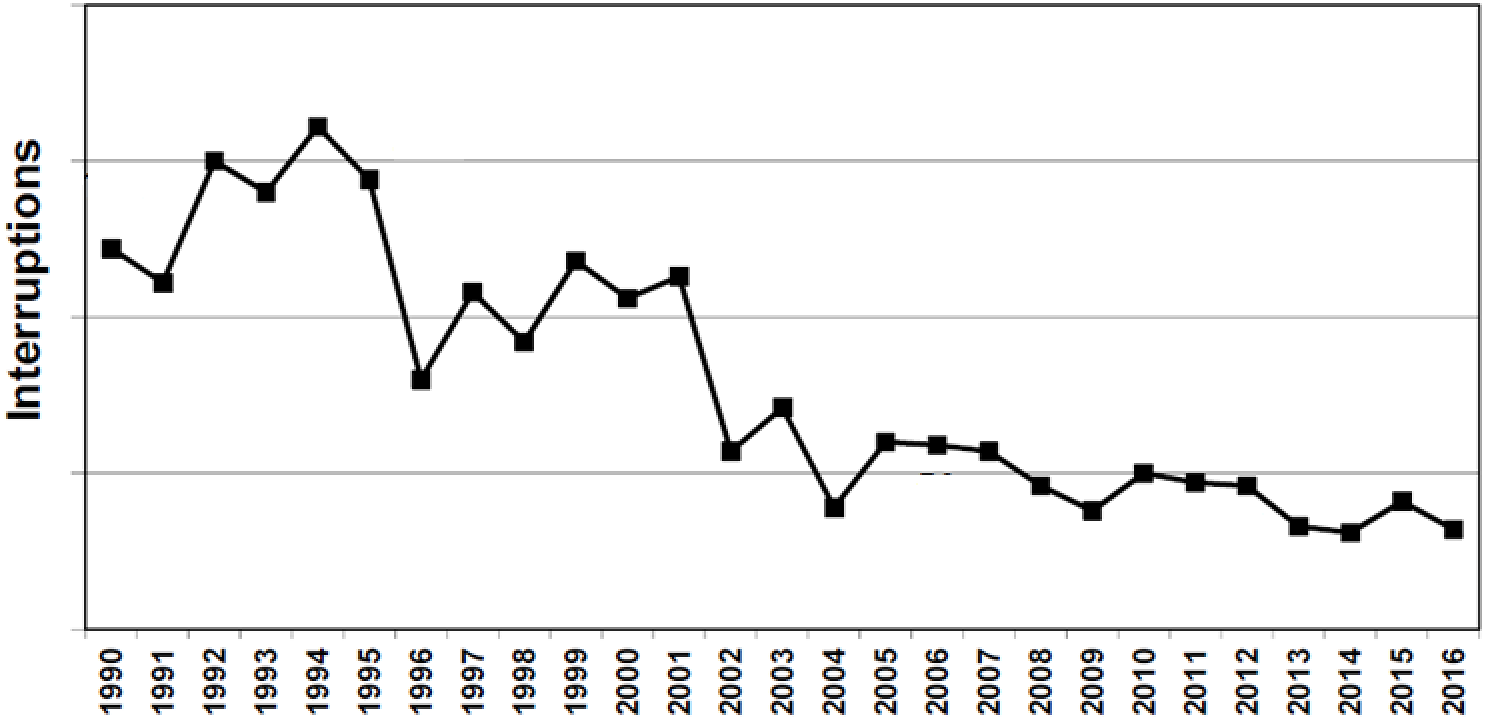
Arresters Excluded in Model – None Simulated

Footing Resistance Ohms All Towers	Minimum CIGRE Surge Current Level Causing 1st Phase to Flash to Ground Line to Ground Fault
20	270-kA
80	49-kA

TVA is currently only experimenting with 500-kV arresters

TVA's primary efforts at the 500-kV level are to reduce footing resistance with counterpoise – radiated ground conductors/ground rods from tower feet

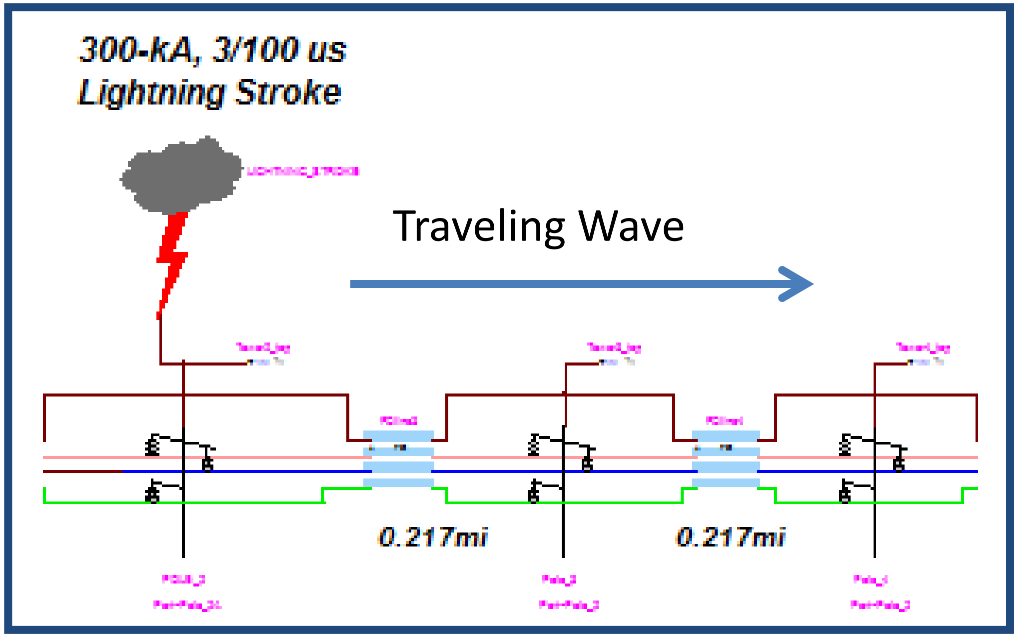
Bulk Transmission TLI

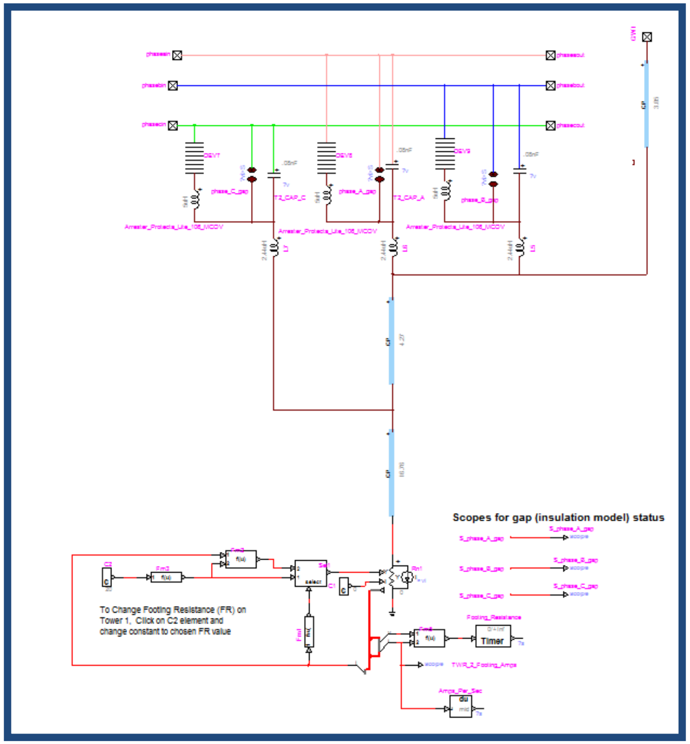


Bulk TLI become official indicator in 2012. Prior data not verified.

Transient Velocity Moving Across Transmission Lines

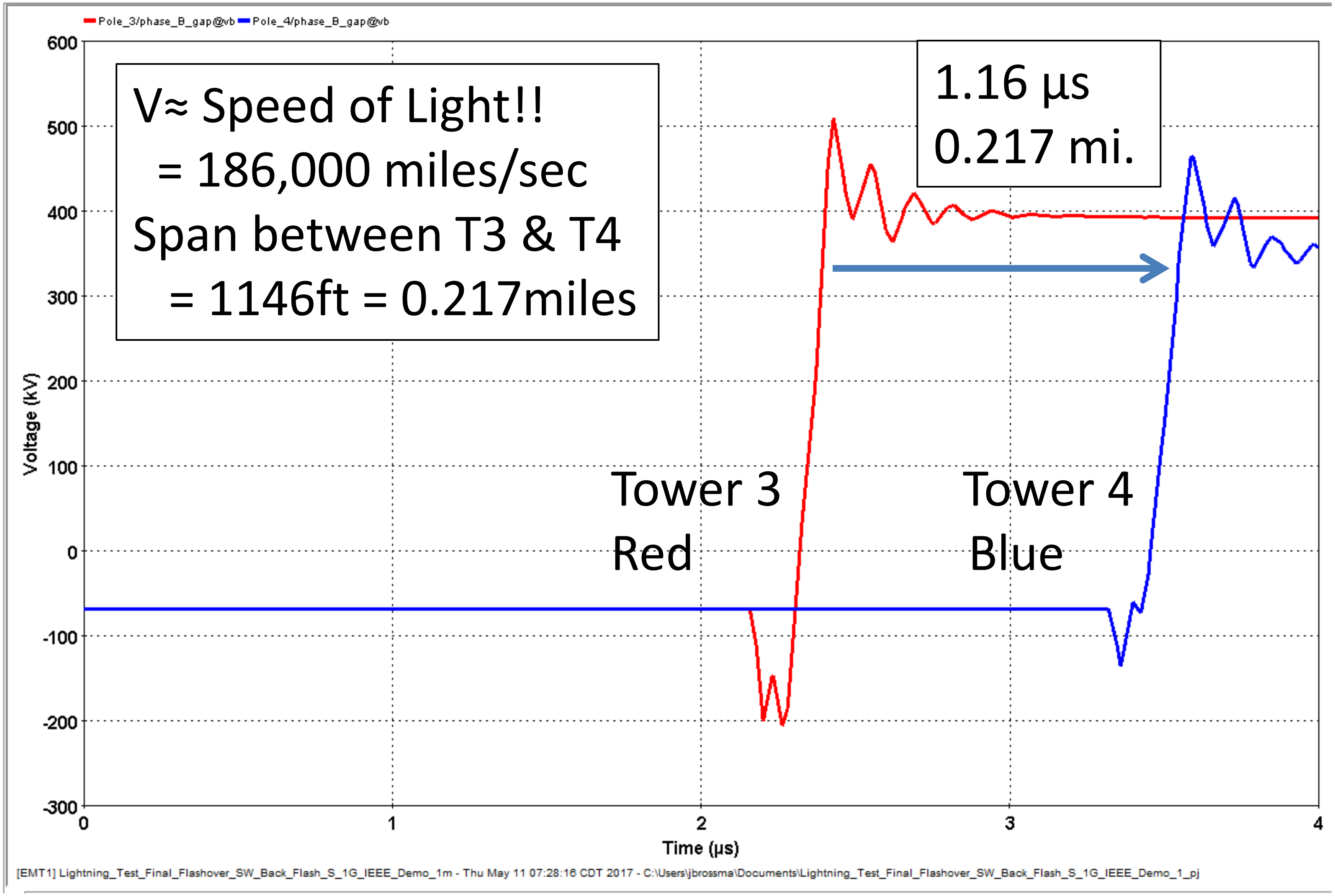
Electromagnetic Transients Program – EMTP-RV Modeling of Lightning Strike on Static Above Pole 2 Wave Transient Moves Towards Pole 4





Pole 2 Pole 3 Pole 4 Typical Pole Model Details

In Transmission Line Traveling Waves Flow Approximately at Speed of Light!!



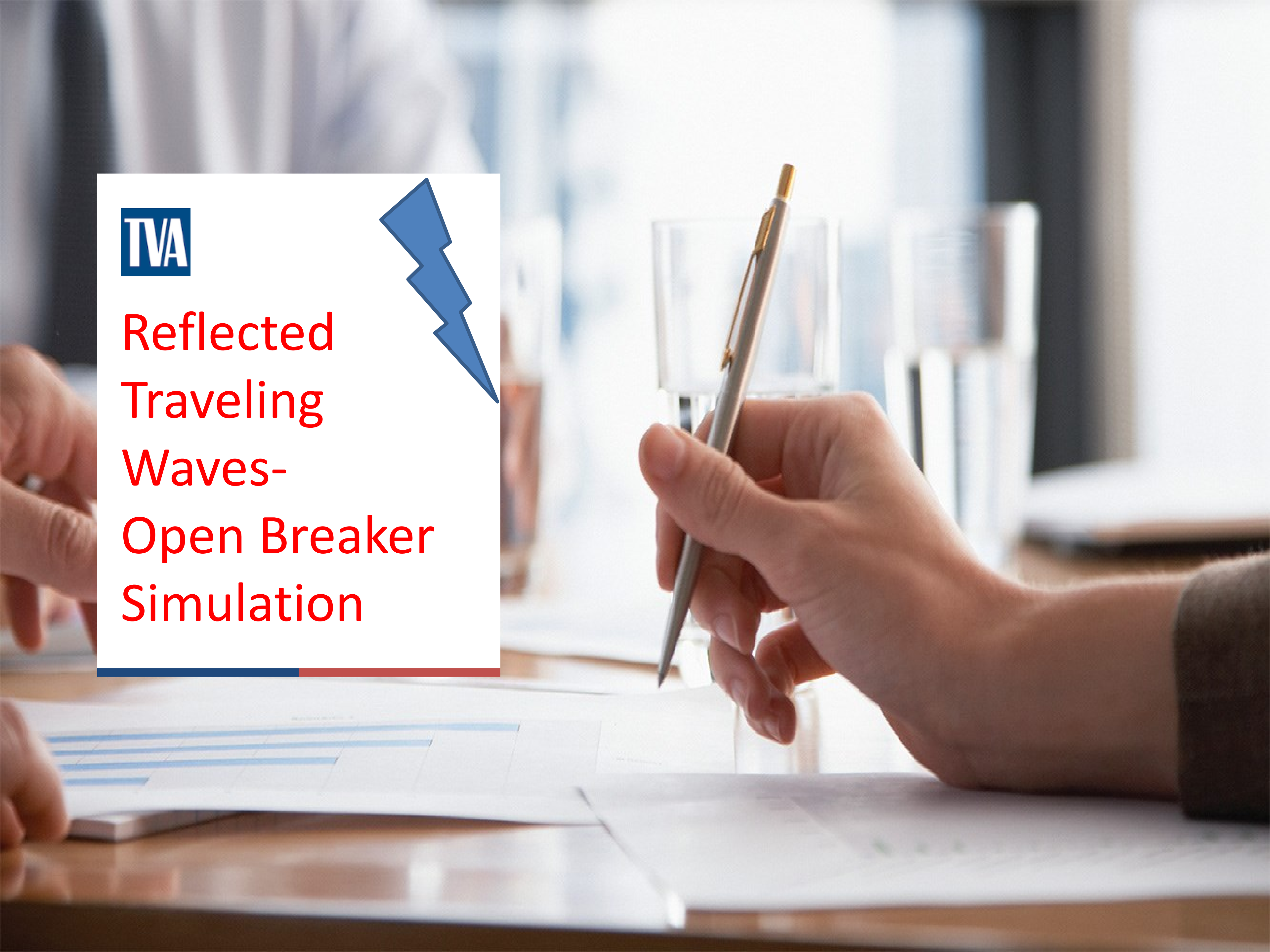
V≈ Speed of Light!!
= 186,000 miles/sec
Span between T3 & T4
= 1146ft = 0.217miles

1.16 µs
0.217 mi.

Tower 3
Red

Tower 4
Blue

[EMT1] Lightning_Test_Final_Flashover_SW_Back_Flash_S_1G_IEEE_Demo_1m - Thu May 11 07:28:16 CDT 2017 - C:\Users\jbrossma\Documents\Lightning_Test_Final_Flashover_SW_Back_Flash_S_1G_IEEE_Demo_1_pj



Reflected Traveling Waves- Open Breaker Simulation

Traveling Wave Enters Substation And Reflects From Open Breaker

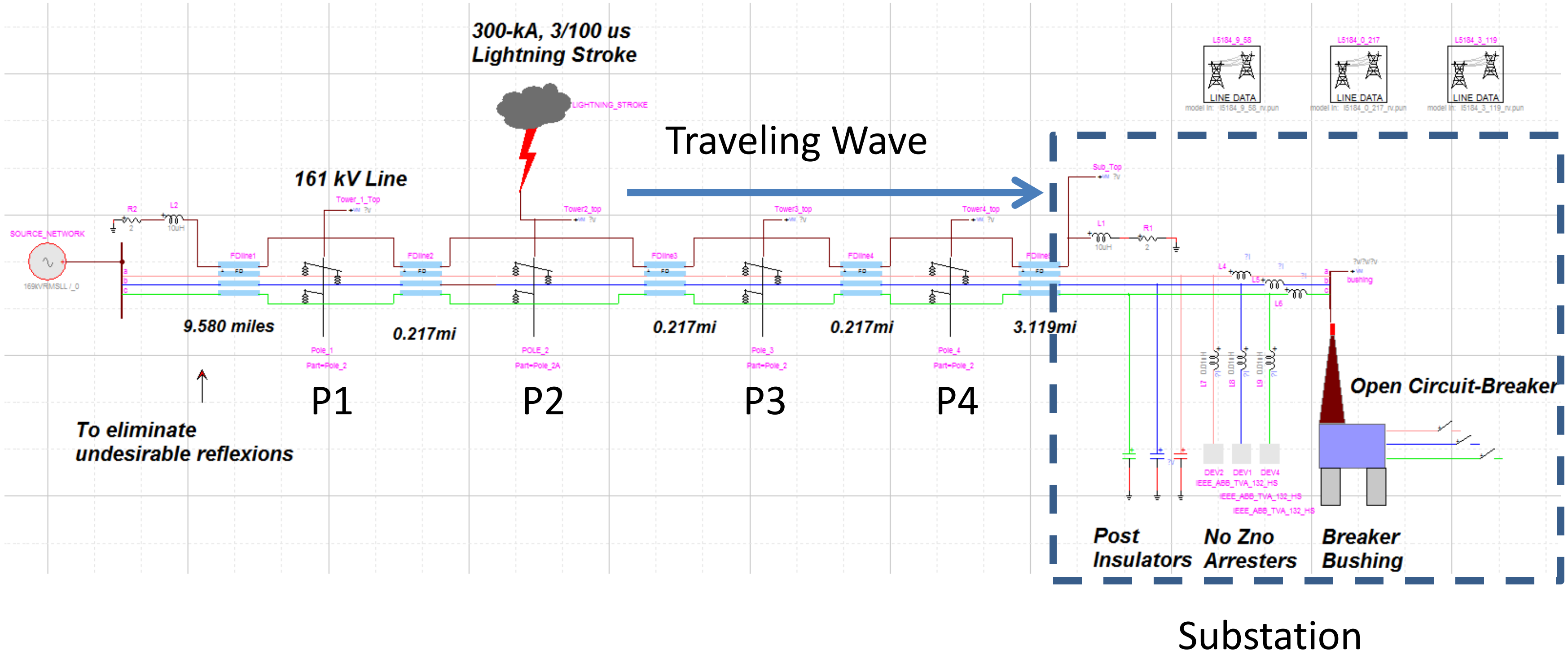
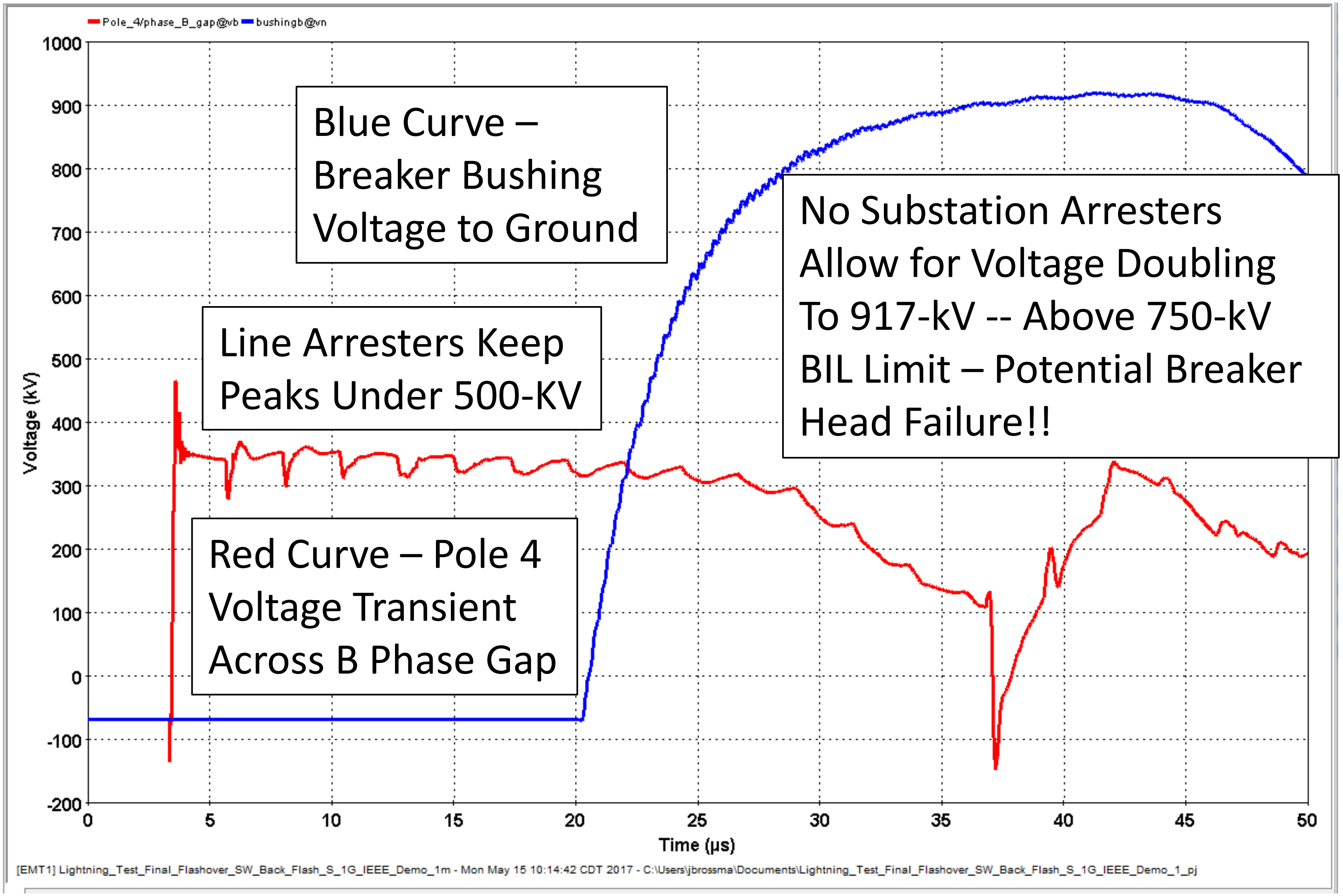


ABB 169PM SF-6 Breaker	**Chopped Wave Impulse – 968-kV**	**Full Wave Bil Rating – 750-kV**

Arresters Are Needed to Protect for Open Substation Circuit Breakers



Blue Curve – Breaker Bushing Voltage to Ground

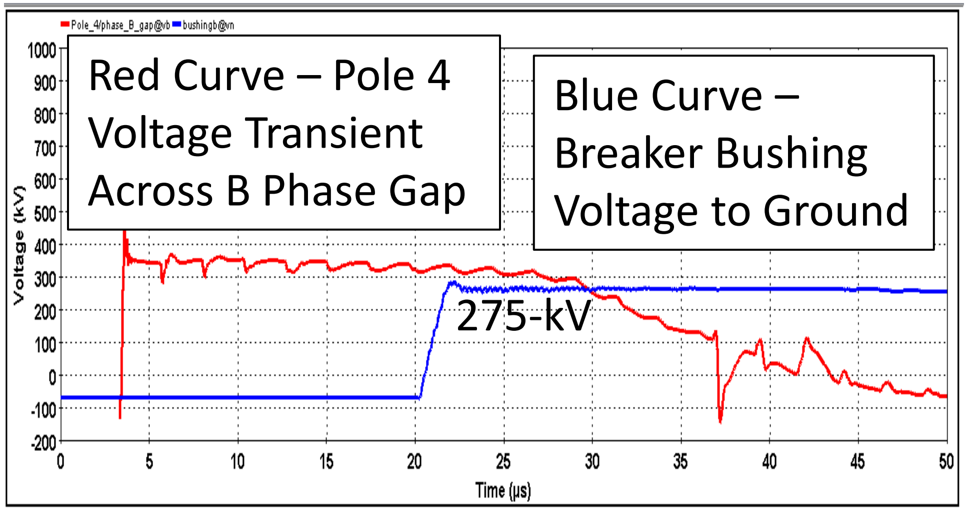
Line Arresters Keep Peaks Under 500-KV

Red Curve – Pole 4 Voltage Transient Across B Phase Gap

No Substation Arresters Allow for Voltage Doubling To 917-kV -- Above 750-kV BIL Limit – Potential Breaker Head Failure!!

[EMT1] Lightning_Test_Final_Flashover_SW_Back_Flash_S_1G_IEEE_Demo_1m - Mon May 15 10:14:42 CDT 2017 - C:\Users\jbrossma\Documents\Lightning_Test_Final_Flashover_SW_Back_Flash_S_1G_IEEE_Demo_1_pj

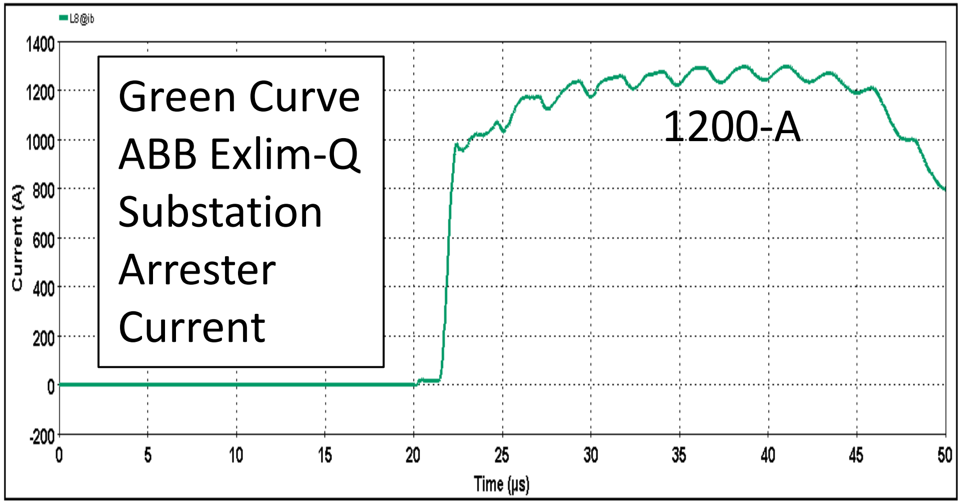
Arresters Are Needed to Protect for Open Substation Circuit Breakers – Voltage Clamped to 275-kV



Red Curve – Pole 4 Voltage Transient Across B Phase Gap

Blue Curve – Breaker Bushing Voltage to Ground

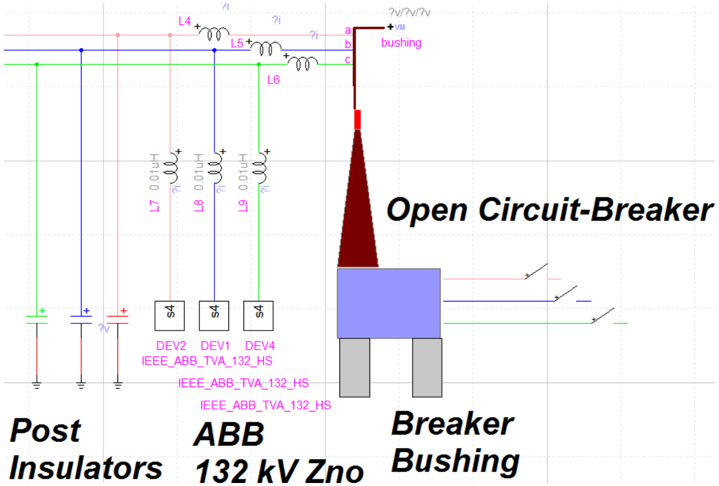
275-kV



Green Curve ABB Exlim-Q Substation Arrester Current

1200-A

[EMT1] Lightning_Test_Final_Flashover_SW_Back_Flash_S_1G_IEEE_Demo_1Am - Mon May 15 10:12:53 CDT 2017 - C:\Users\jbrossma\Documents\Lightning_Test_Final_Flashover_SW_Back_Flash_S_1G_IEEE_Demo_1A_pj



Open Circuit-Breaker

Post Insulators

ABB 132 kV Zno

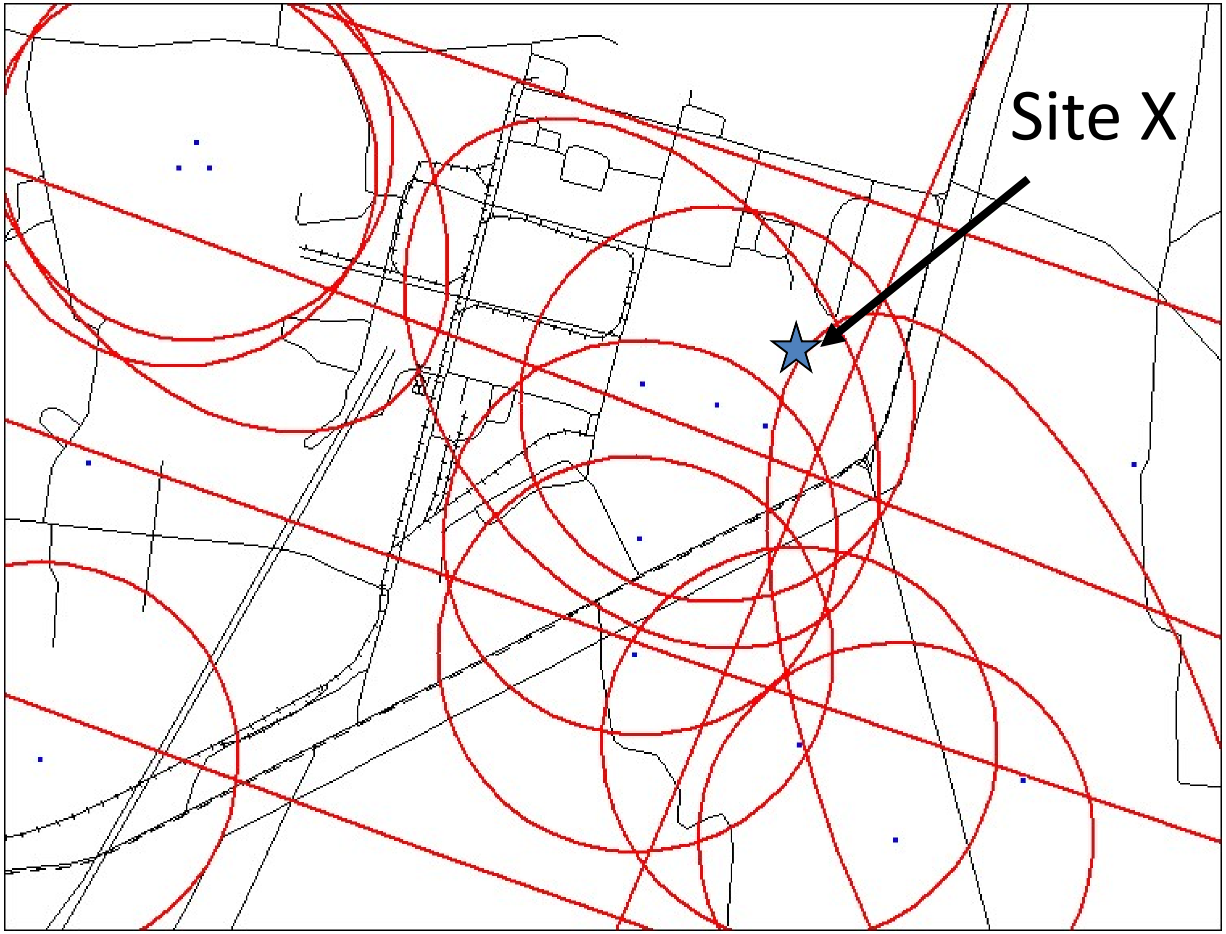
Breaker Bushing

ABB Exlim-Q 132-kV Zno	Clamping Voltage
500-A 30/60uS	260-kV
1500-A 8/20uS	281-kV
3000-A 8/20uS	292-kV

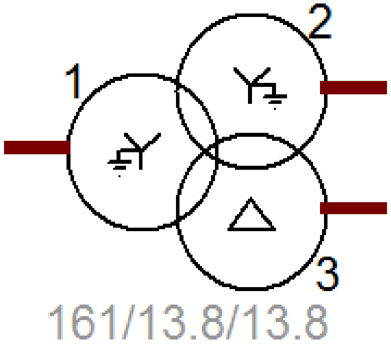
Case 5
Site X
Transformer Delta Winding Failure Due to Lightning – Team Determination

Site X -- 90% Confidence Ellipses - Lightning Strokes

Few Hours Before Transformer Failure



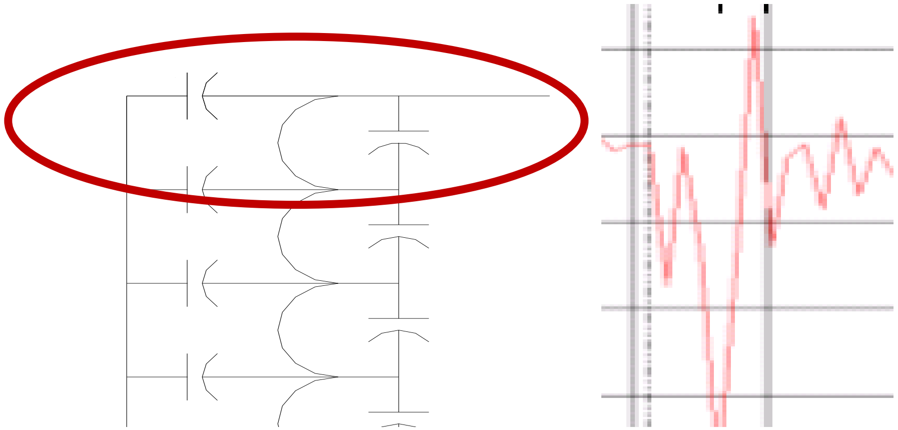
Site X Transformer Configuration



Winding Failure Occurred in Delta Winding

Simple Transformer Winding Model

Inductance and Insulation Capacitance



Lightning energy must move through the network in order for the energy to be dissipated. Unfortunately the steep wave front of lightning occurs so quickly that the capacitance of the first few turns of insulation absorbs most the energy. Therefore it is not uncommon to see lightning related faults in the first few turns of a winding.

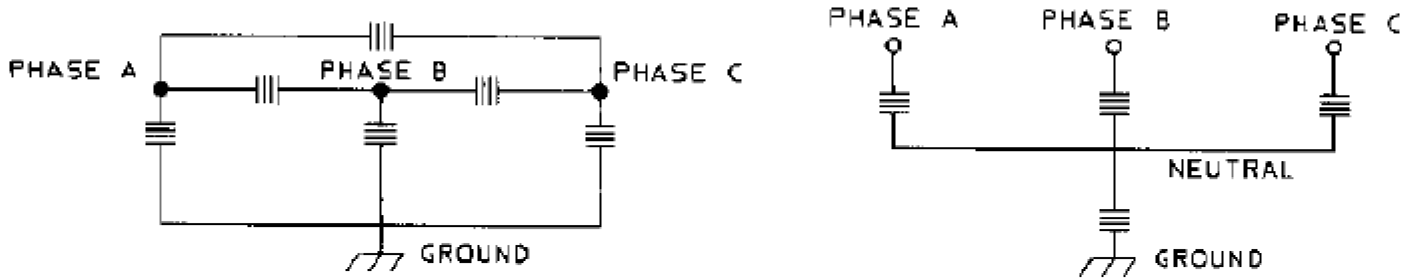
The transformer at Site X failed at the interconnection point on the delta winding. The delta winding had 3-MOV surge arresters installed prior to the fault. Site X later installed 6 arresters, 3-phase to ground and 3-phase to phase to better protect the delta winding.

IEEE Guide for Application of Metal-Oxide Surge Arresters for Alternating-Current Systems

C62.22-2009 – Section 5.2.3.5.2

5.2.3.5.2 Surge protection

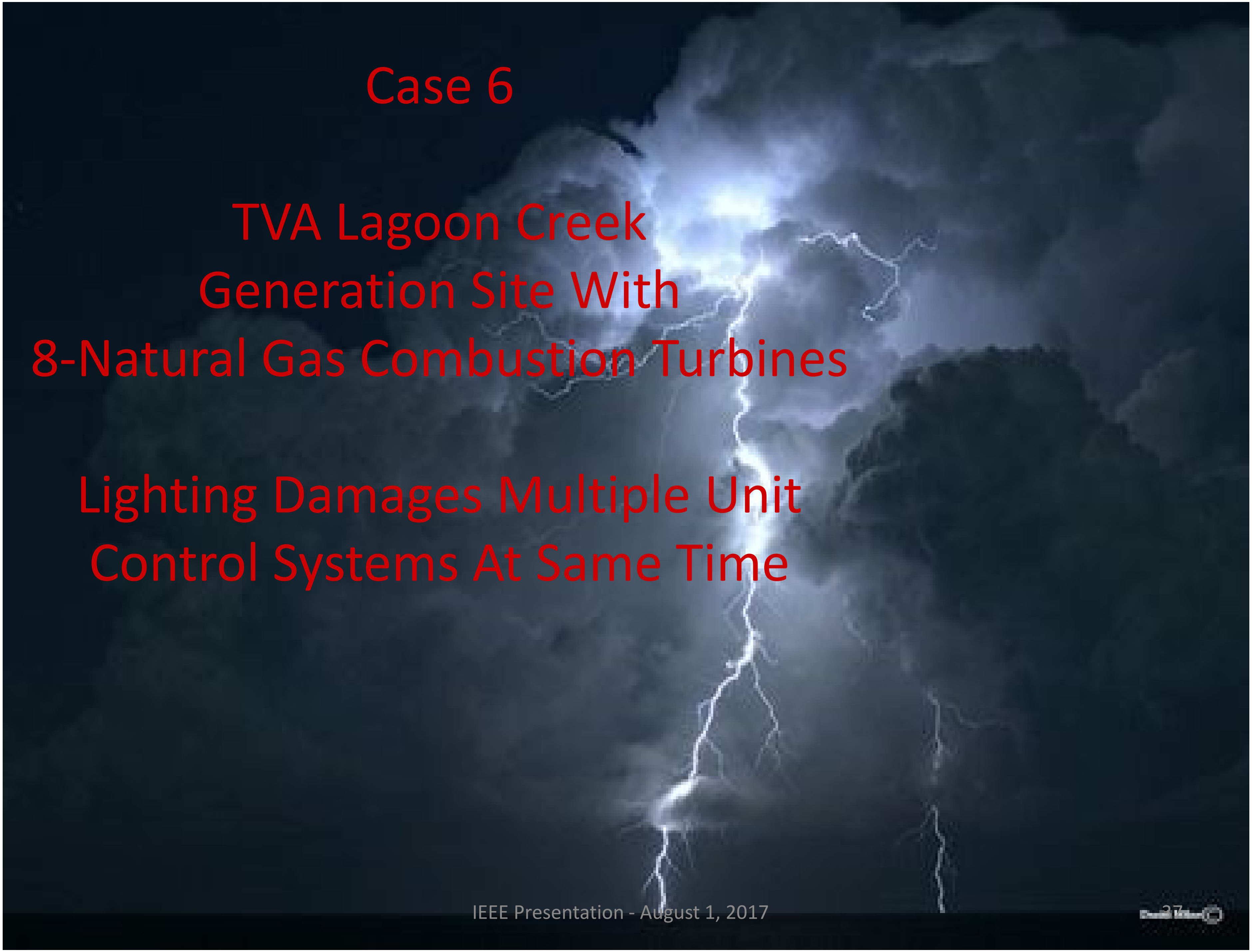
Because surge arresters are typically installed phase to ground at each terminal of the delta-connected transformer windings, each winding is protected by two arresters connected in series through their ground connection. The protective level of the two series-connected arresters may not provide the minimum recommended protective ratios for the transformer insulation. Delta-connected transformer windings can be protected by directly installing phase-to-phase and phase-to-ground surge arresters. This can be accomplished by either of the arrangements shown in Figure 8 (Keri et al. [B109]).



(a) (b)

Figure 8—Phase-to-phase protection

Figure 8(a) represents a six-surge arrester arrangement, consisting of three phase-to-phase and three phase-to-ground arresters for three-phase bank. Figure 8(b) represents a four-legged surge arrester arrangement, consisting of three surge arresters connected from three phases to common neutral, and one arrester connected from the common neutral to ground.

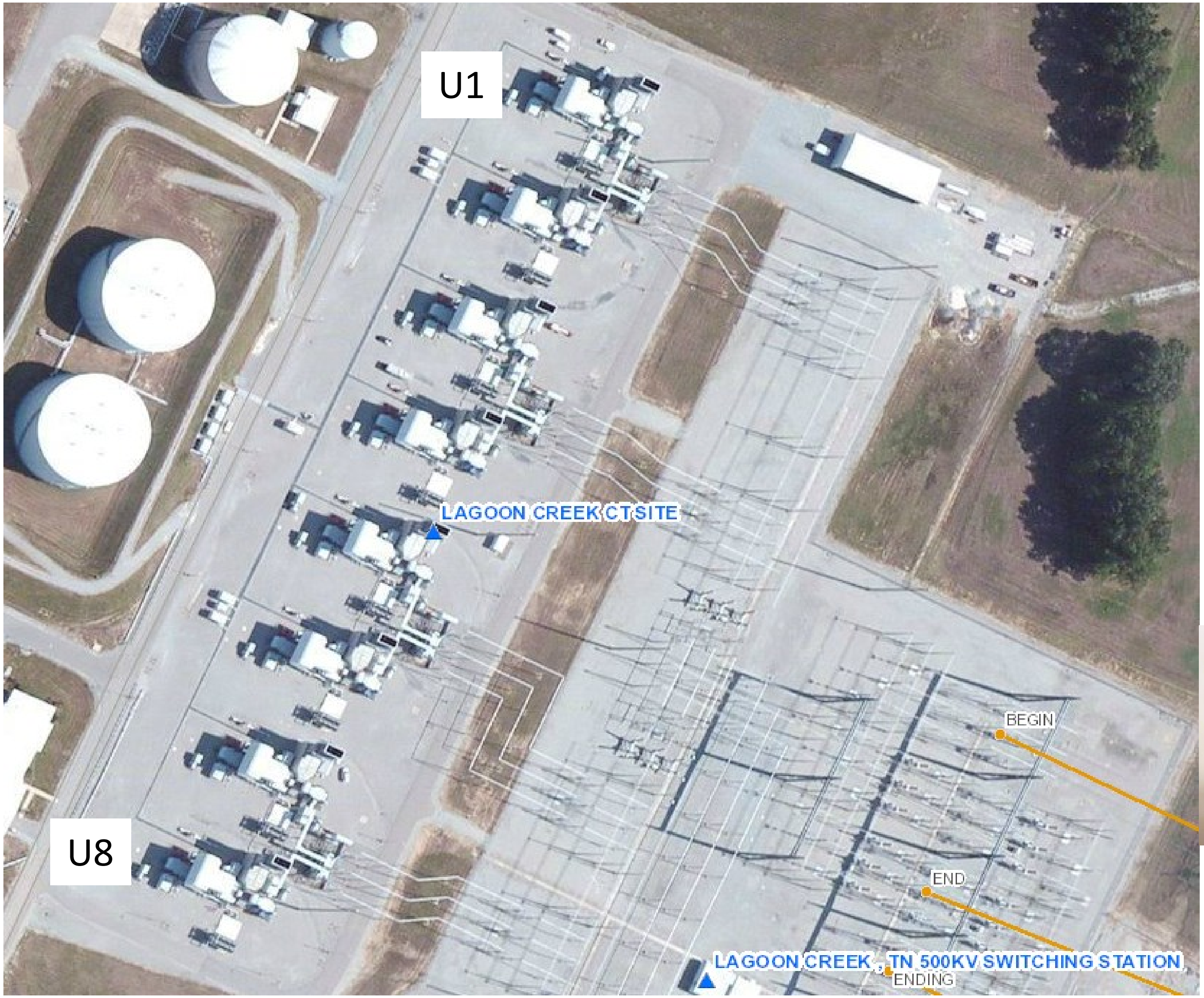


Case 6

TVA Lagoon Creek Generation Site With 8-Natural Gas Combustion Turbines

Lighting Damages Multiple Unit Control Systems At Same Time

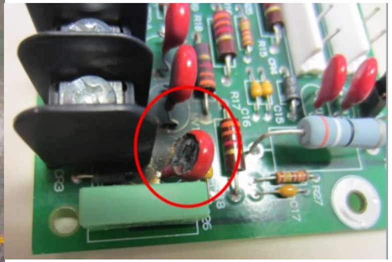
Following Lightning Storms - Damage to Control Systems For U1 and U8 Separated as Shown Below by 300m



Only U1 to U8 Interconnections:

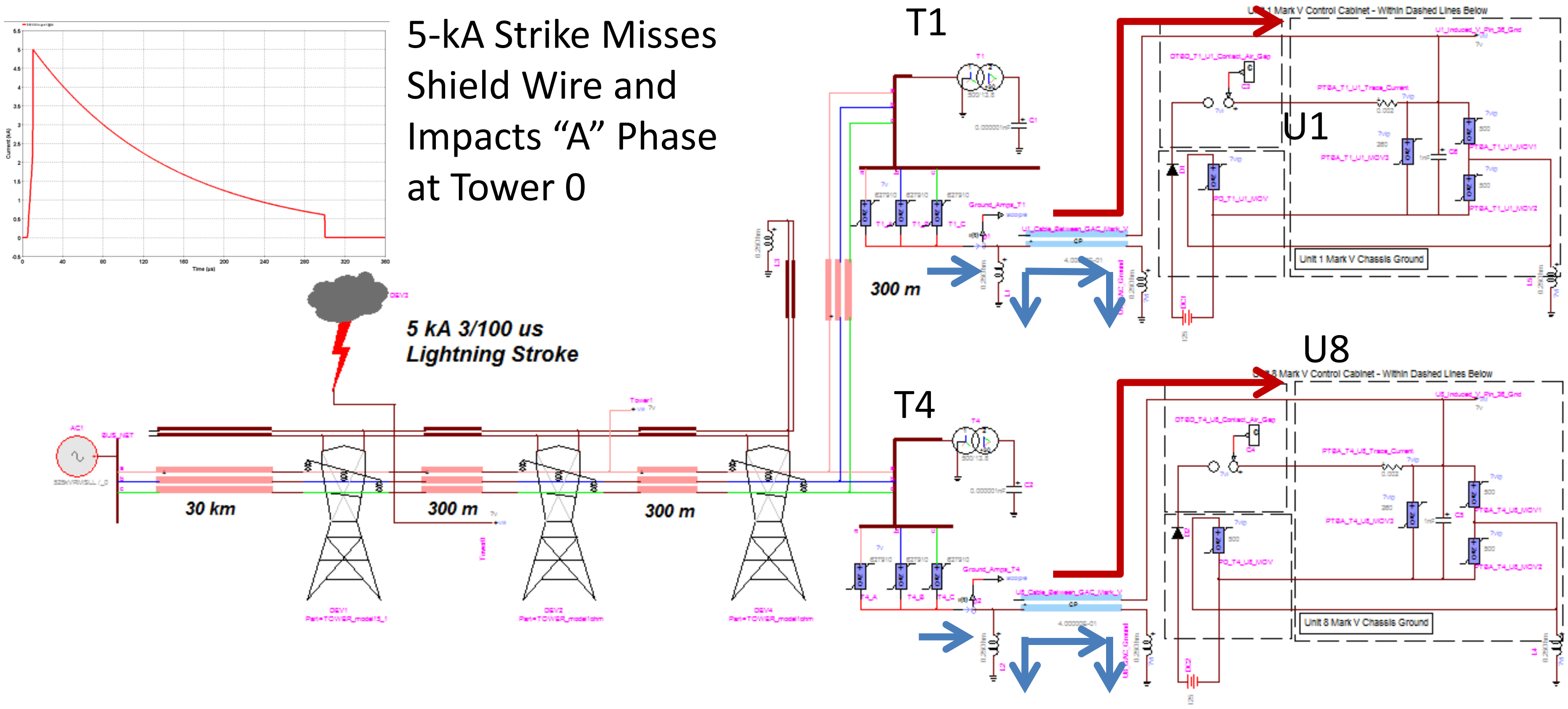
- 500-kV System
- Ground Mat

On Both U1, U8 Same 125-Vdc Control Components Failed Following Storms



Two Generating Unit Control Cabinets (U1, U8) – 300’ Apart

Team Conclusions on Sequence of Events



5-kA Strike Misses Shield Wire and Impacts “A” Phase at Tower 0

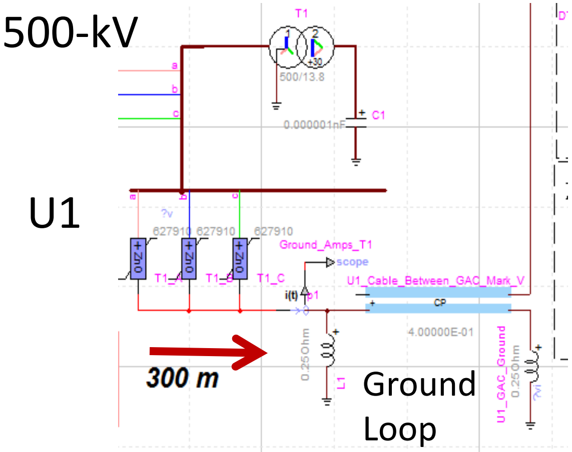
Blue Arrows – Ground Currents Flowing In Shielded Cable - Ground Loops

Red Arrows – Induced Currents on 125-VDC Control Systems

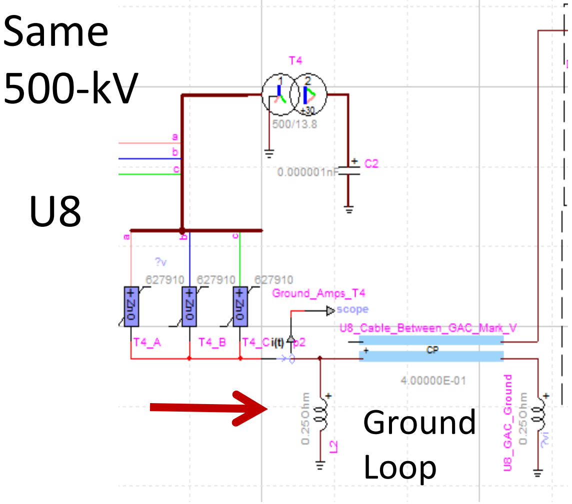
These currents created voltages >1000-V and damaged the control boards

This same pattern occurred on both Units 1 and Units 8 simultaneously

Surge Current Flows Across Multiple Ground Grid Locations Between U1 and U8 GAC and Main Control Buildings



MOVs & Circuit Board Traces Melted



- Here is a reason why you don’t ground shields on both ends of shielded cable.
- Optical isolation was recommended to be installed in every Unit control circuits to break up its ground loop.


Surge Arresters
Catalog Data
CA235025EN

Effective May 2017
Supersedes November 2015

COOPER POWER
SERIES

Metal Oxide Varistor Elbow (M.O.V.E.)
Surge Arrester

Case 7
Application Issue –
Improper Application 1
9-kV Arresters Installed Instead of Proper 10-kV Arresters

Protecting Pad-Mounted Transformer
At 12,470-V – 9-kV is Standard (Historically)
At 13,200-V – 10-kV is Needed

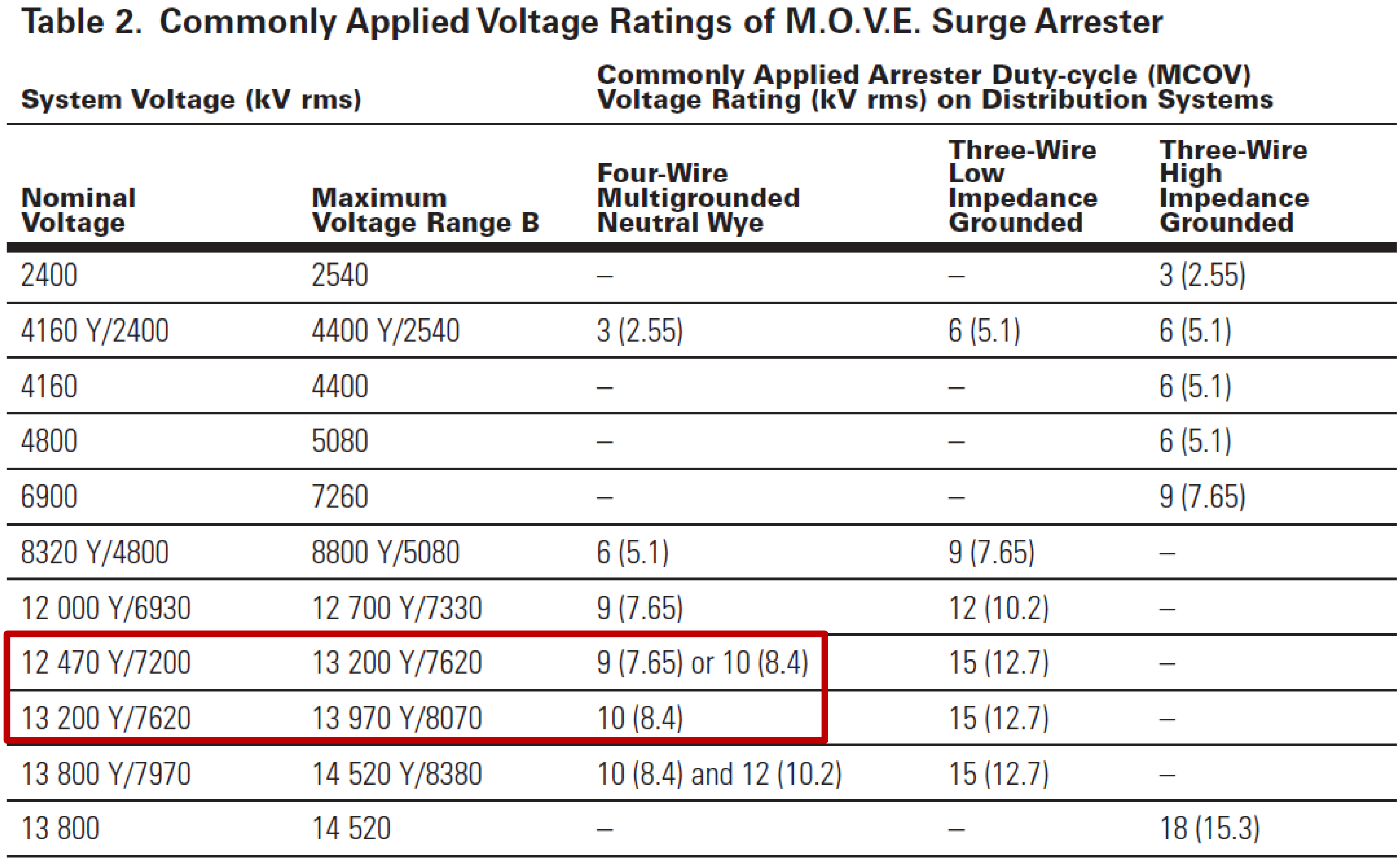
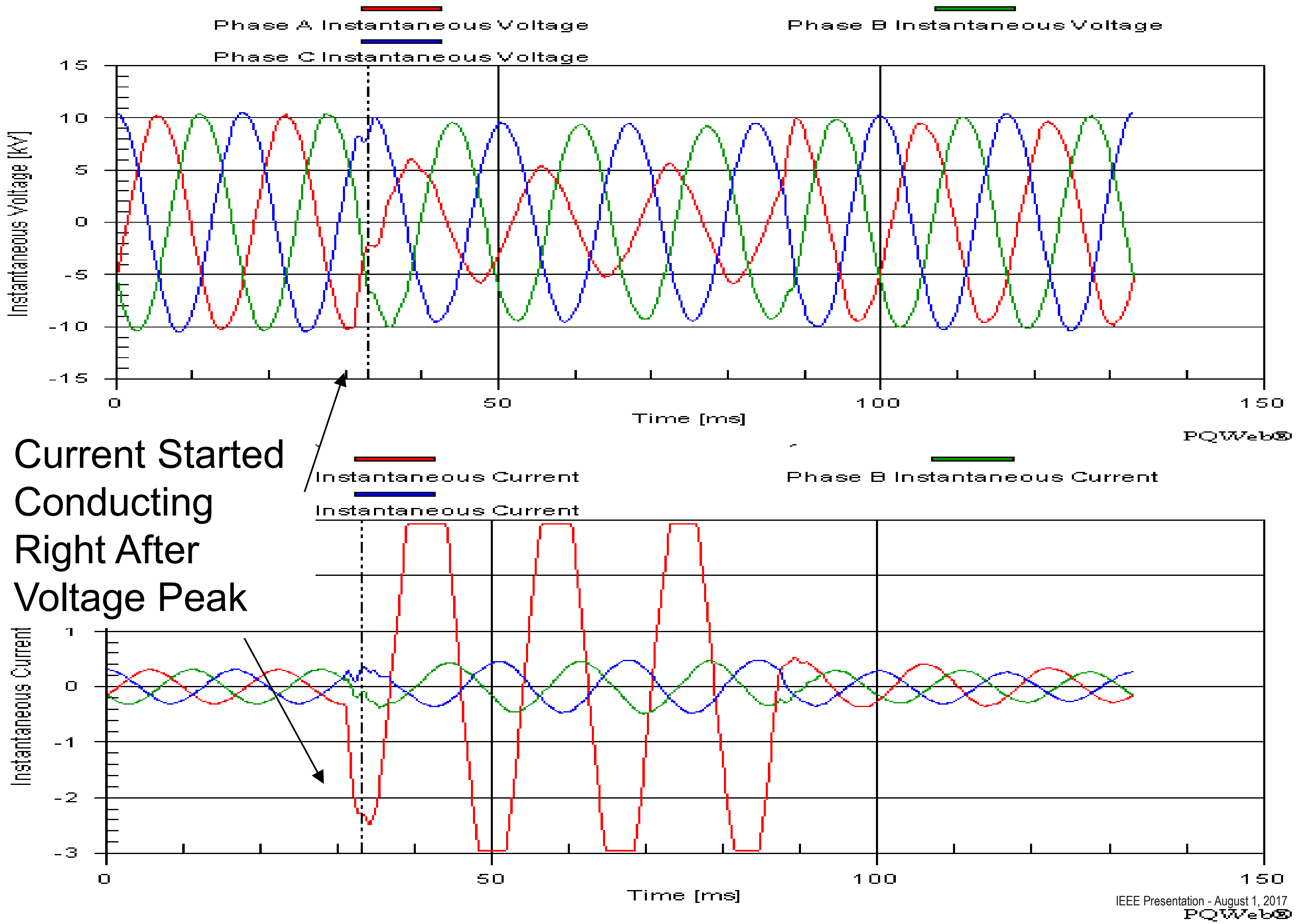


Table 2. Commonly Applied Voltage Ratings of M.O.V.E. Surge Arrester

System Voltage (kV rms)		Commonly Applied Arrester Duty-cycle (MCOV) Voltage Rating (kV rms) on Distribution Systems		
Nominal Voltage	**Maximum Voltage Range B**	**Four-Wire Multigrounded Neutral Wye**	**Three-Wire Low Impedance Grounded**	**Three-Wire High Impedance Grounded**
2400	2540	–	–	3 (2.55)
4160 Y/2400	4400 Y/2540	3 (2.55)	6 (5.1)	6 (5.1)
4160	4400	–	–	6 (5.1)
4800	5080	–	–	6 (5.1)
6900	7260	–	–	9 (7.65)
8320 Y/4800	8800 Y/5080	6 (5.1)	9 (7.65)	–
12 000 Y/6930	12 700 Y/7330	9 (7.65)	12 (10.2)	–
12 470 Y/7200	13 200 Y/7620	9 (7.65) or 10 (8.4)	15 (12.7)	–
13 200 Y/7620	13 970 Y/8070	10 (8.4)	15 (12.7)	–
13 800 Y/7970	14 520 Y/8380	10 (8.4) and 12 (10.2)	15 (12.7)	–
13 800	14 520	–	–	18 (15.3)

Waveform Data Helps Track Down Source of Faults- 9-kV Arresters Operated at Voltages Where 10-KV is Needed



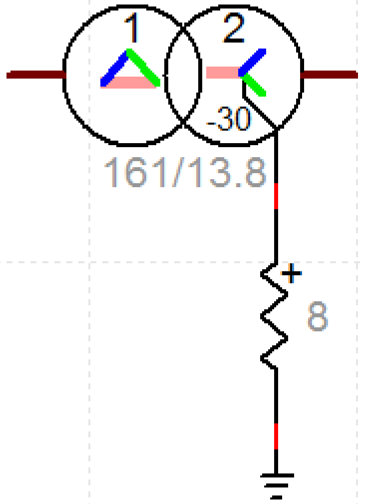
Current Started Conducting Right After Voltage Peak

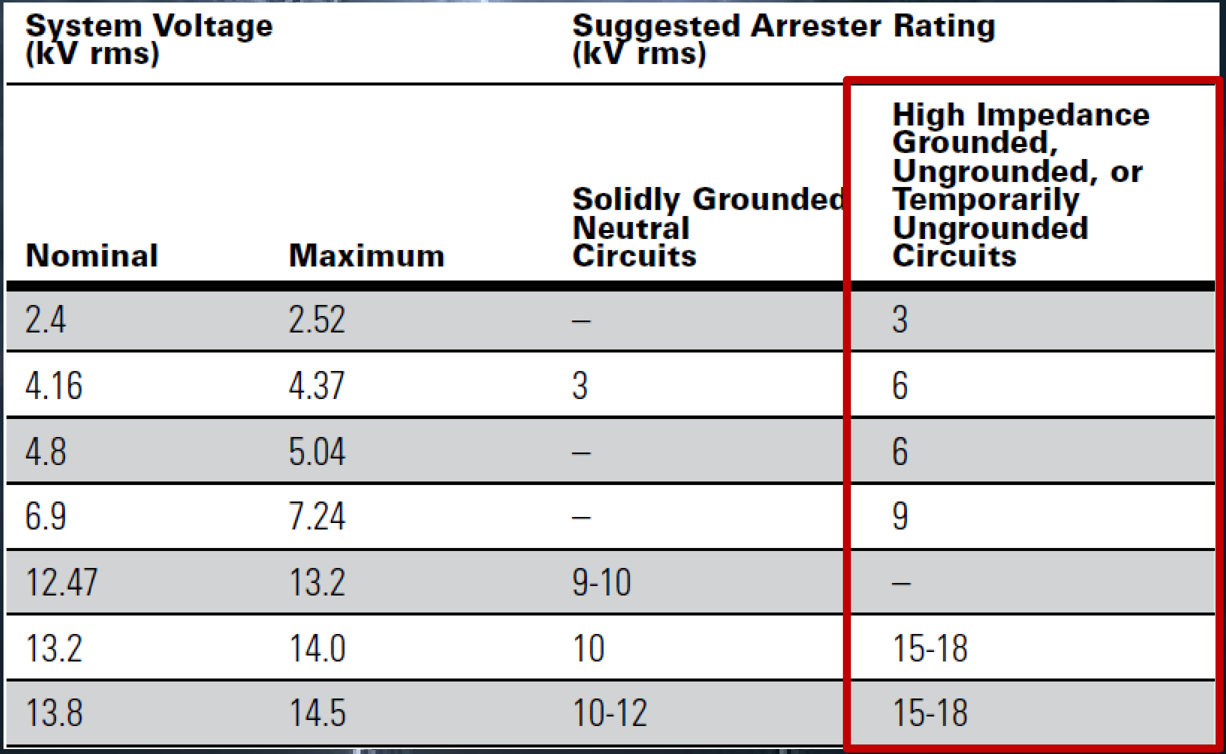
Improper Arrester Application - 1

- Local power company bought a 1500-kVA pad-mounted transformer with primary taps – rating of primary was 12.47-kVLL – they adjusted taps to raise voltage by taps to 13.09-kV.
- The system voltage swing during weekends/nights went as high as 13.5-kV during nights and weekends. The 7.65-kV MCOV limit for 9-kV arresters were exceeded during these operating condition times.
- Nuisance breaker operations occurred and the PQM showed the issue to be with 1500-kVA transformer arrester operations.
- When the arresters exceeded the MCOV limit they started conducting and eventually distribution system feeder tripped due to ground faults.
- **Solution to this issue was to swap out 9-kV arresters for 10-kV arresters. This is a major systematic issue and we have seen multiple events similar to this story.**

Case 8 Application Issue – Improper Application 2 10-kV Arresters Installed Instead of Proper 18-kV Arresters

Impedance Grounded Distribution System (Typical Industrial Site)

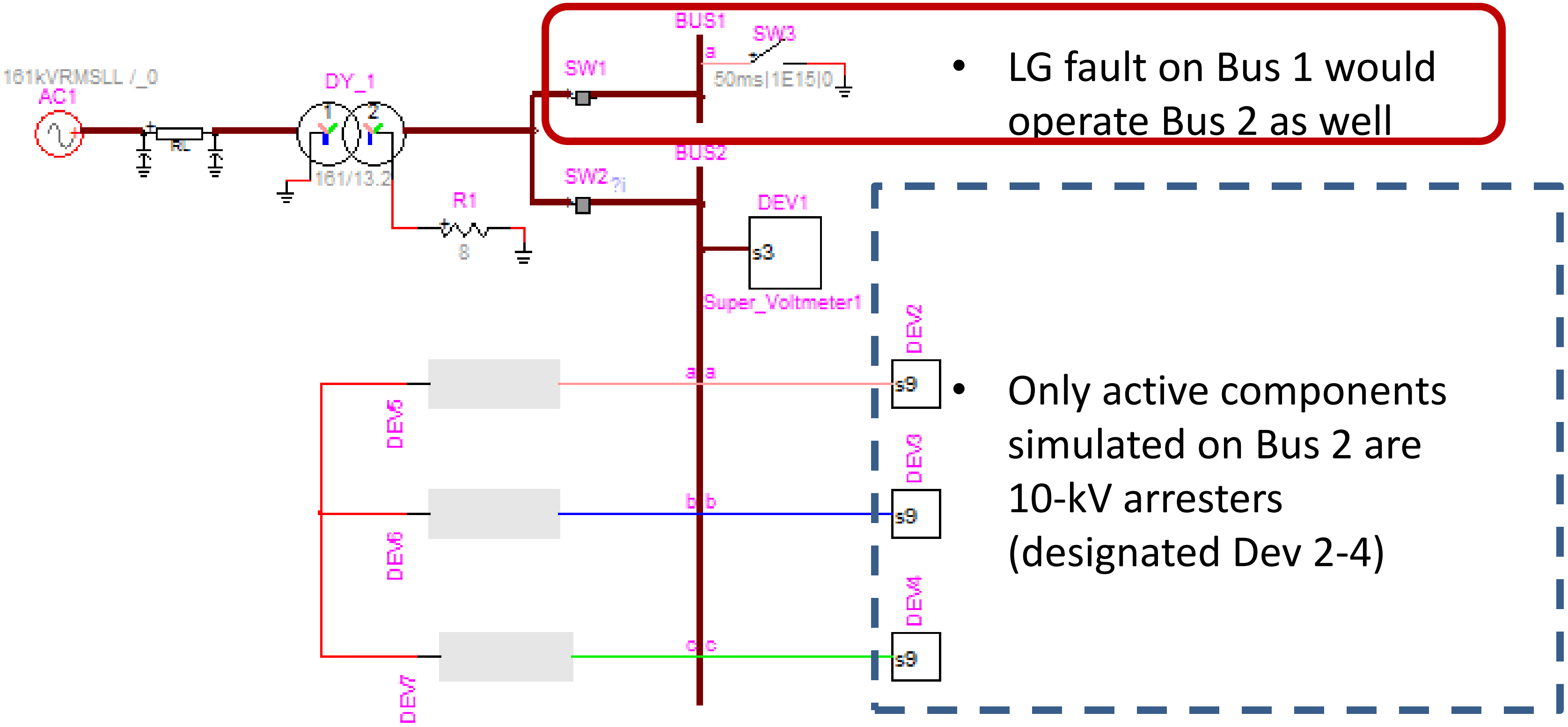




System Voltage (kV rms)		Suggested Arrester Rating (kV rms)	
Nominal	Maximum	Solidly Grounded Neutral Circuits	High Impedance Grounded, Ungrounded, or Temporarily Ungrounded Circuits
2.4	2.52	–	3
4.16	4.37	3	6
4.8	5.04	–	6
6.9	7.24	–	9
12.47	13.2	9-10	–
13.2	14.0	10	15-18
13.8	14.5	10-12	15-18

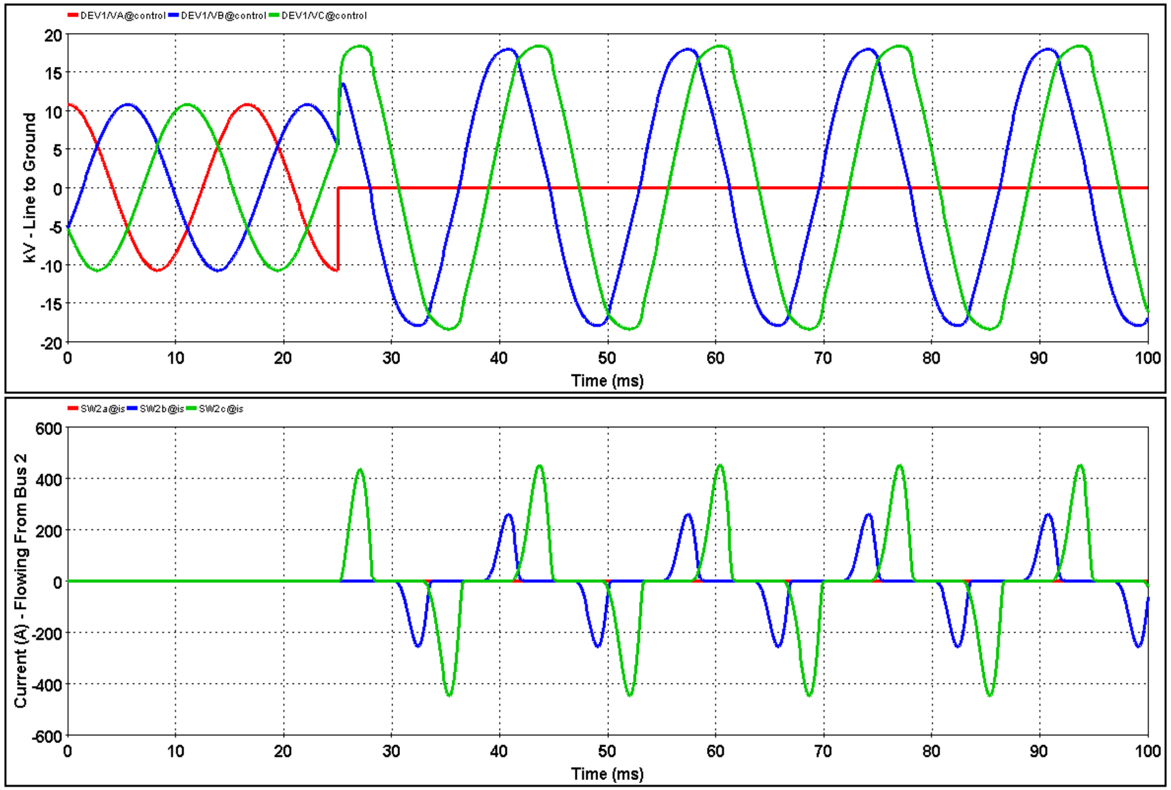
Improper Arrester Application -2

- Industrial Facilities (IF) often operate their distribution systems in an impedance grounded Wye configuration such as 13.2-kVLL or 7.62-kVLG.
- IF had impedance-grounded overhead distribution system fed from multiple substation circuit breakers. **Fault on one circuit makes other circuit trip as well.**



- LG fault on Bus 1 would operate Bus 2 as well
- Only active components simulated on Bus 2 are 10-kV arresters (designated Dev 2-4)

Improper Arrester Application -2 - Continued



[EMT1] Arrester_Demom - Tue May 16 09:30:48 CDT 2017 - C:\Users\jbrossma\Documents\Arrester_Demo_pj

Four Wire High Impedance Grounding Recommendations

ANSI/IEEE Ratings	Max. Cont. Operating Voltage	Arrester Rating - Vr
Kvrms- LL – 13.09 to 14.49-kV	15.3-kV	18

- Simulations show balanced phase voltages prior to A-phase to ground fault at T=25ms.
- Due to impedance grounding, Vbg and Vcg grow to VLL levels.
- 10-kV arresters MCOV rating is exceeding and it starts conducting.
- The breaker relay detects ground fault current and operates.
- Solution to this problem install 18-kV instead of 10-kV arresters.

Arrester Lead Length/ Configuration Can Be Critical

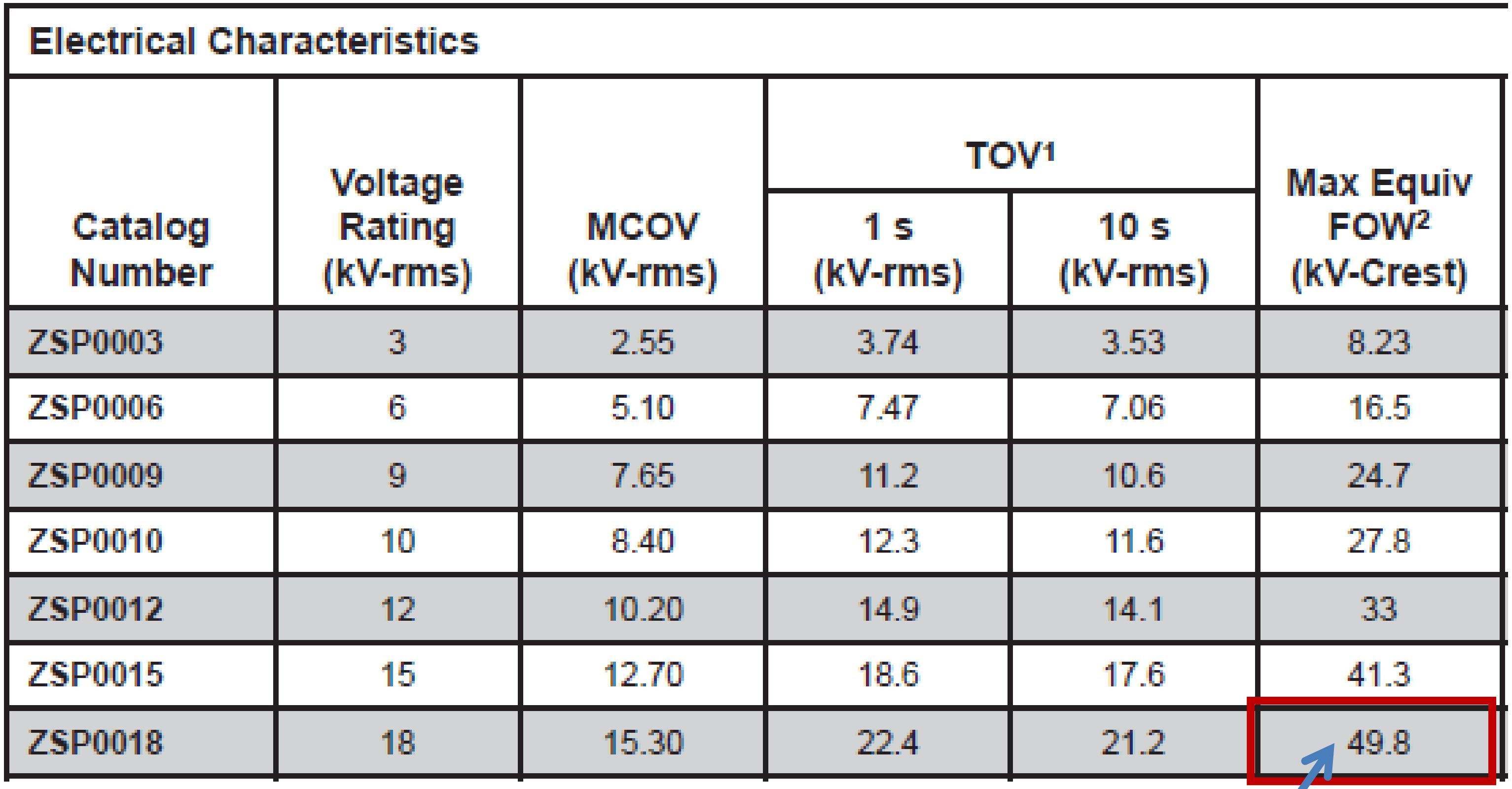
Key Concept – Keep Arrester Leads As Short As Possible

- Distribution insulation performance is characterized with the Basic Lightning Impulse Insulation Level (BIL) – for 15-kV system, this level is **95-kV (BIL).**

- Because the voltage stress does not last as long, with most equipment, the chopped wave withstand (CWW) is higher than the BIL - for 15-kV class transformers and insulators this level is **110-kV (CWW).**

- Surge Arresters are designed to divert lightning to ground and help protect equipment from exceeding their BIL and CWW ratings during lightning strikes. **It is extremely critical to minimize the inductances of the connections from the phase circuit all the way to a low impedance ground plane.**

Typical Customer’s ZSP 18-kV Arresters
(Impedance-Grounded 13-kV System)

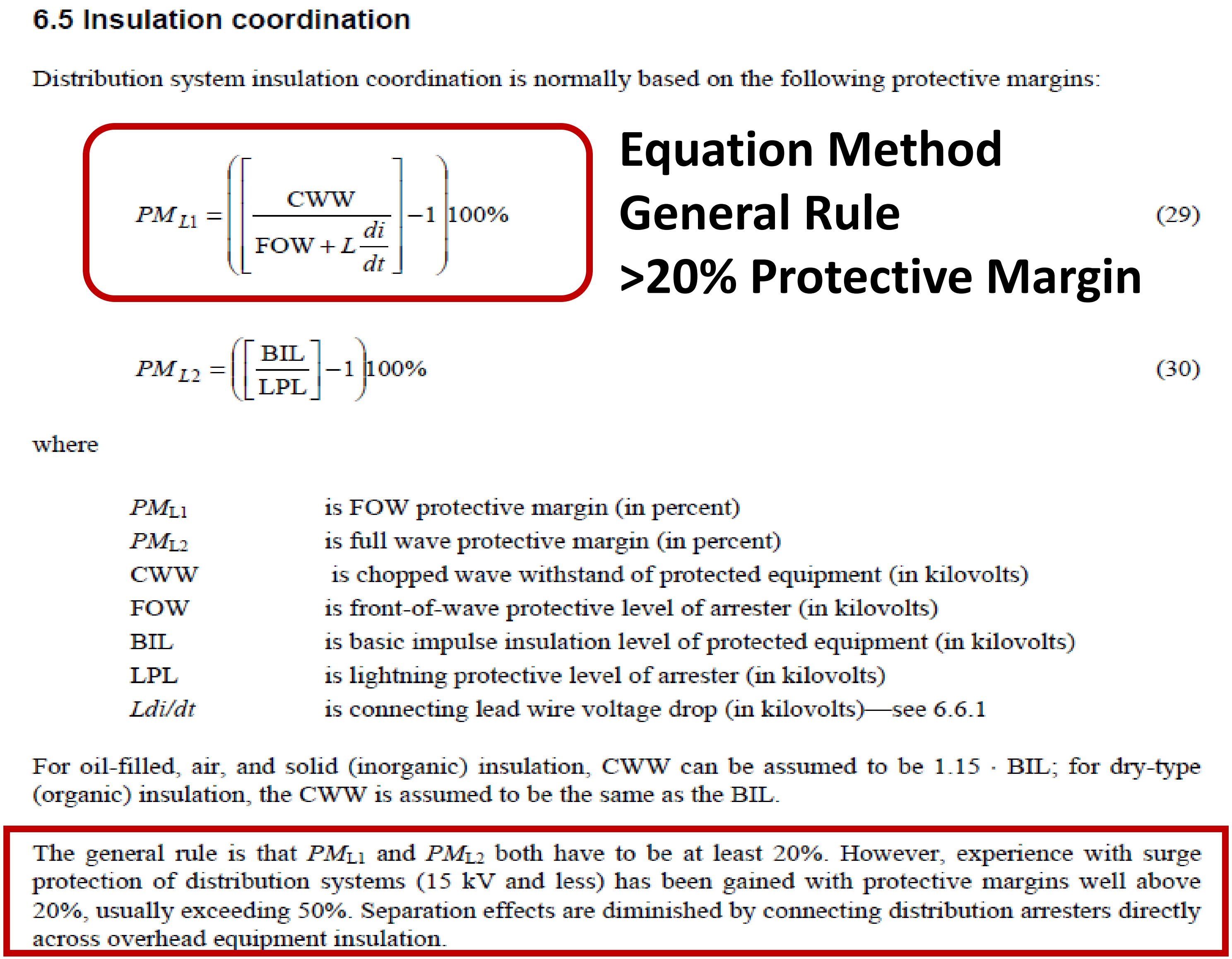


Electrical Characteristics

Catalog Number	Voltage Rating (kV-rms)	MCOV (kV-rms)	TOV[1]		Max Equiv FOW[2] (kV-Crest)
			1 s (kV-rms)	10 s (kV-rms)	
ZSP0003	3	2.55	3.74	3.53	8.23
ZSP0006	6	5.10	7.47	7.06	16.5
ZSP0009	9	7.65	11.2	10.6	24.7
ZSP0010	10	8.40	12.3	11.6	27.8
ZSP0012	12	10.20	14.9	14.1	33
ZSP0015	15	12.70	18.6	17.6	41.3
ZSP0018	18	15.30	22.4	21.2	49.8

FOW Level

IEEE Guide for Application of Metal-Oxide Surge Arresters for Alternating-Current Systems
C62.22-2009 – Section 6.5



6.5 Insulation coordination

Distribution system insulation coordination is normally based on the following protective margins:

$$PM_{L1} = \left(\left[\frac{\text{CWW}}{\text{FOW} + L\dfrac{di}{dt}} \right] - 1 \right) 100\% \quad (29)$$

Equation Method
General Rule
>20% Protective Margin

$$PM_{L2} = \left(\left[\frac{\text{BIL}}{\text{LPL}} \right] - 1 \right) 100\% \quad (30)$$

where

PM_{L1}	is FOW protective margin (in percent)
PM_{L2}	is full wave protective margin (in percent)
CWW	is chopped wave withstand of protected equipment (in kilovolts)
FOW	is front-of-wave protective level of arrester (in kilovolts)
BIL	is basic impulse insulation level of protected equipment (in kilovolts)
LPL	is lightning protective level of arrester (in kilovolts)
Ldi/dt	is connecting lead wire voltage drop (in kilovolts)—see 6.6.1

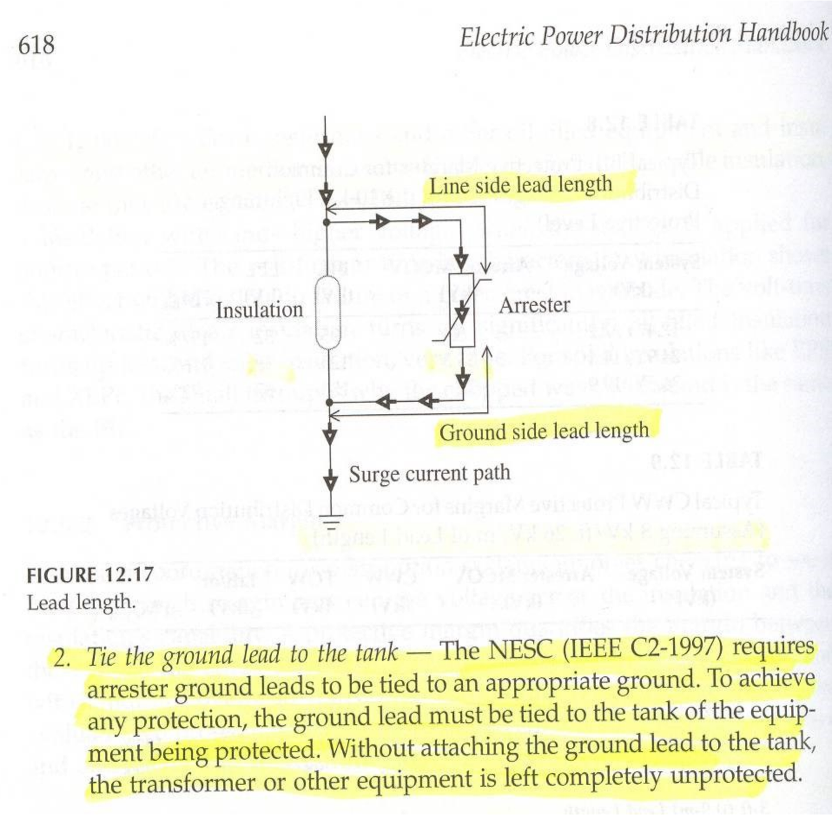
For oil-filled, air, and solid (inorganic) insulation, CWW can be assumed to be 1.15 · BIL; for dry-type (organic) insulation, the CWW is assumed to be the same as the BIL.

The general rule is that PM_{L1} and PM_{L2} both have to be at least 20%. However, experience with surge protection of distribution systems (15 kV and less) has been gained with protective margins well above 20%, usually exceeding 50%. Separation effects are diminished by connecting distribution arresters directly across overhead equipment insulation.

Protective Margin Calculations for 18-kV Arrester Protecting Bushings/Transformer –110-kV CWW Long Connection Length Reduces Protection

Assume **2 foot connections** with 0.4uH/ft inductance and 20kA/usec current change
PML1 = [(CWW/(FOW + Ldi/dt))-1] x 100%
PML1 = [110-kV/(49.8 + 16.0)-1] x 100% = **67% PM >20 so ok**

Assume **8 foot connections** with 0.4uH/ft inductance and 20kA/usec current change
PML1 = [110-kV/(49.8+64.0)-1] x 100% = **- 3% PM <20 so not ok**



618 *Electric Power Distribution Handbook*

FIGURE 12.17
Lead length.

2. *Tie the ground lead to the tank* — The NESC (IEEE C2-1997) requires arrester ground leads to be tied to an appropriate ground. To achieve any protection, the ground lead must be tied to the tank of the equipment being protected. Without attaching the ground lead to the tank, the transformer or other equipment is left completely unprotected.

Long connection length and arresters rated for 18-kV don't meet >20% PM goal

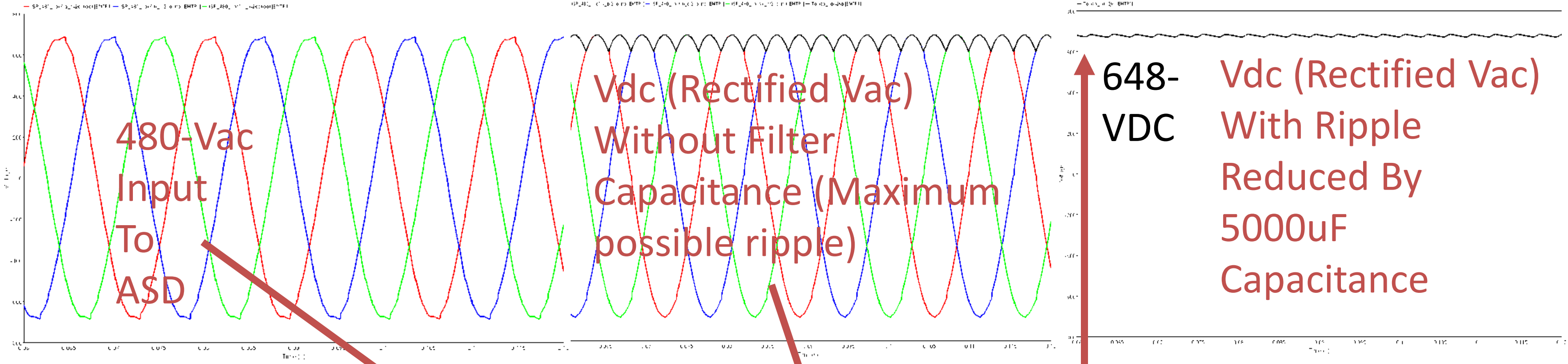
Re-running for 10-kV arrester and 8 foot connection barely meets 20% PM goal

Switching Surges Section

Capacitor Switching Transients

2 Mitigation Strategies Shown:

1) Install Pre-Insertion Resistance In Cap Switchers
2) Add In-line Inductance to make a filter bank instead of cap bank



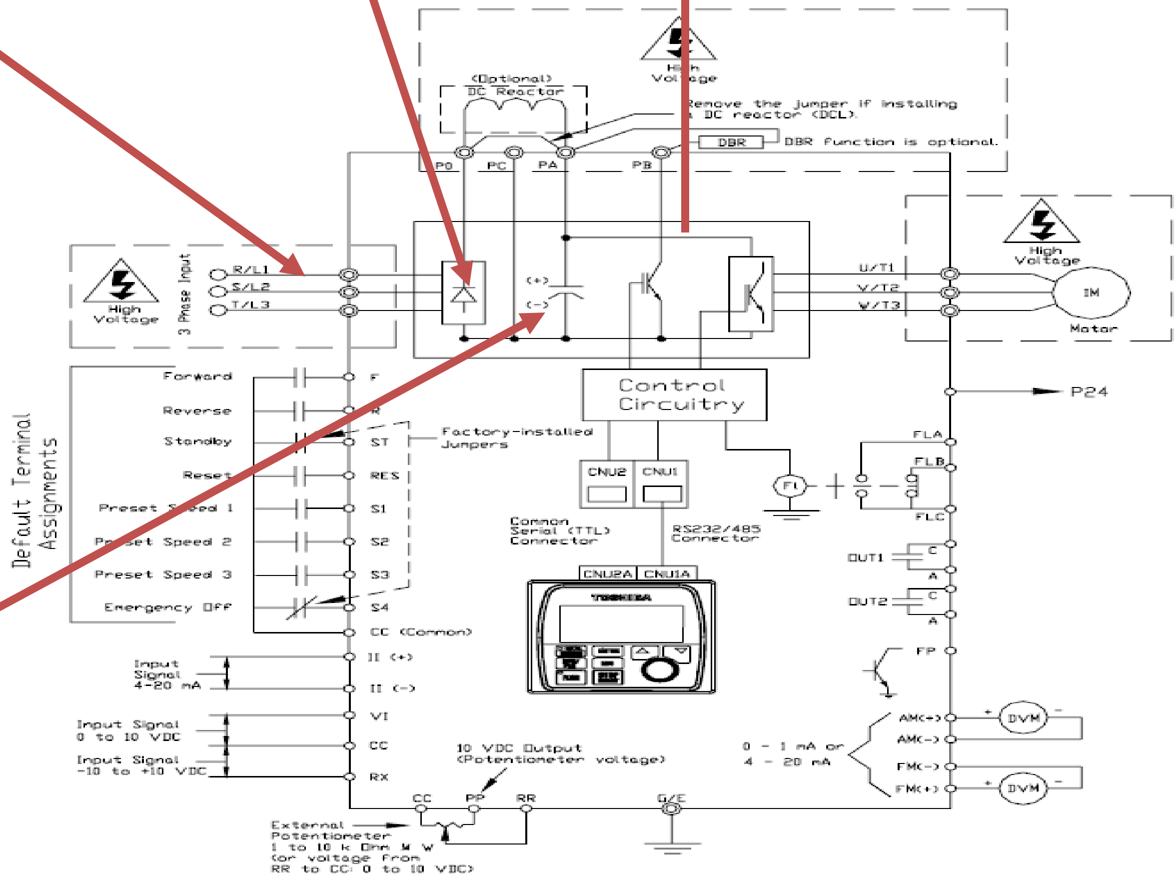
480-Vac Input To ASD

Vdc (Rectified Vac) Without Filter Capacitance (Maximum possible ripple)

648-VDC

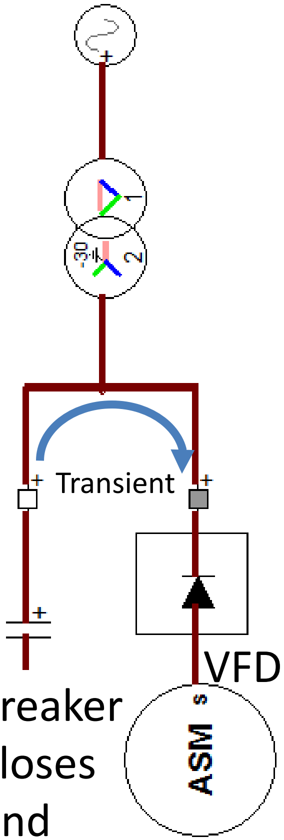
Vdc (Rectified Vac) With Ripple Reduced By 5000uF Capacitance

Toshiba G7 VFD Drive Front - In Rectification 648-VDC Normal Trips When VDC Exceeds 840-VDC 130% Over Normal Peak

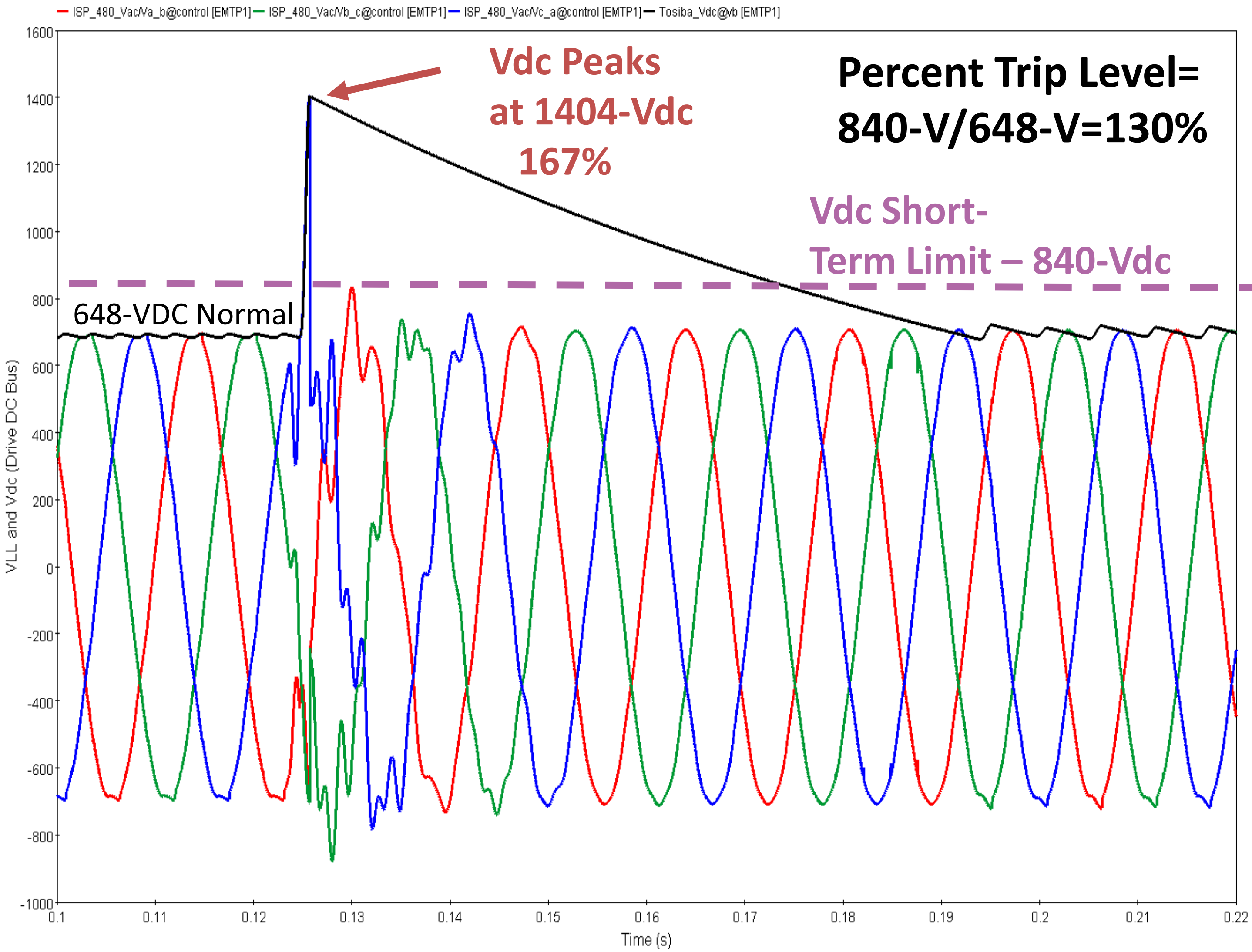


5,000uF,
800-VDC rating

Drive Shut Down Following Capacitor Switching - Transient Raises Voltage on Drive DC Bus > 840-VDC Limit



Breaker Closes And Energizes 3000-KVAR Capacitor



Vdc Peaks at 1404-Vdc 167%

Percent Trip Level= 840-V/648-V=130%

Vdc Short-Term Limit – 840-Vdc

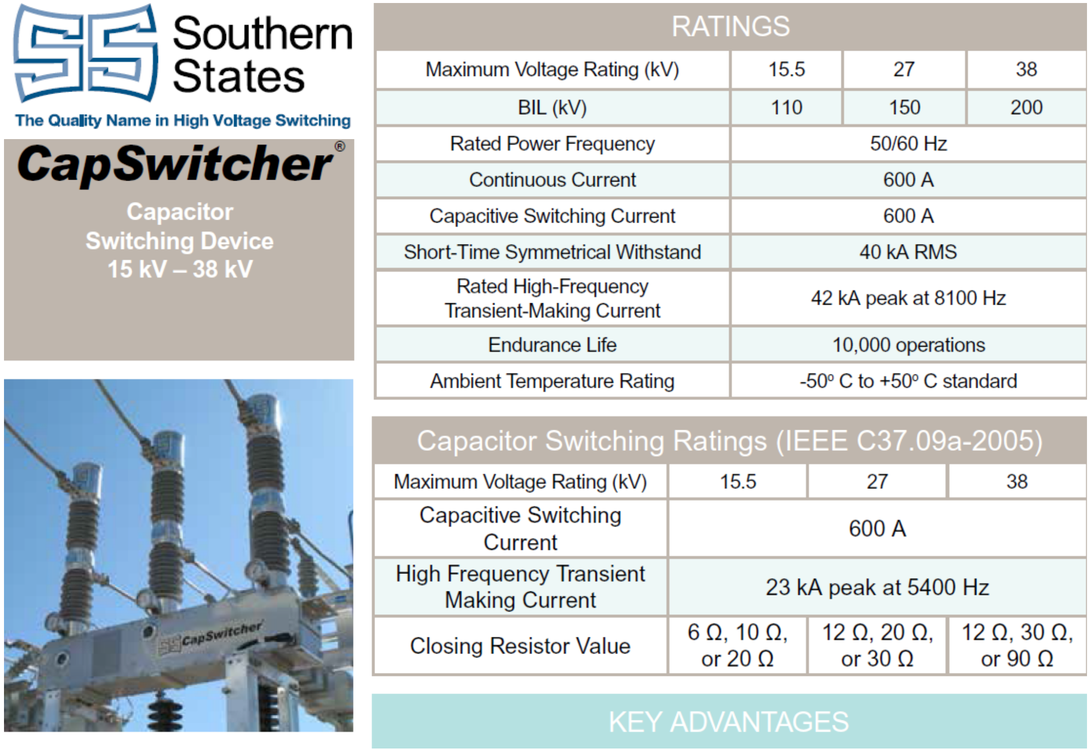
TVA Uses Pre-Insertion Resistors to Reduce Capacitor Switching Voltage Peaks

TVA Historically Used in Designs:

500-kV - Breaker
- ABB 550PM
- **425-Ohms**
- **332-MVAR**

161-kV - Switcher
- S&C Mark V
- **81-Ohms**
- **84-MVAR**

13.2-kV - Switcher
- Southern States CapSwitcher
- **10 ohms**
- **5.4-MVAR**



Southern States

The Quality Name in High Voltage Switching

CapSwitcher®

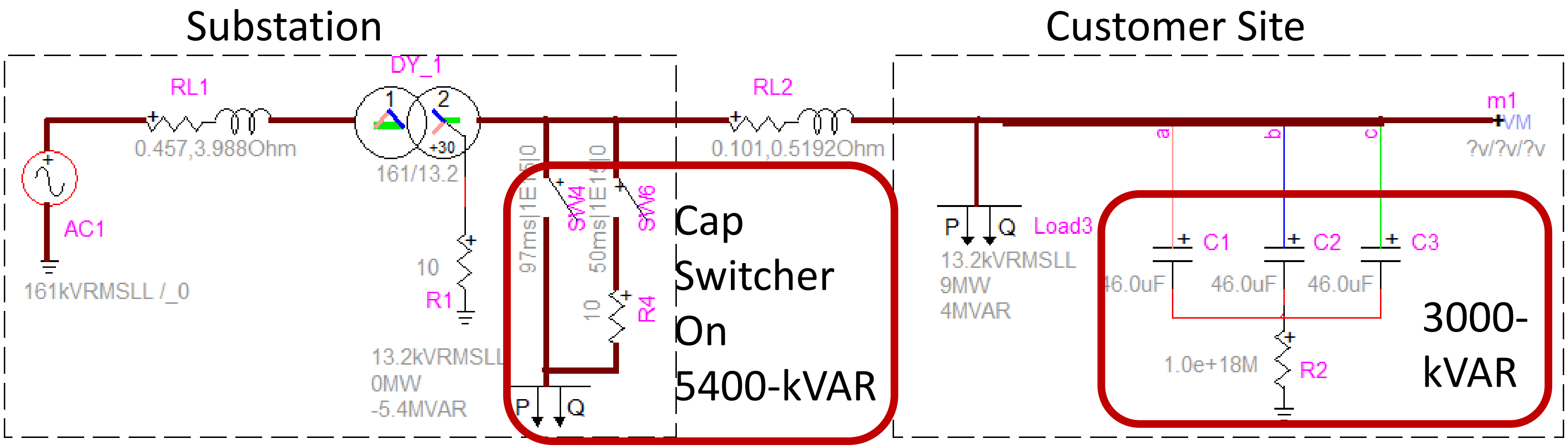
Capacitor Switching Device
15 kV – 38 kV

RATINGS			
Maximum Voltage Rating (kV)	15.5	27	38
BIL (kV)	110	150	200
Rated Power Frequency	50/60 Hz		
Continuous Current	600 A		
Capacitive Switching Current	600 A		
Short-Time Symmetrical Withstand	40 kA RMS		
Rated High-Frequency Transient-Making Current	42 kA peak at 8100 Hz		
Endurance Life	10,000 operations		
Ambient Temperature Rating	-50° C to +50° C standard		

Capacitor Switching Ratings (IEEE C37.09a-2005)			
Maximum Voltage Rating (kV)	15.5	27	38
Capacitive Switching Current	600 A		
High Frequency Transient Making Current	23 kA peak at 5400 Hz		
Closing Resistor Value	6 Ω, 10 Ω, or 20 Ω	12 Ω, 20 Ω, or 30 Ω	12 Ω, 30 Ω, or 90 Ω

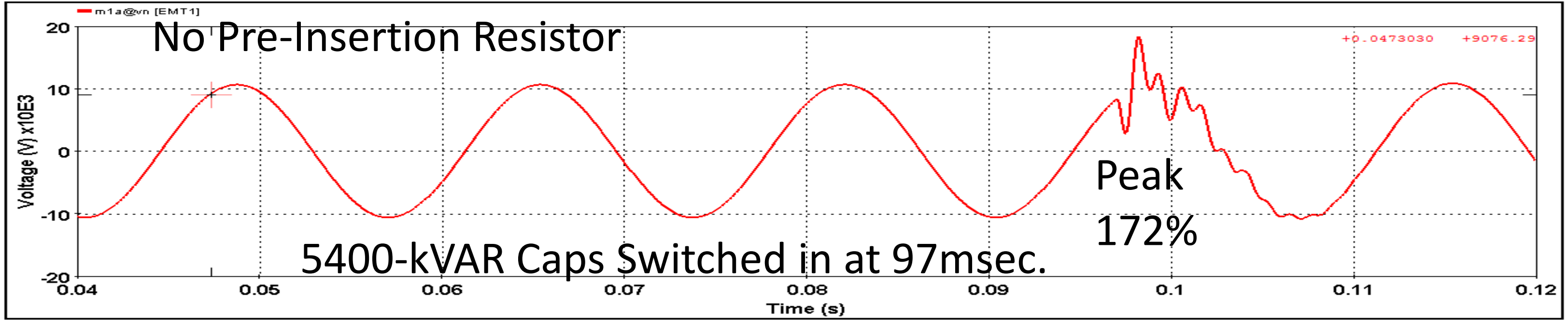
KEY ADVANTAGES

Pre-Insertion Resistor Illustration – Voltage Peak Reduced From 172% to 121% of Normal Peak



Cap Switcher On 5400-kVAR

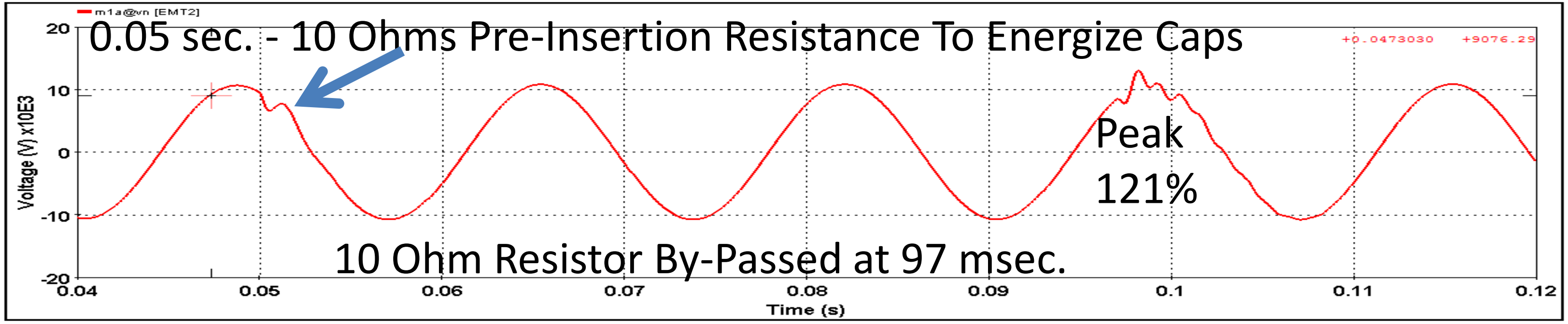
3000-kVAR



No Pre-Insertion Resistor

Peak 172%

5400-kVAR Caps Switched in at 97msec.



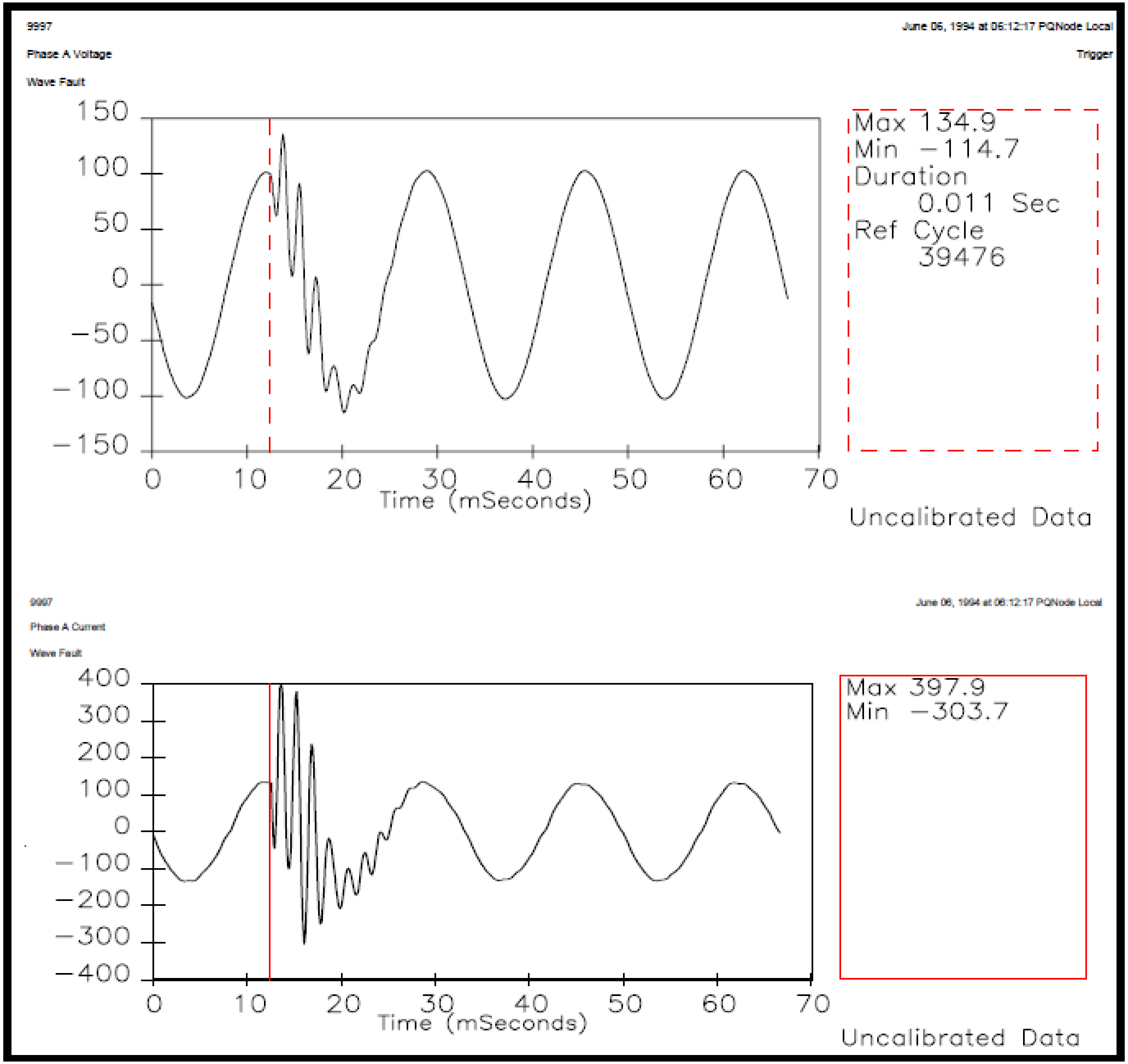
0.05 sec. - 10 Ohms Pre-Insertion Resistance To Energize Caps

Peak 121%

10 Ohm Resistor By-Passed at 97 msec.

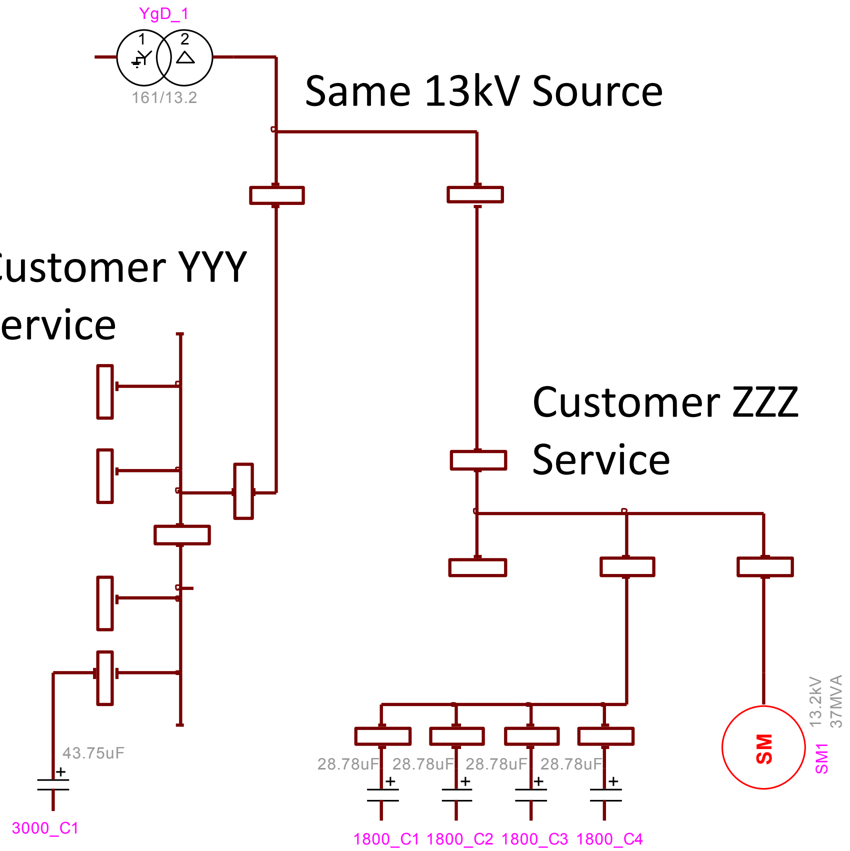
Case 9

How Can Your Protect Yourself From Switching Transients?



One Line Diagram 13-kV Service to Customers YYY and ZZZ

Customer ZZZ Cap Switching Impacts Customer YYY



Same 13kV Source

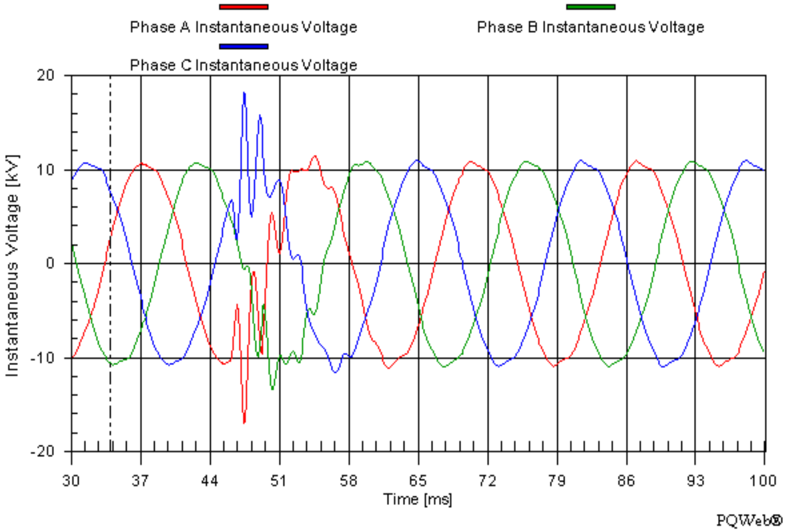
Customer YYY Service

Customer ZZZ Service

3000-KVAR Cap Bank At YYY

Four Steps of 1800-KVAR at ZZZ

PQ Recording from Customer YYY Site

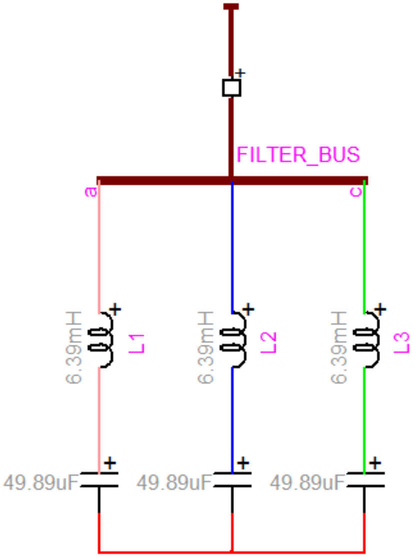


Customer ZZZ switched 5400-kVAR of Capacitors at One Time - Switching Transient Damaged Neighboring Customer YYY's VFD

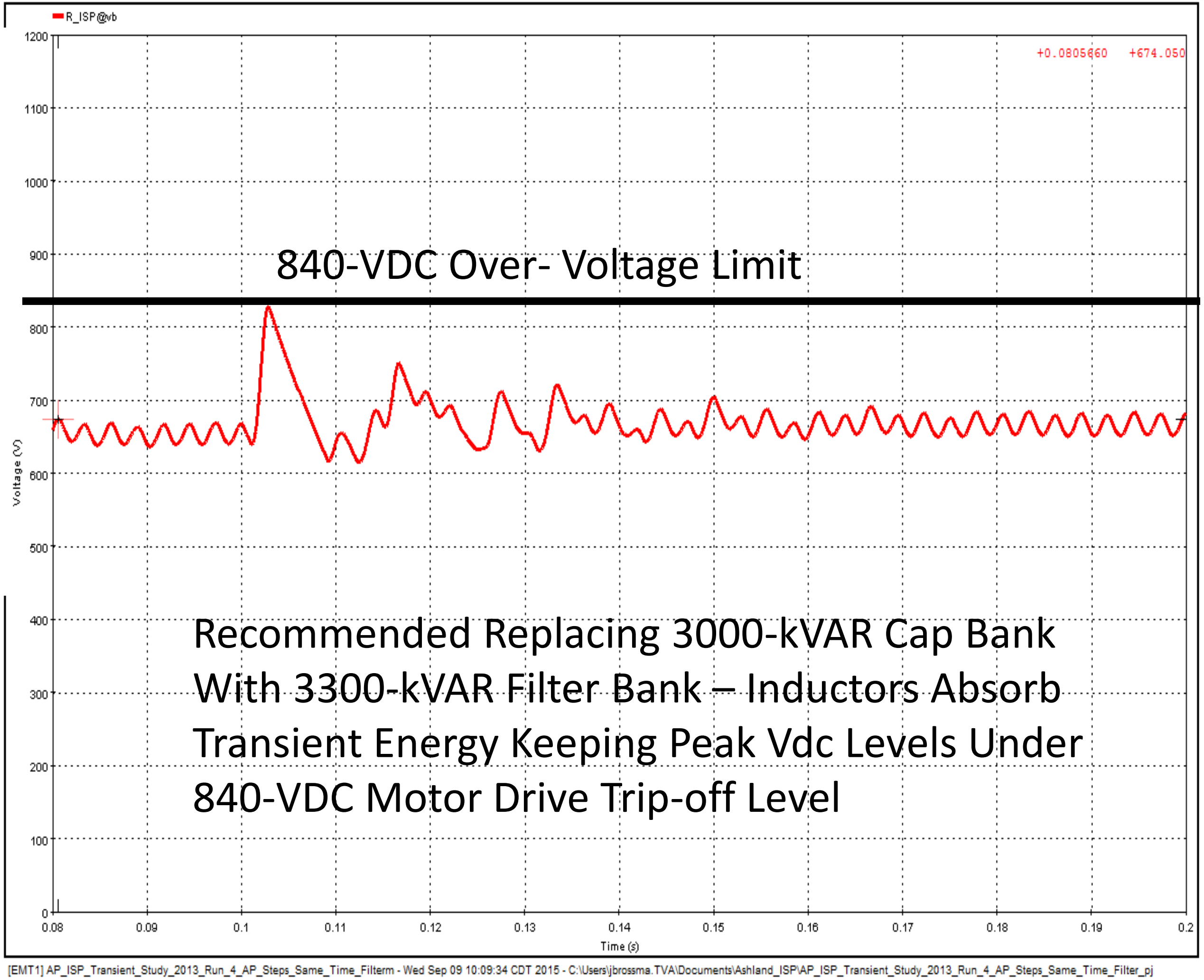
Solution Install Filter Instead of Capacitors

Simulated Switching 7200-kVAR at ZZZ – 4 Steps

In-Line Inductance Keeps Voltage Under 840-VDC VFD Limit



Instead of a Capacitor Bank – Install Filter Bank with Reactors



840-VDC Over- Voltage Limit

Recommended Replacing 3000-kVAR Cap Bank With 3300-kVAR Filter Bank – Inductors Absorb Transient Energy Keeping Peak Vdc Levels Under 840-VDC Motor Drive Trip-off Level

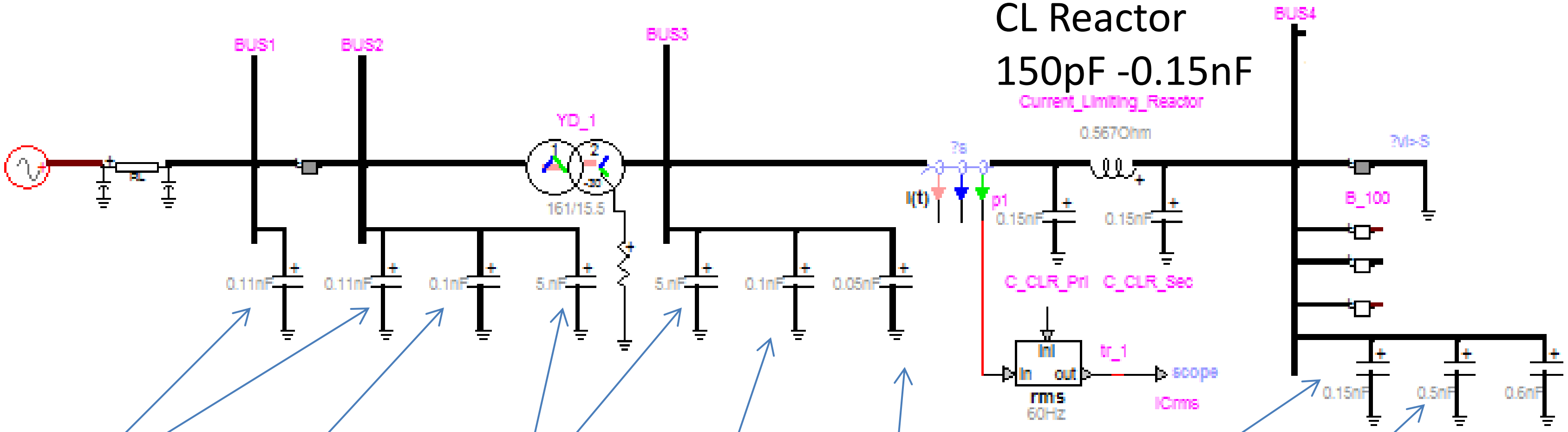
[EMT1] AP_ISP_Transient_Study_2013_Run_4_AP_Steps_Same_Time_Filterm - Wed Sep 09 10:09:34 CDT 2015 - C:\Users\jbrossma.TVA\Documents\Ashland_ISP\AP_ISP_Transient_Study_2013_Run_4_AP_Steps_Same_Time_Filter_pj

Breaker Operation Demonstrating Transient Recovery Voltage

At High Speeds Equipment Look Like Shunt Capacitors/Series Inductors

IEEE C37.011-2011 Transient Recovery Voltage for AC High-Voltage Circuit Breakers

Table B.8
CL Reactor
150pF -0.15nF



110pF
0.11nF
20 ft x
5.5pF/ft.
Bus Cap
Table B.5

100pF
0.1nF
Arrester
Table B.8

5000pF
5nF
Transformer
Primary/Sec
Provided By
Manufacturer

100pF
0.1nF
Arrester
Table B.8

50pF
0.05nF
20 ft x
2.5pF/ft.
Bus Cap
Table B.5

150pF
0.15nF
Voltage
Trans-
former
Table B.3

500pF
0.5nF
200 ft x
2.5pF/ft.
Bus Cap
Table B.5

600pF
0.6nf
4 x 150/Br
Open
Table B.7

Consider Application Using Substation-Type Breaker on 15.5-kV Bus

Note TRV Table for 100% Loading – 29.2-kV Peak/Time to Peak at 32uS

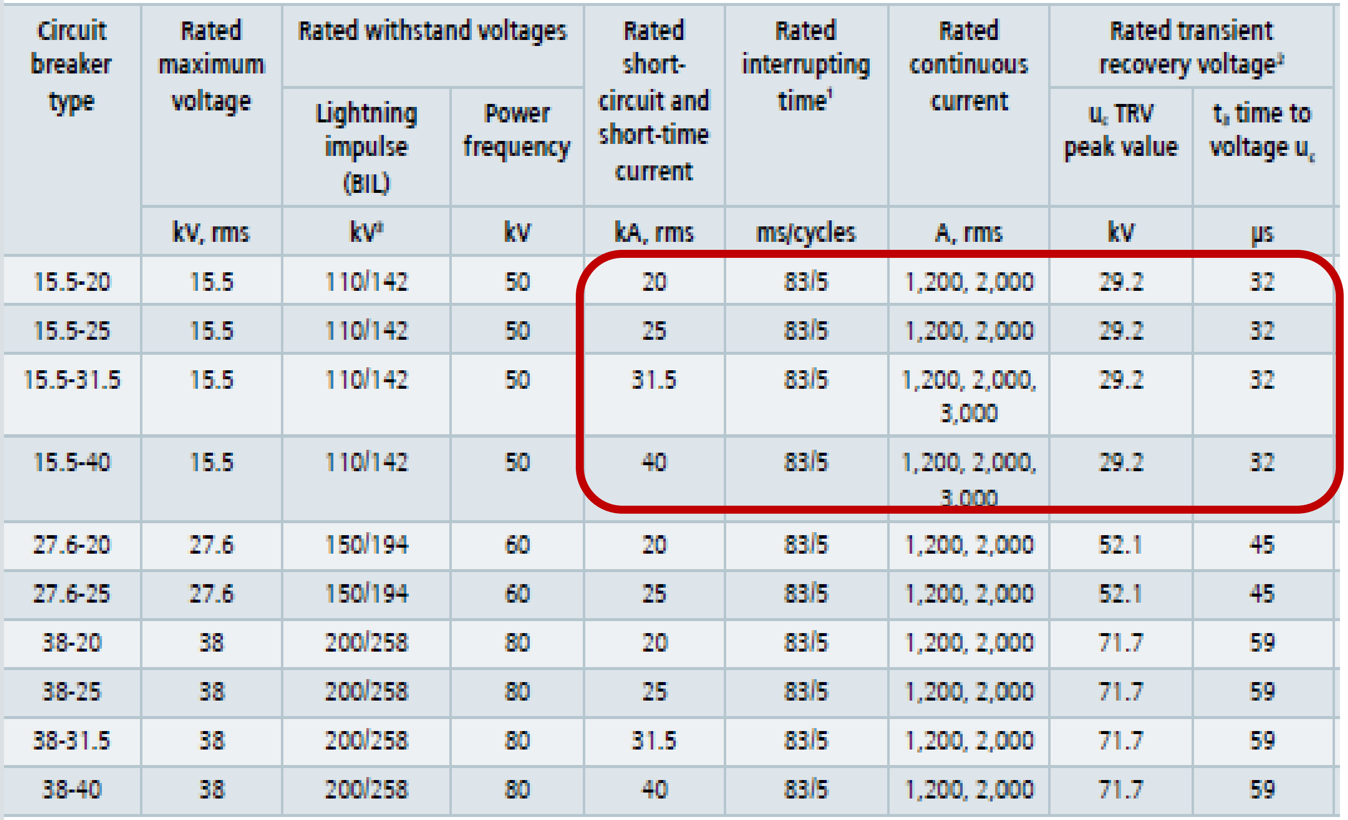
Ratings available:

15.5 kV
20 kA or 25 kA
1,200 A or 2,000 A
110 kV BIL

15.5 kV
31.5 kA or 40 kA
1,200 A, 2,000 A or 3,000 A
110 kV BIL

27.6 kV
20 kA or 25 kA
1,200 A or 2,000 A
150 kV BIL

38kV
20 kA, 25 kA, 31.5 kA or 40 kA
1,200 A or 2,000 A
200 kV BIL



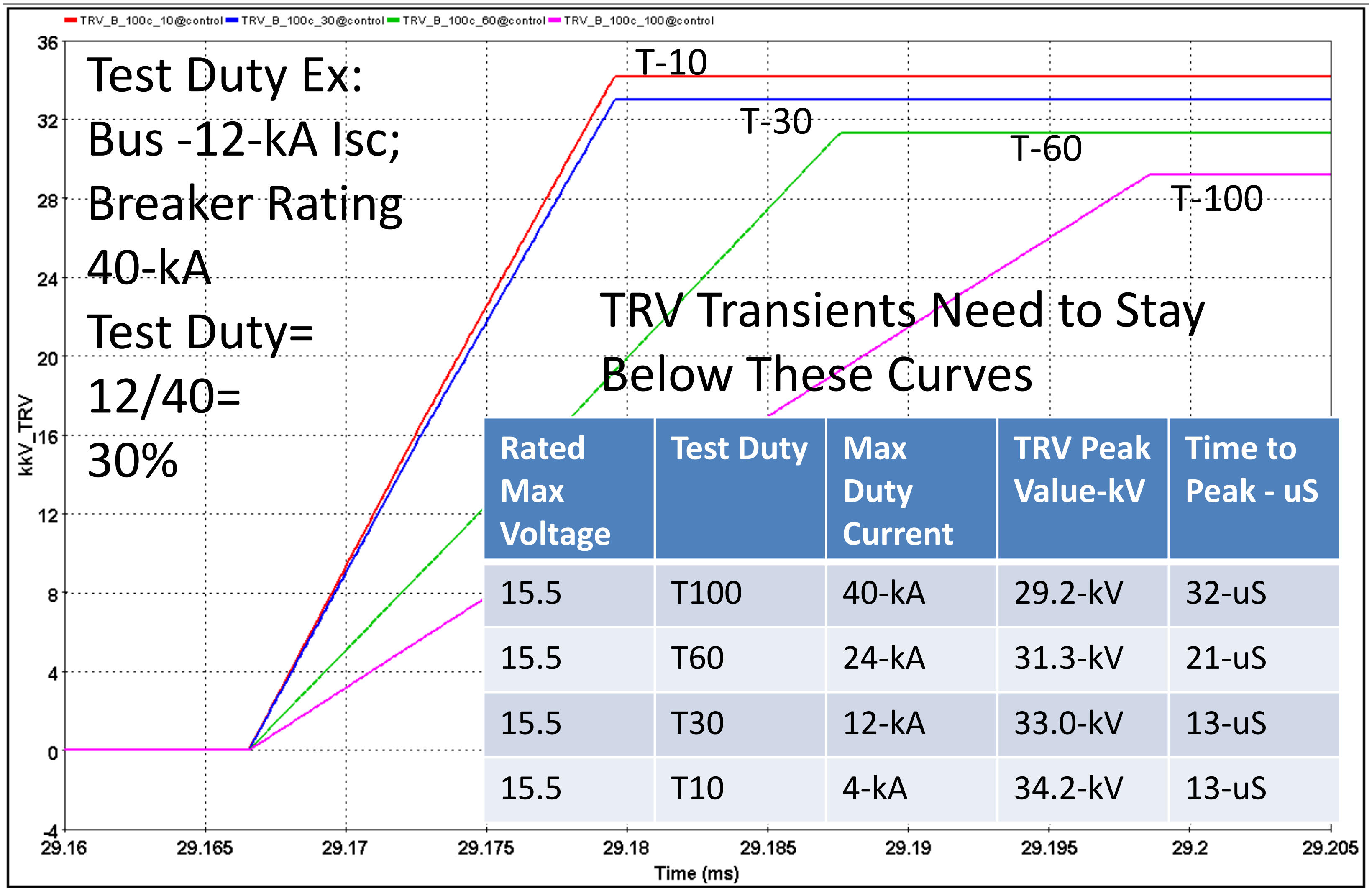
Circuit breaker type	Rated maximum voltage	Rated withstand voltages		Rated short-circuit and short-time current	Rated interrupting time[1]	Rated continuous current	Rated transient recovery voltage[3]	
		Lightning impulse (BIL)	Power frequency				u_c TRV peak value	t_3 time to voltage u_c
	kV, rms	kV[2]	kV	kA, rms	ms/cycles	A, rms	kV	µs
15.5-20	15.5	110/142	50	20	83/5	1,200, 2,000	29.2	32
15.5-25	15.5	110/142	50	25	83/5	1,200, 2,000	29.2	32
15.5-31.5	15.5	110/142	50	31.5	83/5	1,200, 2,000, 3,000	29.2	32
15.5-40	15.5	110/142	50	40	83/5	1,200, 2,000, 3,000	29.2	32
27.6-20	27.6	150/194	60	20	83/5	1,200, 2,000	52.1	45
27.6-25	27.6	150/194	60	25	83/5	1,200, 2,000	52.1	45
38-20	38	200/258	80	20	83/5	1,200, 2,000	71.7	59
38-25	38	200/258	80	25	83/5	1,200, 2,000	71.7	59
38-31.5	38	200/258	80	31.5	83/5	1,200, 2,000	71.7	59
38-40	38	200/258	80	40	83/5	1,200, 2,000	71.7	59

Values Listed Are for 100% Isc Rating of the Breaker
If You Design for Max Available Isc Below Max Breaker Ratings – TRV Performance Improves

IEEE Std C37.06-2009 Table 7 – TVA Ratings for Class S2 Breakers

Worse Case – Not Effective Grounded Substation – Line-Type Load

Note When Breaker Has Less Test Duty (% Rating) It Performs Better



Test Duty Ex:
Bus -12-kA Isc;
Breaker Rating
40-kA
Test Duty=
12/40=
30%

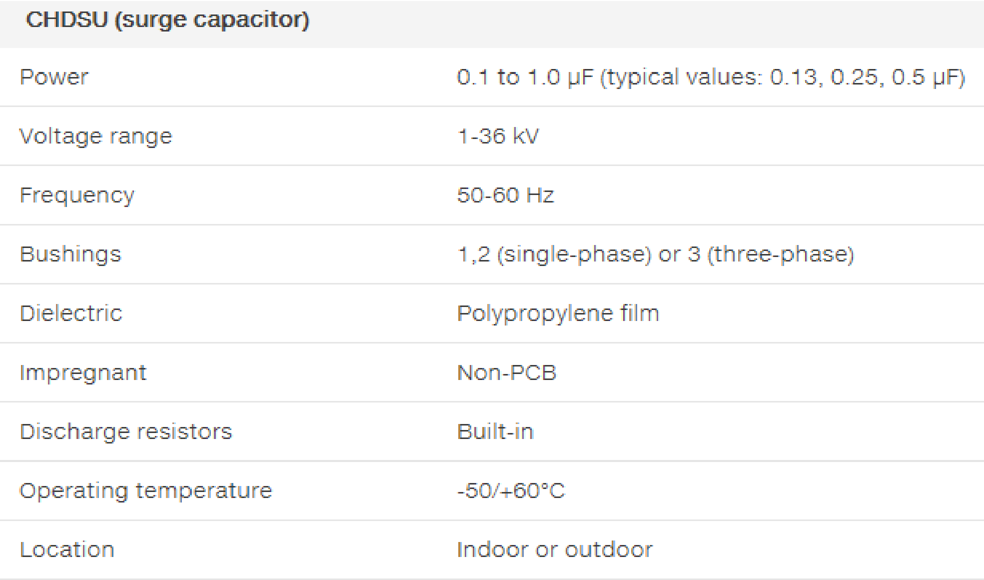
TRV Transients Need to Stay Below These Curves

Rated Max Voltage	Test Duty	Max Duty Current	TRV Peak Value-kV	Time to Peak - uS
15.5	T100	40-kA	29.2-kV	32-uS
15.5	T60	24-kA	31.3-kV	21-uS
15.5	T30	12-kA	33.0-kV	13-uS
15.5	T10	4-kA	34.2-kV	13-uS

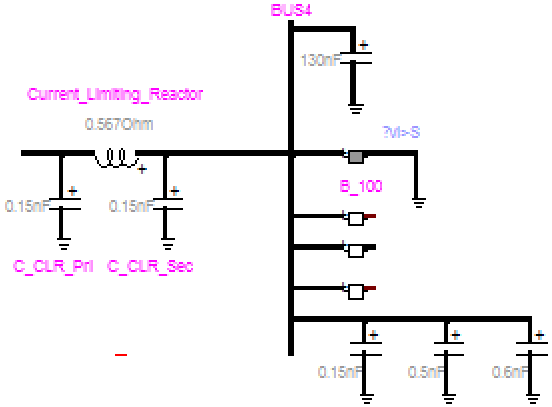
Adding Surge Capacitance to Bus Delays TRV Peak Time

What Surge Capacitance is Commercially Available for 15.5-kV?

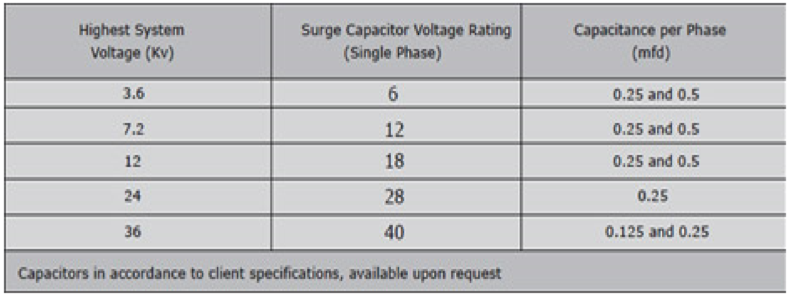
Consider Higher Rated Voltage Units – Say 3-36-kV Units



CHDSU (surge capacitor)	
Power	0.1 to 1.0 μF (typical values: 0.13, 0.25, 0.5 μF)
Voltage range	1-36 kV
Frequency	50-60 Hz
Bushings	1,2 (single-phase) or 3 (three-phase)
Dielectric	Polypropylene film
Impregnant	Non-PCB
Discharge resistors	Built-in
Operating temperature	-50/+60°C
Location	Indoor or outdoor



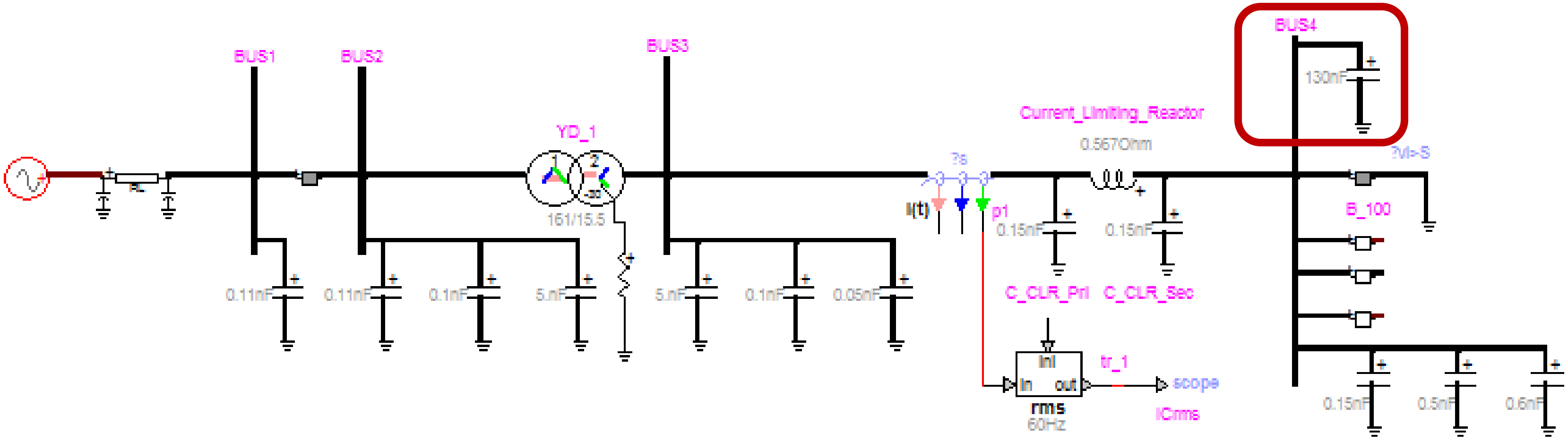
Typical for 34.5-kV
0.125 to 0.130 micro-F
125 to 130 nano-farads



Highest System Voltage (Kv)	Surge Capacitor Voltage Rating (Single Phase)	Capacitance per Phase (mfd)
3.6	6	0.25 and 0.5
7.2	12	0.25 and 0.5
12	18	0.25 and 0.5
24	28	0.25
36	40	0.125 and 0.25
Capacitors in accordance to client specifications, available upon request		

IEEE C37.011-2011

IEEE Guide for the Application of Transient Recovery Voltage for AC High-Voltage Circuit Breakers

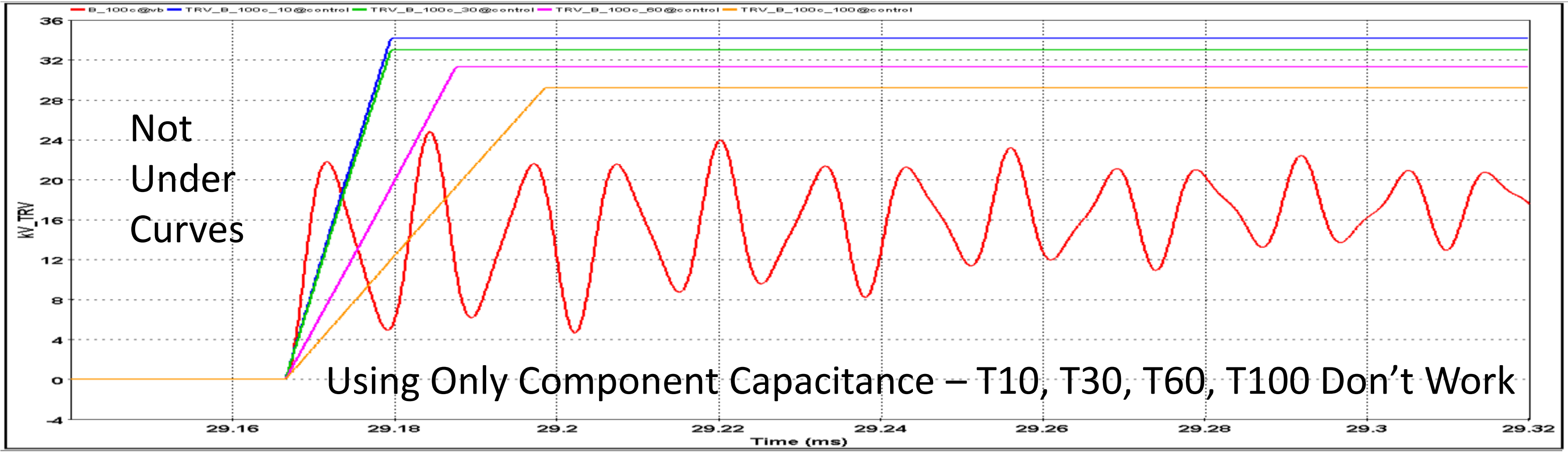


130nF

Example from IEEE C37.011-2011, Section 4.4.2.2 –Modified for 15.5-kV

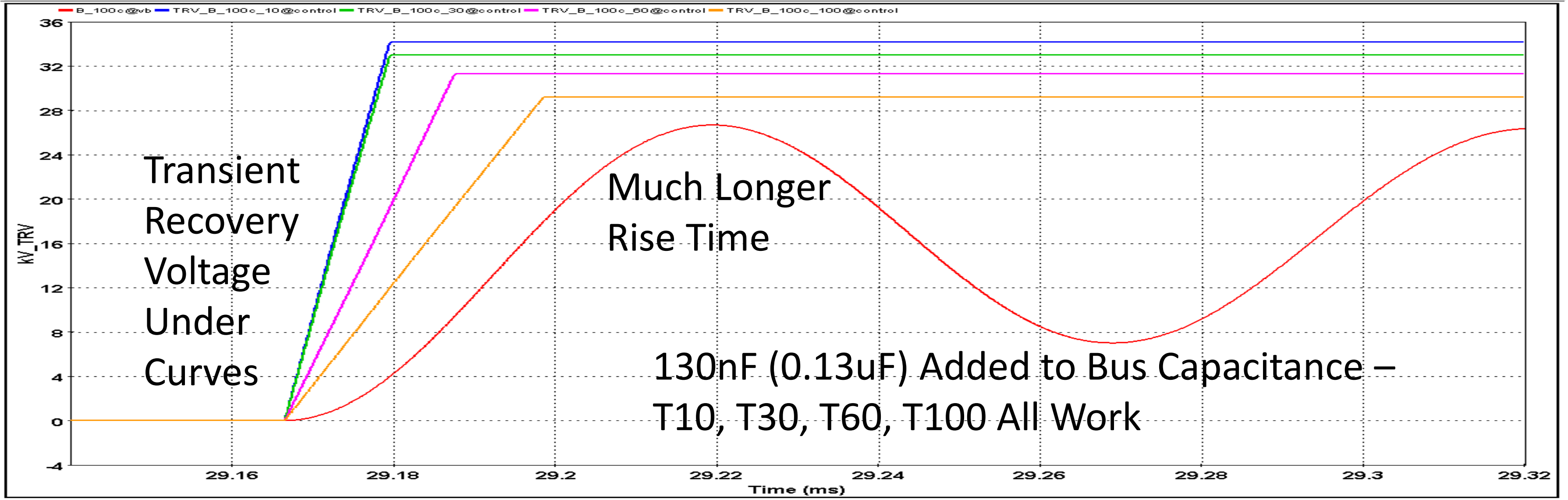
- Given:
  - 15.5-kV System with Isc=50-kA, Reactor Installed to Limit Isc to 12-kA
  - Find TRV Performance for 3-phase Fault Across Circuit Breaker (B_100)
  - Will Adding 130nF of Capacitance Get TRV Under Curves?

Simulation Showing Impact of Adding Capacitance to Obtain Better TRV Performance - By Adding 130nF of Capacitance, Breaker Can Be Isc Rated 12-kA or Higher – Minimum Siemens Size – 20-kA



Not Under Curves

Using Only Component Capacitance – T10, T30, T60, T100 Don’t Work



Transient Recovery Voltage Under Curves

Much Longer Rise Time

130nF (0.13uF) Added to Bus Capacitance – T10, T30, T60, T100 All Work

Surges From Vacuum Contactor Operations

Transients Likely to Be Seen at Motors

Due to Breaker Issues

- Prestrikes – Arcing Across Contacts Upon Closing
- Re-Strikes – Arcing Across Contacts After Already Interrupted
- Current Chopping

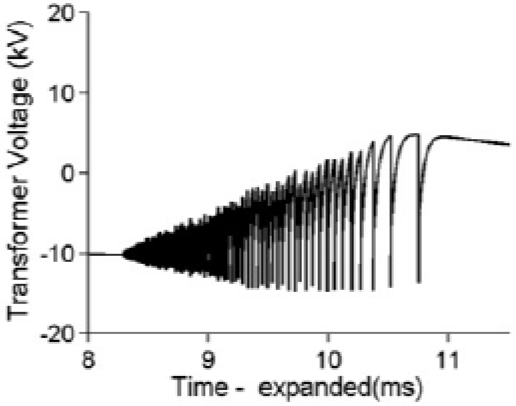
Load Related Issues

- Motor Stalls on Startup
- Starting/Stopping Motor Related Transients
- Arcing Faults

Per EPRI's 1988 Study, most motors see surges of magnitudes and rise times as shown below:

Typical/Study Peak	4160-V	6600-V	13200-V
Typical 2.8 pu (0.2-0.6us)	9.5-kV	15.1-kV	30.2-kV
Peak From Study 4.6 pu (0.6us)	15.6-kV	24.8-kV	49.6-kV

Switching Transient
IEEE C57.142 Figure 17
Current Chopping



Simulation Drawing
6600-V Motor 6-Turn Coil Impacted by, 24.8-kV Surge (0.5 us rise time)

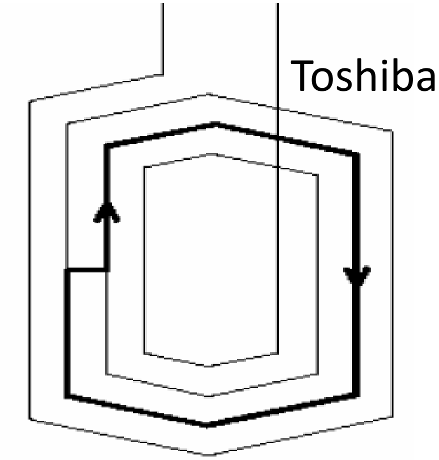
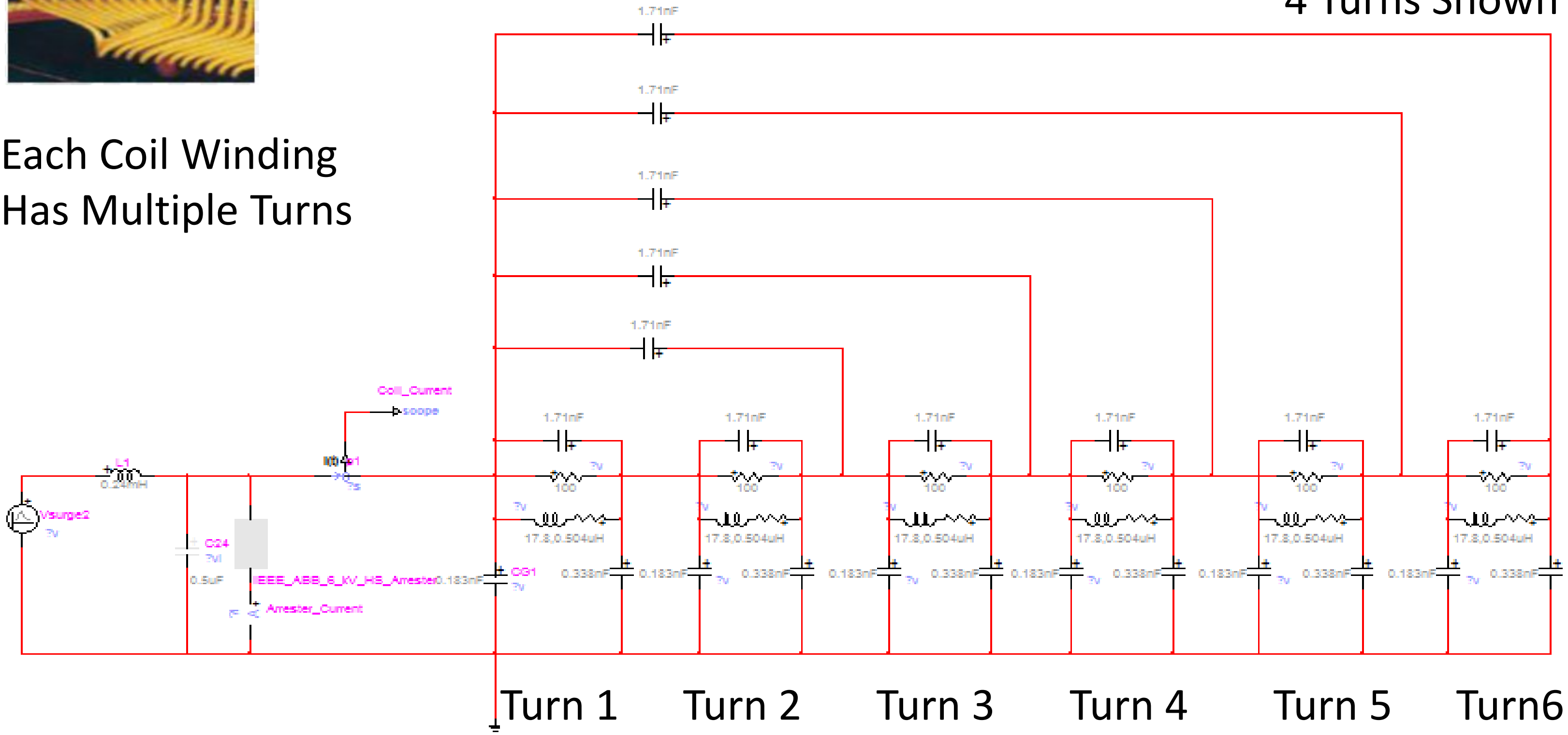


Fig 1: Turn to Turn Short

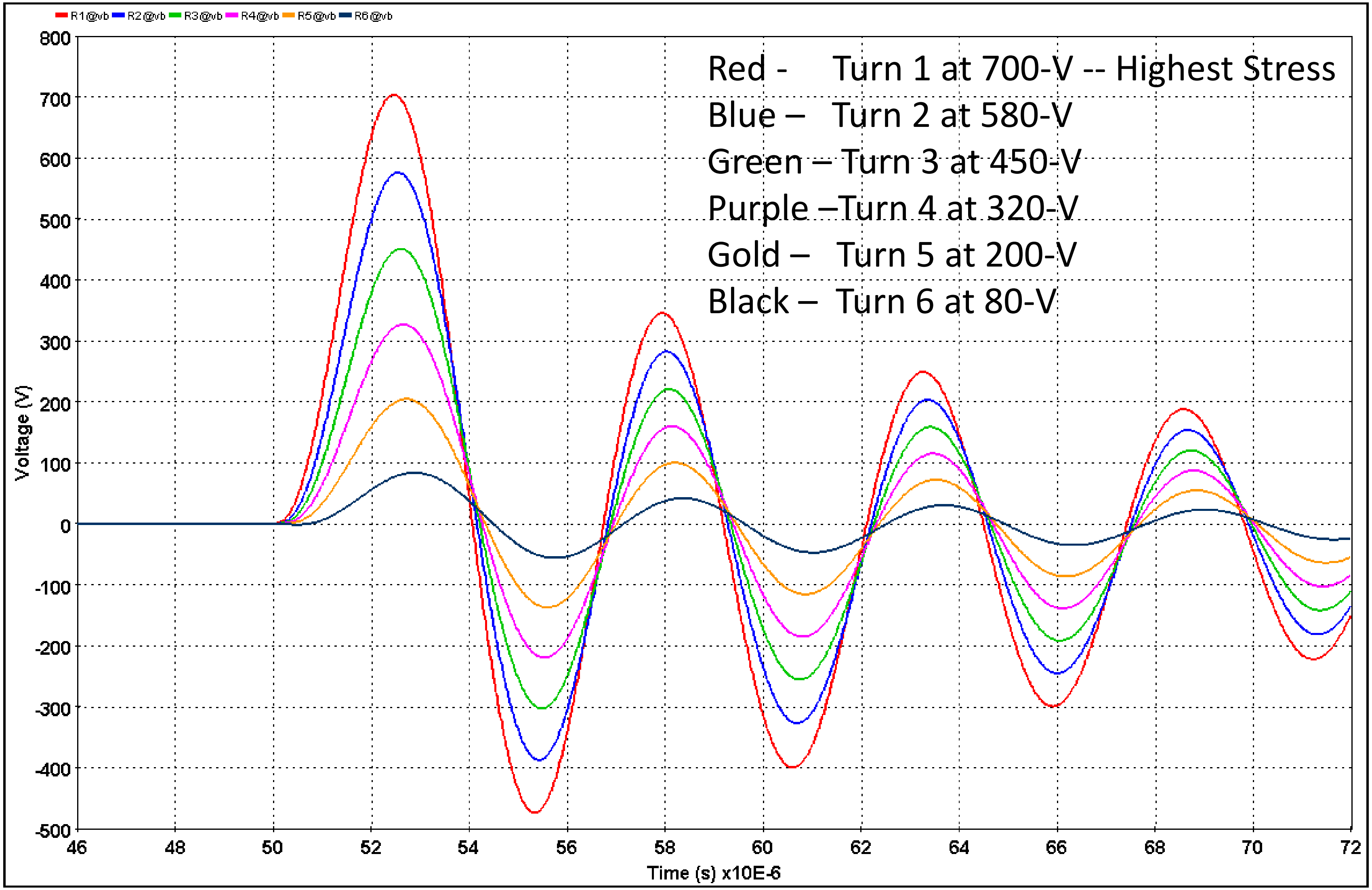
4 Turns Shown

Each Coil Winding
Has Multiple Turns



Simulation Results W/O Protection

Voltage Stress Per Turn Due to Incoming Voltage Surge



Red - Turn 1 at 700-V -- Highest Stress
Blue – Turn 2 at 580-V
Green – Turn 3 at 450-V
Purple –Turn 4 at 320-V
Gold – Turn 5 at 200-V
Black – Turn 6 at 80-V

ABB Surge Arrester and Surge Capacitor Combination – Typical Protection Available For Use At Motor

Minimize Wiring Distance Between Cable Shield, Motor Grounds and Enclosure Grounds!!
I.E., Mount With Electrical Connections at Motor Termination

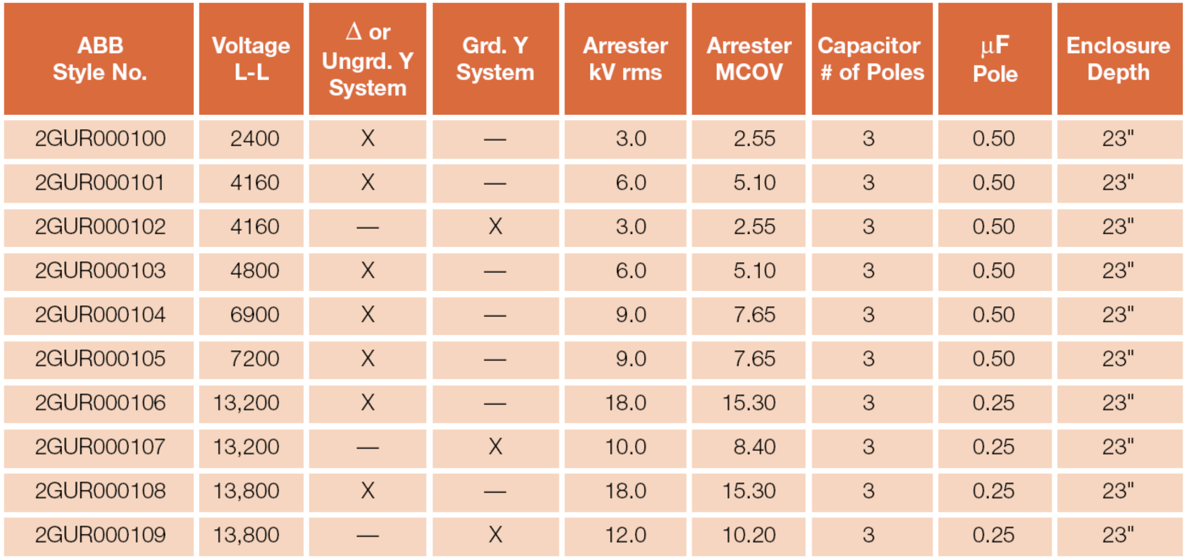
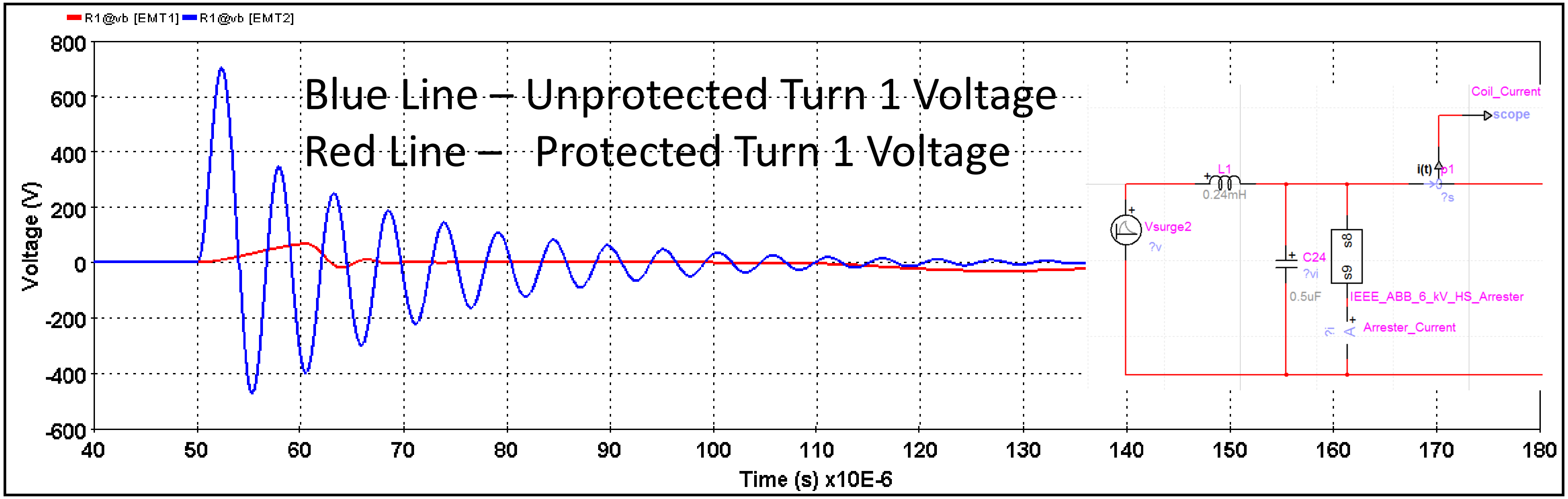


ABB Style No.	Voltage L-L	Δ or Ungrd. Y System	Grd. Y System	Arrester kV rms	Arrester MCOV	Capacitor # of Poles	μF Pole	Enclosure Depth
2GUR000100	2400	X	—	3.0	2.55	3	0.50	23"
2GUR000101	4160	X	—	6.0	5.10	3	0.50	23"
2GUR000102	4160	—	X	3.0	2.55	3	0.50	23"
2GUR000103	4800	X	—	6.0	5.10	3	0.50	23"
2GUR000104	6900	X	—	9.0	7.65	3	0.50	23"
2GUR000105	7200	X	—	9.0	7.65	3	0.50	23"
2GUR000106	13,200	X	—	18.0	15.30	3	0.25	23"
2GUR000107	13,200	—	X	10.0	8.40	3	0.25	23"
2GUR000108	13,800	X	—	18.0	15.30	3	0.25	23"
2GUR000109	13,800	—	X	12.0	10.20	3	0.25	23"

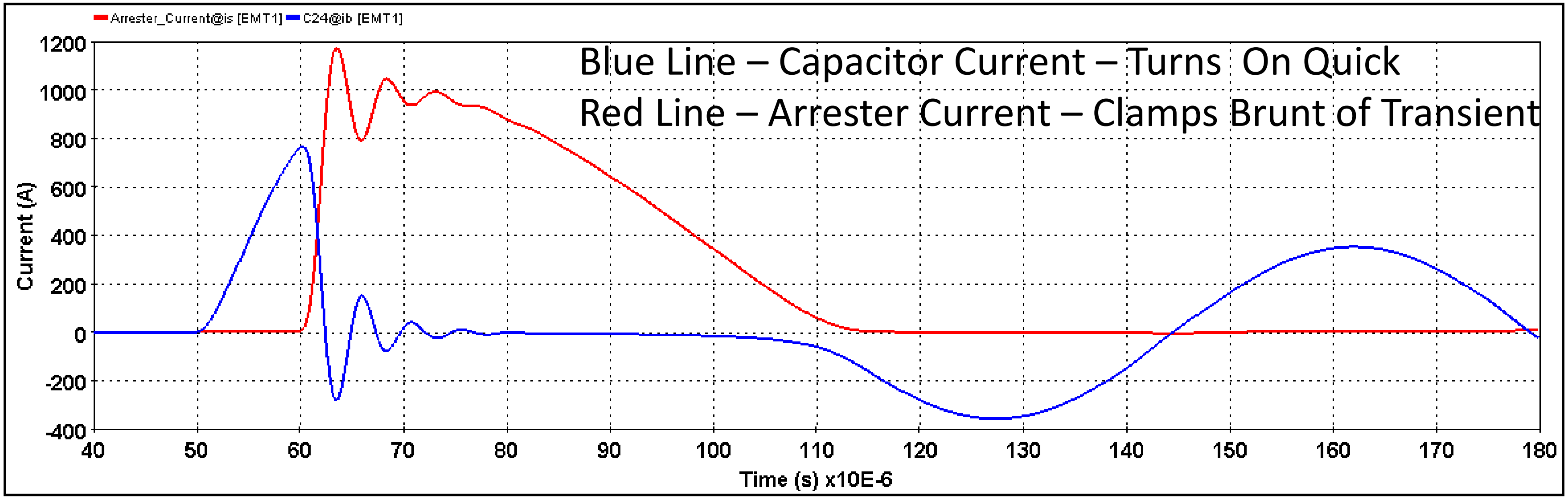
4160-V Motor
0.5uF
6-kV Surge Arrester

Simulation Results With Protection – 4.16-kV Motor

0.5uF Capacitor, 6-kV Arrester


Blue Line – Unprotected Turn 1 Voltage

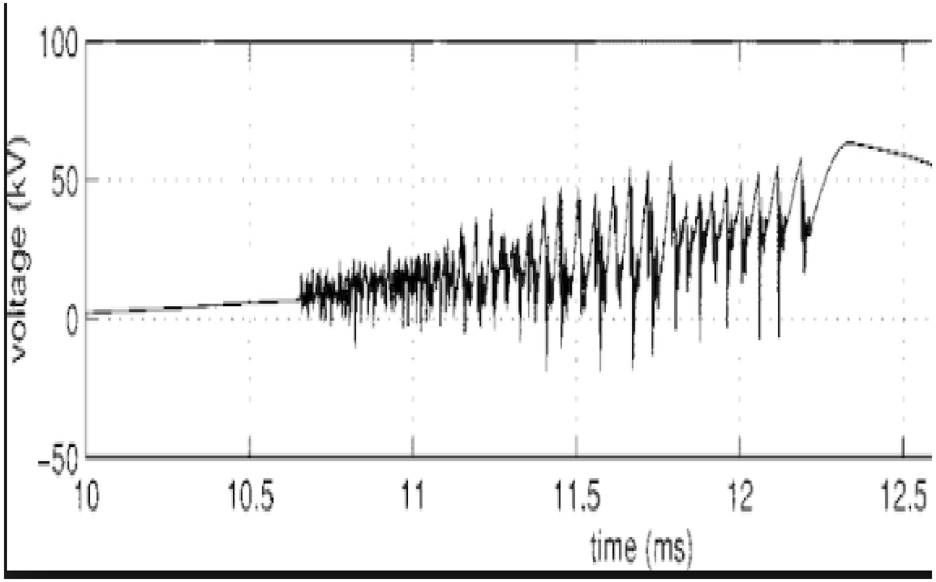
Red Line – Protected Turn 1 Voltage


Blue Line – Capacitor Current – Turns On Quick

Red Line – Arrester Current – Clamps Brunt of Transient

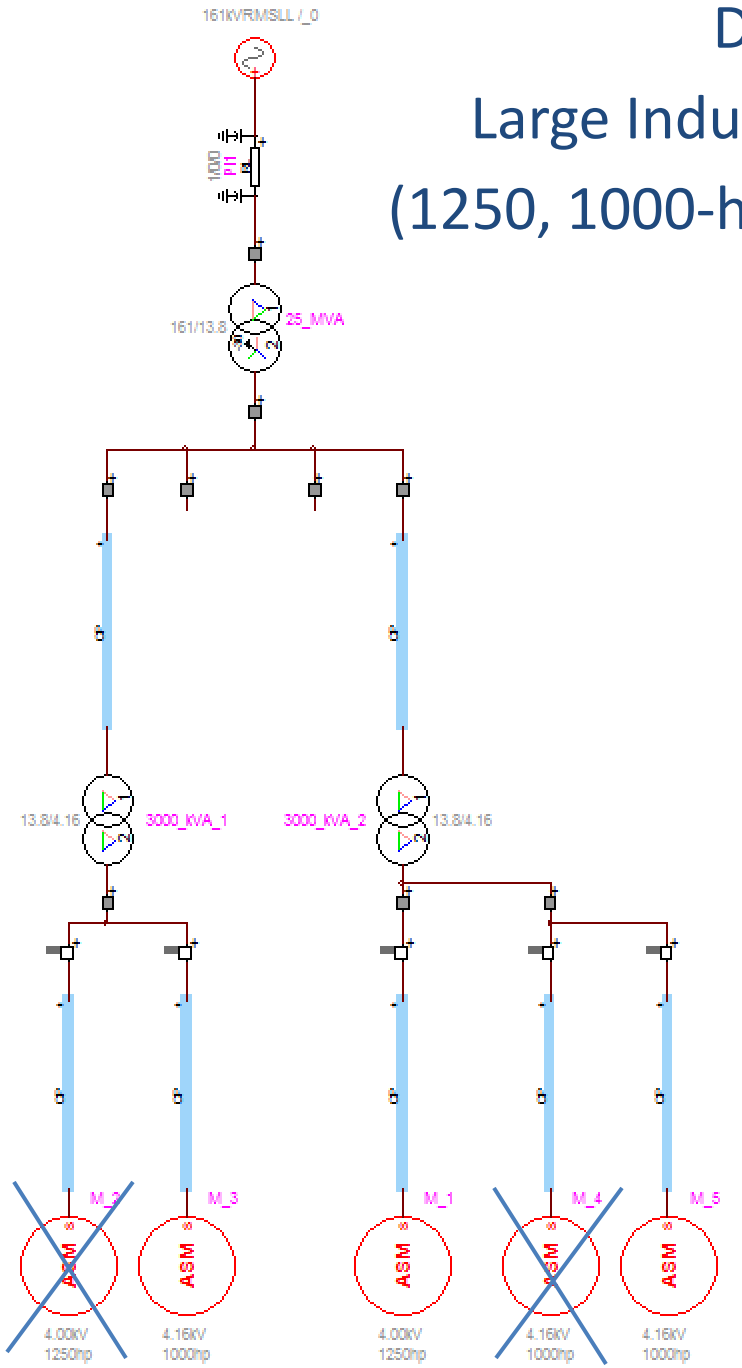
Case 10
Application Issue – Multiple 4160-V Motors Damaged

Switching Transients



Due to Switching Surges

Large Industry Damaged Two- 4-kV Motors (1250, 1000-hp) Fed From Separate Transformers



Known Issues:

- Motors Shut Down
- Upon Re-Start Motor Damage Became Apparent – M_2 and M_4 (see diagram)
- Each Motor Fed off of Different 3000-kVA Transformer – **Each Delta-Delta – Ungrounded**
- Short Distance Cable Runs From Motor Vacuum Contactors to Motors – Little Capacitance (Quick Rise Time)

Case Study #10 Recommendations

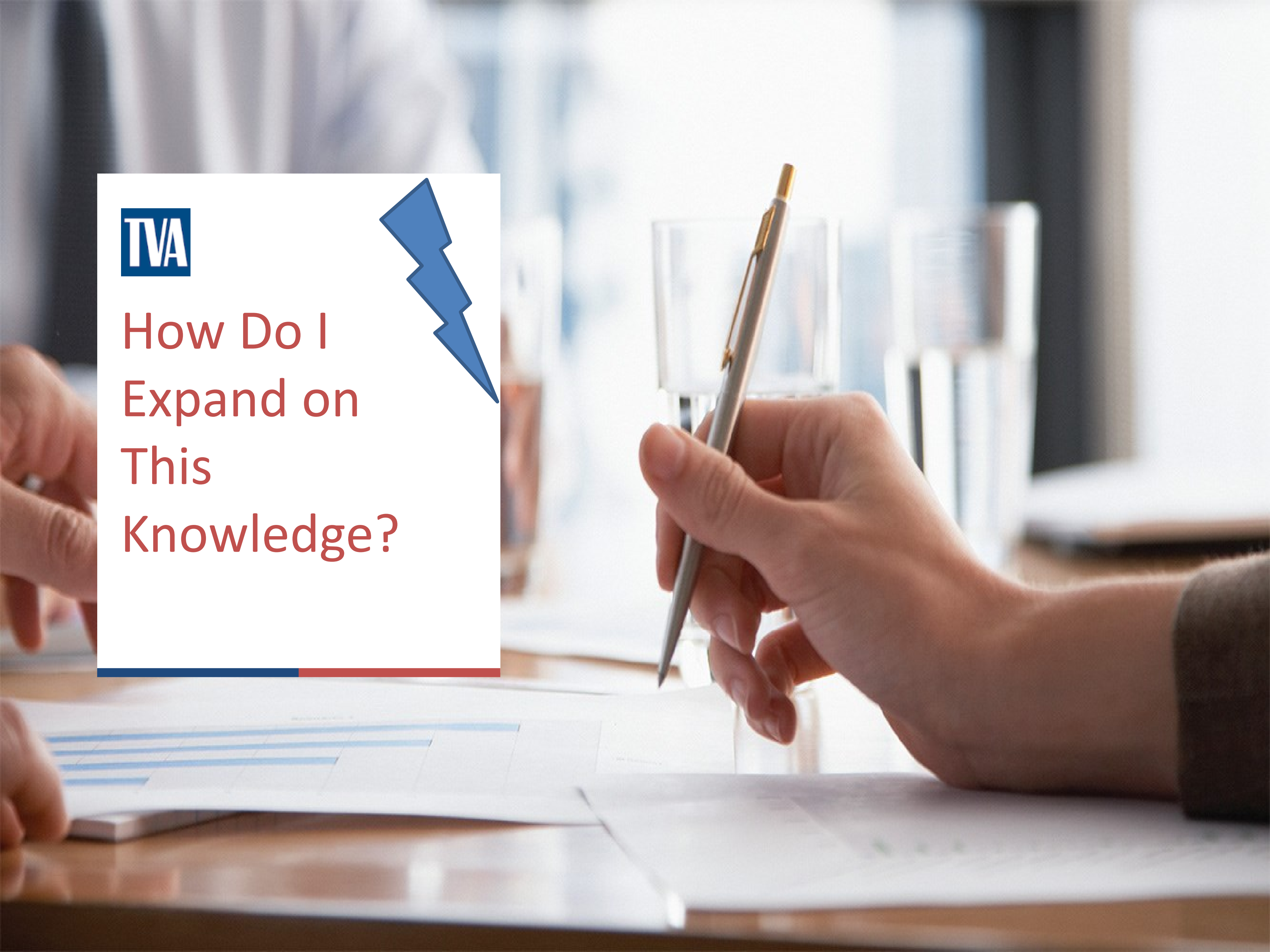
- Motors don't need to be operated ungrounded – best to specify solidly-grounded Wye secondary - When transformer secondary is delta and ungrounded, install zig/zag transformer to establish ground

- Ground cable shields only at motor location – recommendation from 1988 EPRI study

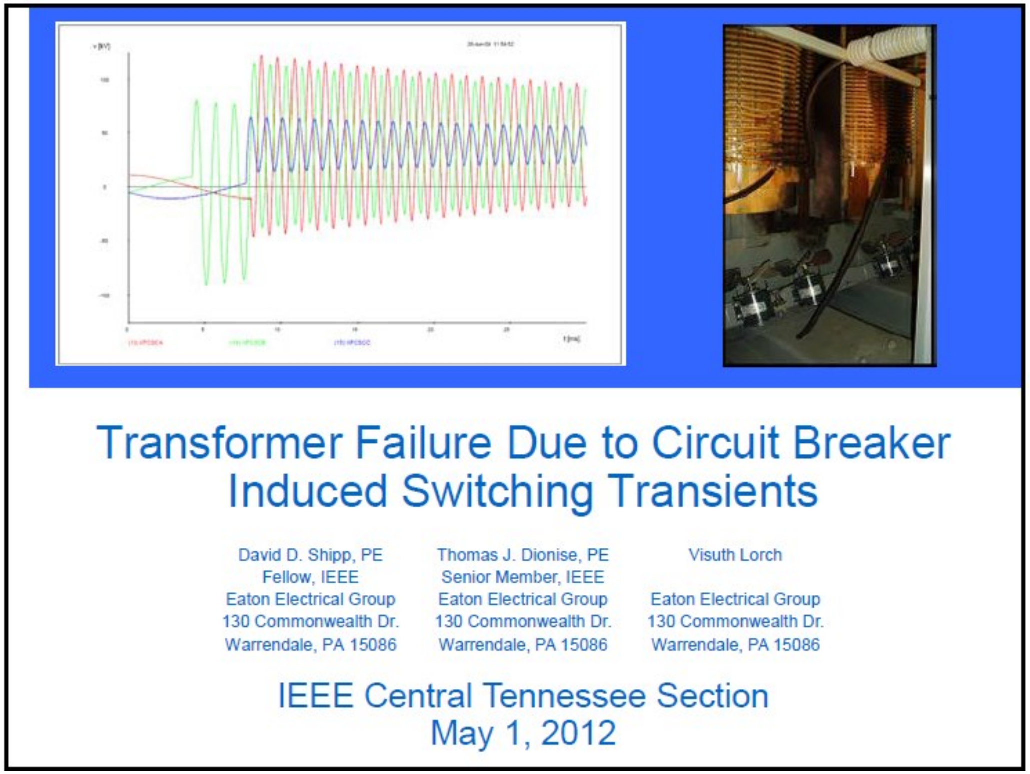
- Install surge arrester/capacitor protection – especially if cable runs are short - Routine vacuum contactor operations tend to generate problematic switching transients harmful to motor life The chemical and petro-chemical industry routinely installs surge protection at motor locations

- Properly ground Arrester/Capacitor protection systems at motor location

How Do I Expand on This Knowledge?



Start Here - Presentation From 5-Years Ago Discussing Transformer Issues Similar to Motor Starting Protection



Transformer Failure Due to Circuit Breaker Induced Switching Transients

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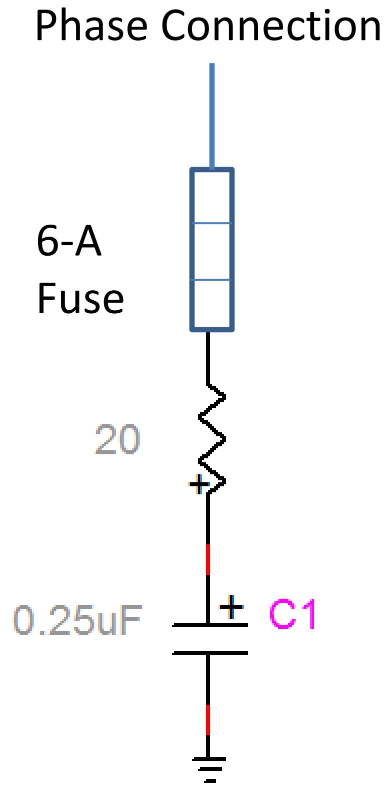
IEEE Central Tennessee Section
May 1, 2012

Siege Electric
13.8-kV RC Snubber



Instead of Motor Capacitor/ Arrester Parallel Combination, Mr. Shipp Recommends Series RC Snubbers for Protection of Transformers