Bushing Monitoring: Motivation, Application and Successes

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  - Safety, financial, reliability
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- Cases:
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  - GE Type U
  - Westinghouse O+
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- Bonus Cases:
  - Expectations?
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Introduction

- The aim of this presentation is to review the motivations for bushing condition monitoring, look at some of the features which appear in *good* monitoring systems, and discuss practicalities based on some real cases.
- We have successful cases from many sources, many of which have been presented at the International Conference of Doble Clients; full papers available on request.

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Motivations: safety, financial, reliability

- All assets will fail – it's a matter of 'when' not 'if':
  - We can prevent failures if we have adequate warning of deterioration
- To quote singer/song-writer Paul Simon:

  'Everything put together, sooner or later, falls apart'
- Bushing failure usually leads to transformer failure[1,2]:
  - The results may be catastrophic – safety impacts severe
  - Business interruption costs and environmental clean-up costs may greatly exceed asset replacement costs
- Appropriate monitoring may prevent failures:
  - Detect and diagnose failure modes and have a planned response!

1: "Evaluation and Identification of Typical Defects and Failure Modes in 110-750 Kv Bushings", V. Sokolov & V. Vanin, 64th International Conference of Doble Clients, Boston, USA, 1997
2: CIGRE Technical Brochure 755 "Transformer Bushing Reliability" 2019

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Motivation: Industry Experience

- A technical paper by Sokolov and Vanin at the 1997 International Conference of Doble Clients[1] noted results of a survey:
  - *…irrespective of their geographical location or differences in design, high-voltage bushings remain one of the weakest components and may have been the cause of up to 30% of all of the large transformer failures. Because of preventive maintenance, the number of defective bushings removed from service annually is ten times the number of failed bushings.*
- CIGRE Working Group A2.43:
  - *A failure of any of the bushings results in a transformer failure as well. According to various researches, bushings cause 5 to 50 % of the total number of transformer failures, often followed by transformer damages, fires, huge collateral damage and ecological incidents.*

1: "Evaluation and Identification of Typical Defects and Failure Modes in 110-750 Kv Bushings", V. Sokolov & V. Vanin, 64th International Conference of Doble Clients, Boston, USA, 1997
2: CIGRE Technical Brochure 755 "Transformer Bushing Reliability" 2019

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Motivation: some failure modes

- As the insulation deteriorates, the bushing will eventually fail
  - Electrical stress will accelerate ‘natural’ deterioration
- What can cause deterioration? Some modes include:
  - Moisture/contamination ingress through seals, filler caps or flanges
  - Damaged outer covers (porcelain or other material) allowing ingress of moisture/contamination
  - Damage during storage, from animals, vandalism etc
  - Manufacturing defects which provide uneven electrical stress
  - Overheating

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Motivation: Bushings and Failure Types

- Bushings have two distinct failure mode timescales:
  - 'Graceful': exemplified by GE Type U bushings where deterioration may take place over several weeks to months[1]
  - 'Rapid Onset': found in Trench COT(A) bushings where deterioration may become evident over a few hours[2]

1: "Chronicling the Degradation of a 345kV GE Type U Bushing", R. Wancour *et al*, 76th International Conference of Doble Clients, Boston, USA, 2009
2: "Condition Monitoring in the Real World", K. Wyper *et al*, 80th International Conference of Doble Clients, Boston, USA, 2013

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Motivation: Identify Failure Modes to Prevent Failure

- A bushing allows a current to pass through a barrier
  - Usually, a conductor at elevated voltages and a grounded barrier
- If the insulation deteriorates, the bushing may be compromised and then fail
  - And transformers, breakers etc may fail as a consequence
- Check 2019 Doble Client Conference paper:
  - "Bushing Monitoring – What We Can Measure And Implications For Deterioration Detection"
  - Paper discusses thermography/IR, PD, current/phase, power factor and capacitance etc
- As we're interested in the deterioration of insulation, measuring parameters which relate to the deterioration makes sense.
  - We can measure currents/voltages and then derive other parameters

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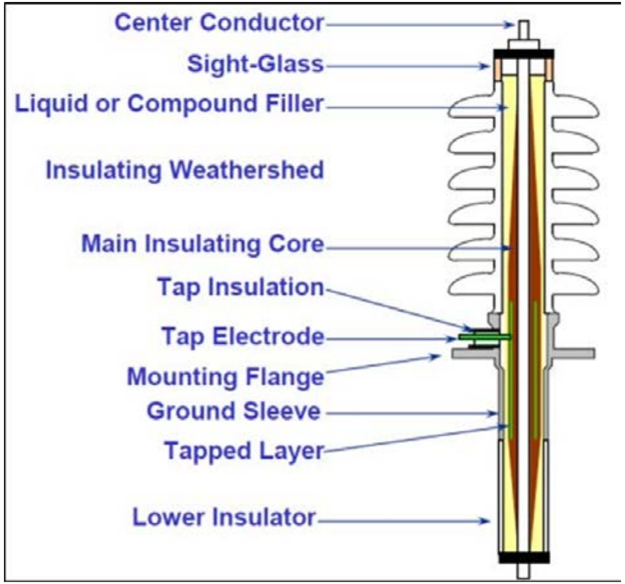
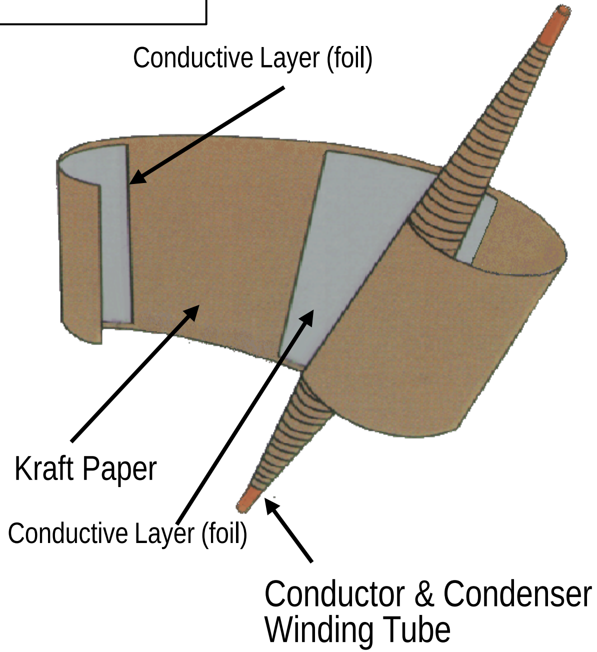
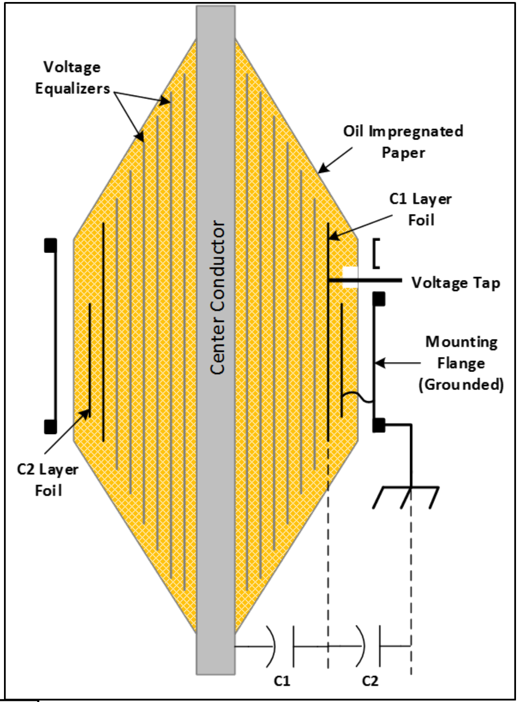
Motivation: Inside a bushing… much can go wrong

Bushings are complex devices!







The conductive layers even out the voltage stress

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Monitoring: Parameters

- There are several parameters which may be monitored to indicate deterioration:
  - Leakage current: which allows derivation of power factor, capacitance and harmonic content
  - Temperature
  - EMI/RFI: allows detection and diagnostics of partial discharge (PD): this may be a complex analysis as PD signals propagate extensively
- Power Factor, Capacitance can be directly compared with:
  - Nameplate values
  - Offline test values

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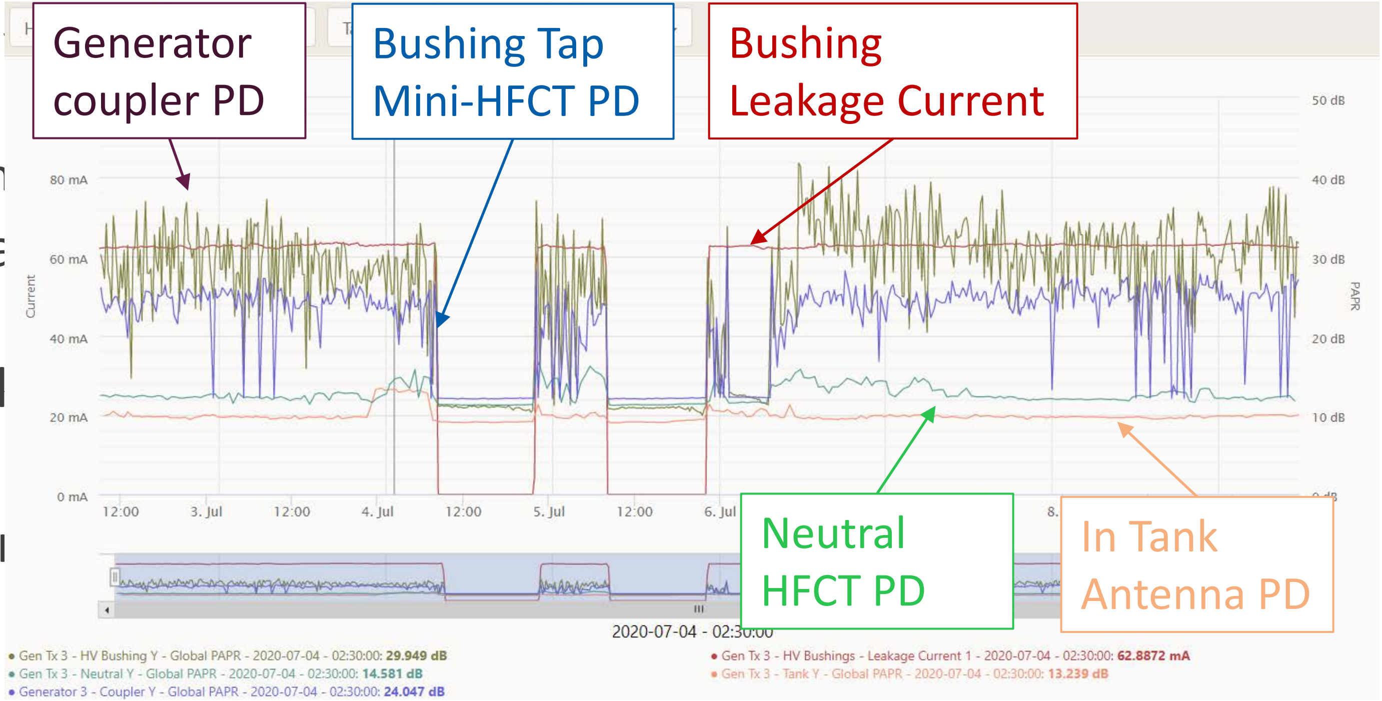
Bushing PD

- Measuring PD via the bushing test tap is useful – if you can make sense of the data:
  - Statistical anal
  - Time resolved
  - Detailed PD an
- PD signals propa source
- Who will be lool
- Who will set ale
- Example at a gei phase bus, noth



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Leakage Current

- Bushing insulation is not perfect:
  - There is a capacitive/resistive leakage which flows to ground
  - Each bushing will have its own leakage current depending on:
    - System voltage driving the current
    - Bushing characteristics
- Variation in the leakage current may thus indicate:
  - Variation in system voltage
  - Variation in bushing characteristics
- We need to identify the root cause of variation!
  - Which we can do – and thus save bushings from failure

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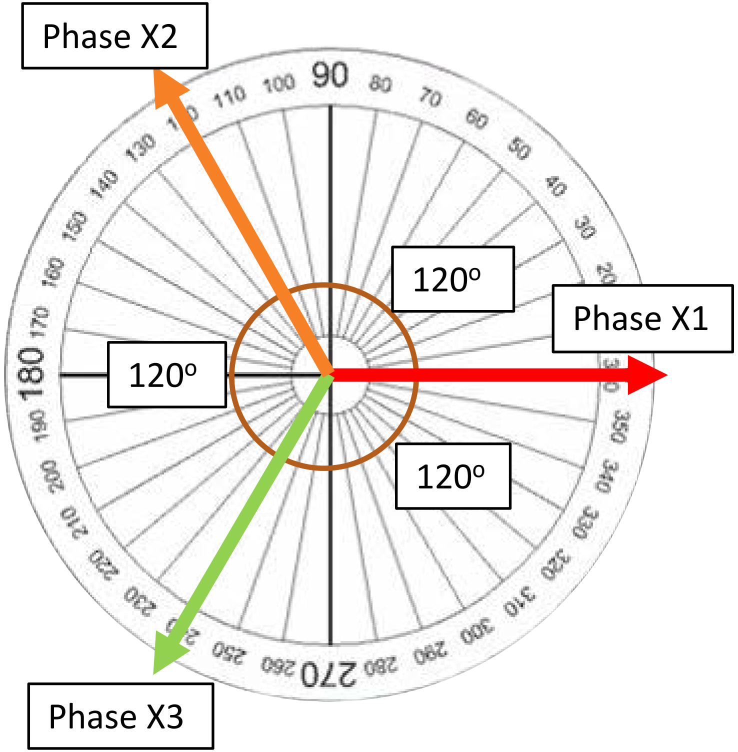
Ideal 3 phase system – balanced voltages, currents etc



- **Relative phase angles** all equal
  - X1->X2 = 120º
  - X2->X3 = 120º
  - X3->X1 = 120º
- **Magnitudes all equal**
  - |X1| = |X2| = |X3|
- Applies to system voltages, currents including leakage currents

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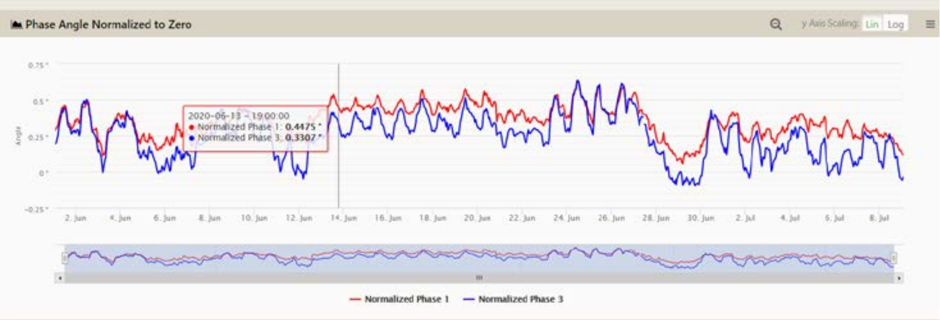
In a perfect world: leakage currents are identical

The world is not perfect… system voltage magnitude and phase variations are usually present.

This chart shows leakage current magnitude for each of three bushings in a set: the magnitudes vary over time, and also vary relative to each other

This chart shows relative phase of currents for two of three bushings in a set: each should be 120°. We have normalized to 0° so we can easily measure variation from 'ideal'.



The three relative phase angles sum to zero – all information is available in any 2 values. A chart with three angles is also to be made available.

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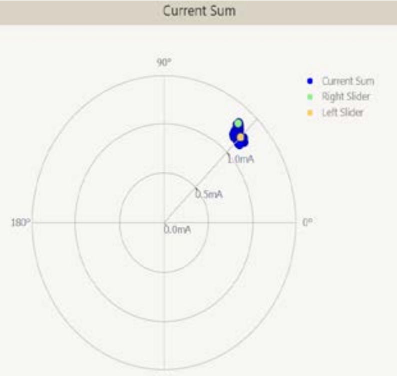
In a perfect world – 3 balanced Phases Sum to Zero

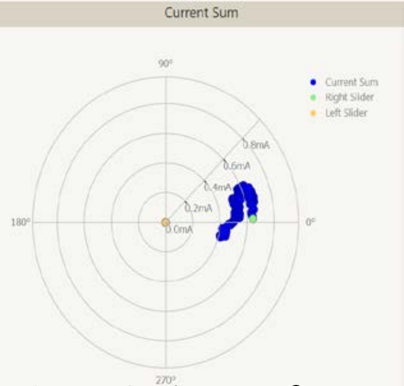
- Sum Current can be a detector, but system variations mean **too many false positives**
- Doble moved on from this ~20 years ago: look at individual currents

The sum current chart is available in Doble PRIME for ‘old time sake’…



Case A: is this bad?

Case B: and this?



Case B: Getting Better?

Case B: Bushing Confused?

The sum should be zero: the cases here are false positives!

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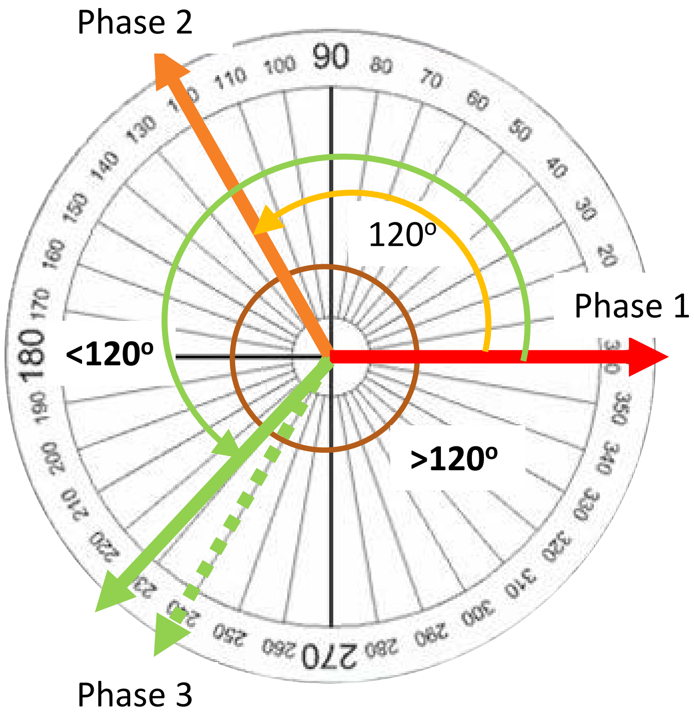
How much phase change would a ‘bad bushing’ give?



- Relative phase angles **NOT** all equal
  - X1->X2 = 120º
  - **X2->X3 = <120º**
  - **X3->X1 = >120º**
- A variation of 0.2º or less would indicate a bad power factor

How do we find this against the ‘noisy’ system voltage variation?
A simple way is to use averaging.

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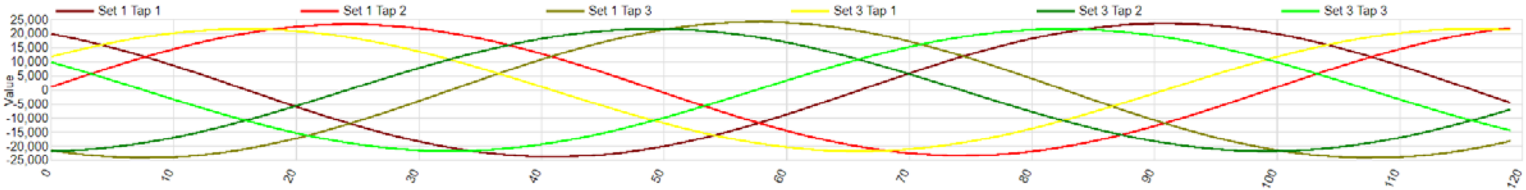
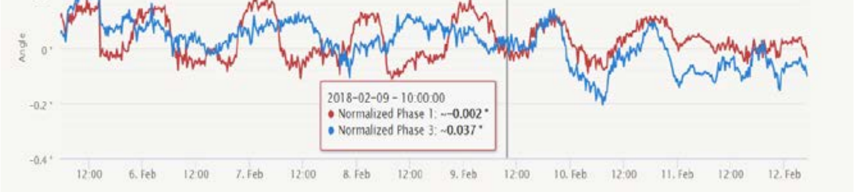
Raw and derived data



Capture raw sine-waves for every current/voltage reading - these are then used to calculate:

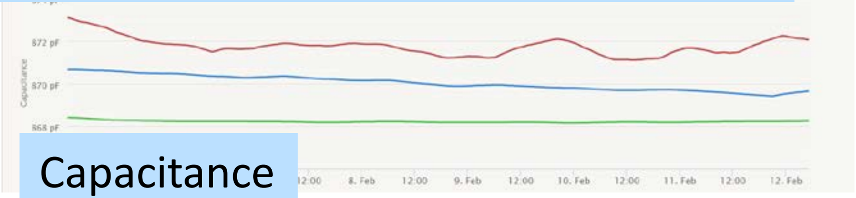
Leakage current rms: 7 days shown here

Phase angle: 7 days shown here



For each bushing we can then calculate averaged values: daily, weekly, monthly

Power factor



Capacitance

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Power Factor: Offline, Online Relative and Online True

- Three measurements – why are they not all the same?
  - In offline tests we supply the voltage and can control it very precisely
  - In online measurements we have to find a way to measure the voltage
  - The instrument transformer or voltage transformer is ALSO under test
- We measure both relative power factor (**RPF**) and true power factor (**TPF**) **simultaneously**
- **We can identify either bad bushings or bad VTs**

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What alerts do we need?

- For each parameter we expect 3 levels of alert:
  - INFO, WARNING, ACTION
- That means 3 alerts for each parameter:
  - RMS current
  - Phase angle
  - Daily, weekly, monthly Capacitance
  - Daily, weekly, monthly Power factor
  - Total Harmonic Distortion (calculated with current RMS and Phase)
- Plus an ‘instant’ alert on any parameter should it exceed a specified value – removes any averaging effects which could delay an alert

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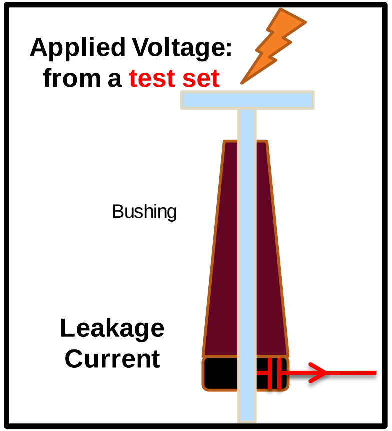
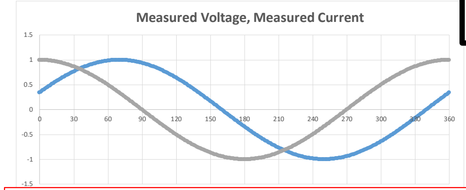
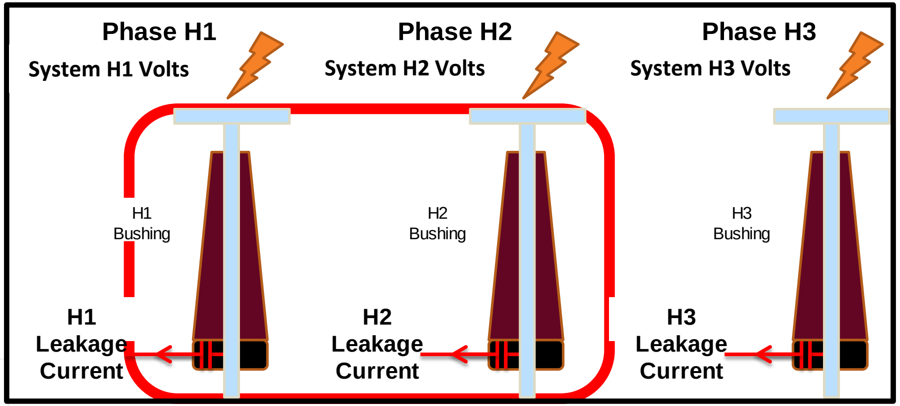
Power Factors: Offline v. Online Relative (RPF) v. Online True (TPF)

Offline test



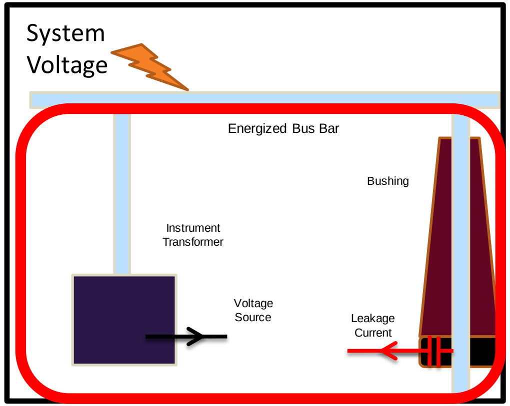


Online monitoring – we do not control the voltage: it becomes a source of variation



We measure both RPF and TPF together so can identify a bad bushing or a bad IT

True Power Factor: Bushing and Instrument Transformer both included



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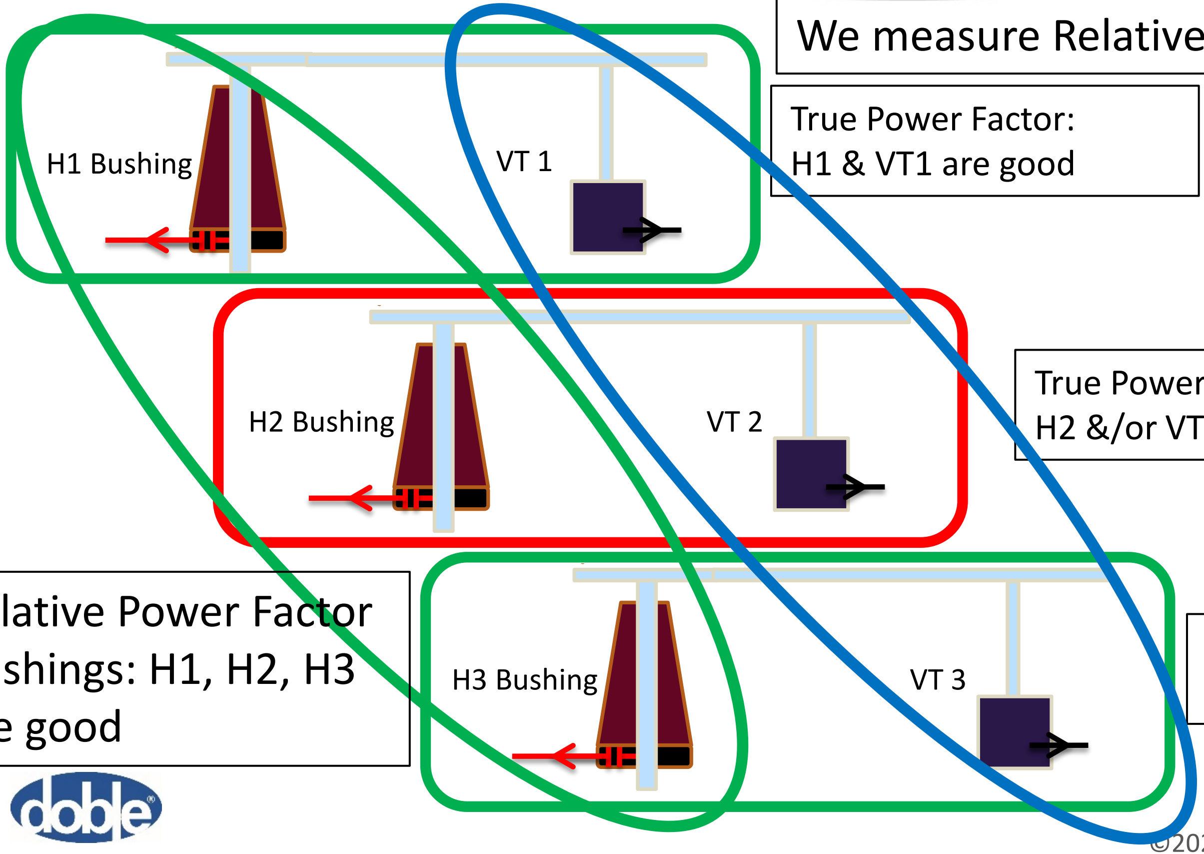
True Power Factor: is it a bad bushing or bad VT?

We measure Relative and True simultaneously



True Power Factor:
H1 & VT1 are good

TPF: Bushing H2 or VT2 bad
RPF: Bushings are good
So: bad VT

True Power Factor:
H2 &/or VT2 is bad

True Power Factor:
H3 & VT3 are good

Relative Power Factor
Bushings: H1, H2, H3 are good

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Cases

- We have had many cases over the years, several of which have been shared at the Doble Client Conference and elsewhere.
- The cases presented here are examples of different bushing designs and failure modes

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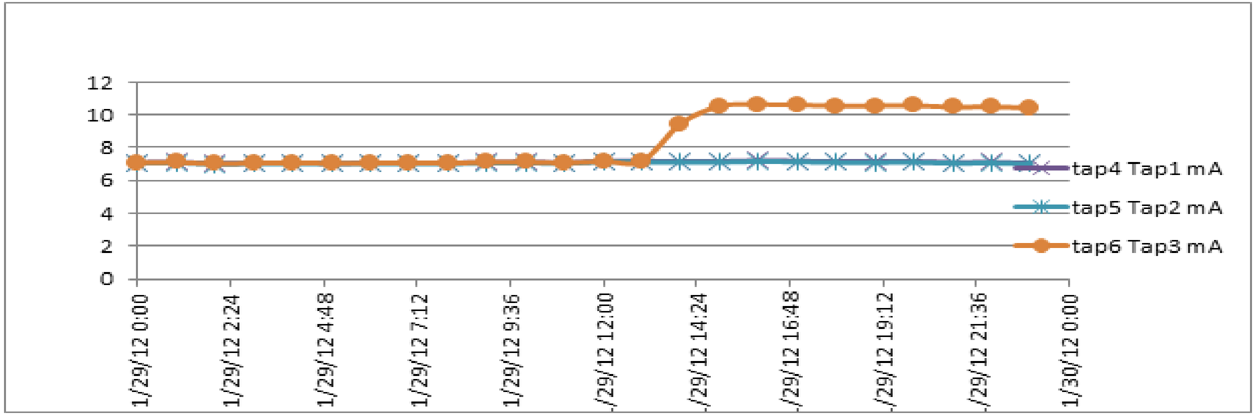
Trench Bushing: learning from the past

Monitoring Trench COT bushings, known to have a catastrophic failure mode, on >65 transmission transformers at up to 345kV[1]. Current rose rapidly for one bushing, generating a top level ACTION alert. **The operators had a written and agreed policy requiring switching out and offline testing after an ACTION alert.**



As a result of applying the policy a likely catastrophic failure was avoided. (Detailed analyses on next slide.)

1: "Condition Monitoring in the Real World", K. Wyper *et al,* 80th International Conference of Doble Clients, Boston, USA, 2013

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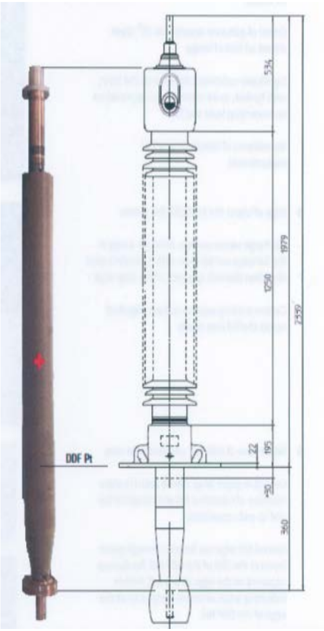
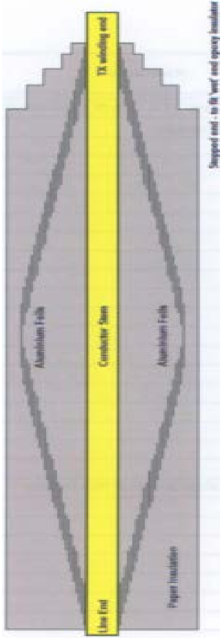
Trench Bushing: close the feedback loop - forensics

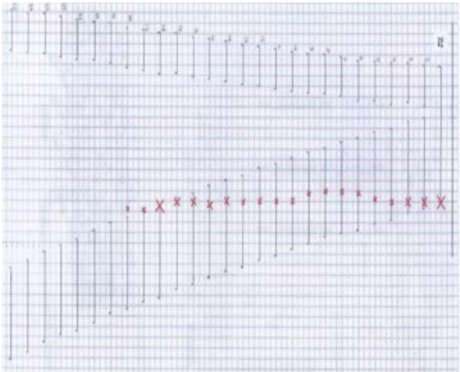
Bushing construction and foil layout.





Burning at a foil edge at a point corresponding to the red x in the construction.

A map of how far through the foils the deterioration had progressed. Offline tests confirmed the incipient failure.



1: "Condition Monitoring in the Real World", K. Wyper *et al,* 80th International Conference of Doble Clients, Boston, USA, 2013

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GE Type U Bushing: Graceful failure

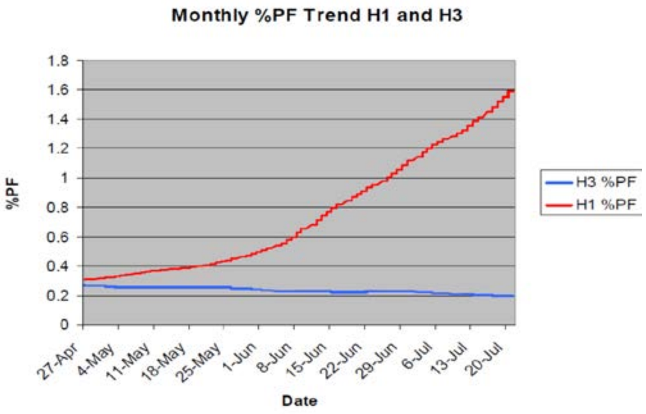
Bushing monitoring was used to identify a deteriorating bushing.

Alert limits and response plans were put in place before the bushings were returned to service after a maintenance outage.

The rise in power factor was detected and failure averted. Forensic details in the paper[1].

March 2008 Off-Line C1 Test Results

ID	Serial	NP %PF	NP Cap	Test kV	mA	Watts	%PF corr	Cap(pF)
H1	1796658	.26	401	10.007	1.488	0.0410	0.28	394.74
H2	05-105312	.27	492	10.007	1.869	0.0500	0.27	495.89
H3	1797916	.26	406	10.007	1.502	0.0430	0.29	398.36
X1	96-71129	.26	377	10.011	1.421	0.0380	0.27	377.03
X2	3030410394	.24	385	10.008	1.420	0.0390	0.26	376.74
X3	96-71113	.26	381	10.007	1.431	0.0390	0.27	379.57
N	04-218906	.68	464	10.008	1.739	0.1090	0.60	461.26



1: "Chronicling the Degradation of a 345kV GE Type U Bushing", R. Wancour *et al*, 76th International Conference of Doble Clients, Boston, USA, 2009

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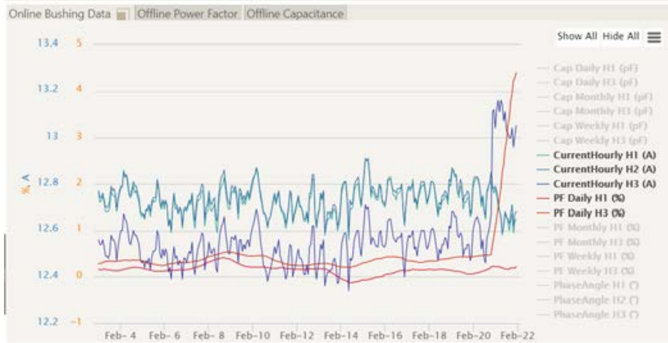
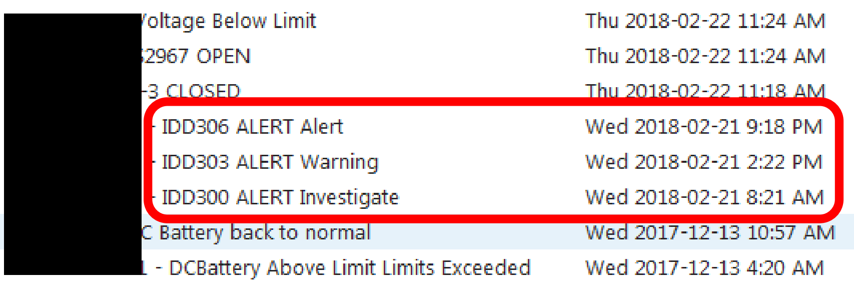
Westinghouse O+ Bushing

A Westinghouse O+ Bushing generated alerts showing rapid deterioration. The ACTION alert followed ~13 hours after the INFO alert.





Power factor for one bushing rose sharply, and its leakage current rose by ~0.6mA, or about 5%. Offline tests were performed confirming the deterioration: a 9x rise in power factor.

Test No	Bushing Nameplate					Test Mode	TEST kV	Capacitance C (pF)	POWER FACTOR %		
	Dsg	SERIAL #	CAT. #	PF	ap. (pF)				Measured	@ 20°C	Corr Factor
11	H1	K728058		0.26	426.00	UST-R	10.01	416.76	0.29	0.29	1.000
12	H2	K7282187		0.25	425.30	UST-R	10.00	416.24	0.28	0.28	1.000
13	H3	K7296687		0.30	402.80	UST-R	10.01	420.10	2.41	2.41	1.000

An incipient failure was thus avoided.

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Successes: Common Theme

- What we see in successful condition monitoring cases includes:
  - Setting expectations: for the monitor, the measurement to be made and the organization
  - For each bushing in each individual application, identify what to expect for leakage current magnitude, for power factor and for capacitance, for PD?
  - Identify limits for each level of alert
  - Have a planned response for each alert on each bushing
  - Ensure the plan is agreed and ‘written up’ – names, timescales, actions
  - When an alert comes in: FOLLOW THE PLAN!

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In Conclusion

Bushing Monitoring provides benefits:

- Bushing ‘saves’
- Transformer ‘saves’

Needs some understanding of what the numbers mean:

- Failure modes likely to be found in a bushing
- Symptoms of failure modes
- Data for detection of anomaly (not all anomalies are bad)
- Analyses to alert: who, why, what to do, by when?

Need the organization to embed monitoring in daily activities

What is common in successful cases is a response plan agreed by stakeholders and decisive action!

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Case Study: Setting Expectations: 2012 install, 2014 test results

Bushing Test (C1)

ID	Serial #	Test kV	mA	Watts	Corr Fctr	PF*TCF [%]	NP %PF	Cap (pF)	NP Cap	FRANK™	Manual
H0	[redacted]	10	1.394	0.033	0.856	0.206	0.23	369.71	369	Good	
H1		10	2.05	0.05	0.856	0.206	0.25	543.77	546	Good	
H2		10	2.101	0.056	0.856	0.231	0.28	557.44	561	Good	
H3		10	2.046	0.05	0.856	0.206	0.25	542.8	546	Good	

$H2_{C1}/H1_{C1} * 100 = 561 / 546 * 100 = 102.75\%$

Expect H2 current to be ~3% higher than H1 or H3

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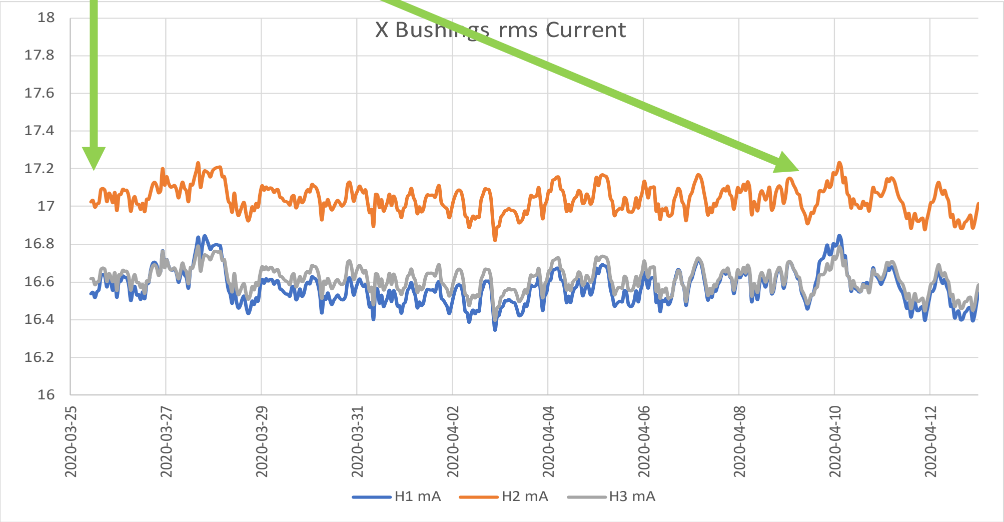
Checking Expectations: Measured Current ratio

Date range: March 25th to April 12th 2020

Checking ratio at two points

DATE/TIME	H1 mA	H2 mA	H3 mA	H2/H1 %
3/25/2020 10:00	16.535	17.024	16.618	102.96
4/9/2020 10:00	16.454	16.908	16.484	102.76



Ratio in line with expectations of about 3%…

… which is good!

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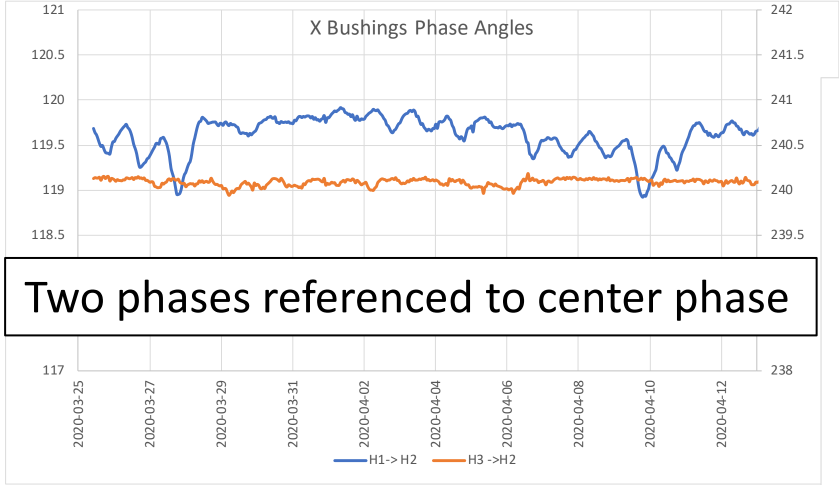
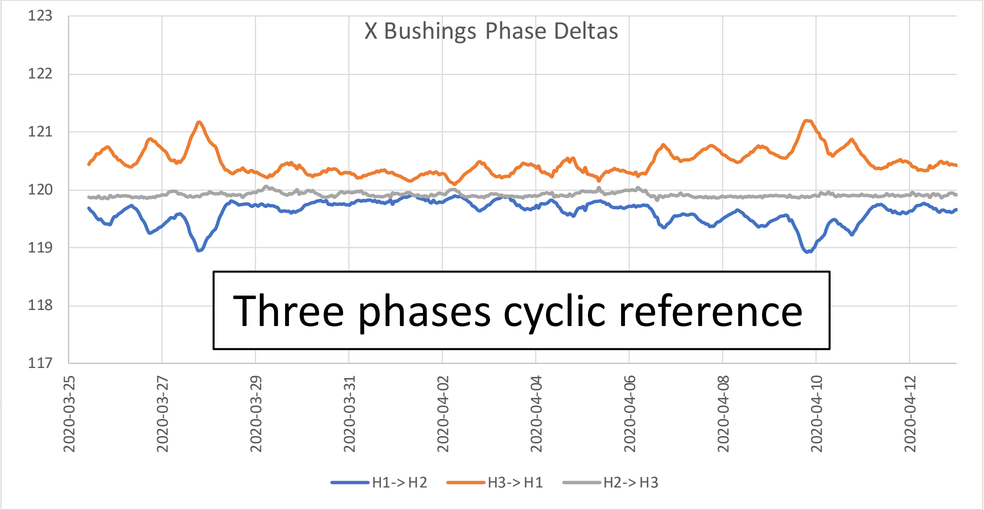
Same dates: Variation in Relative Phase: 2 or 3 angles?

- Three relative phase angles must sum to 360º
- All the 'information' is in two angles





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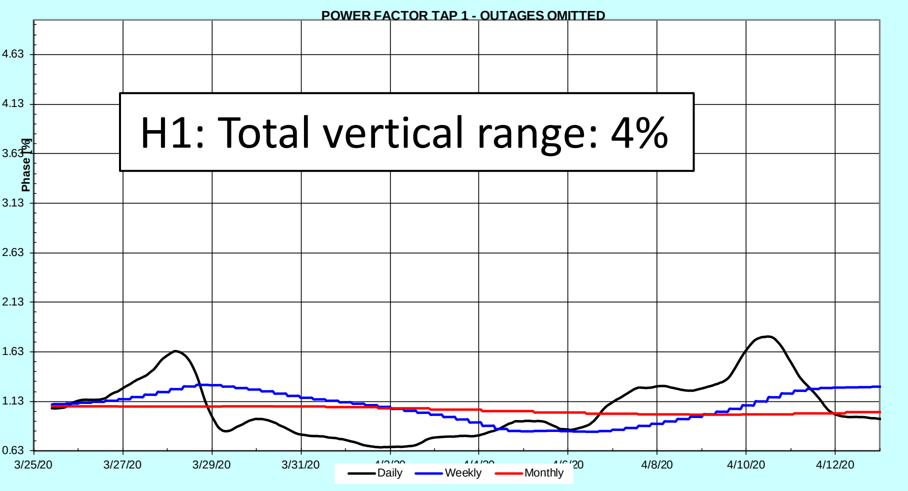
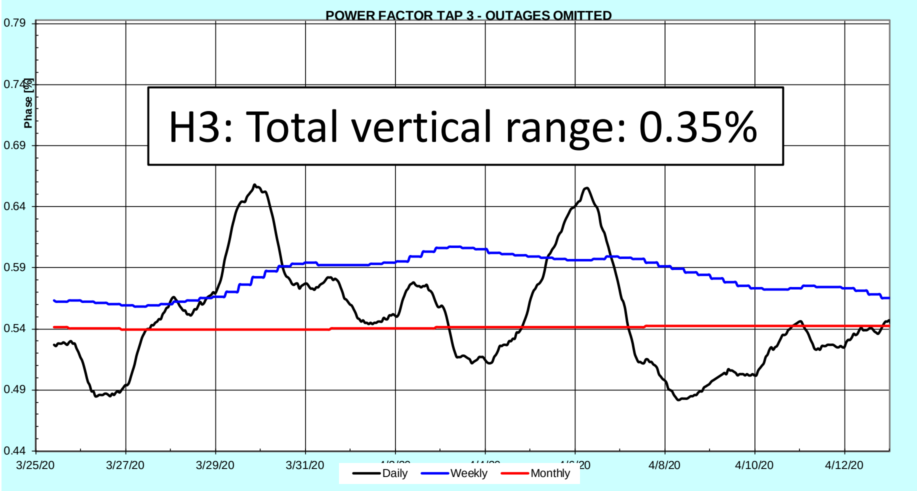
3/25 – 4/12 Daily, Weekly, Monthly Power Factor





No cause for alarm… again, note longer time periods smooth the system variations

Timescale for typical failure mode?

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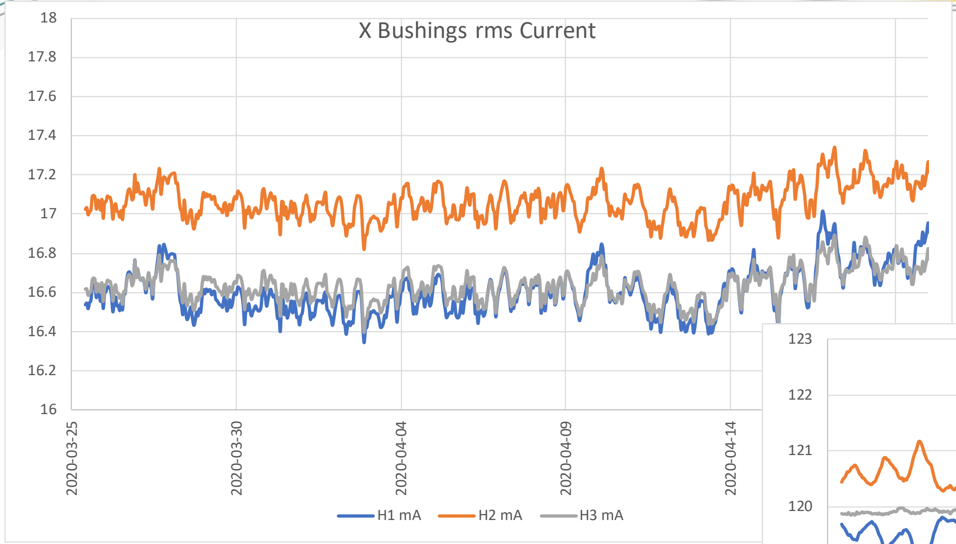
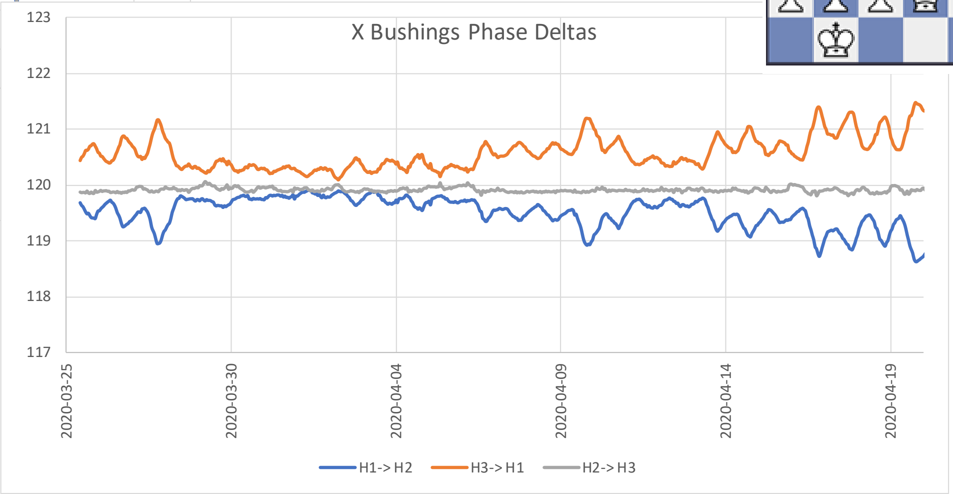
Now Extending Range by a week to April 19th





Anything interesting?
Actionable?

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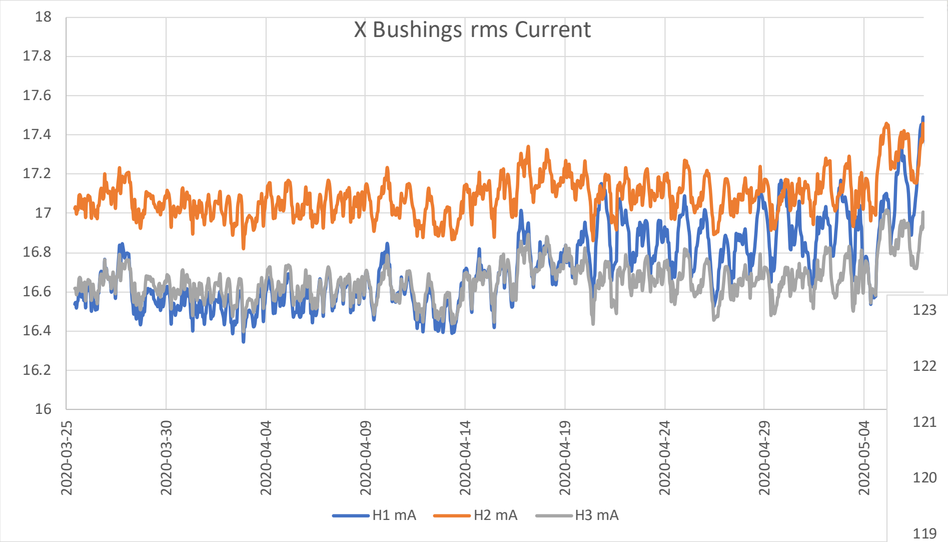
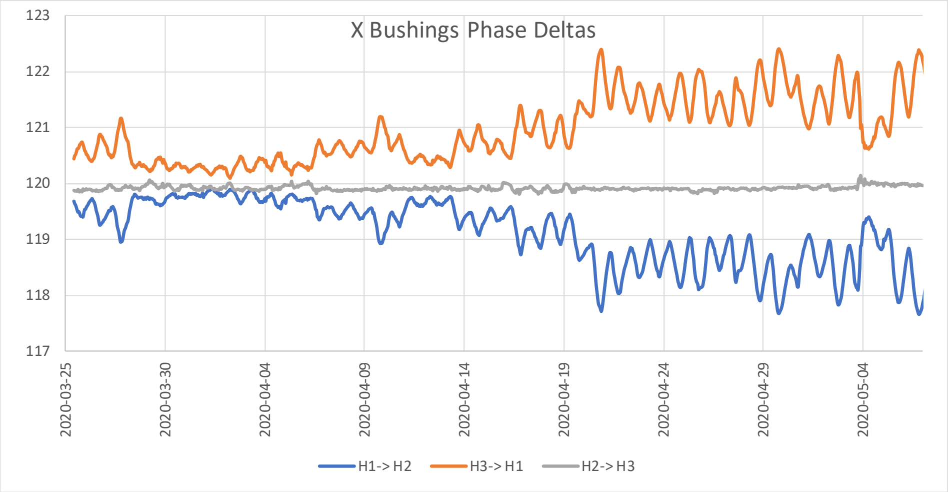
Now Extending Range to May 7th 2020





Anything interesting?

Actionable?

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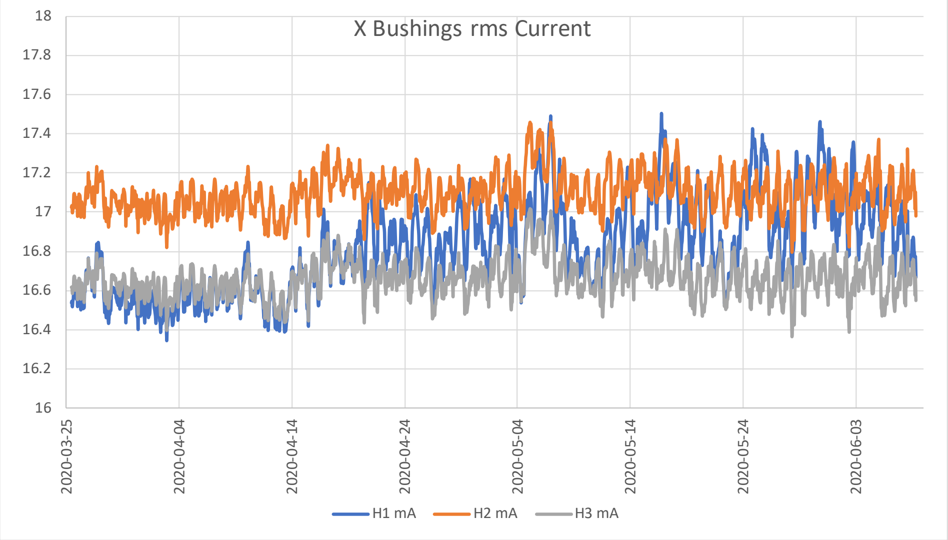
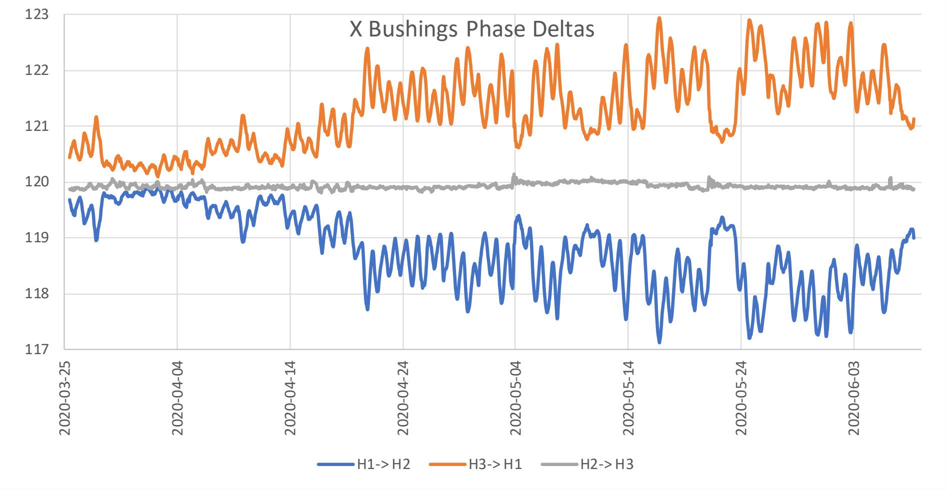
Now Extending Range to June 6th 2020





Stabilized?

Actionable?

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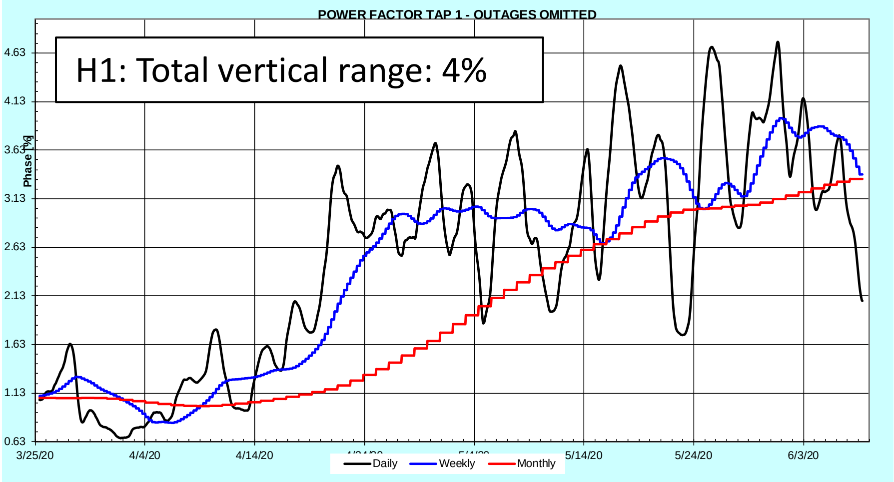
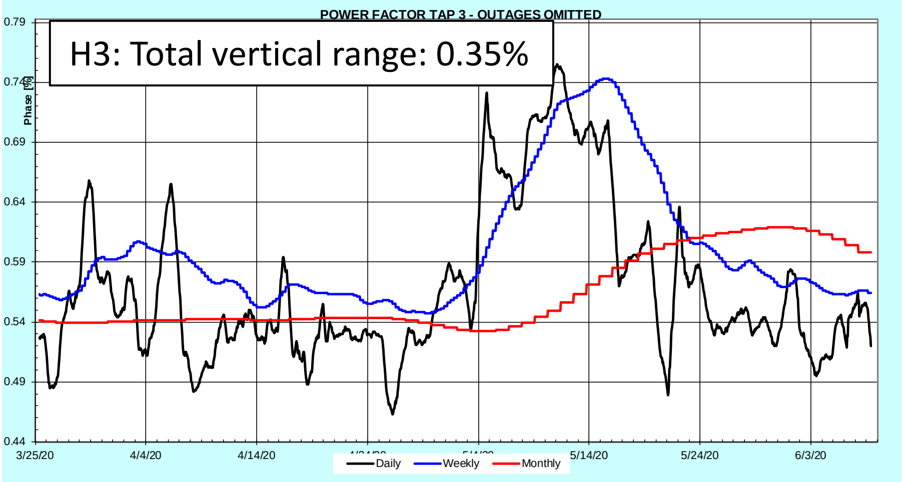
3/25 – 6/8 Daily, Weekly, Monthly pF & PF





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Offline Test Results: June 2020

- “Bad” bushing: notice anything interesting?

Bushing Test (C1)

ID	Serial #	Test kV	mA	Watts	Corr Fctr	PF*TCF [%]	NP %PF	Cap (pF)	NP Cap	FRANK™
H0	11F0215-152 AXT	10.000	1.394	0.029	1.035	0.220	0.23	369.903	369	Good
H1	11F0261-118 ALR	9.999	2.061	0.051	1.035	0.248	0.25	546.620	546	Good
H2	11F0261-119 ALR	9.999	2.102	0.057	1.035	0.279	0.28	557.618	561	Good
H3	11F0261-120	10.000	2.064	0.444	1.035	2.134	0.25	547.247	546	Bad

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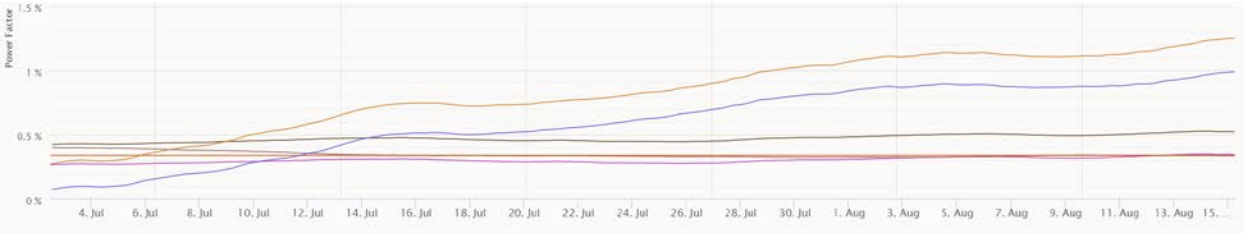
And what next? 13kV Tertiary Bushing

Over several weeks one of the three bushings shows graceful deterioration

Deterioration picked up here using both ‘relative’ and ‘true’ power factor measurements



It’s the bushing! That is the only thing common to both measurements

Plan an outage for offline tests and confirmation

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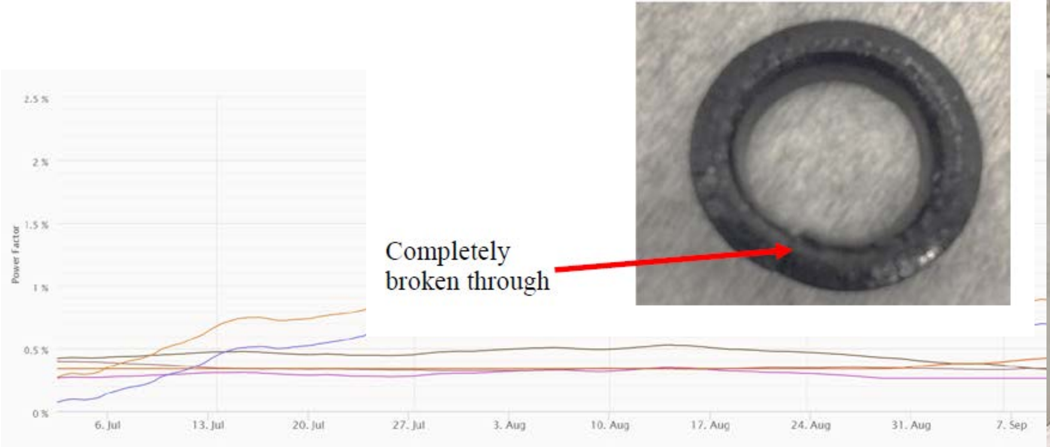
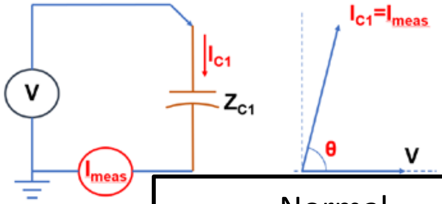
So what? So then it started to get better…

What scenarios do we have for 'improving' power factor???

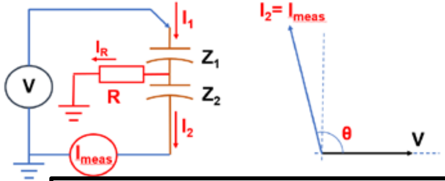
They usually involve contamination of the test object[1,2]

Can we find a scenario here?





Normal Measurement



Anomalous Measurement

If contamination gets into the oil, that w
deteriorating power factor

If that contamination provides an alternate path to ground it can reduce the power factor – seemingly improving it

Cracked gasket? Let's posit that and check offline

1. "Negative Power Factor of Doble Insulation Test Specimens (An Analysis)", D. Kopaczynski, S.J. Manifase, 55th International Conference of Doble Clients, Boston, USA, 1987
2. "Review of Negative Power Factor Test Results And Case Study Analysis", L. Pong, 70th International Conference of Doble Clients, Boston, USA, 2002

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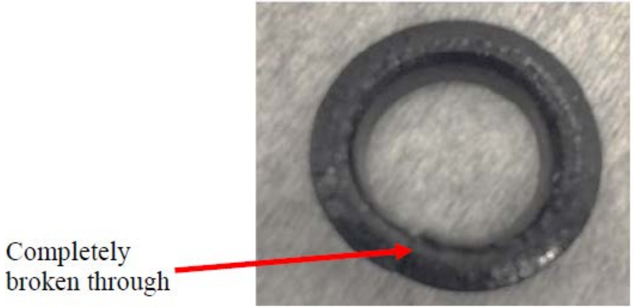
Discussion

- The 'improving' power factor was an example of a rare occurrence
  - Not well known, even among industry specialists
  - Cracked gasket? Moisture degrades the oil, then builds up an alternate ground path
  - Of all the scenarios, this was the simplest, and reflected the bushing structure

- Outage planned and taken:
  - Online monitoring results confirmed
  - Cracked gasket theory confirmed
  - All three bushings replaced



- Case discussed at 90th International Conference of Doble Clients, 2022:
  - "Online Monitoring Detection of Bushing Condition Change – Case Studies"
  - Thanks to Phil Prout of National Grid

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