SWITCHING TRANSIENTS INDUCED TRANSFORMER FAILURES

Presented to
IEEE-IAS – Atlanta Chapter
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By David Shipp, PE

Case Study Overview: Data Center Transformer Failure Attributed to Circuit Breaker Induced Switching Transients

System Configuration, Failure Analysis
and RC Snubber Fix

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D. Shipp – Eaton Electrical – Pgh, PA

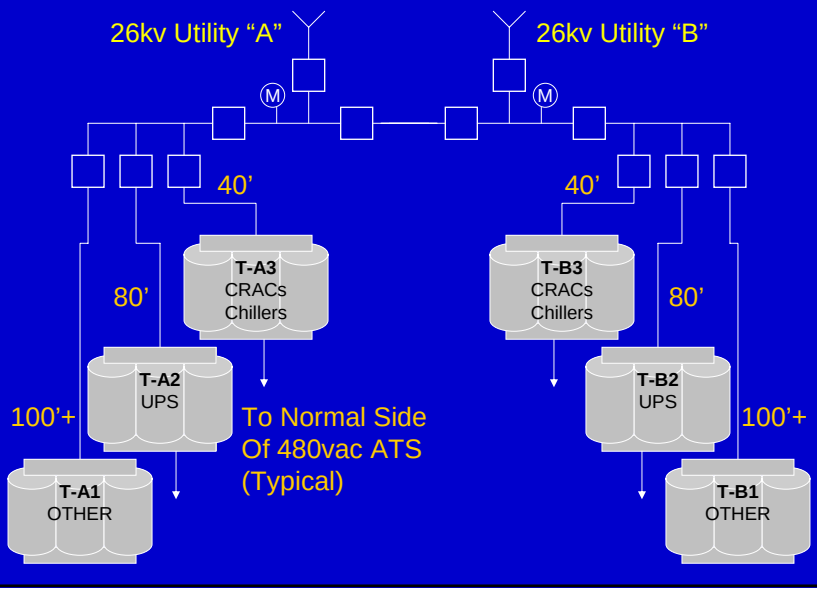
Presentation Purpose/Summary

- Purpose #1 Safety:
  - Alert Design & User Community
  - Drive Solutions Through Market Interest
- Unique Case History
  - Forensic Evidence
  - High Speed Power Quality Capture
- Presentation Summary
  - Simplified System Overview
  - Forensic Review
  - Power Quality Snapshots
  - Installed RC Snubber Fix
- Presentation Summary: David Shipp, Eaton
  - Phenomenon Detailed Explanation
  - Science of RC Snubber Design

Site Specifics

- Utility Service:
  - 26kV
  - Double Ended Loop Through
- Transformers
  - (6) Total
  - 26kV Primary, 480V Secondary
  - VPI
  - 3000kVA AA / 3990 kVA FA
  - 150 kVbil
- Switching Device
  - Vacuum Circuit Breaker
- Cable
  - 35kV, 133% EPR Insulation, 1/3 Concentric Ground

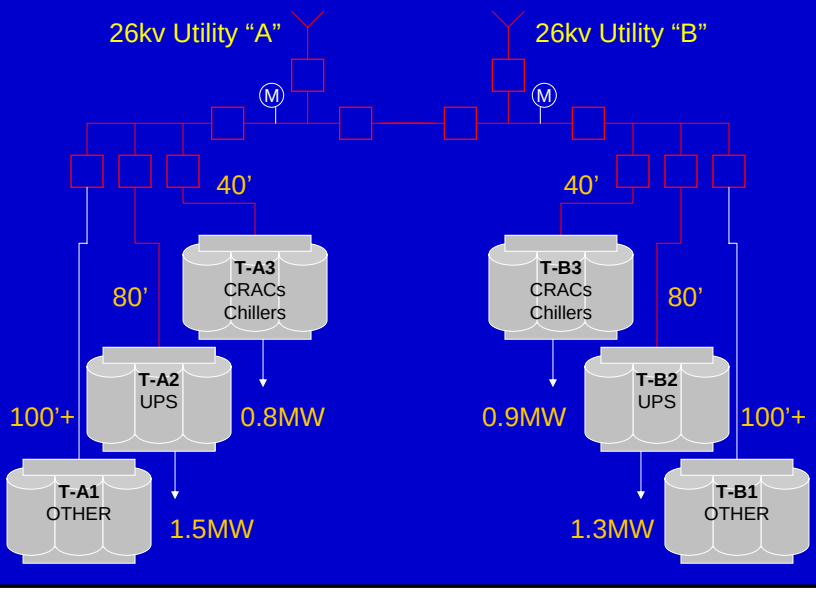
Simplified System Configuration



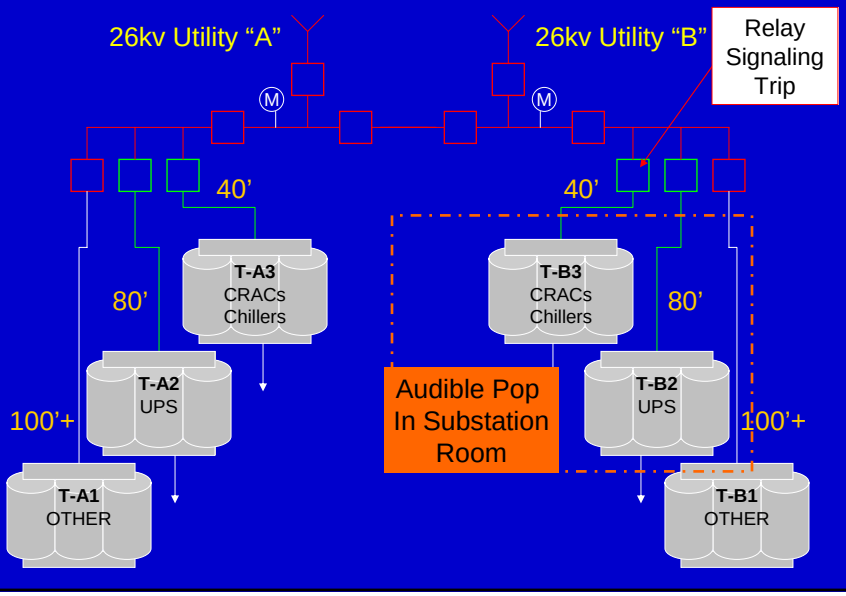
Failure/Sequence of Events

- **All Transformers Fully Tested:**
  - Pre-functional: Turns Ratio, Insulation Resistance, etc
  - Functional: UPS Full Load Tests, UPS Transient Tests, Data Center Room Validation Testing
- **Final Pull The Plug Test (PTP)**
  - 4 Electricians "simultaneously" open (4) 26KV vacuum breakers to simulate a general utility outage.
    - All systems successfully transfer to standby generation but:
      - Loud Pop heard in Substation Room B
      - Relay for VCB feeding TB3 signaling trip
    - Decision made to shutdown generator test and investigate issue in "B" substation room
  - 2 Electricians "simultaneously" close (2) 26KV vacuum breakers to Substation Room "A"
    - Transformer TA3 fails catastrophically.

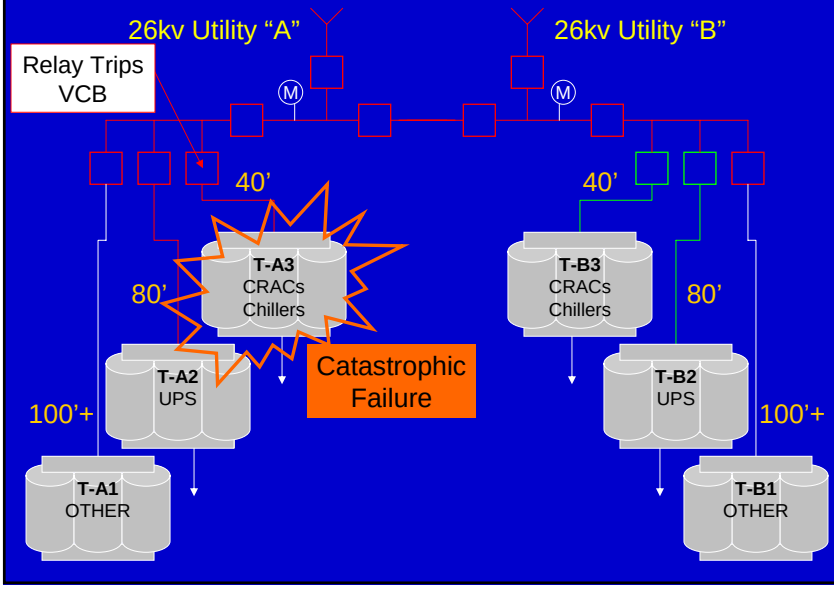
Pre-PTP Condition



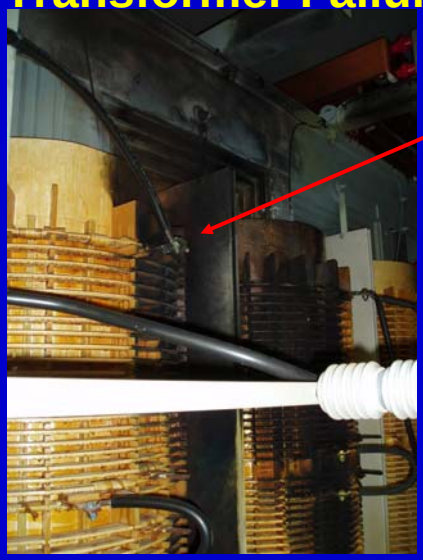
Failure #1: De-Energization During PTP



Failure #2: Energization During PTP



Failure #2
Transformer Failure On Energization



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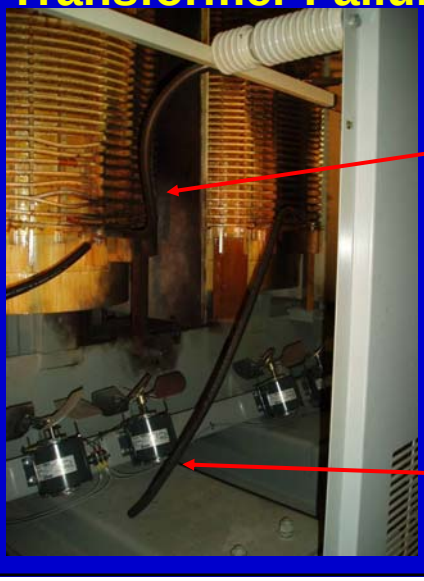

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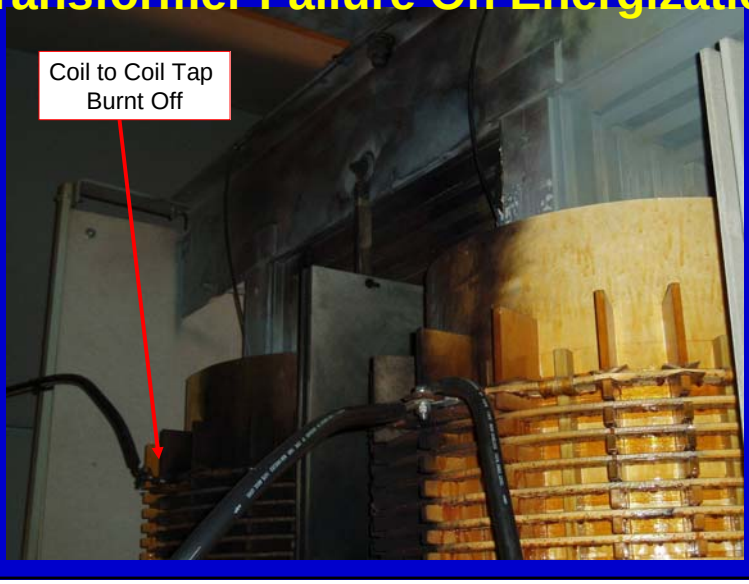

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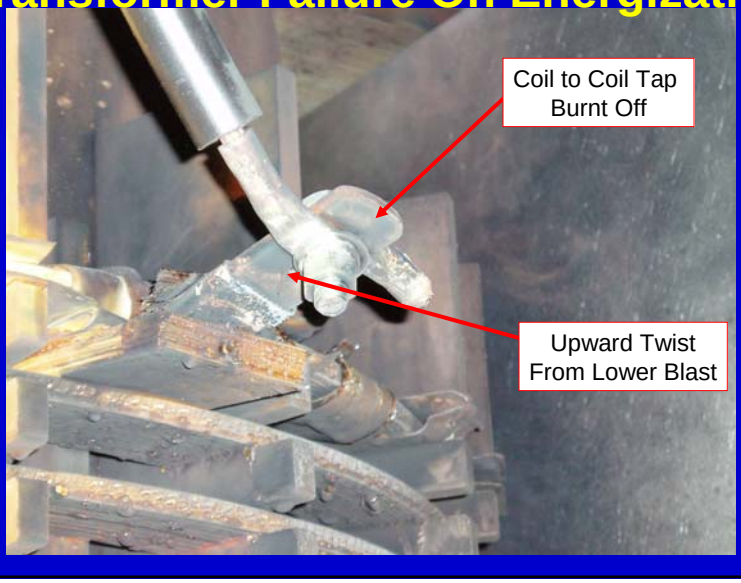

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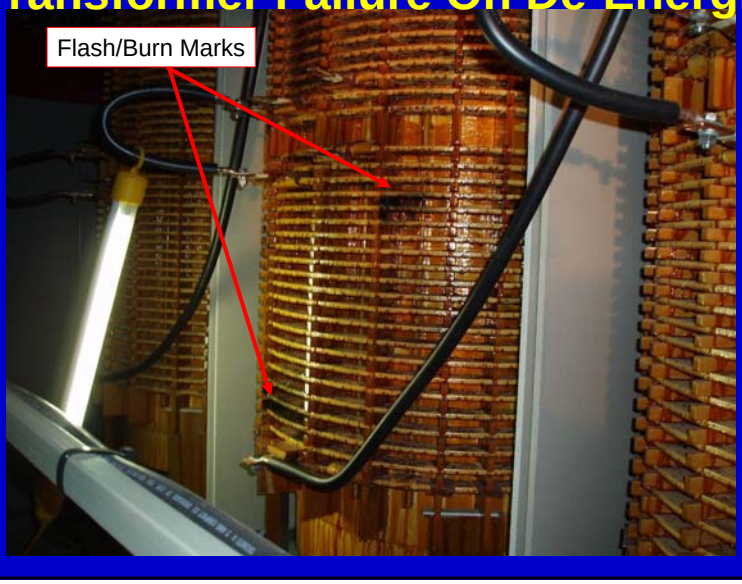
Transformer Failure On De-Energization



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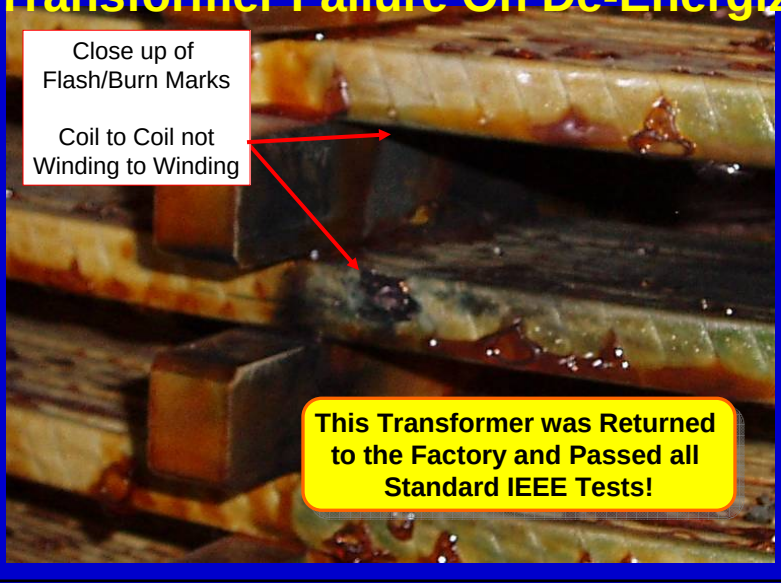
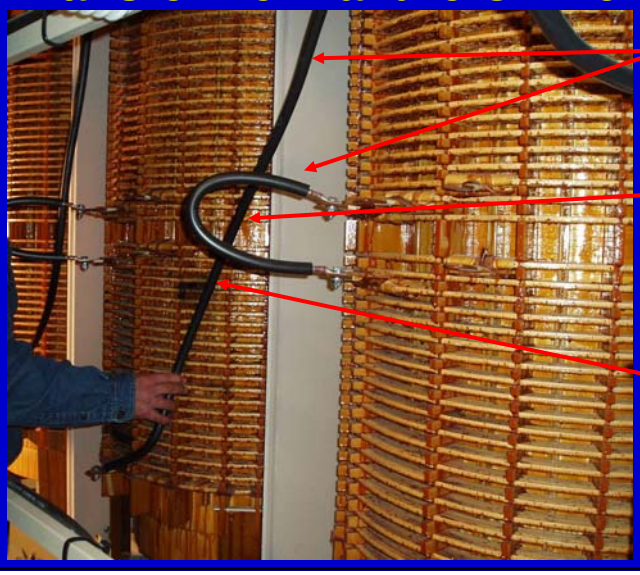
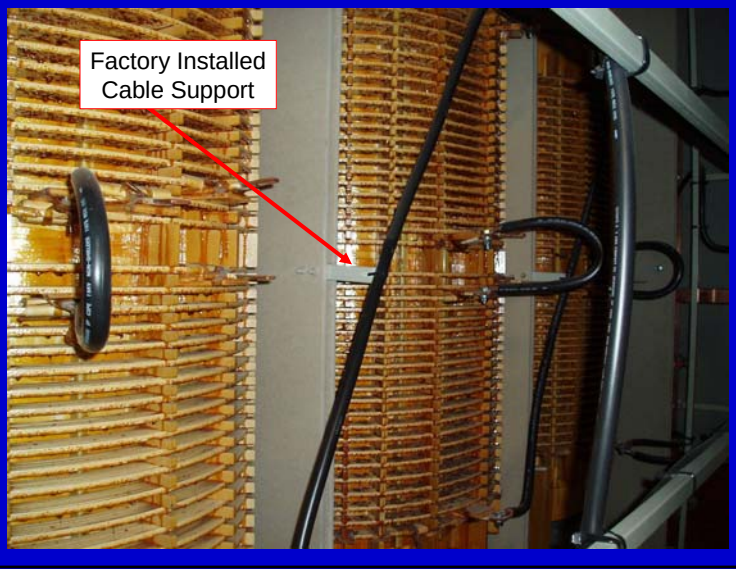


Failure #1
Transformer Failure On De-Energization

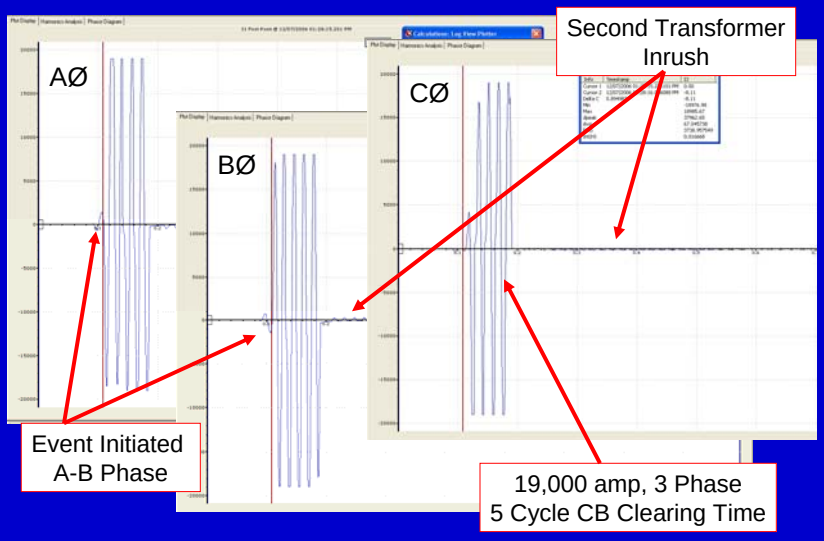


Failure #1
Transformer Failure On De-Energization

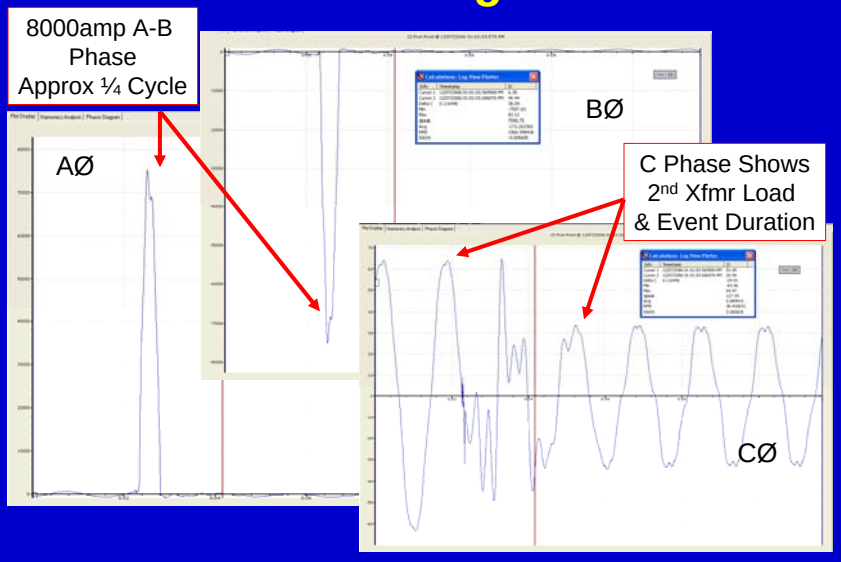
Unaffected Transformer



Current Transient: Failure #2 Transformer Energization



Current Transient: Failure #1 Transformer DeEnergization



Breaker Induced Switching Transients

Case 1
Hydro Dam, MT 2005

- MV Vac Bkr Replacements Vendor “A”
- 13.8 kV
- 20 feet of cable
- 50 kV BIL (W) ASL Dry Type Txmrs
- Customer Energized before Vendor OK
- Txmr Failed
- No Surge Protection Applied

CASE 2
Cleveland Hospital 3/06

- Vacuum Breakers – Vendor “A” and Vendor “C”
- 13.8 kV
- 95 kV BIL
- Dry Type Txmr
- 27 feet of Cable
- Bkr Manufacturer Paid to Repair Failed 2500 KVA Txmr
- Surge Protection Added Afterwards

CASE 3
RAILROAD SUBSTATION 11/06

- Vacuum Breaker – Vendor “A”
- 26.4 kV
- 150 kV BIL
- Generic Liquid Filled Rectifier Txmr
- 37 feet of Cable

CASE 4
NJ DATA CENTER 12/06

- 26.4 kV – Vendor “B”
- 4 Txmrs Switched Under Light Load
- 2 Txmrs Failed-1 on Closing/1 on Opening
- 40 Feet of Cable
- 2 other Txmrs Did Not Fail - 80 Feet of Cable
- Arresters Were Present

CASE 5
OIL FIELD – AFRICA 6/07

- Vacuum Breaker – Vendor “D”
- 33 kV
- 7 Feet of Cable
- Dry Type Txmr in 36 Pulse VSD
- Arresters Were Applied
- Txmr Failed Upon Energization

CASE 9
Oil Drilling Ship – 6/2002

- Vendor “A” IEC Vac Bkrs in Vendor “D” Swgr
- 11kV, 60 HZ
- Cast Coil Dry Type IEC VSD Propulsion Txmr Failed (7500 kVA) – 75 kV BIL?
- < 30 feet of Cable
- Fed from Alternate Bus – Now 80 feet of Cable
- No further Failures Reported

Case 10
Ferry – NY City – Feb 2010

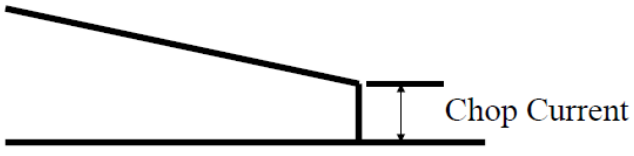
- 4.16 KV System
- Vendor A – IEC BKR
- 15 Feet of Cable
- IEC Cast Coil Txmr – 30 kV BIL
- Failed upon Closing

SWITCHING TRANSIENTS DUE TO VACUUM / SF6 BREAKERS

- Opening -- Current Chop
- Closing -- Prestrike/Re-ignition/Voltage Escalation
- Vacuum Bkrs --Both Closing and Opening
- SF6 -- Opening
- Air -- Generally Acceptable

Current Chop

- Vacuum Arc Burns in Metal Vapor From Contacts
- Requires High Temperature Arc Roots
- Heat Supplied by Current Flow
- As Current Goes to Zero, Metal Vapor Production Decreases
- When Metal Vapor Cannot Support the Vacuum Arc,
  - It Suddenly Chops Out



Current Chop

Current Chop in Vacuum is a Material Problem

- Older VIs - GE - Use Copper-Bismuth
  - GE 1st tried 5% Bi - didn't interrupt
  - Reduced Bi to 0.15% - weak welds - interrupts
  - Chop current still high like copper at up to 21 A
- Modern VIs - C-H - Use Copper-Chromium
  - Lower chop current of up to 5 A
  - Excellent Interruption performance
  - Moderate weld strength

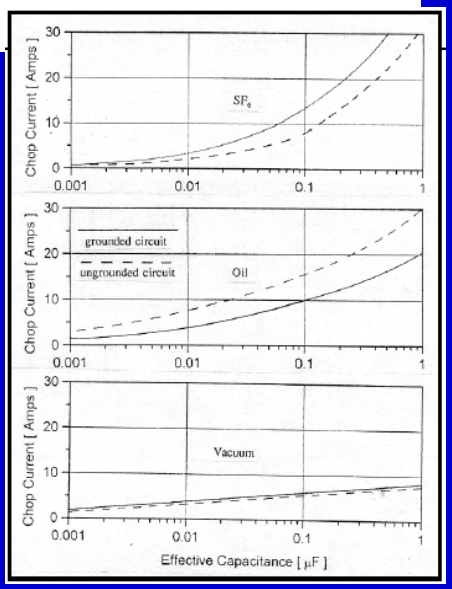
Modern VI →

Older VI →

Contact Material	Average (A)	Maximum (A)
Cu	15	21
Ag	4	7
Cr	7	16
W	14	50
Cr-Cu (75 wt %)	3	5
Cr-Cu-Bi (5 wt %)	1	3
Cr-Cu-Sb (9 wt %)	4	11
Cu-Bi (0.15 wt %)	6	21
WC-Ag (50 wt %)	1.5	2.5
W-Cu (30 wt %)	5	10
Co-Ag-Se	0.4	0.8
Cu-Bi-Pb	1	9

Current Chop

- All Types of Interrupters Chop Current
- This is not a Unique Feature of Vacuum

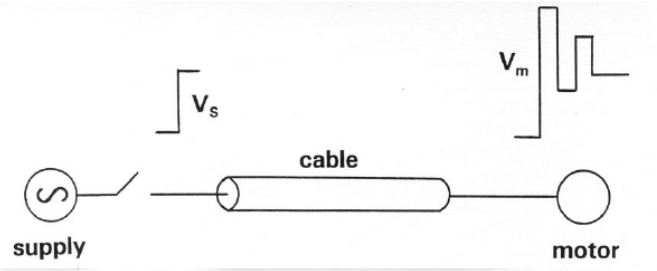


Switching Inductive Circuits

- Closing
- Opening
- Voltage Escalation
- Surge Suppression

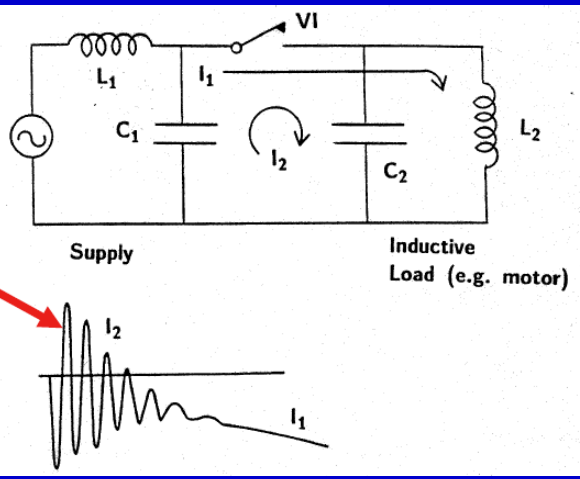
Switching Inductive Loads CLOSING

- Travelling wave in cable reflects & doubles at load
- All Interrupter Technologies (Vacuum, SF6, Air, Oil) Have Similar Effect



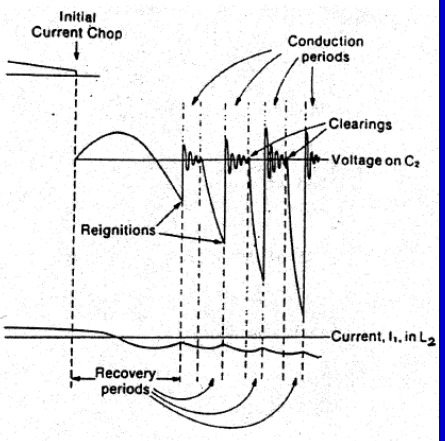
Switching Inductive Loads
OPENING

- If a restrike occurs on opening, a high frequency current flows with current zeros



Switching Inductive Loads
VOLTAGE ESCALATION

- Repetitive re-ignition can occur when contacts part just before a current zero & interrupt at high frequency zeros
- Voltage builds up & breaks down several times before interrupting



SWITCHING TRANSIENT THEORY

- "Thou Shalt Not Change Current Instantaneously in an Inductor"
- Conservation of Energy –
  - – You Cannot Create or destroy Energy – You Can Only Change Its Form

ENERGY EQUATION

$$\frac{1}{2}LI^2 = \frac{1}{2}CV^2$$

OR

$$V = I\sqrt{\frac{L}{C}}$$

TOTAL VOLTAGE

- Vt = Venergy + Vdc + Vosc
- Venergy is from the Energy Equation
- Vdc = DC Off-set that Sometimes is Present
- Vosc = the Oscillatory Ring Wave

TRANSFORMER LIMITS

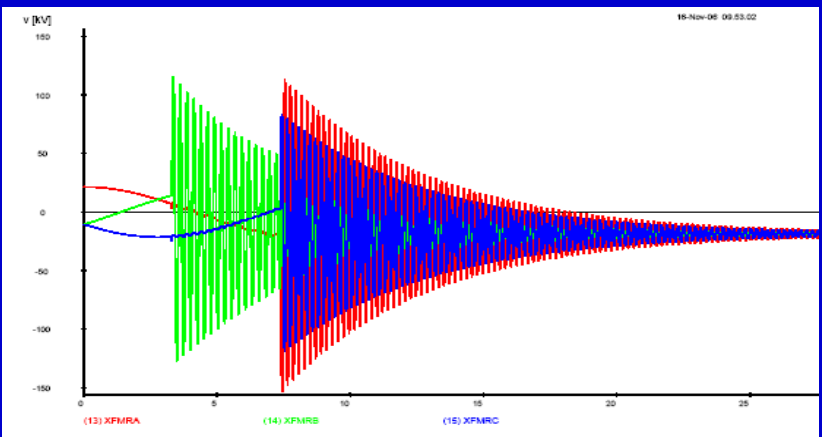
- Magnitude – BIL Ratings
- Dv/dt Limits
- Both MUST Be Met
- Dry Type Txmrs Particularly Susceptable
- Liquid Filled Not Immune.
- Consider “Hammer Effect”

ANALYSIS

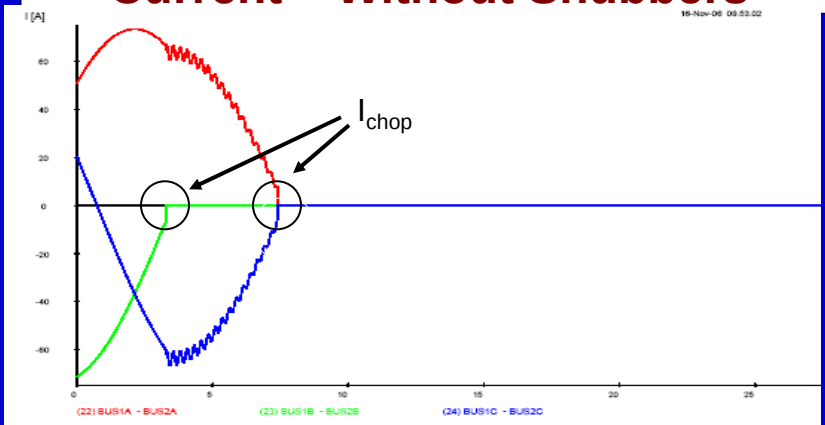
- When Open Bkr, Txmr is Left Ungrounded
- Ring Wave is a Function of its Natural Frequency

$$NF = \frac{1}{2\pi\sqrt{LC}}$$

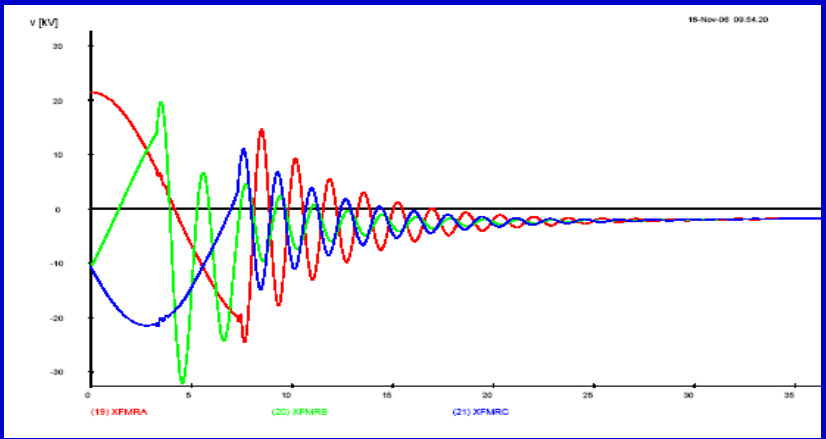
CASE 3
Waveforms Without Snubbers



CASE 3
Current – Without Snubbers



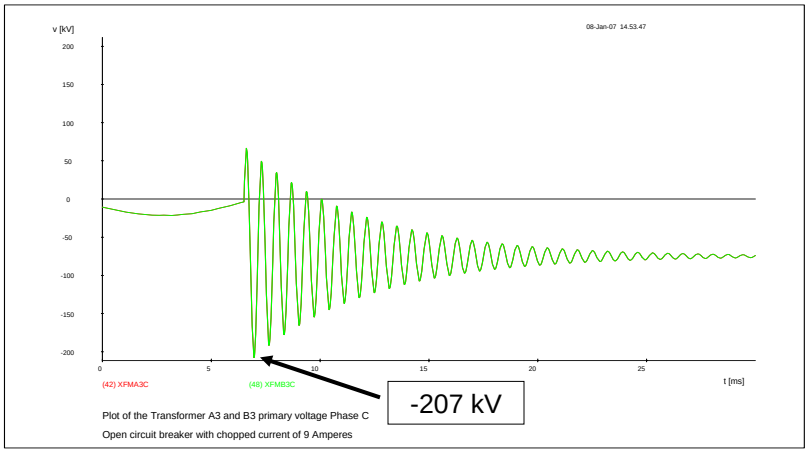
CASE 3
Waveforms With Snubbers



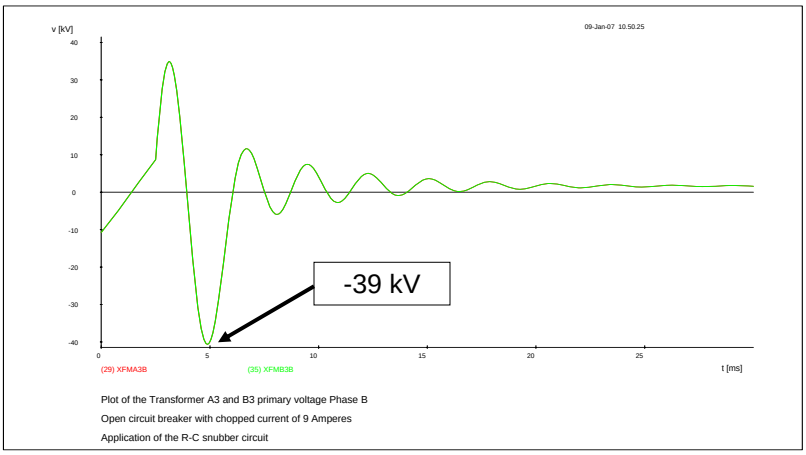
CASE 4
Data Center 12/06

- 26.4 kV
- Vendor “B” Breakers
- 4 Bkrs Switched at Once
- 2 Dry Type Txmrs Failed (40 Ft of Cable)
- 2 Txmrs Did not Fail (80 Ft of Cable)
- Unfaulted Txmr Winding Failed BIL @162 kV (Rated 150 kV)

CASE 4
Data Center, NJ 12/06 - W/O Snubbers



CASE 4
Data Center, NJ 12/06-With Snubbers

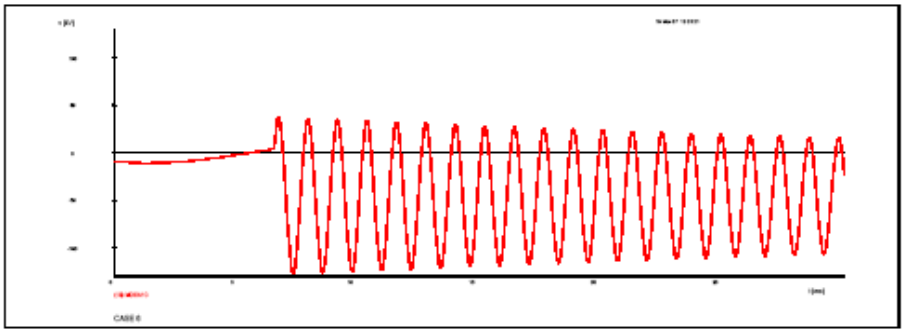


Plot of the Transformer A3 and B3 primary voltage Phase B
Open circuit breaker with chopped current of 9 Amperes
Application of the R-C snubber circuit

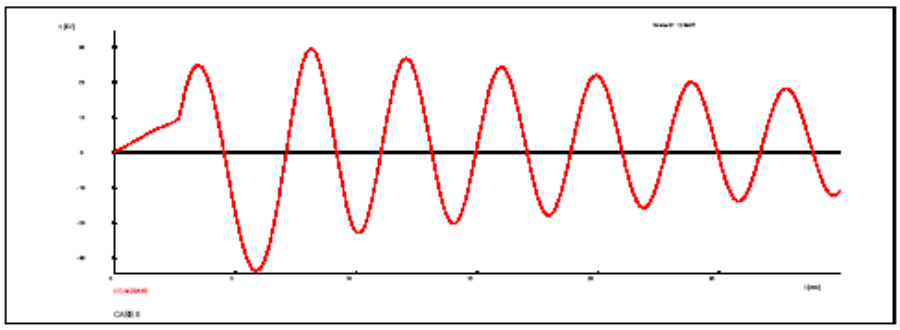
CASE 6
Data Center 2, NJ 12/06

- 13.2 kV
- Vendor “B” Breakers
- 3 MVA Dry Type Txmrs
- 60 ft Cable – Required Snubbers
- 157 ft Cable – Required Snubbers
- No Problem at Startup

CASE 6
13.2 kV SYSTEM – 119 kV @ 678 HZ



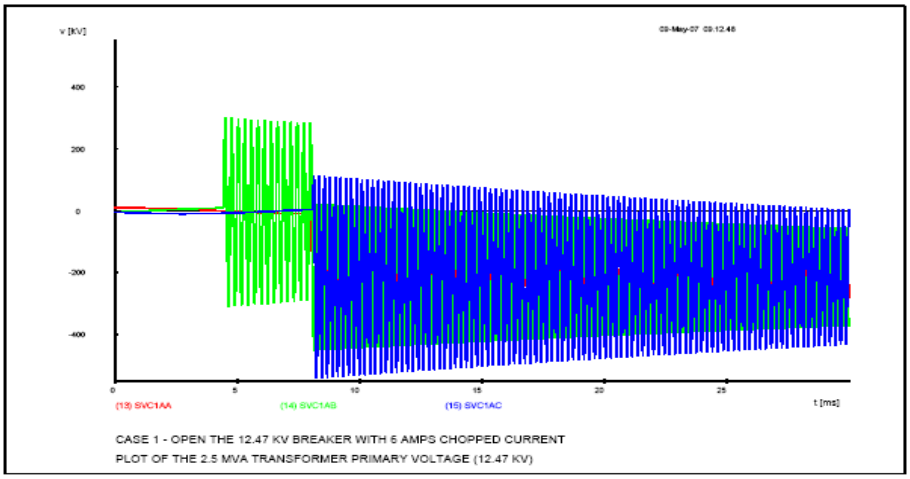
CASE 6
WITH SNUBBERS – 33.6 kV @ 236 HZ



CASE 7
Chemical Plant, NC 3/07

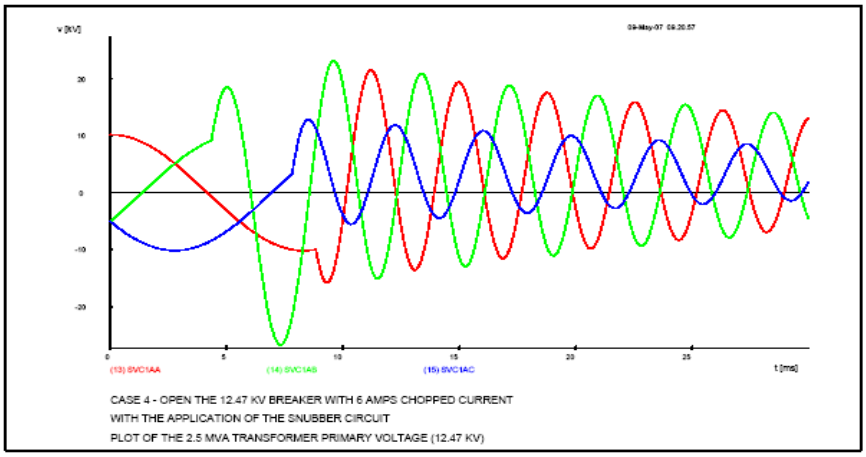
- 12.47 kV System
- 20+ Year Old Oil Filled Txmrs
- Vendor “A” Vacuum Bkrs retrofitted on Primary
- 10 Feet of Cable
- No Problem at Startup

CASE 7
425 kV - 12. 47 kV - 23 kHZ Ring Wave



CASE 1 - OPEN THE 12.47 KV BREAKER WITH 6 AMPS CHOPPED CURRENT
PLOT OF THE 2.5 MVA TRANSFORMER PRIMARY VOLTAGE (12.47 KV)

CASE 7
Added Snubbers – 12.47 kV

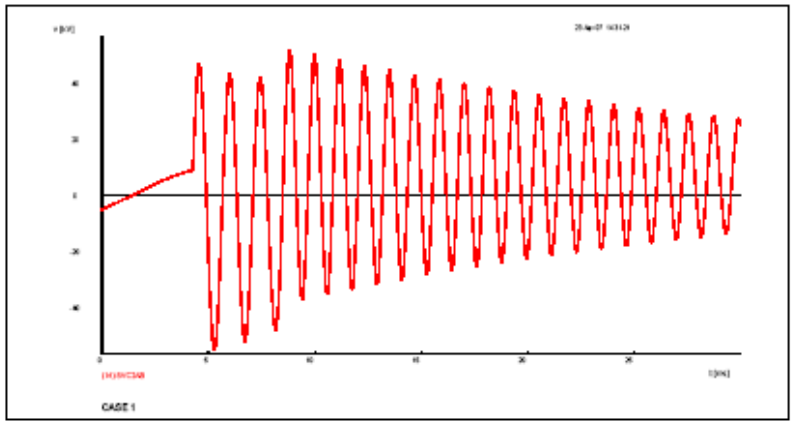


CASE 4 - OPEN THE 12.47 KV BREAKER WITH 6 AMPS CHOPPED CURRENT
WITH THE APPLICATION OF THE SNUBBER CIRCUIT
PLOT OF THE 2.5 MVA TRANSFORMER PRIMARY VOLTAGE (12.47 KV)

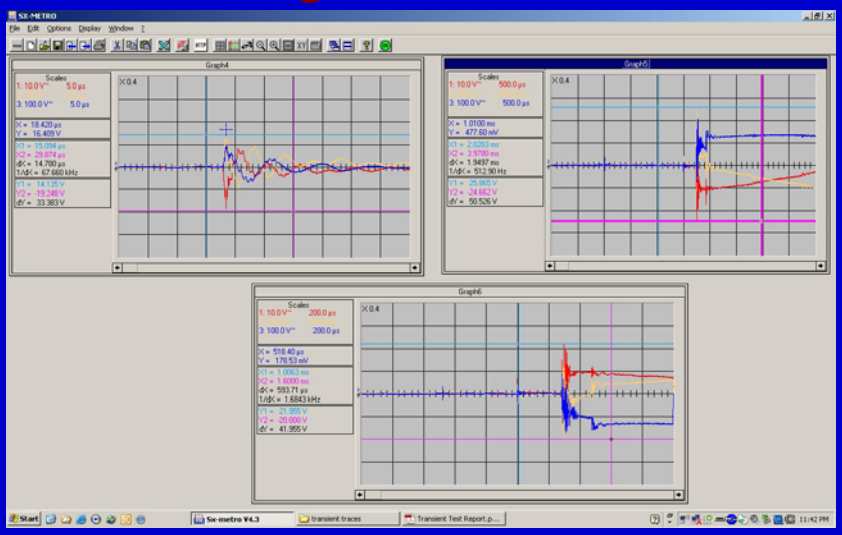
CASE 8
DATA CENTER – Indiana 6/07

- 12.47 kV System
- Vendor “A” Breakers
- 270 Feet of Cable
- No Additional Surge Protection Required

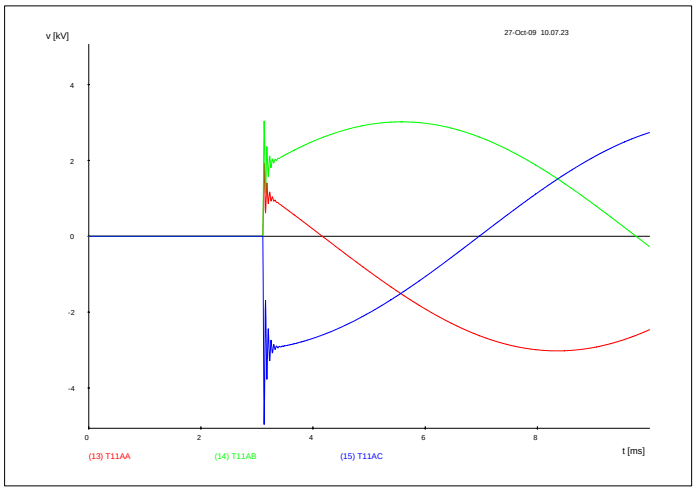
CASE 8
-55 kV at 800 HZ



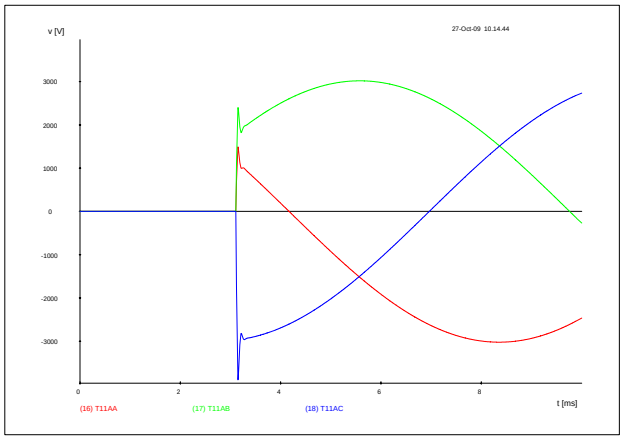
Case 10
Closing Measurements



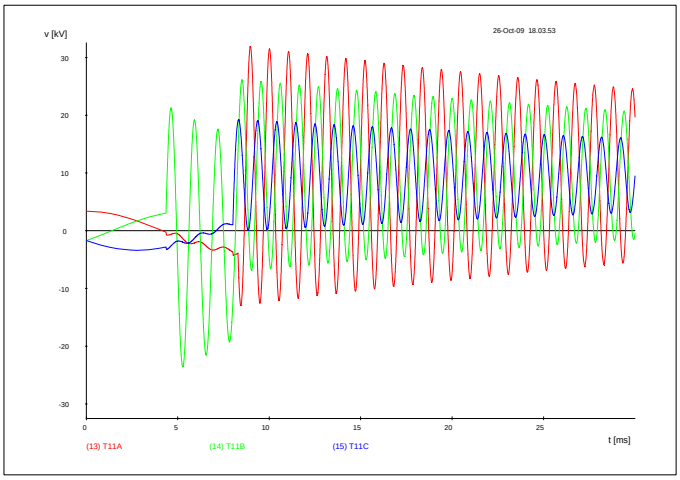
Case 10
Closing 20.2 kHZ



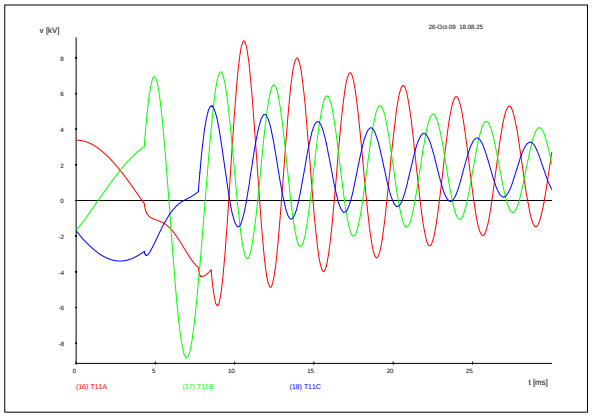
Case 10
Closing –Snubbers



Case 10
Opening – 31 kV



Case 10
With Snubbers-31kV to 9 kV @299HZ



MITIGATING TECHNIQUES

- Arresters
- Surge Capacitors
- Snubbers (RC)
- Hybrid / Combinations
- Liquid vs Dry Type
- Electronic Zero Crossing Switching

Snubber - 3 Phase Capacitor Generally Solidly Grounded System

- Paper Mill - AL
- 13.8 kV

Snubbers – 2nd paper mill - beta site

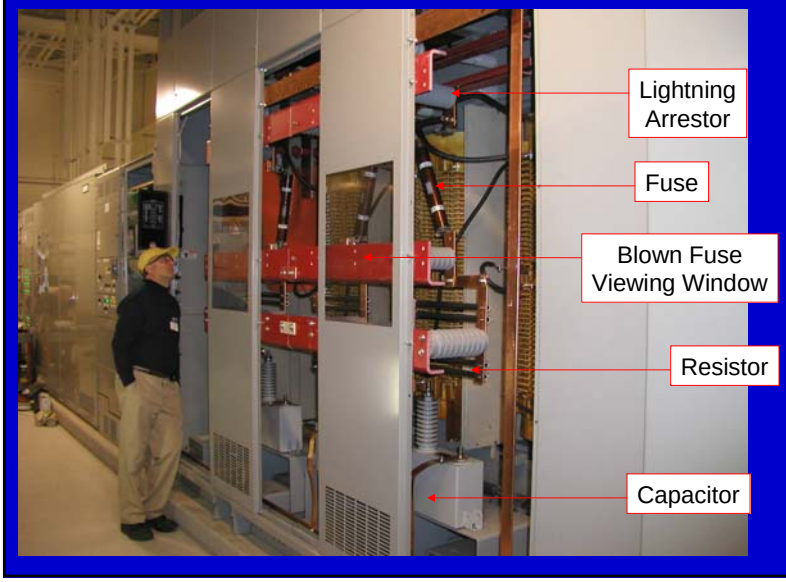
Snubber – Single Phase Capacitors Low Resistance Grounded Systems

- Paper Mill
- Vendor “A” Swgr
- 13.8 kV

Snubber – Single Phase Capacitors

- Silicon “Chip” Plant
- Montana
- Very Specialized Dry Type Txmrs
- 13.8 kV
- Cables < 100 feet
- Primary Fused Switch AF Solution
- Vendor “A” Vac Bkrs

RC Snubber Installed – Case 4



RC Snubber Installed – Case 4

RC Snubber Installed – Case 4

SWITCHING TRANSIENT STUDY

- Quantifies Problem
- Predict Exposure / Risk
- Select Best / Most Cost Effective Solution
- Do “What if” Cases
- Verify Results

RECOMMENDATIONS

- Factor into Design Up-front
- Do Study – Results Are Bkr Manufacturer Specific
- Use Protection Only When / Where Needed (if not there, cannot fail)
- Fused or Unfused Snubbers??
- Loss of Fuse Detection??
- Fear Not! - Mitigating Techniques Have Been Proven.
- Discrete Snubber Components??

Conclusion/Next Steps

- This is a System Problem
  - Transformer, Cable, Switching Device, Proximity
  - Statistical Event , Possible Undetected Failures
- Data Centers Fall into the Highest Risk Category
  - High Power Density
  - Close Proximities
  - Frequent Switching
- Draft IEEE C57.142
  - A Guide To Describe The Occurrence and Mitigation Of Switching Transients Induced By Transformer And Switching Device Interaction
  - Does not accurately warn users of all areas of concern
  - This case did not meet the areas of concern noted in Draft C57.142
  - Need to push for formalization of the standard with new lessons learned
- RC Snubbers
  - Transformer Manufacturer appears best positioned to implement the solution
  - Limited Cataloged Product (One Manufacturer)
  - Not embraced by all transformer manufacturers
  - Design Parameters of RC Snubber not clearly defined
- Lives, Property and Uptime are all at risk

QUESTIONS ?