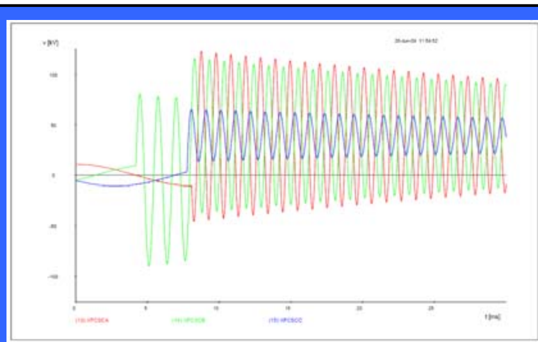

Transformer Failure Due to Circuit Breaker Induced Switching Transients

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IEEE Central Tennessee Section
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Introduction

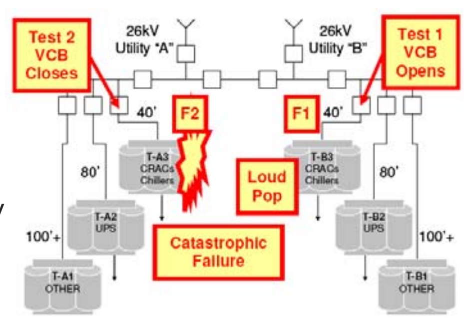
- Switching transients associated with circuit breakers observed for many years
- Breaking opening/closing interacts with the circuit elements producing a transient
- The severity of the transient is magnified by breaker characteristics
  - Current chopping on opening
  - Pre-strike or re-ignition on closing
- In limited instances, the transient overvoltage exceeds transformer BIL resulting in failure
- RC snubber in combination with surge arrester mitigates the transient

Introduction - Outline

- Forensic evidence and history of failures
- Underlying concepts
- Predicting performance with simulations
- Mitigating the transients with snubbers
- Concerns for data centers & overall industry
- Custom designing the snubber
- Snubber performance measurements
- Other considerations

Data Center NJ – Forensic Evidence

- Four electricians "simultaneously" opened four 26kV VCBs
  - simulate utility outage
  - systems transferred to standby generation
  - "loud pop" in Sub Rm B
  - the relay for VCB feeding transformer TB3 signaled trip
- Minutes later, two electricians "simultaneously" closed two 26kV VCBs
  - breakers to Sub Rm A
  - transformer TA3 failed catastrophically

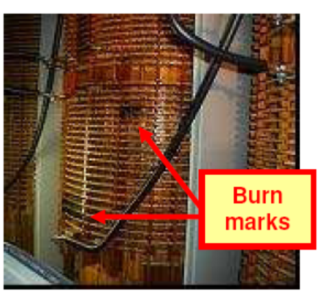


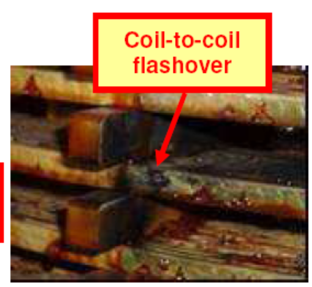
Transformer Failure #2 - Energization

- Examination of primary windings
  - Coil-to-coil tap burn off
  - Winding showed an upward twist
  - Burn marks from the initial blast
  - Transient on first turns of windings

Transformer Failure #1 – De-energization

- Examination of primary windings
  - Flash and burn marks on b-phase at bottom & middle
  - Bottom - Indicate a coil-to-coil flashover (high dv/dt)
  - Middle – cable used to make delta swung free (lack of support)
  - Transformer passed BIL test at 150kV but failed at 162kV





Both failed units:
- 40 feet of cable
- High efficiency design
- VCB switching

History of Failures – Forensic Review

		Circuit			Transformer***			Vacuum Breaker	
Case	Facility	Voltage	Cable Feet	Bil	Type	Arrester	Failure Mode	Vendor	Switching
1*	Hydro Dam	13.80	20	50	Dry	No	1st turn	A	Close
2	Hospital	13.80	27	95	Dry	No	1st turn	A	Close
3	Railroad	26.40	37	150	Liquid	N/A	middle	A	Open
4	Data Center	26.40	40	150	Cast coil	Yes	1st turn	B	Close/Open
			80	150	Cast coil	Yes	None	B	Close
5	Oil Field	33.00	7		Dry	No	1st turn	C	Close
6**	Oil Drill Ship	11.00	<30	75	Cast coil	Yes	1st turn	C	Close

Notes: * = 40-50yrs. old with new breaker. ** = 2 yrs. old. All others new.
*** = All transformers unloaded or lightly loaded when switched.

Common Parameters

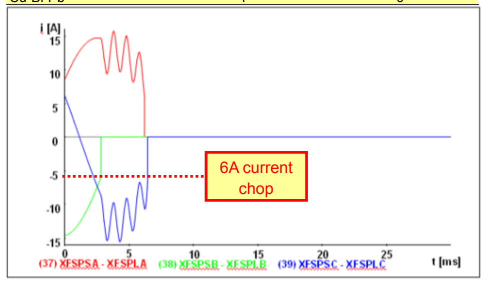
"Rules of Thumb" to screen applications:

- Generally, short distance between circuit breaker and transformer
  - about 200 feet or less
- Dry-type transformer
  - oil filled and cast coil not immune and low BIL
- Inductive load being switched
  - transformer, motor, etc. (light load or no load)
- Circuit breaker switching characteristics:
  - chop (vacuum or SF6) or restrike (vacuum)

Underlying Concepts - Current Chop

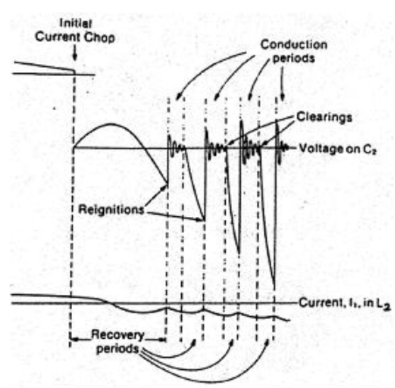
- VCB opens, arc burns metal vapor
- Heat supplied by current
- As current goes to zero, metal vapor ceases
- Arc ceases or "chops"
- All breaker chop current
  - low end 3 – 5A
  - high end 21A

Contact Material	Average (A)	Maximum (A)
CU	15	21
Ag	4	7
Cr	7	16
W	14	50
Cr-Cu (75 wt %) ←Modern VI	3	5
Cr-Cu-Bi (5 wt %)	1	3
Cr-Cu-Sb (9 wt %)	4	11
Cu-Bi (0.15 wt %) ←Older VI	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



Reignition and Voltage Escalation

- Current chop plus system C and L imposes high frequency TRV on VCB contacts
- If TRV exceeds breaker rated TRV, then reignition occurs
- VCB closes and then opens high frequency current
- Multiple reignitions lead to voltage escalation



Switching Inductive Circuits

- Current cannot change instantaneously in an inductor (conservation of energy)
- Energy Equation $\frac{1}{2} LI^2 = \frac{1}{2} CV^2$ or $V = I \sqrt{L/C}$

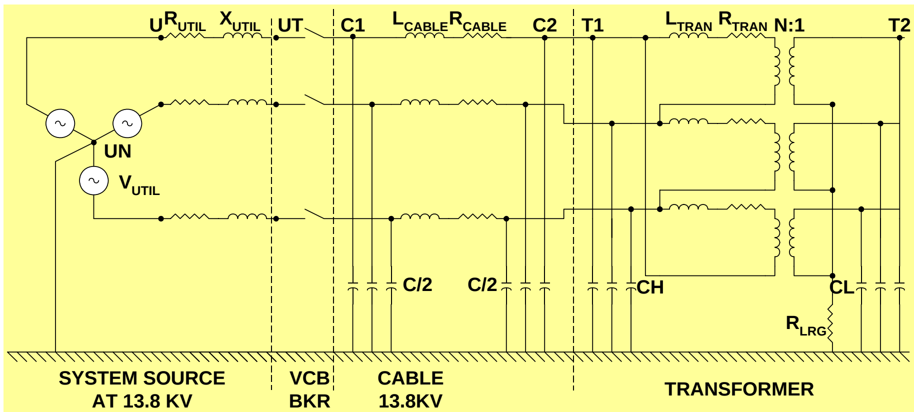
- Vtransient = Venergy + Vdc + Vosc
- Venergy is from the Energy Equation
- Vdc = DC Off-set due to system X/R
- Vosc = the Oscillatory Ring Wave

Transformer Limits

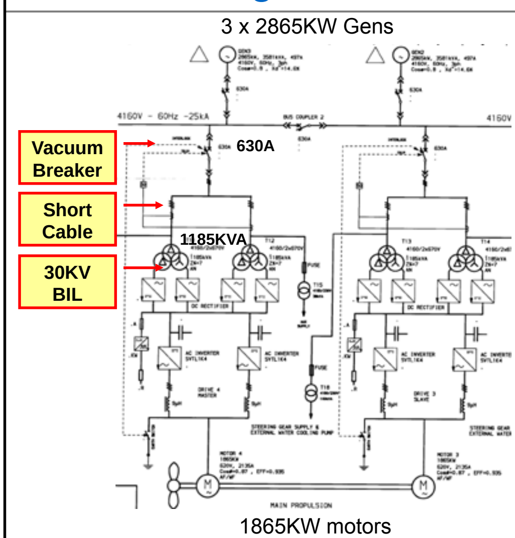
- Magnitude – BIL Ratings
- Rate-of-change (dv/dt) Limits
- Both MUST Be Met
- Dry Type transformers particularly susceptible
- Liquid Filled Not Immune
- Consider the "Hammer Effect"

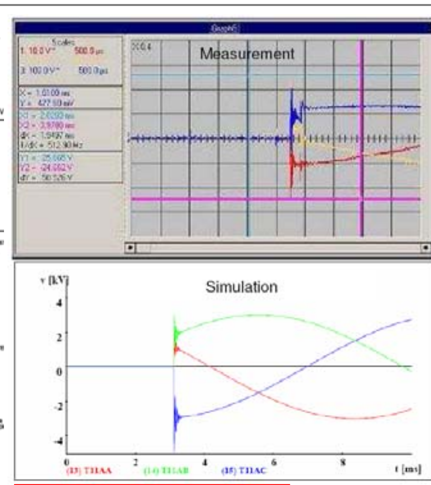
Predicting Performance – EMTP Simulations

- For purposes of screening applications for damaging TOVs
- Source, breaker, cable and transformer modeled
- Breaker models for current chop and re-ignition



Matching Model to Measurements





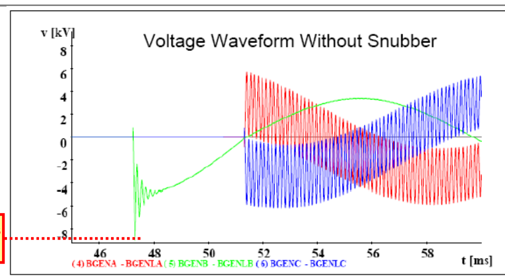
V max of 4.96kV < 30kV BIL
Oscillation of 20.2kHz

Transient Mitigation

- Surge Arrester
  - Overvoltage protection (magnitude only)
- Surge Arrester + Surge Capacitor
  - Overvoltage protection
  - Slows down rate-of-rise
- Surge Arrester + RC Snubber
  - Overvoltage protection
  - Slows down rate-of-rise
  - Reduces DC offset and provides damping

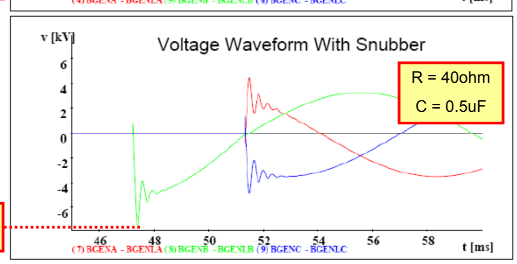
Breaker Opening Followed by Reignition

Transient Recovery Voltage		IEEE ANSI C37.06 C37.011	Note
E2 (kV)	9.044	8.9	U
T2 (μsec)	79	50	
RRRV (kV/μsec)	.1145	.1780	



TRV exceeds limit

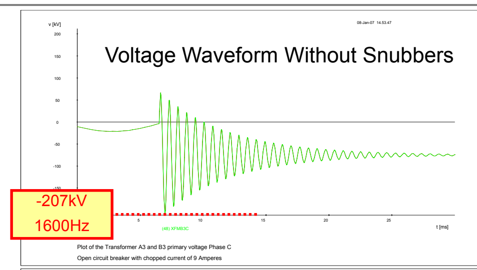
Transient Recovery Voltage		IEEE ANSI C37.06 C37.011	Note
E2	7.702	8.9	A
T2	149	50	
RRRV	.0517	.1780	

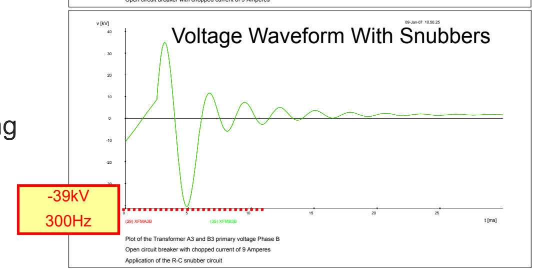


TRV within limit

Case 4 Data Center – New Jersey

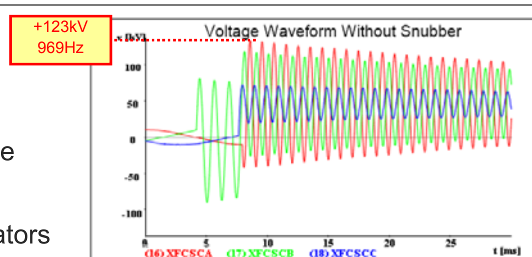
- Commissioning Failure
  - 26.4 kV
  - Vendor "B" VCBs
  - 4 Bkrs Switched at Once
    - 2 Dry Type Txmrs Failed
    - (40 Ft of Cable)
    - 2 Txmrs Did not Fail
    - (80 Ft of Cable)
  - Unfaulted Txmr Winding
    - Failed BIL @162 kV
    - Rated BIL 150 kV

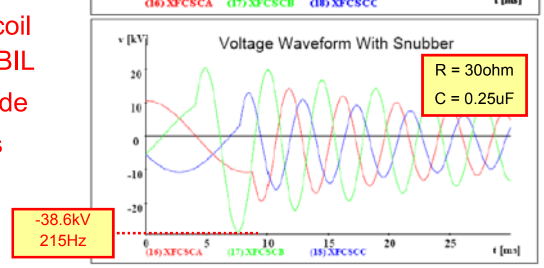




Data Center - Georgia

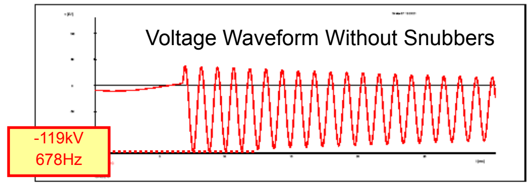
- Proactive Analysis
  - 2x 24.8kV lines
  - 2 x 12.5MVA service
  - 13.2kV ring bus
  - 2 x 2250KW generators
  - 6 x 3750KVA cast-coil transformers 90kV BIL
  - VCBs on primary side
  - 109 – 249 ft. cables

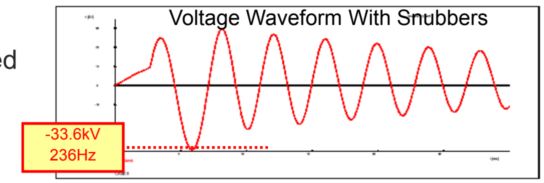




Case 6 Data Center 2 – New Jersey

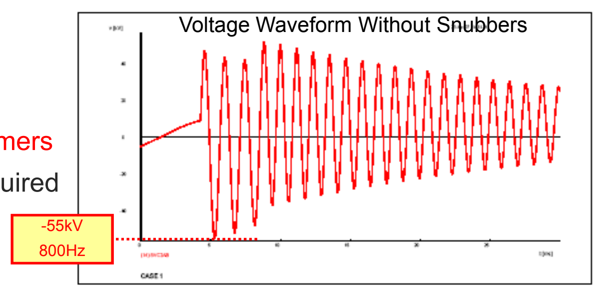
- Proactive Analysis
  - 13.2 kV
  - Vendor "B" VCBs
  - 3 MVA Dry Type Txmrs
  - 60 ft Cable – Required Snubbers
  - 157 ft Cable – Required Snubbers
  - No Problem at Startup





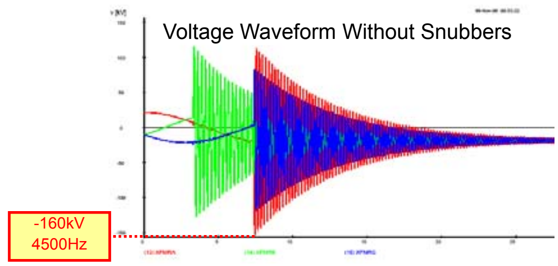
Data Center – Indiana

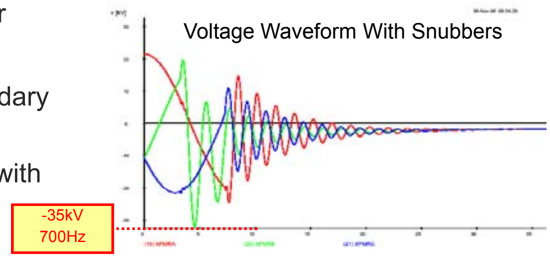
- Proactive Analysis
  - 12.47 kV System
  - Vendor "A" VCBs
  - 270 Feet of Cable
  - 95kV BIL transformers
  - No Snubbers Required



Case 3 - Railroad Substation Nov. 2006

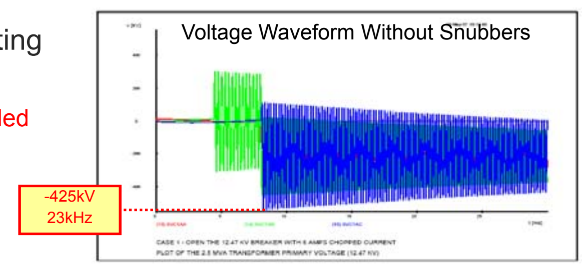
- Failure Analysis
  - Vacuum Breaker – Vendor "A"
  - 26.4 kV
  - 150 kV BIL
  - Generic Liquid Filled Rectifier Transformer
  - 37 feet of Cable
  - Switched with secondary Rectifier Capacitors
  - Internal Resonance with DC bus capacitor

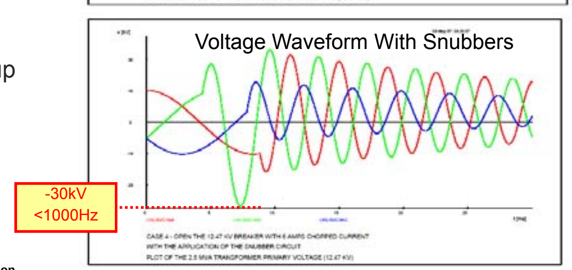




Case 7 - Chemical Plant - NC March 2007

- Study before operating
  - 12.47 kV System
  - 20+ Year Old Oil Filled Transformers
  - Vendor "A" Vacuum Breakers retrofitted on Primary
  - 10 Feet of Cable
  - No Problem at Startup





Case 5 - Oil Field – Africa June 2007

- Vacuum Breaker – Vendor "D"
- 33 kV
- 7 Feet of Cable
- Dry Type Transformer
- 36 Pulse VSD, 4000HP motor
- Arresters Were Applied
- Transformer Failed Upon Energization

Case 11 Paper Mill – 13.8 kV

- 4 x Cast Coil Transformer failures Vender E, 13.8kV/600V, 1.5MVA and one 2MVA.
- Vendor C vacuum breaker
- Failure 2/3 into winding – internal resonance

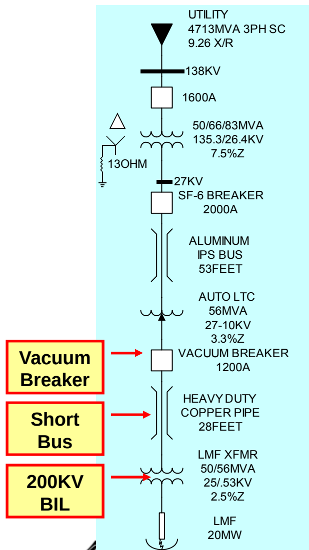
Case 12 Hospital – Kentucky – 12.47 kV

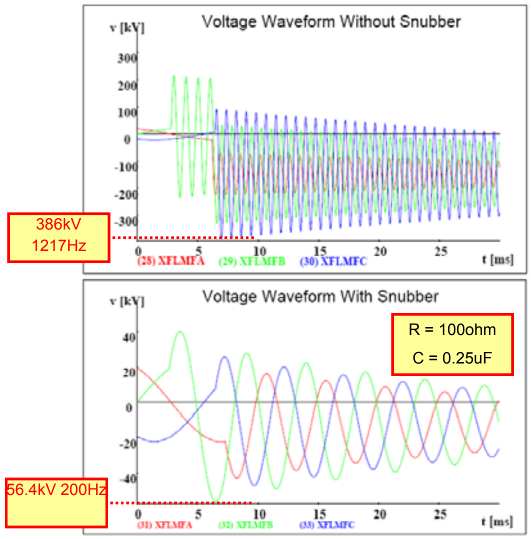
- Failure during commissioning
  - Emergency Room Transformers
  - Vendor C Vacuum Breakers
  - Vendor F, Transformer
- VPI transformer

Special Conditions

- Highly Inductive Circuits
- Internal Resonance
- Switching Transients – Opening
- Switching Transients – Closing
- Ferro-Resonance – Closing
- Ferro-Resonance – Opening (20 HZ Saturation)

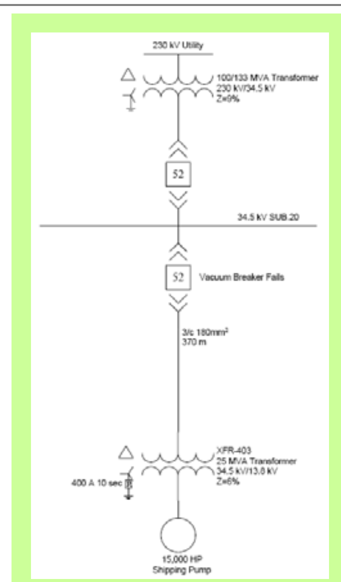
Special Condition: Switching a Highly Inductive Circuit





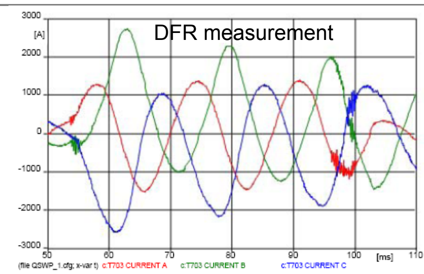
Case 14 – another highly inductive circuit Breaker Failure – TRV / RRRV

- 34.5 kV Vacuum Breaker Feeding Slave Transformer
- 13.8 kV 15,000 HP Motor
- VCB opened during starting sequence

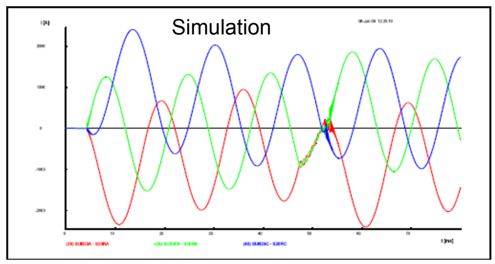


Case 14 – another inductive circuit Breaker Failure – TRV / RRRV

- Locked rotor amps recorded by DFR
- 3 cycles then VCB opens

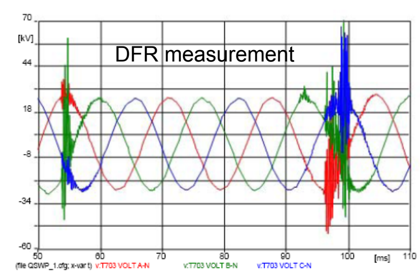


Current waveform passing through switchgear incomer A recorded by DFR
TR—4 at Sub 20, 17:06:15.922960 Wed 11 Mar 2009 (70)

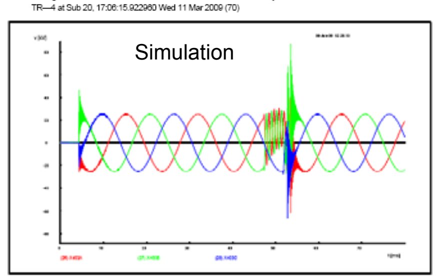


Case 14 – another inductive circuit Breaker Failure – TRV / RRRV

- VCB interrupts highly inductive current at 3cy
- Transient overvoltage
- Excessive TRV & RRRV
- Causes breaker failure



Voltage waveform at 34.5kV bus 020-SG-402-B1 recorded by DFR
TR—4 at Sub 20, 17:06:15.922960 Wed 11 Mar 2009 (70)



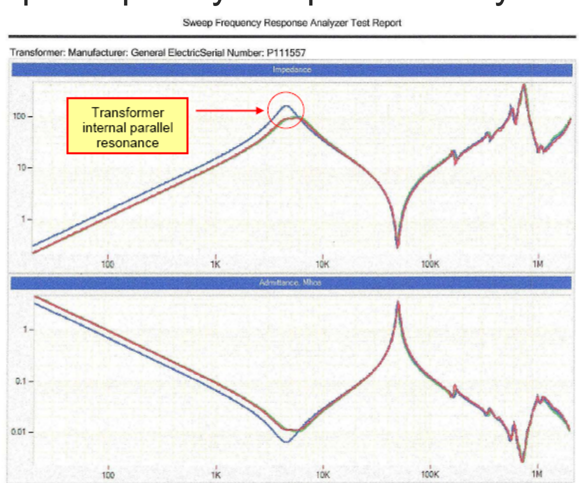
Special Condition: Internal resonance

- Each transformer has a natural frequency
- Natural frequency due to characteristics of design
- Circuit breaker switching may excite natural frequency of transformer

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

Field Tests – transformer natural frequencies

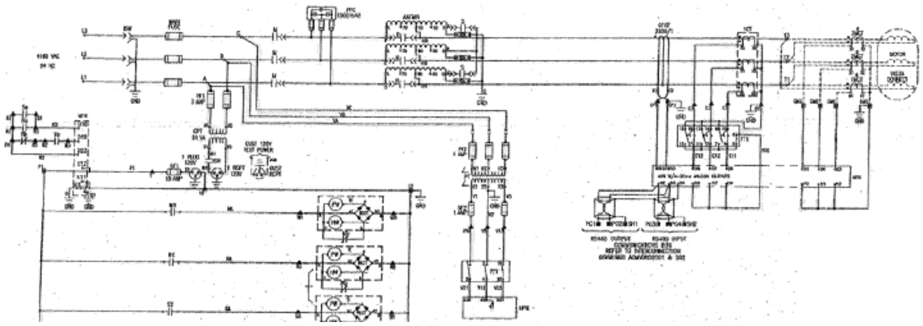
- Sweep Frequency Response Analysis



Legend: Green = X1-X0, Black = X2-X0, Red = X3-X0

Special condition: Case 13 4160V Motor Starter RVAT Failures

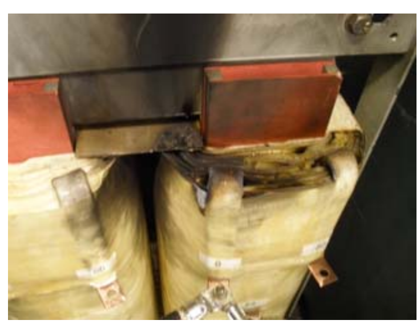
- 4160V Motor Starter
- 5000HP
- Reduced voltage auto transformer (RVAT) starter
- 3 failures on 1 of 5 starters
- Wye point failure – SA on wye
- Tap point failure
- Internal resonance
- Layer wound
- Failed layer-to-layer



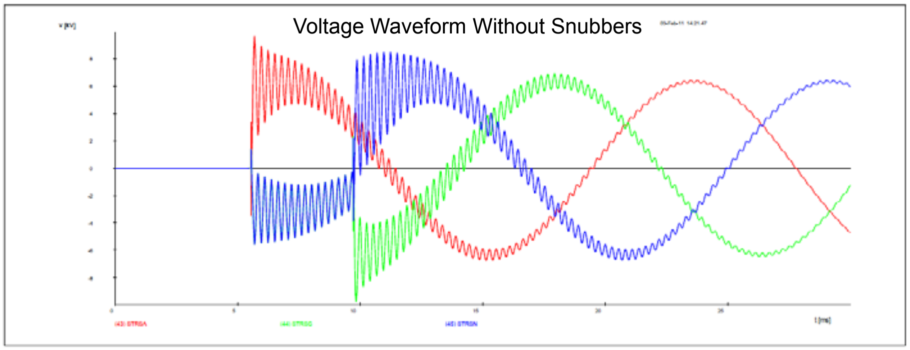
Case 13 RVAT Starter – 1st Failure

Case 13 RVAT – 1st Failure a closer look

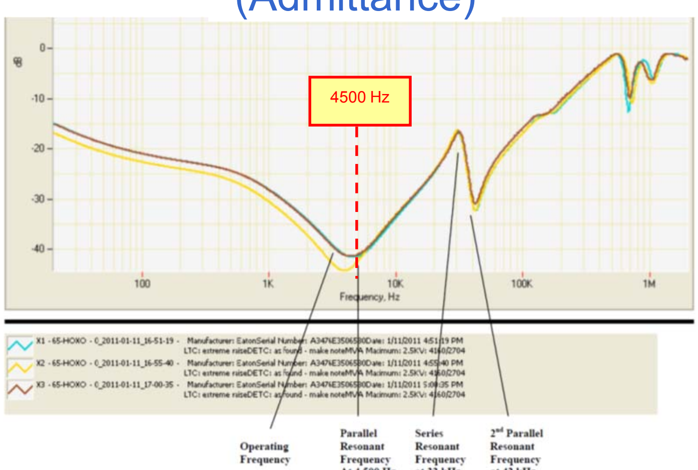
Case 13 RVAT Starter – 2nd Failure



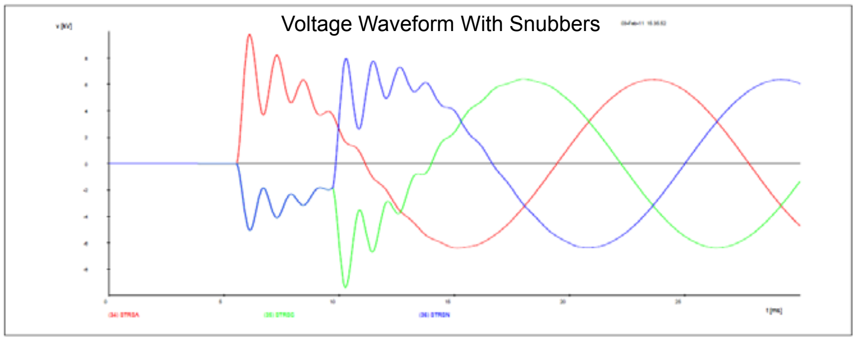
Case 13 - Run Contactor Closes 3516 HZ



Case 13 - Sweep Frequency Test 4500 Hz (Admittance)



Case 13 - Run Contactor Closes 844 Hz With Snubber



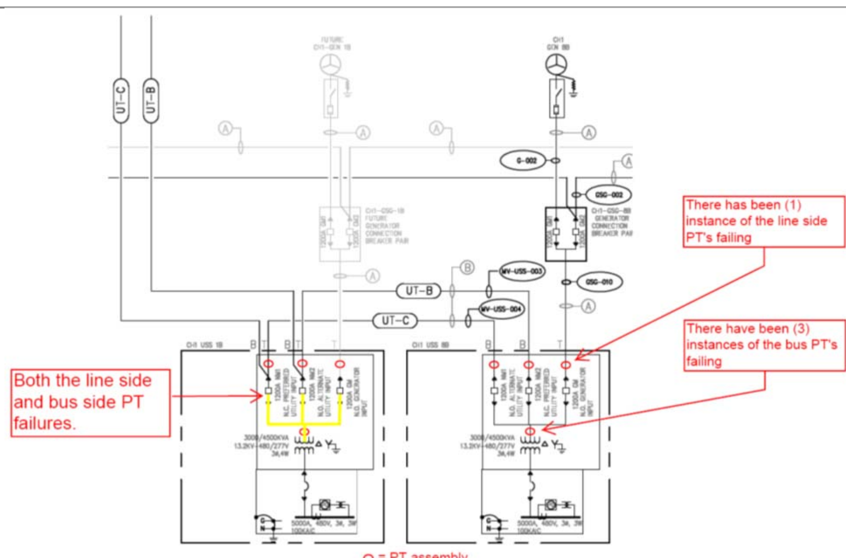
Special Condition: Case 15 PT failures Midwest Data Center

- 12.47 kV System / 120 MW Load
- Bkr Pairs with Unloaded wye-wye PTs for Auto Transfer Sensing at Load End of Cables
- Multiple Open and Closed Operations were Performed Preceding the Failure.
- 1st failure – Smoke But fuses did not Blow – Cleared Manually.

Case 15
Midwest Data Center

- 2nd Failure – Identical Switching Events
- Open Transitioned Back to Source “A”
- A few Minutes Later A Load “Pop” Was heard.
- More Smoke + B Phase Fuse Blew
- Measurements Were Taken – Snuck Up on Problem without PT Loading – Risked Failure

Case 15 Data Center Illinois – PT Ferroresonance



Special Condition: PT Ferroresonance

- upstream circuit breaker opens
- a DC trapped voltage is left on the open cable
- saturates the transformer magnetizing impedance
- results in erratic voltage waveform
- Low current – fuse does not blow
- oscillation will last for a long period of time until eventual failure of the PT
- PT failure may be immediate or may occur over time after many exposures
- PT ferroresonance may also be called PT saturation

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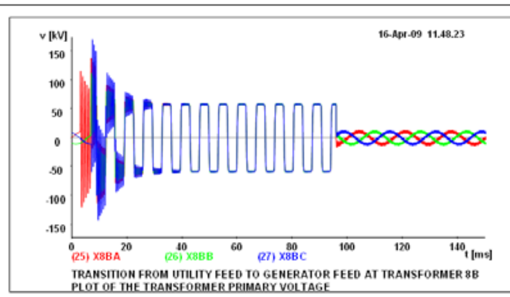
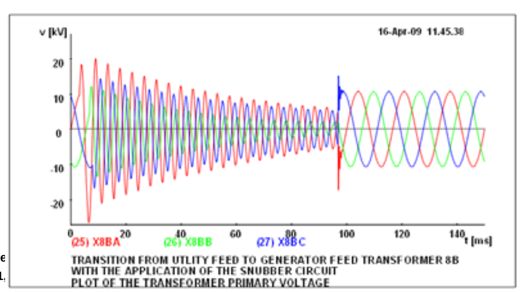
Data Center Illinois – PT Ferro-Resonance
Switched Utility Off – Source Side PTs

- No Snubber
- 170 kV peaks
- 22 kHZ
- 20 HZ Ferro
- Open Delta



- With Snubber
- 2000 HZ
- No Ferro R



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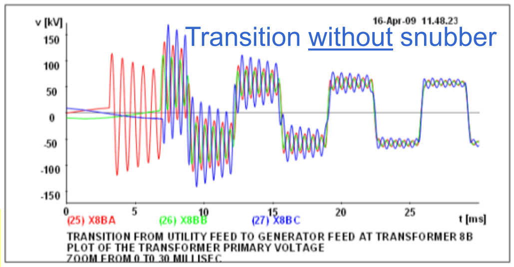
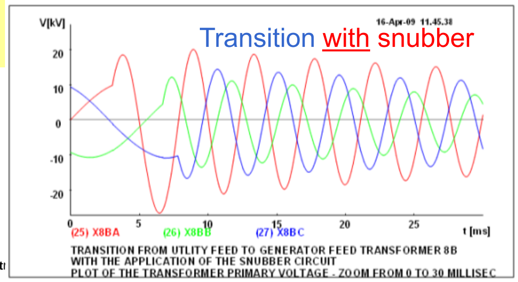
Data Center Illinois – PT Ferro-Resonance

Zoom of Previous Slide

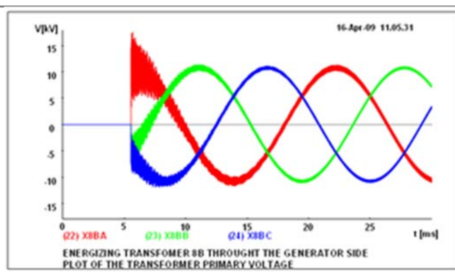
Transition from utility to gen (utility breaker opening)



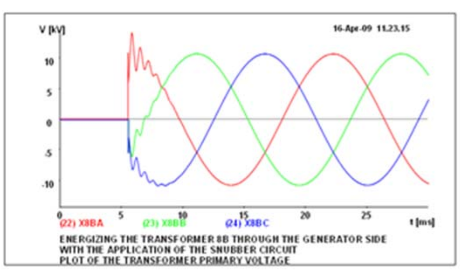


Data Center Illinois – PT Ferro-Resonance

Wye-Wye Load Side PTs / 3 MVA - Closing



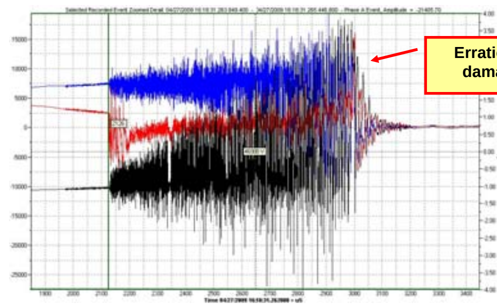
- Close Gen Breaker Without Snubbers



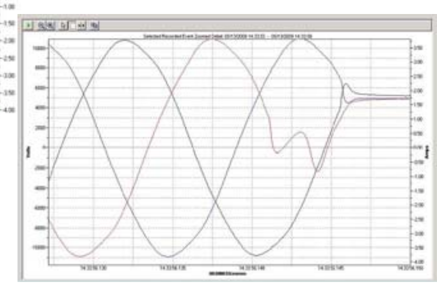
- Close Gen Breaker With Snubbers

Data Center Illinois – PT transient overvoltage

De-Energize without snubber

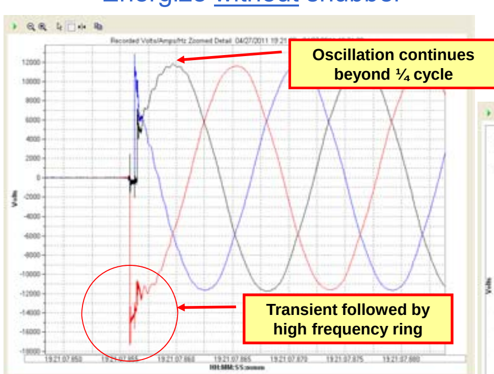


De-energize with snubber

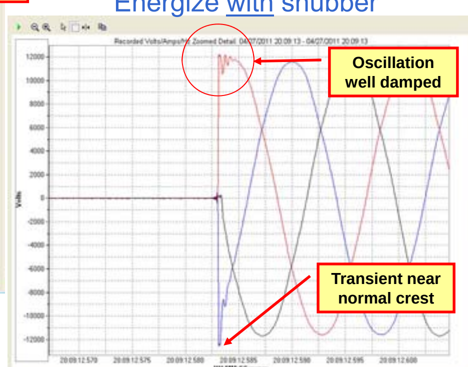


PT transient overvoltage on Energization

Energize without snubber

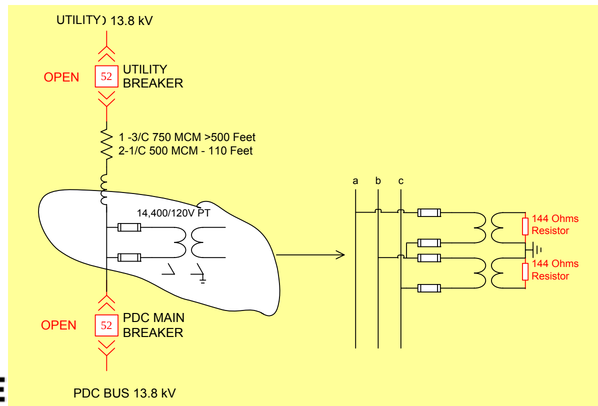


Energize with snubber



Special Condition: PT Ferroresonance – Damping Resistor Commercial Bldg – NY City

- Corrective measures:
  - RC snubber
  - Damping resistor

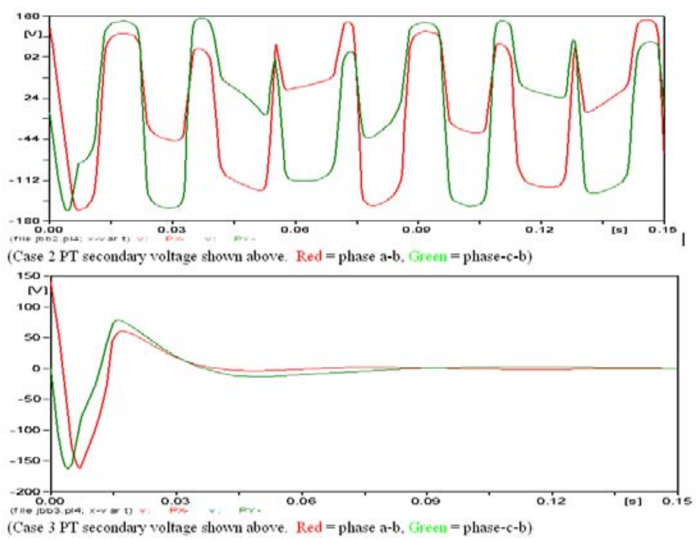


IEEE

PT Ferroresonance – Damping Resistor

De-energize without damping R

De-energize with damping R



(Case 2 PT secondary voltage shown above. Red = phase a-b, Green = phase-c-b)

(Case 3 PT secondary voltage shown above. Red = phase a-b, Green = phase-c-b)

IEEE Central Tennessee Section
May 1, 2012

Concerns for Data Centers

- Data Centers Fall into the Highest Risk Category
- High Power Density
- Close Proximities
- Frequent Switching
- High Efficiency Designs

Concerns for Industry at Large

- VCB retrofit for primary load break switch (LBS)
  - Units subs with LBS and no secondary main
  - Arc flash issues on sec main (no room to install secondary main breaker)
  - Retrofit VCB in LBS box solves AF issue
- VCB for rectifier (or isolation) transformer
  - DC drives for feed water pumps
  - VCB on primary
  - Short run of cable to transformer (often dry type)
- New unit sub with primary VCB
  - Metal enclosed vacuum switchgear
  - 7500KVA transformer for gen boilers to meet EPA requirement
  - 5 feet of bus

Snubber Design and Application

How do you start?

- Results of the transient switching study
  - Resistor and surge capacitor specification
  - The location of the snubber equipment.
  - What are you trying to protect?
- A spec ? or Customer discussions?
  - Fuses, alarm circuits, pilot light indications, horn
- Physical layout of the area
  - Indoors, or outdoors ? What are space limitations?
- Design examples and photos.

Considerations

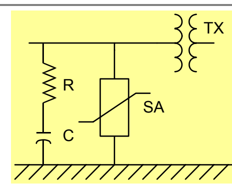
- Where do we locate the snubber?
- Where does the high frequency transient come from?
- What are the clearance requirements for the voltage level? Metal enclosed equipment standards C37.20.
- What configurations are necessary for high frequency transients?

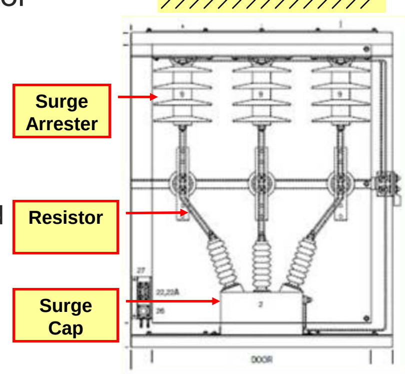
Considerations for Potential Transformers / CPTs Where Switching May be an Issue

- Switching Unloaded PTs on the line side of the Main Bkr
- Switching PTs with Cables longer than 100 feet
- Switching PTs with Unloaded Power Txmrs
- Open-Delta Connections
- Failure Investigations

Designing the Snubber

- 15kV typical snubber & arrester
  - transformer protection
- non-inductive ceramic resistor
  - 25 ohms to 50 ohms
- surge capacitor
  - Standard capacitor ratings
    0.15 μF to 0.35 μF
  - 3-phase 13.8kV solidly ground
  - 1-phase 13.8kV LRG





15kV snubber for mounting inside transformer (open design)

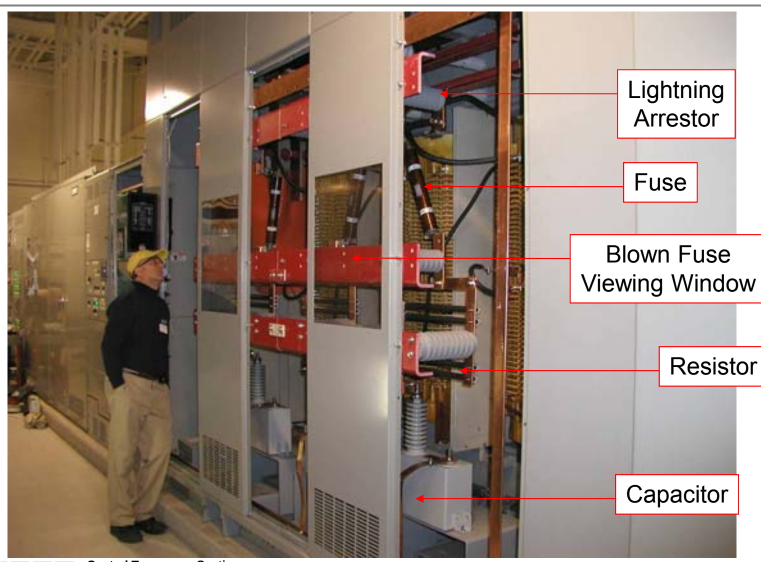
Top hat and switchgear designs

15kV snubber for mounting above transformer (top hat)

15kV snubber in MV switchgear (switchgear design)

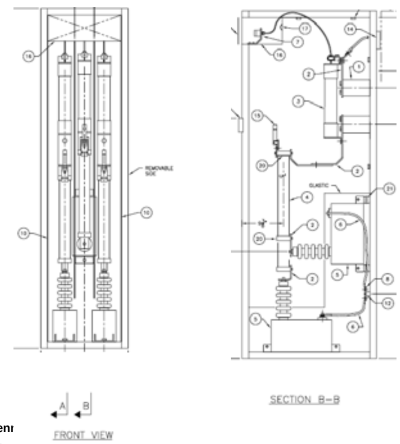
13.8kV snubber in metal enclosed switchgear

Data Center New Jersey - design



Data Center Georgia - compact design

- Compact 15 kV design
- 20” wide x 30” deep x 78” high



Snubber - Compact design

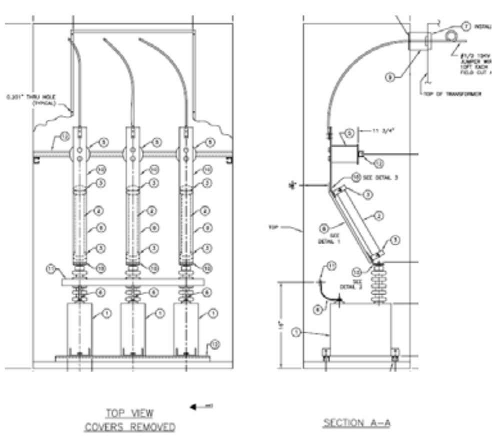
15kV snubber (compact) NEMA1 enclosure

15kV snubber (compact) next to MV switch to transformer

Casino - horizontal mount

12.47kV snubber mounted
horizontally above transformer
78” L x 45” W x 24” H

Snubber - horizontal mount



12.47kV snubber mounted
horizontally above transformer

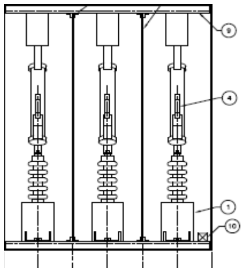
Office Building – top hat

- This 15 kV design was mounted above the MVS. The resistors had not been installed.

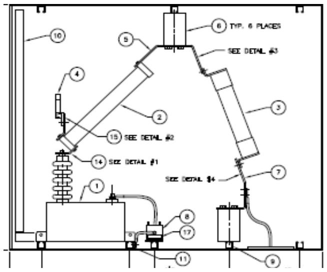
  36”L x 54”D x 45”H.

Snubber - top hat

- Note the fuse and resistor are mounted at angle
- contains the high frequency switching transients.



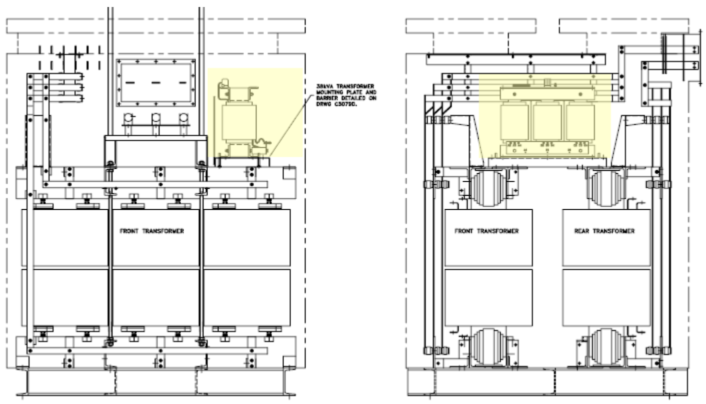
FRONT VIEW



RIGHT SIDE VIEW

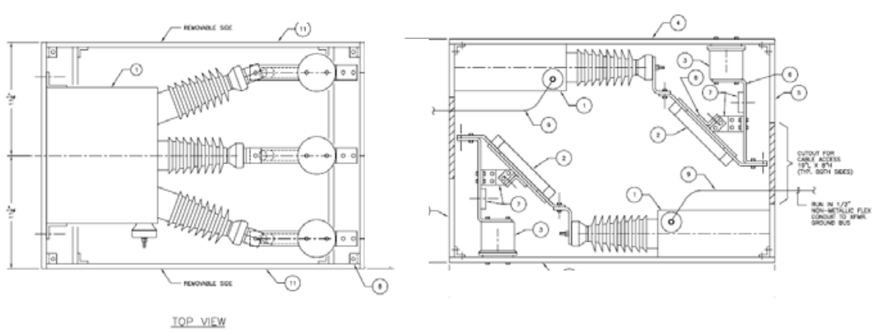
Ferry Propulsion System – 5 kV Snubber

- Install within an existing transformer enclosure



Ferry Propulsion System – 5 kV Snubber

- Top view and side view – 32”L x24”D x 24”H



Custom Designs – grounding considerations

- 13.8 kV solidly grounded system
  - VCB retrofit for load break switch
  - 3-phase surge cap
- 13.8 kV low resistance grounded
  - VCB retrofit for Load break switch
  - 1-phase surge cap
  - 2 x resistors in parallel

- 13.8 kV low resistance grounded
  - new VCB
  - New 13.8/2.4kV 7500 KVA transformer
  - 1-phase surge caps and single resistors

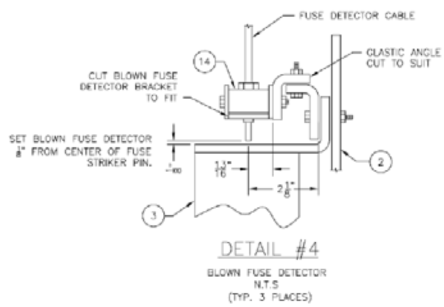
Design Options – Detect Functionality

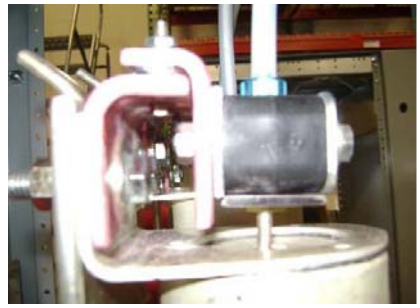
- None (oversized and treated like a lightning arrester)
- Glow tube indicators
  - visible through a window in the switchgear door
  - provide a visual indication of snubber continuity
- Current sensors
  - monitor the continuity of the resistor and fuse
  - alarm on loss of continuity
- fused protection
  - Mandated by some industries
  - alarm signal can be sent to the plant DCS or SCADA system
  - alert the operating personnel that these snubber components have failed

Glow Tube

Current Sensor

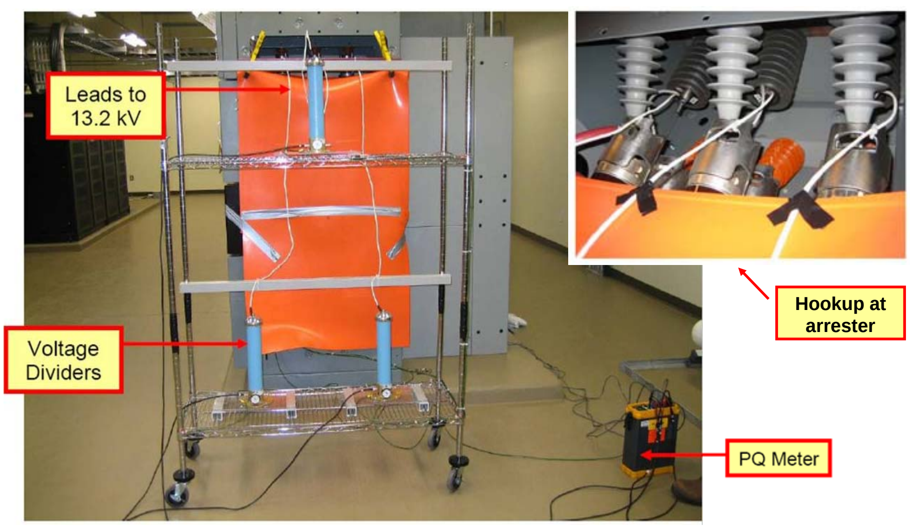
Design Options - Fuse Blown Detection





- The fuse striker pin operates a mechanical linkage and operates a micro switch when the fuse blows.

Snubber Performance Measurements



Test Procedure

- Test Procedure required by contractor
- Prepared 2 weeks in advance of testing
- Develop instructions for site personnel
- Included safety briefing each day
- Site specifics supplied by the contractor
  - LO/TO instructions
  - Breaker operations
- All meter connections made de-energized & LO/TO
- No one in transformer room during tests
- Signature of "Responsible Engineer" before test
- See detailed test procedure form

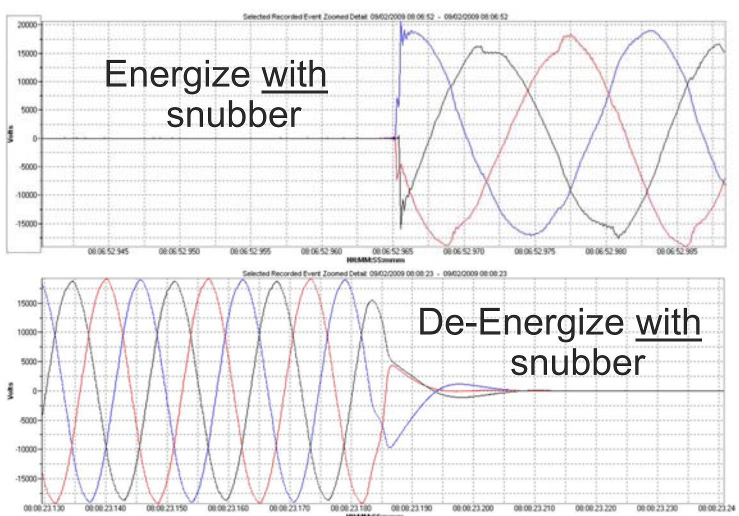
Test Equipment

- Test equipment included voltage dividers and a transient recording device
- Voltage Dividers
  - Capacitive and resistive elements
  - 10MHz frequency response
  - SF6 insulated
- Three-Phase Power Quality Recorder
  - transient voltage waveshape sampling
  - 8000 Vpeak full scale, 200 nsec sample resolution
  - 5 Mhz sampling

Voltage Divider Connections

- Highly stranded No. 8, 15 kV insulated hookup wire requested (10KV DC supplied)
- Insulated wire was a precaution – could have used bare conductor
- maintained 8inch minimum separation for 15kV between phases and ground
- Routed wires with gradual curve – no 90 degree bends
- Connection at surge arrester at bus to transformer primary windings

Measurements – Energize & De-energize

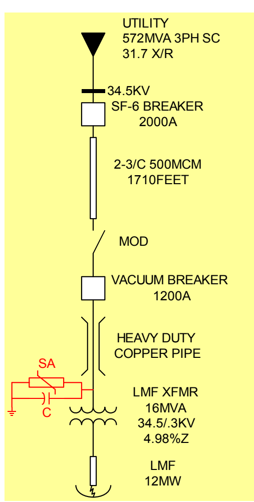


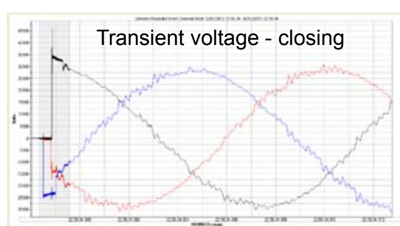
Special Measurements – Electric Arc Furnace

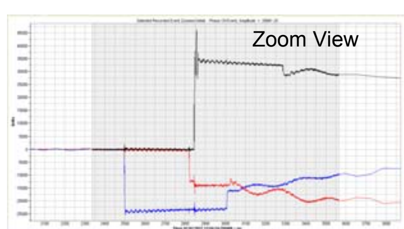
Voltage Dividers Installed
at Primary Bushings of Transformer

PQ Meter and Test Leads

EAF Measurements – Energize

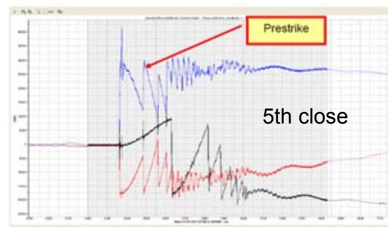






EAF Measurements – Prestrike on closing

- 5 open/close operations in less than 4.5 min. !!!



Conclusions

- This is a System Problem
  - Transformer, Cable, Switching Device, Proximity
  - Statistical Event , Possible Undetected Failures
- Data Centers = Highest Risk Category
  - High Power Density
  - Close Proximities
  - Frequent Switching
- Other industries also at risk
  - oil, paper, chemical, hospitals, propulsion, etc.
- Lives, Property and Uptime are all at risk

Conclusions

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

Conclusions

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

Conclusions

- "Rule of Thumb" - Vacuum breaker, short cable or bus and dry type transformer (aged or low BIL liquid filled)
  - Not all VCB primary switching of transformers require snubbers
  - Transformer failures due to primary VCB switching transients do occur
  - Current chop and re-ignition combine with unique circuit parameters
- RC Snubbers
  - plus arresters mitigate the transient
  - Retrofits require custom design of snubber
  - Field measurements confirm snubber performance