Bushing Power Factor Testing: In-Depth

Author Biography

Brandon Dupuis received a B.S. Electrical Engineering from the University of Maine. He joined OMICRON electronics Corp, in 2013, where he presently holds the position of Regional Application Specialist for transformer testing. Brandon's focus is currently on standard and advanced electrical diagnostics for power transformers and circuit breakers. Presently, Brandon is a well-known OMICRON instructor teaching electrical transformer diagnostic testing theory, application, and test result analysis, which includes both presentations and hands-on training. Brandon is an active member of the IEEE/PES Transformers Committee.

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2019 OMICRON Academy Transformer Trainings

January 30th and 31st – Houston, TX
https://www.omicronenergy.com/en/events/training/detail/electrical-diagnostic-testing-of-power-transformers/471/

April 16th and 17th – Toronto, ON
https://www.omicronenergy.com/en/events/training/detail/electrical-diagnostic-testing-of-power-transformers/472/

August 28th and 29th – Houston, TX
https://www.omicronenergy.com/en/events/training/detail/electrical-diagnostic-testing-of-power-transformers/171/

Bushing Power Factor Testing: In-Depth

1) An Introduction to Bushing Power Factor Testing

2) An Introduction to Performing Power Factor Sweep Tests on Bushings

3) Bushing Power Factor Test Analysis

4) Bushing C1 Power Factor Test Examples

5) Using the Power Factor Sweep Tests to Identify Invalid Bushing Measurements

Bushing Power Factor Testing: In-Depth

6) Bushing C2 Power Factor Test Examples

7) Energized Collar (Hot Collar) Test Examples

8) A Bushing’s Influence on the Overall Power Factor Test

9) Troubleshooting a Questionable Bushing Power Factor Test

10) Testing a Spare Bushing (Outside of a Transformer)

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Bushing Power Factor Testing: In-Depth

Bushing Power Factor Tests

- **Performing routine Power Factor measurements on bushings is critical for extending the life of a power transformer**
- Bushing insulation problems can be detected by performing periodic electrical tests,
    - C1 Power Factor Test – A “bushing tap” is required
    - C2 Power Factor Test – A “bushing tap” is required
    - Energized/Hot Collar Test – A “bushing tap” is NOT required

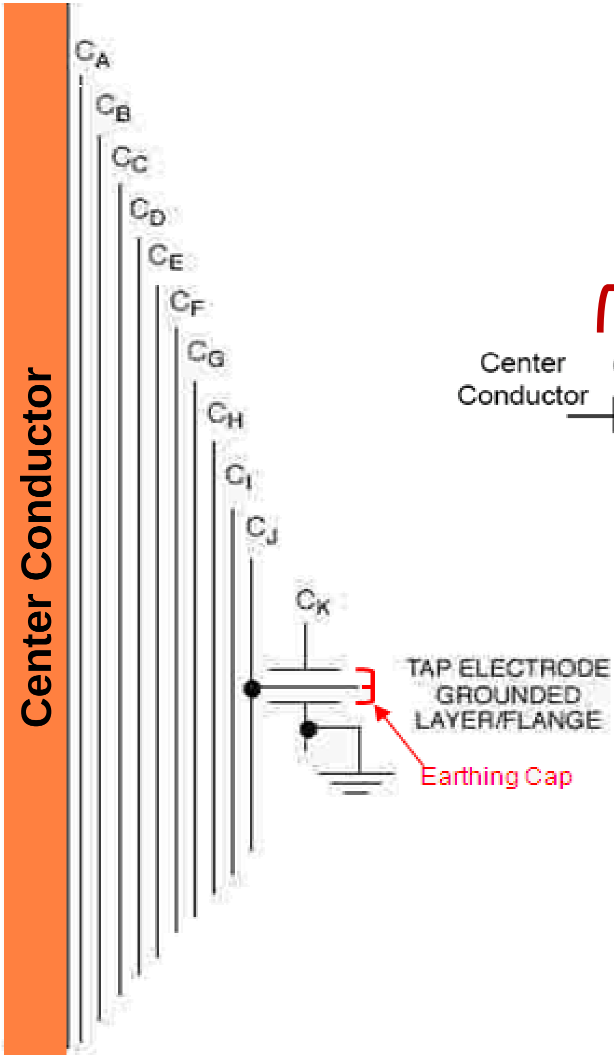
Power Transformer Bushings

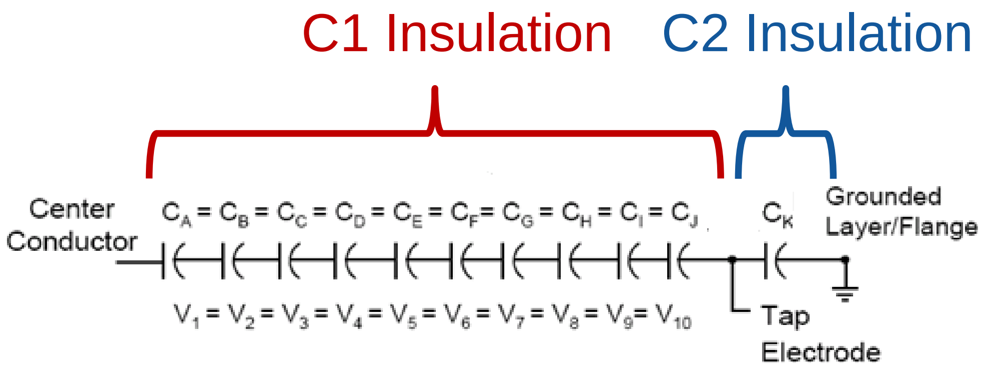
- Required to pass system voltage through grounded transformer tank

- Condenser type (capacitive graded)
    - ❑ Oil impregnated paper (OIP, POC, O+C)
    - ❑ Resin-impregnated paper (RIP, PRC)
    - ❑ Resin-bonded paper (RBI)

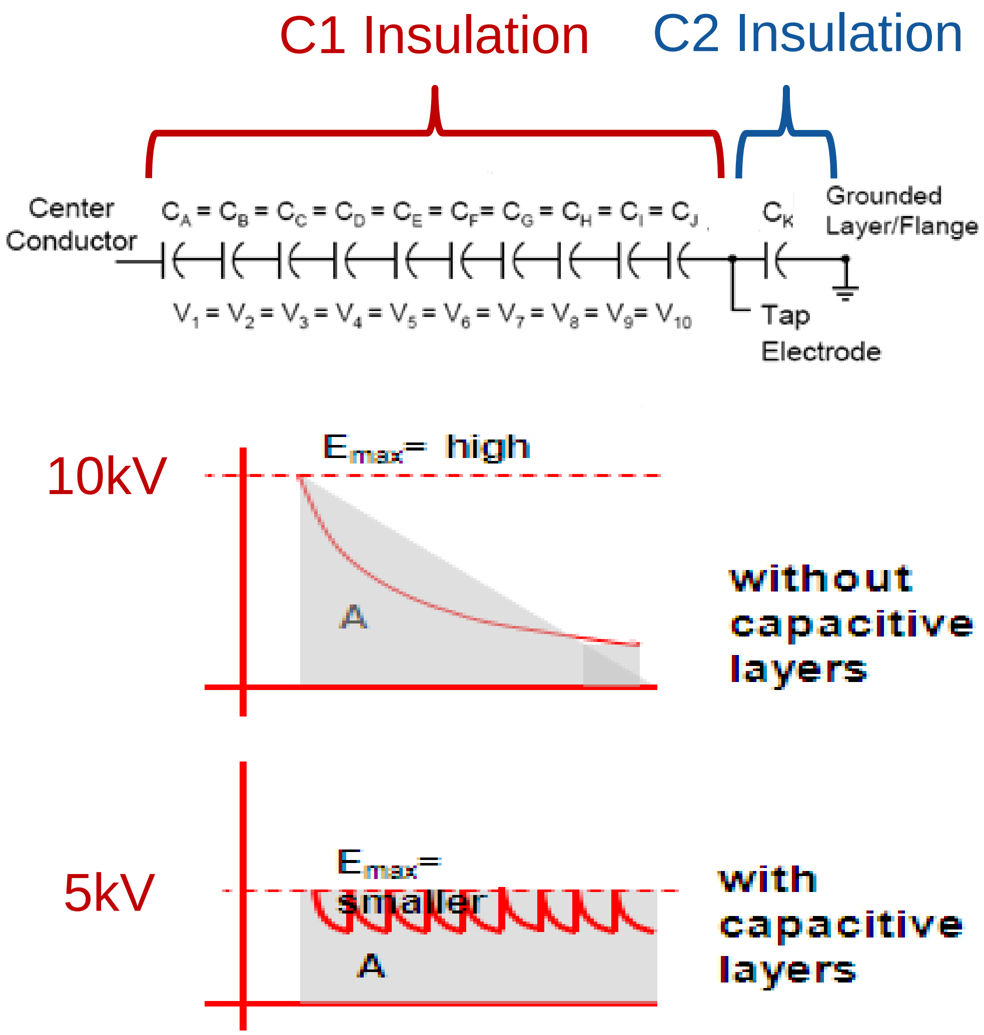
- Non-condenser type (solid bushing)
    - ❑ Composite bushing
    - ❑ Compound filled bushing
    - ❑ SF6

Condenser Bushing Design (Capacitive Graded)





Condenser Bushing Design (Capacitive Graded)



Bushing Taps and “Tap Cap”

Bushing Test Tap Vs. Potential Tap

- Bushings rated ≤ 350kV BIL have test taps
- Tap grounded in service
- **C2 test voltage typically 500V**
- **C2 Cap ≈ C1 Cap ≈ 200 - 500pF**

- Bushings rated > 350kV BIL have potential taps
- Tap grounded in-service or used as a supply
- **C2 test voltage typically 2000V**
- **C2 Cap >> C1 Cap**
- **C2 Cap ≈ 2000-5000pF**

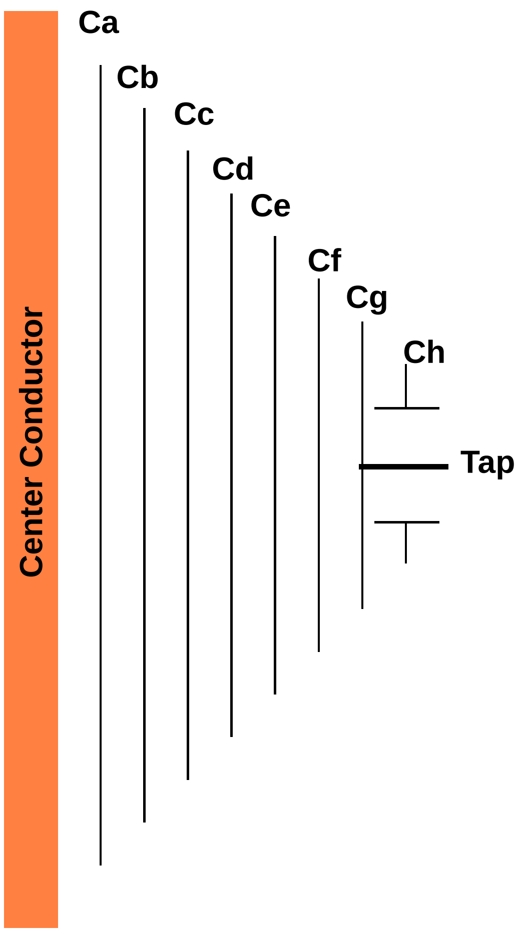
C2 Bushing Power Factor Test

Bushing with Test Tap

		No.	Measurement	Test mode	V test	Freq.	V out	I out @10 kV	Watt losses @10 kV	PF meas	PF corr	Cap. meas
Start	+	1	H1	GSTg-A	0.50 kV	60.00 Hz	0.50 kV	2.00 mA	57.13 mW	0.2856 %	0.2885 %	518.3 pF
Start	+	2	H2	GSTg-A	0.50 kV	60.00 Hz	0.50 kV	9.20 mA	504.11 mW	0.5479 %	0.5534 %	2412.5 pF
Start	+	3	H3	GSTg-A	0.50 kV	60.00 Hz	0.50 kV	2.00 mA	54.12 mW	0.2706 %	0.2733 %	503.7 pF

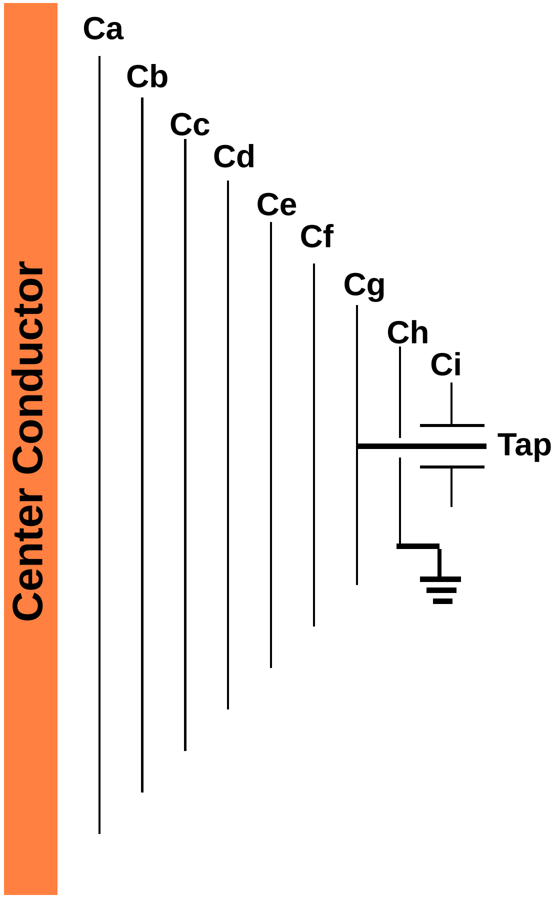
Bushing with Potential Tap

Bushing Construction with Test Tap



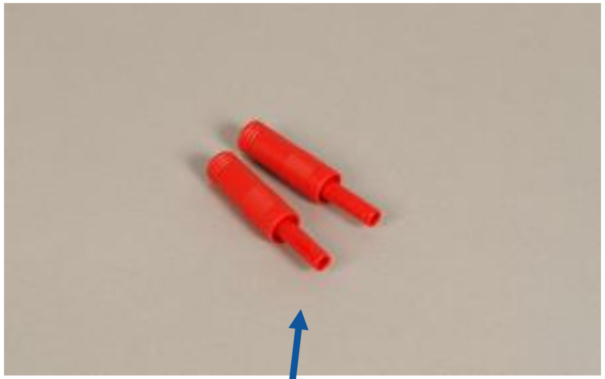
- Bushings rated ≤ 350kV BIL have test taps
- Tap grounded in service
- **C2 test voltage typically 500V**
- **C2 Cap ≈ C1 Cap ≈ 200 - 500pF**

Bushing Construction with Potential Tap



- Bushings rated > 350kV BIL have potential taps
- Tap grounded in-service or used as a supply
- **C2 test voltage typically 2000V**
- **C2 Cap >> C1 Cap**
- **C2 Cap ≈ 2000-5000pF**

Bushing Power Factor Tap Adapters



Westinghouse Type O
(hockey stick)

ASEA GO Types

Westinghouse Type OS, S

Westinghouse O Plus

“The Power Factor Checklist"

- **The Power Factor measurement is highly sensitive, and is one of the most difficult measurements to “get right”** (i.e. to perform correctly)
- The **“Power Factor checklist”** is a series of steps that must be observed, when performing a Power Factor measurement on an insulation system, to ensure that the correct measurement is obtained
- **Failure to observe all the steps in the “Power Factor checklist” often results in “bad” Power Factor measurements** (i.e. invalid Power Factor measurements)

“The Power Factor Checklist"

- ❑ **Is the transformer tank solidly grounded to earth-potential?**
- ❑ **Is the test-equipment solidly grounded to earth-potential?**
- ❑ **Are the bushing terminals of the transformer completely disconnected and isolated from any cable, bus-bar, support insulators, surge arrestors, etc.?**
  - ❑ When applying a test-voltage of 10kV, a minimum clearance of 3in. must be observed (which is the minimum distance required between the bushing terminals that are energized, and any other surface at a different potential)
  - ❑ Avoid using a rubber blanket or any other insulator to isolate the bushing terminals from any other surface at a different potential
- ❑ **Are the surfaces of the bushings clean and dry? People often do not respect how significantly moisture on the bushings can influence a Power Factor measurement**
  - ❑ If the bushings have a porcelain exterior → use Windex or Colonite
  - ❑ If the bushings have a silicone exterior → use a clean, dry rag

What Should I Use to Clean and Dry the Bushings?

- Use a clean, dry rag
- Use Windex
- Use Collinite
- Use a Heat gun
- Do NOT use alcohol – The application of the alcohol will cool the surface of the bushings and attract moisture

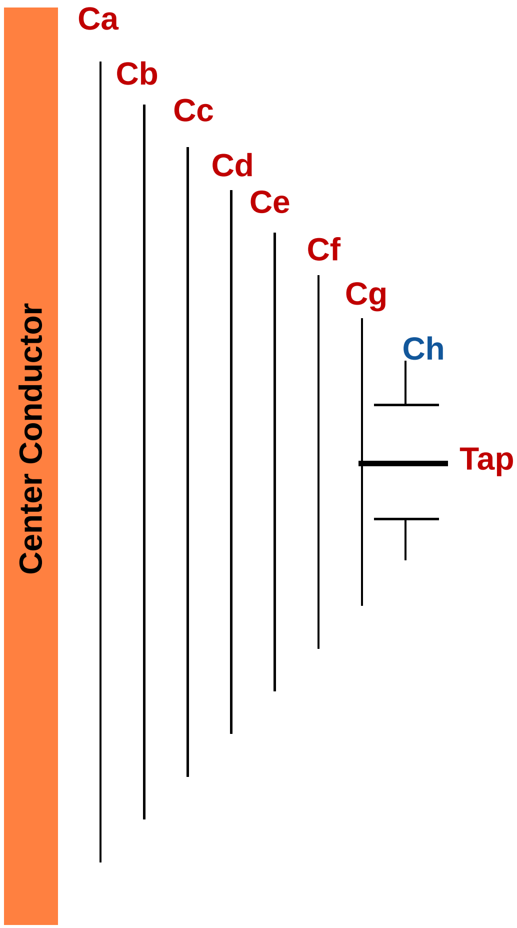
“The Power Factor Checklist"

- ❑ **Are the groups of bushing terminals short-circuited together (i.e. all HV bushing terminals shorted together, all LV bushing terminals shorted together, etc.)?**
  - ❑ Use bare copper, to short-circuit the bushing terminals together – Do not use insulated leads!
  - ❑ Connect the shorting jumpers as tightly as possible from bushing terminal-to-bushing terminal
- ❑ **Remove all in-service grounds from any neutral bushing terminals –** For example, remove the in-service ground-connection from the X0 bushing terminal, if applicable
- ❑ **Place the LTC in any off-neutral tap-position** - Some LTCs have a “tie-in resistor”, which may be inserted into the test-circuit when the LTC is in the Neutral tap-position. This “tie-in resistor” can influence a Power Factor measurement
- ❑ **Ensure that the HV cable is “in the clear”**, and that the last two feet of the HV cable is not touching any surface of the transformer (e.g. the transformer tank, the bushing surfaces, etc.)

"The Power Factor Checklist"

- ❑ Do not Power Factor test in the rain
- ❑ Avoid testing in high-humidity situations
- ❑ Do not Power Factor test when the temperature of the oil is close-to, or below, 5°C
- ❑ Power Factor test after lunch, if possible

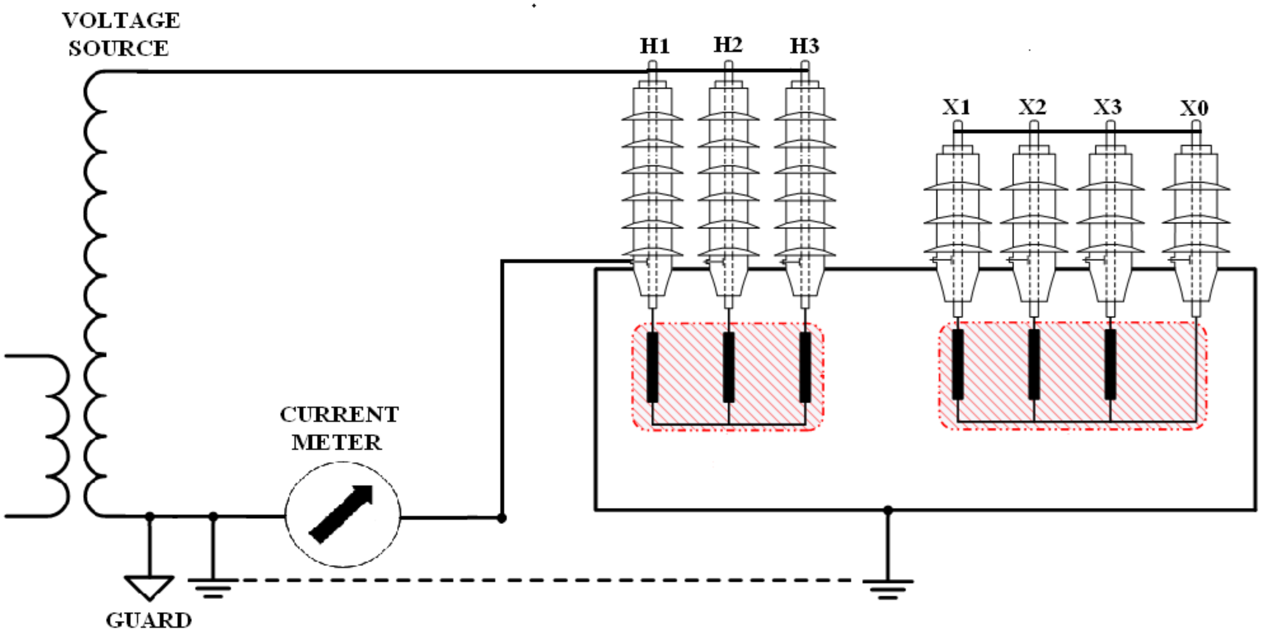
The Bushing C1 Power Factor Test



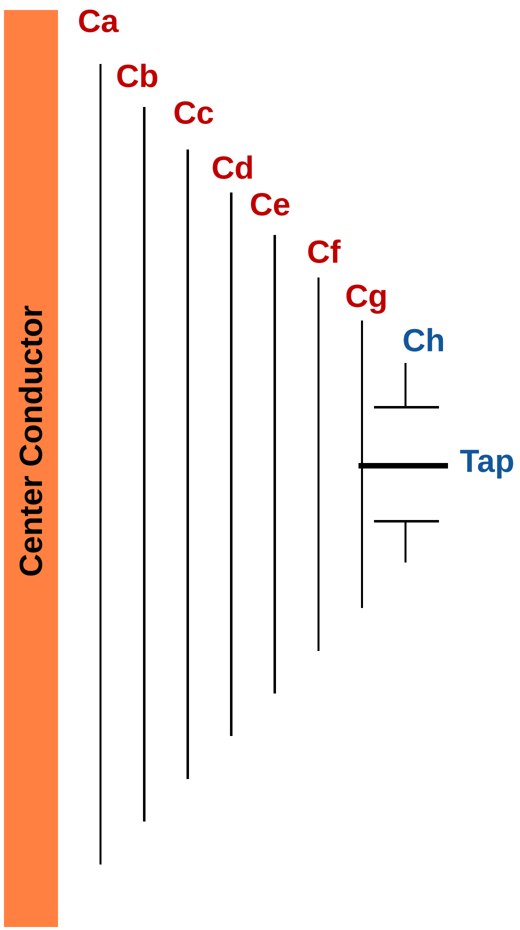
- **The C1 Power Factor measurement tests the majority of a bushing's insulation system (from "inside-out")**
- **The C1 Power Factor Test is a solid indicator of the condition of a bushing**; however, the C2 Power Factor Test should not be "skipped"
- **Review the "Power Factor Checklist" prior to testing**
- **Remove one "tap-cap" at a time**
- **The test-voltage should not exceed the line-to-ground voltage rating of the bushing under test**

Bushing C1 Power Factor Test Procedure

- Place the high voltage lead on the center conductor of the bushing (or anywhere on the shorted electrode)
- Place the current measurement lead on the tap of the bushing (tap adapter may be required depending on bushing type)
- Perform a UST test to measure the C1 insulation system of the bushing

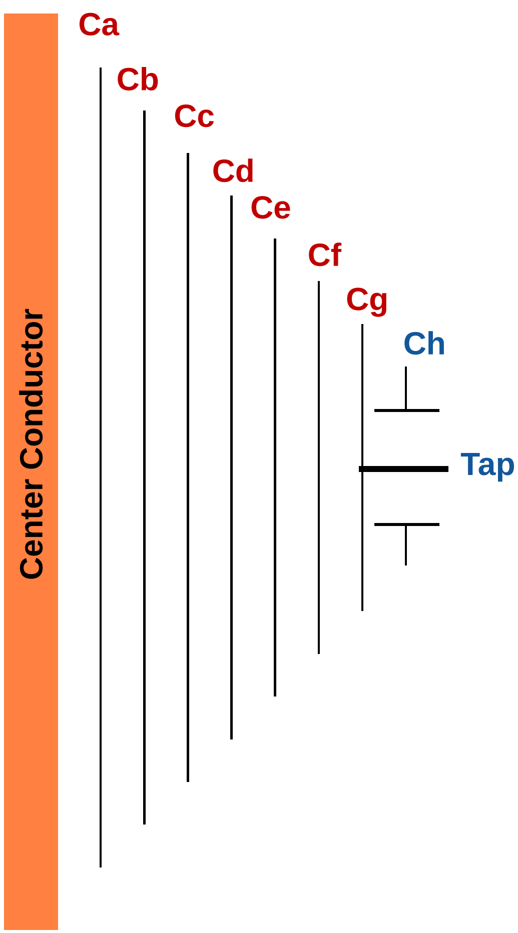


The Bushing C2 Power Factor Test

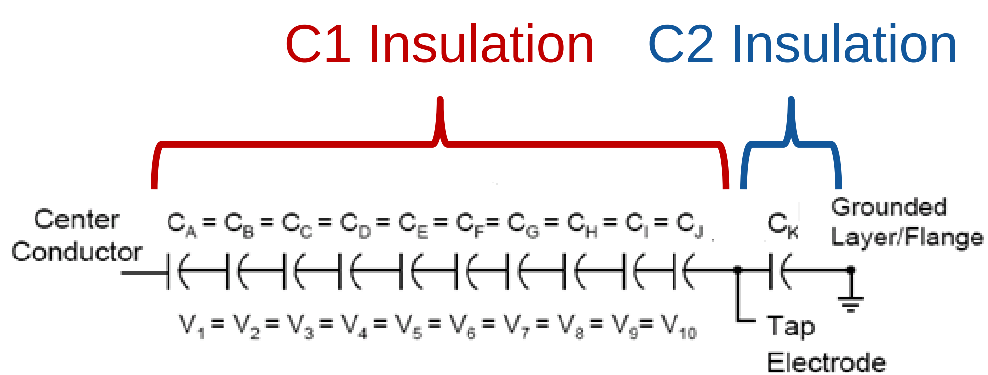


- **The Bushing C2 Power Factor measurement tests the small piece of insulation between the tap and ground-flange of the bushing**
- **The Bushing C2 Power Factor Test should not be skipped,** because it tests the integrity of the bushing's tap-connection, and tests the last layer(s) of insulation of the bushing
- **The Bushing C2 Power Factor Test can be significantly influence by moisture and/or a foreign substance inside the "tap-area" of the bushing**
- **Ensure that the "tap-area" of the bushing is "clean and dry" before performing the C2 Power Factor Test**

Bushing C2 Power Factor Test Procedure

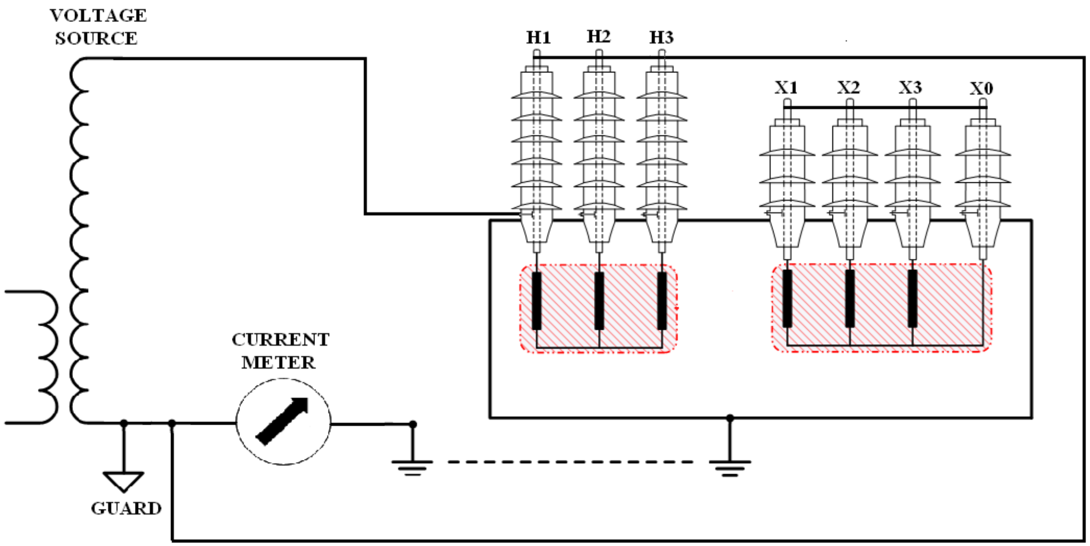


- **C2 measurement can be heavily influenced by the environment or any foreign substance in the tap area**
- Test voltage determined by the tap type (test tap = 500V, potential tap = 2kV)
- Some bushing manufacturers do not “control” the C2 capacitance (especially on “low-voltage” bushings)
- Get the high-voltage cable “in-the-clear”



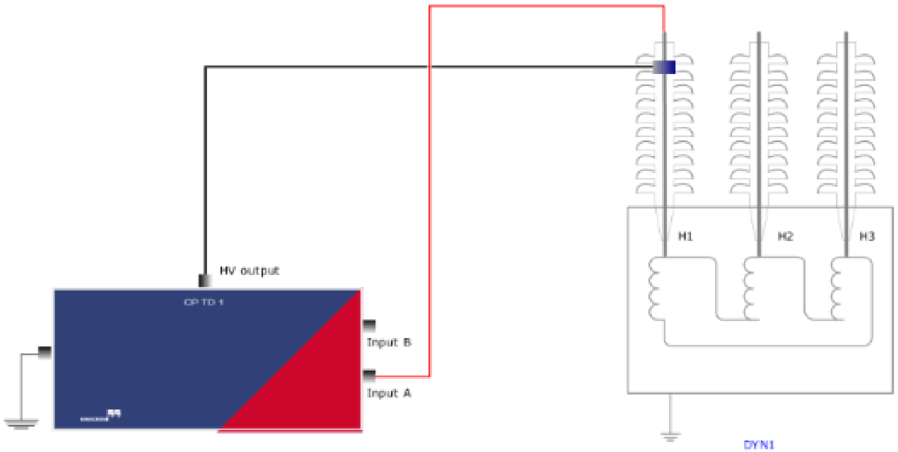
Bushing C2 Power Factor Test Procedure

- Place the high voltage injection lead on the tap of the bushing (tap adapter may be required depending on bushing type)
- Place the current measurement lead on the center conductor of the bushing (or anywhere on the shorted electrode, if the bushings are shorted together)
- Perform a GST-Guard test to measure the C2 insulation



Energized Collar/Hot Collar Test Overview

- Typically only performed on bushings without a tap
- Does not stress the bushing insulation as well as the C1 Power Factor test
- **Not as sensitive to insulation failures as the C1 test (but when a bushing has no tap, it is the only electrical test we can perform on the bushing)**
- The measurement is especially useful for verifying the oil level of a bushing that does not have a sight glass
- The test voltage for the Hot Collar Test is typically 10kV, regardless of the voltage rating of the bushing



Energized Collar/Hot Collar Test Overview

- **The Hot Collar test essentially only tests the insulation near the area of the collar**
- Therefore, the collar may have to be moved around to different locations on a bushing, to test the different sections of the bushing's insulation system...
    1) At the top of the bushing
    2) In the middle of the bushing
    3) At the bottom of the bushing
- The customer must weigh the diagnostic value against the amount of time it takes to perform a thorough Hot Collar measurement, to determine if the measurement is worthwhile
- One option could be to only perform the Hot Collar measurement when there is a reason to suspect that there is a problem with the bushing (e.g. due to a visual inspection or due to a higher than normal Overall PF measurement)

Energized Collar/Hot Collar Test Result Analysis

- We typically do not assess the Power Factor value when performing the Hot Collar Test (due to the relatively low capacitance of the measurement)
- We typically analyze the measured Current (mA) and Watts Loss (W)
- **The industry accepted rule-of-thumb is that, if the measured Watts Loss is below 0.1W, then the Hot Collar measurement is "acceptable"**
- **The measured Current and Watts Loss should also be reasonably similar to any previous measurements performed on the same bushing**
- **The measured Current and Watts Loss should be reasonably similar when comparing measurements amongst "sister unit" bushings**

Hot Collar Test - UST vs. GST Mode

- When using the UST test mode
    1) Tests area under and near the hot collar strap
    2) Tests the oil level of the bushing (if the strap is applied under the top skirt of the bushing)
- When using the GST test mode
    1) Tests area under and near the hot collar strap
    2) Tests the oil level of the bushing (if the strap is applied under the top skirt of the bushing)
    3) May include leakage current across the surface of the bushing (which could be due to a defect or due to the test environment)

Bushing Investigation Tests

- *Visual Inspection (check oil level, oil color, look for cracks, leaks, etc.)*
- *Power Factor Frequency Sweep Test (aka variable frequency power factor)*
- *Power Factor Voltage Sweep Test (aka “voltage tip-up test”)*
- *Overall Power Factor Test*
- Inverted C1 Test
- C1+C2 Test
- Multiple Energized Collar Tests

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An Introduction to Performing Power Factor Sweep Tests on Bushings

Bushing Power Factor Sweep Overview

- Perform Power Factor measurement at different test **voltages**
- Perform Power Factor measurement at different test **frequencies**
- The Power Factor sweep measurements are valuable when testing,
  - ❑ Overall Insulation (CH, CL, and CHL)
  - ❑ Bushing Insulation (C1)

Bushing Power Factor Sweep Overview

- In general, a questionable sweep measurement can help **identify or confirm**,
  - ❑ Compromised insulation
  - ❑ User-error
  - ❑ When the test environment is adversely affecting measurements

Who Can Benefit from Performing the Sweep Measurements?

The Test Equipment Operator

- Due to many factors, such as the influence of the test environment and time constraints, obtaining the correct (i.e. valid) Power Factor measurements in the field is challenging
- In many cases, a questionable measurement is not identified until the test equipment operator has left the job-site and the transformer is back in service
- With a Power Factor measurement at one test voltage and one test frequency, it is difficult for the test equipment operator to determine if the measurement is valid
- **However, invalid measurements often become obvious when the Power Factor sweep measurements are performed and analyzed**
- **The test equipment operator should use the sweep measurements as a tool to quickly identify and correct “bad” measurements, before they leave the job-site with the incorrect test results**

Who Can Benefit from Performing the Sweep Measurements?

The Engineer

- The engineer is responsible for assessing the condition of the insulation system to determine the appropriate course of action
- Typically, the engineer is not on-site when the measurements are performed, and therefore, it is difficult for the engineer to be confident that the measurements are valid
- **If the engineer has the Power Factor sweep results in-hand, then they can better identify invalid measurements, which helps prevent an incorrect condition assessment**
- Many asset owners do not have a collection of reliable, previous test results for their transformer fleet, which makes assessing the condition of a given insulation challenging
- **The Power Factor sweep measurements can be used to better assess the condition of an insulation system at a given point in time, especially when there are no historical test results to compare to**

Bushing Power Factor Sweep Analysis

- The analysis of the sweep measurements should not be made complicated
- The analysis of the sweep measurements is performed visually
- The condition of the insulation is assessed based on the shape of the plots (aka traces)
- The analysis involves determining if the shape of a trace is “normal” or “abnormal”
- If either of the sweep measurements produce an “abnormal” trace, then the insulation system should be investigated

Power Factor Voltage Sweep Test (aka Voltage Tip-Up Test)

- Performing a Power Factor measurement at multiple test voltages helps identify both compromised insulation and “bad” measurements
- The voltage sweep test involves performing Power Factor measurements at several different test voltages (e.g. 2kV, 4kV, 6kV, 8kV, and 10kV)
- At a minimum, an oil-and-paper insulation system should be tested at two different voltages (e.g. 2kV and 10kV)
- Typically, the measured Power Factor value for an oil-and-paper insulation system should not be sensitive to the applied voltage
- Of note, when bushing insulation begins to deteriorate, the C1 Power Factor measurement for that bushing often becomes voltage sensitive

Power Factor Frequency Sweep Test

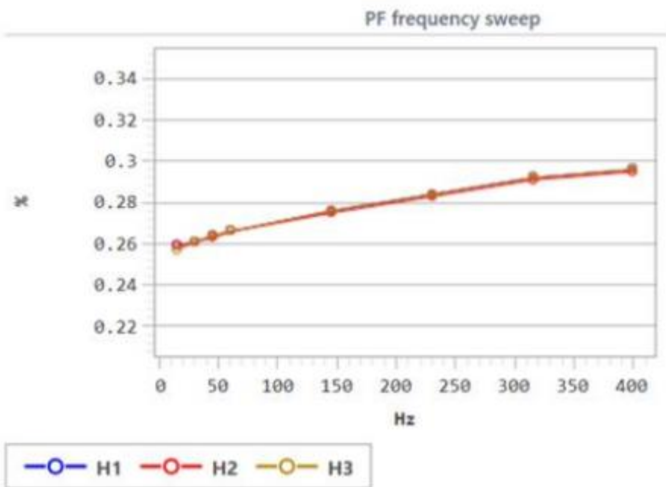
- Performing a Power Factor measurement at multiple test frequencies helps identify both compromised insulation and “bad” measurements
- The frequency sweep test involves performing Power Factor measurements at different test frequencies (e.g. 15Hz, 40Hz, 60Hz, 80Hz, etc.)
- Emphasis is typically placed on the measurements at the frequencies below 60Hz
- The Power Factor measurement at a frequency below 60Hz is more sensitive to an insulation problem than a Power Factor measurement at 60Hz
- The guidelines provided for assessing the frequency sweep measurement are most appropriate for Power Factor measurements performed with an oil temperature at or close to 20°C

Power Factor Frequency Sweep Analysis Guidelines

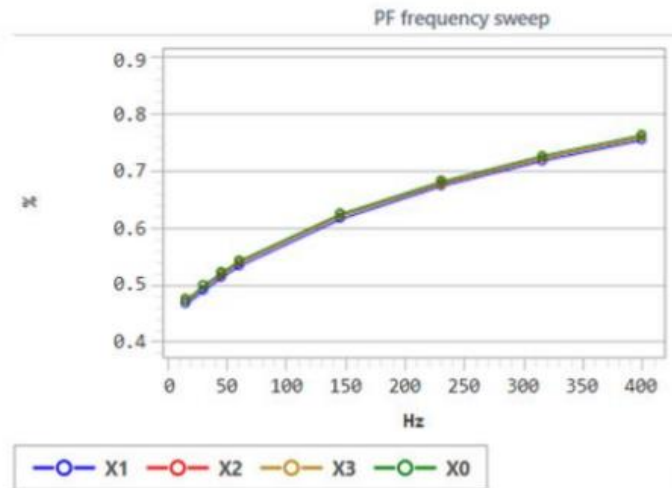
- In general, if the insulation system is healthy, then the Power Factor will **increase** (from left to right) versus frequency for the majority of the sweep
- In general, if the insulation system is compromised, then the Power Factor will **decrease** (from left to right) versus frequency for the majority of the sweep
- Compromised insulation typically produces a distinctive **fish-hook** in the low frequency range (i.e. at frequencies below 60Hz)
- In general, the frequency sweep measurements should behave similarly when comparing similar unit bushings
- The shape of the frequency sweep trace should be reasonably similar when comparing similar unit bushings

Acceptable Bushing Frequency Sweep Measurements

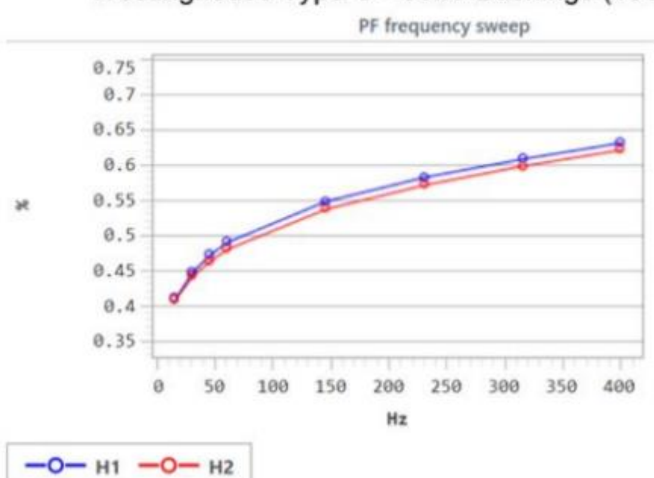
ABB O+C II - 115kV Bushings (2015)



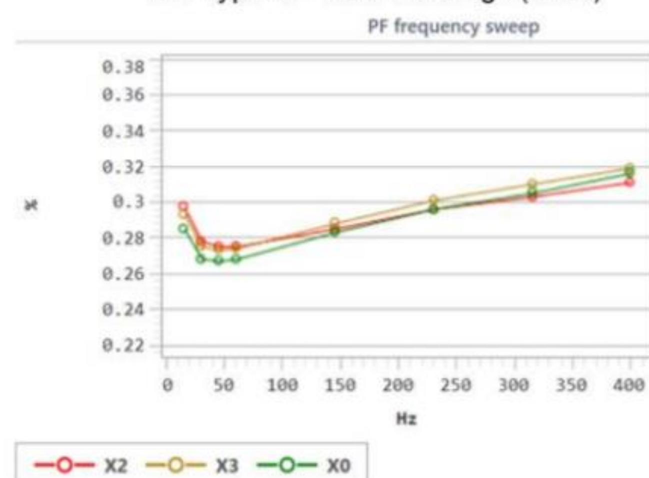
Hubbell PCORE PRC - 15kV Bushings (2014)



Westinghouse Type O - 69kV Bushings (1969)



GE Type U - 16kV Bushings (1978)



Bushing Power Factor Test Analysis

Bushing Power Factor Analysis – Time-Based Comparison

- **Having previous test results to compare to is important and significantly helps to assess the integrity of the bushing insulation system**
- In general, if the **Power Factor** increases, then the insulation system has deteriorated since the previous test date
- An “abnormally low” or negative **Power Factor** could also be an indication of compromised insulation (typically, an “abnormally low” **Power Factor** value is defined as less than 0.1%)

Bushing Power Factor Analysis – Nameplate Comparison

- If the measured **Power Factor** exceeds ± 1.5x the nameplate value, then the bushing is typically deemed questionable (investigate, test more frequently, or replace)
- If the measured **Power Factor** exceeds ± 2x the nameplate value, then the bushing is typically deemed unacceptable for service – Placing the bushing back into service poses a risk (investigate, test more frequently, or replace)
- If the measured **Power Factor** has increased relative to the nameplate value, then this typically indicates that the condition of the insulation system has worsened since the factory test
- These relative limits apply to both the C1 and C2 Power Factor measurements

Bushing Power Factor Analysis – Nameplate Comparison

- If the measured **Capacitance** exceeds ± 5% of the nameplate value, then the bushing is typically deemed questionable (investigate, test more frequently, or replace)
- If the measured **Capacitance** exceeds ± 10% of the nameplate value, then the bushing is typically deemed unacceptable for service – Placing the bushing back into service poses a risk (investigate, test more frequently, or replace)
- If the measured **Capacitance** changes significantly relative to the nameplate value or relative to a previous test result, then this typically indicates that the insulation system has physically changed
- These relative limits apply to both the C1 and C2 Power Factor measurements

Absolute Limits for Oil Impregnated Bushings – C1 Test

		Absolute limits		
Assessment against	Limit	OIP	RIP	RBP
Absolute limits	Low limit (fail)	0.000 %	0.000 %	0.000 %
	Low limit (warn.)	0.150 %	0.150 %	0.150 %
	High limit (warn.)	0.500 %	0.850 %	2.000 %
	High limit (fail)	1.000 %	1.500 %	3.000 %

Absolute Limits for Resin Impregnated Bushings – C1 Test

		Absolute limits		
Assessment against	Limit	OIP	RIP	RBP
Absolute limits	Low limit (fail)	0.000 %	0.000 %	0.000 %
	Low limit (warn.)	0.150 %	0.150 %	0.150 %
	High limit (warn.)	0.500 %	0.850 %	2.000 %
	High limit (fail)	1.000 %	1.500 %	3.000 %

Absolute Limits for Resin Bonded Paper Bushings - C1 Test

Assessment against	Limit	Absolute limits		
		OIP	RIP	RBP
Absolute limits	Low limit (fail)	0.000 %	0.000 %	0.000 %
	Low limit (warn.)	0.150 %	0.150 %	0.150 %
	High limit (warn.)	0.500 %	0.850 %	2.000 %
	High limit (fail)	1.000 %	1.500 %	3.000 %

Absolute Limits for Oil Impregnated Bushings – C2 Test

Assessment against	Limit	Absolute limits		
		OIP	RIP	RBP
Absolute limits	Low limit (fail)	0.000 %	0.000 %	0.000 %
	Low limit (warn.)	0.150 %	0.150 %	0.150 %
	High limit (warn.)	1.000 %	4.000 %	2.000 %
	High limit (fail)	2.000 %	10.000 %	3.000 %

Absolute Limits for Resin Impregnated Bushings – C2 Test

		Absolute limits		
Assessment against	Limit	OIP	RIP	RBP
Absolute limits	Low limit (fail)	0.000 %	0.000 %	0.000 %
	Low limit (warn.)	0.150 %	0.150 %	0.150 %
	High limit (warn.)	1.000 %	4.000 %	2.000 %
	High limit (fail)	2.000 %	10.000 %	3.000 %

Absolute Limits for Resin Bonded Paper Bushings – C2 Test

		Absolute limits		
Assessment against	Limit	OIP	RIP	RBP
Absolute limits	Low limit (fail)	0.000 %	0.000 %	0.000 %
	Low limit (warn.)	0.150 %	0.150 %	0.150 %
	High limit (warn.)	1.000 %	4.000 %	2.000 %
	High limit (fail)	2.000 %	10.000 %	3.000 %

Abnormally Low or Negative Power Factor

- **An "abnormally low" or negative Power Factor is typically caused by a high resistive path to ground**, which could be due to one of the following,
  - ❑ User error (e.g. a bad ground connection or a poor test connection)
  - ❑ Test environment – Moisture, high-humidity, rain, snow, cold temperatures, etc.
  - ❑ A test specimen that has a relatively low Capacitance value (typically defined as less than 80pF)
  - ❑ A loose or poorly connected bushing ground flange (typically only relevant when performing the C1 and C2 Power Factor measurements)
  - ❑ Compromised insulation

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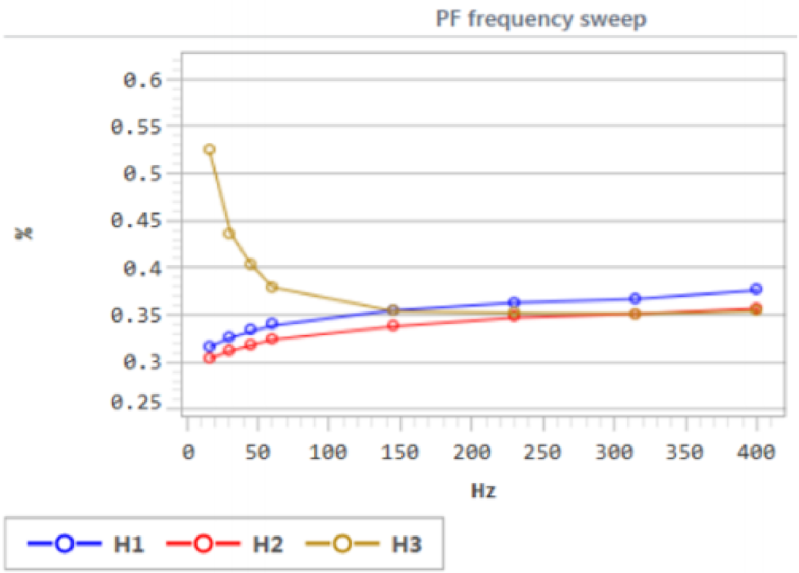
Bushing C1 Power Factor Test Examples

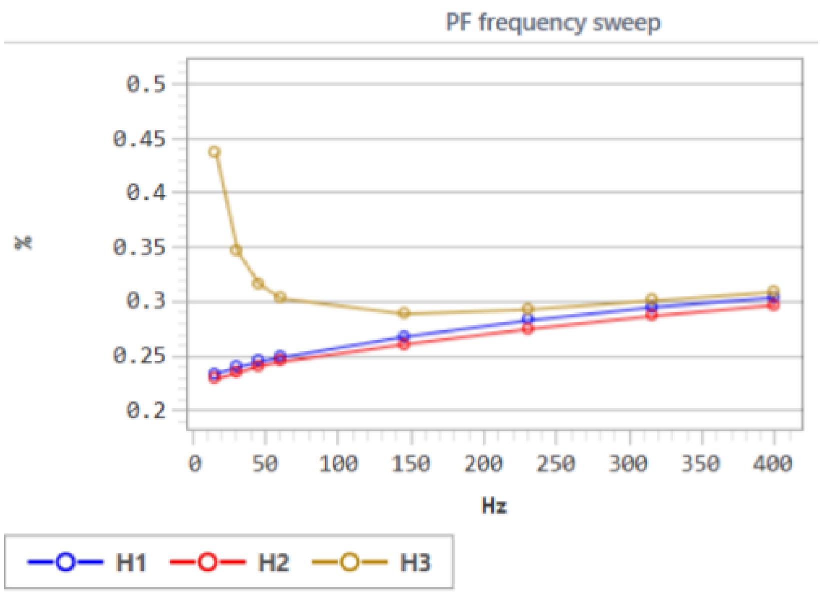
Questionable Bushing C1 Power Factor Measurements

HAEFELY 115kV Bushings (2000)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
H1	0.34%	0.34%	0.00%	0.38%
H2	0.32%	0.32%	0.00%	0.37%
H3	0.38%	0.41%	0.03%	0.35%



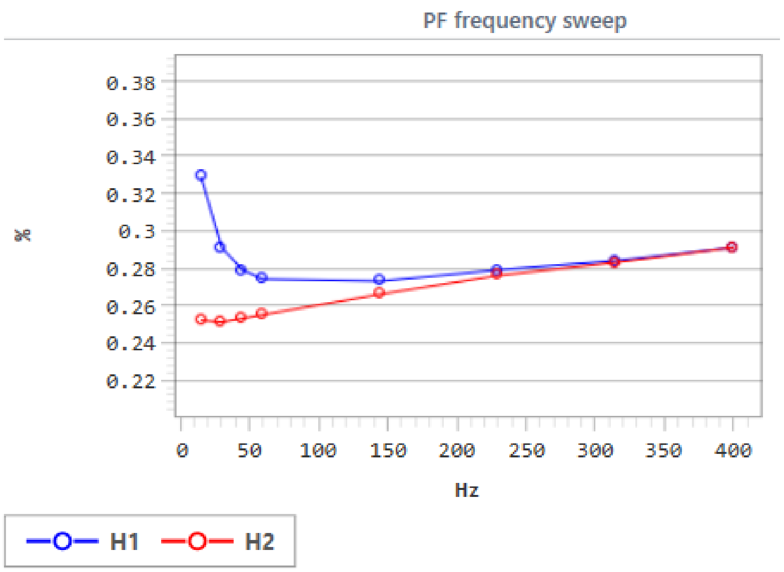
Questionable Bushing C1 Power Factor Measurements

ABB O+C 115kV Bushings (1992)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
H1	0.25%	0.25%	0.00%	0.26%
H2	0.24%	0.24%	0.00%	0.24%
H3	0.30%	0.31%	0.01%	0.25%



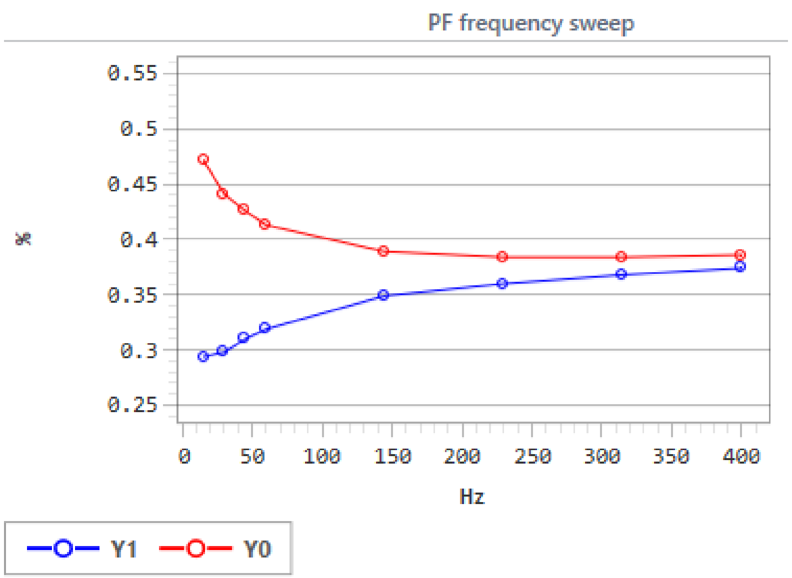
Questionable Bushing C1 Power Factor Measurements

Lapp POC Series 2 115kV Bushings (1998)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
H1	0.27%	0.28%	0.01%	0.25%
H2	0.25%	0.25%	0.00%	0.25%
H3	0.66%	0.76%	0.10%	0.24%



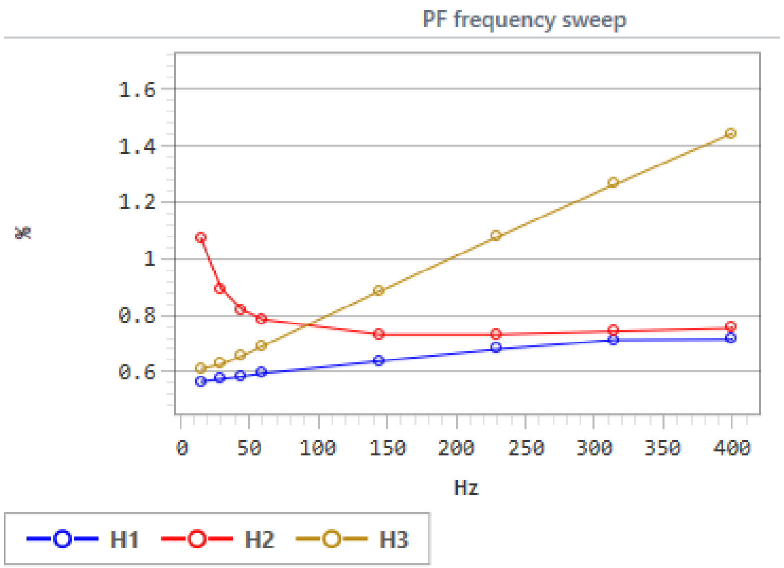
Questionable Bushing C1 Power Factor Measurements

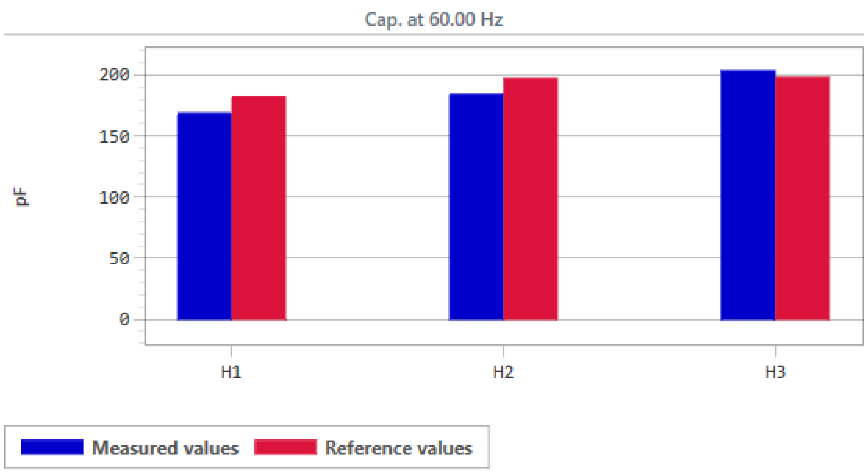
GE Type-U 16kV Bushing (1964)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
Y1	0.32%	0.32%	0.00%	-
Y0	0.41%	0.44%	0.03%	-



Questionable Bushing C1 Power Factor Measurements

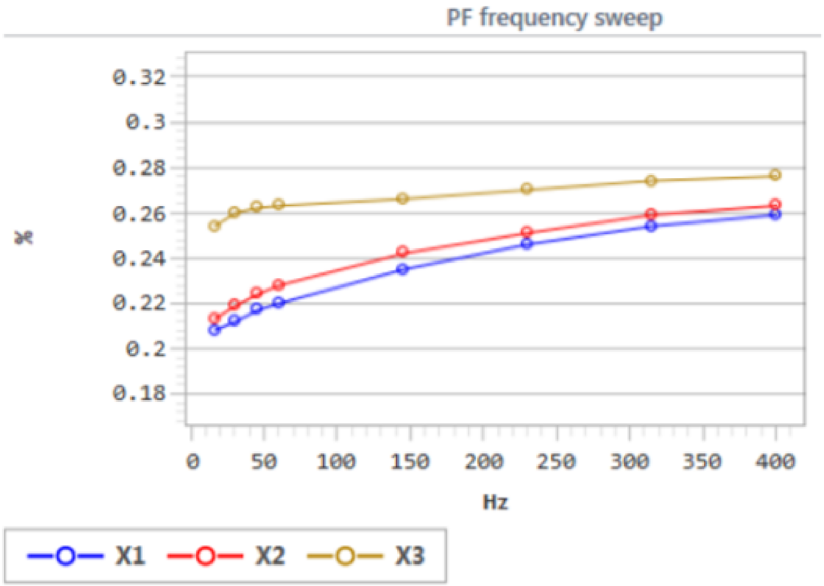
Westinghouse Electric Type S 37kV Bushings						
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor	Measured Capacitance	Nameplate Capacitance
H1	0.60%	0.58%	-0.02%	0.65%	169pF	182pF
H2	0.79%	0.78%	-0.01%	0.72%	184pF	197pF
H3	0.69%	0.69%	0.00%	0.66%	203pF	198pF





Questionable Bushing C1 Power Factor Measurements

ABB O+C 72kV Bushings (2012)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
X1	0.22%	0.22%	0.00%	0.25%
X2	0.23%	0.23%	0.00%	0.24%
X3	0.26%	0.28%	0.02%	0.24%

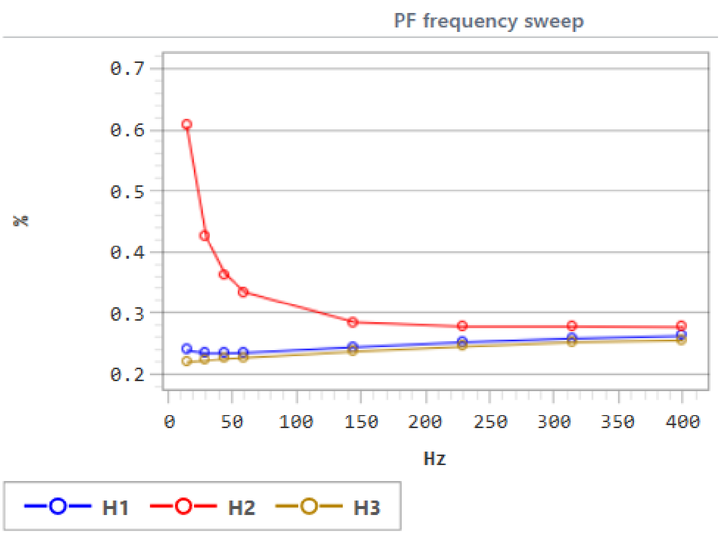


Questionable Bushing C1 Power Factor Measurements

"Our preliminary observation/evaluation is that the X3 bushing is loose to the point of arcing and heating the conducting bushing rod"

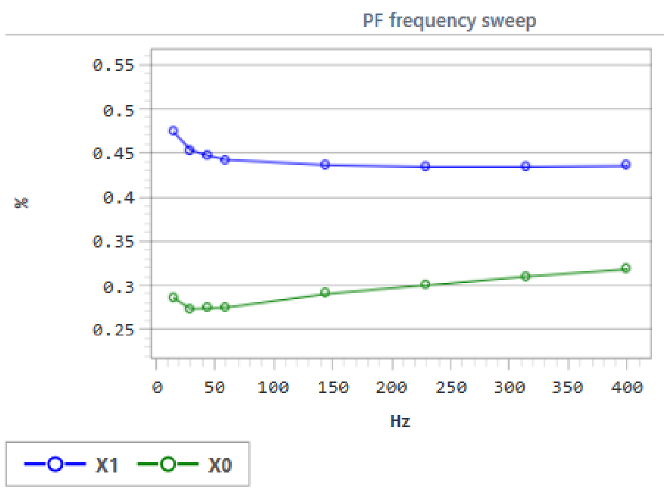
Questionable Bushing C1 Power Factor Measurements

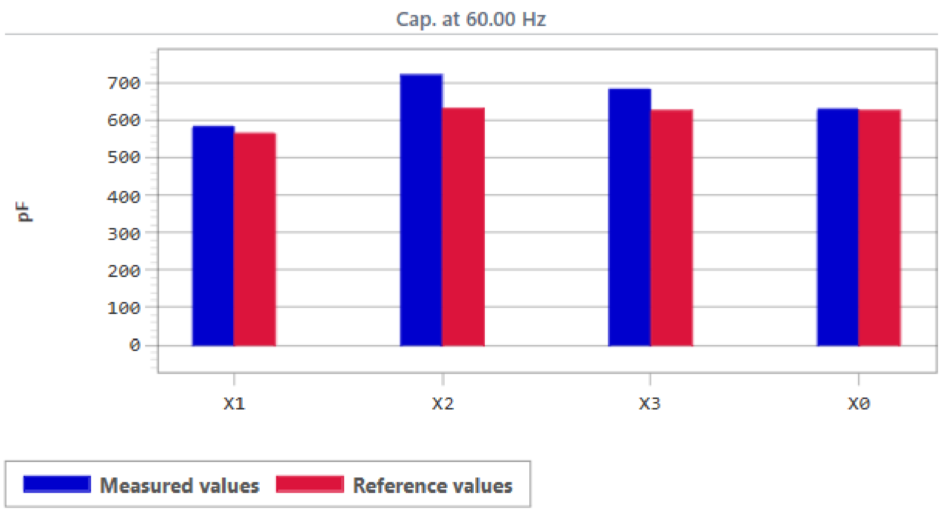
ABB O+C 142kV Bushings (2010)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
H1	0.24%	0.24%	0.00%	0.26%
H2	0.33%	0.36%	0.03%	0.26%
H3	0.23%	0.23%	0.00%	0.24%



Questionable Bushing C1 Power Factor Measurements

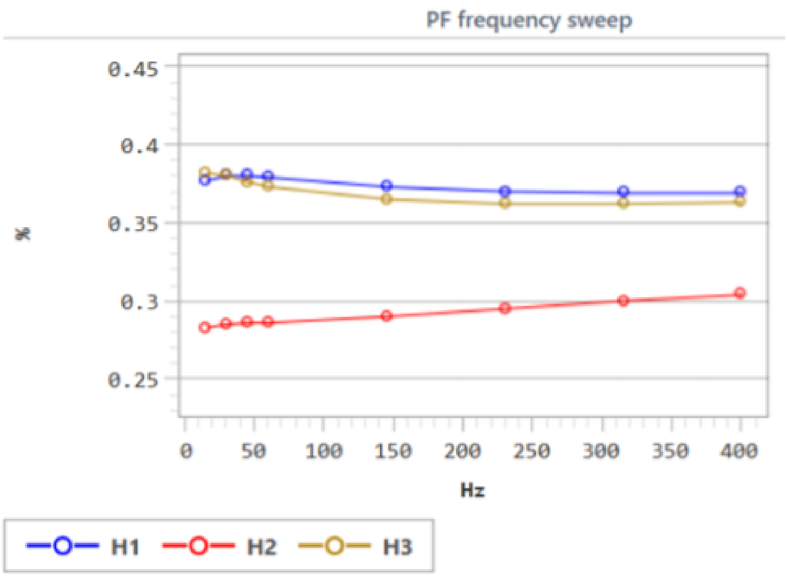
ABB O+C 25kV Bushings (1993)						
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor	Measured Capacitance	Nameplate Capacitance
X1	0.44%	0.46%	0.02%	0.28%	582pF	564pF
X2	1.64%	1.70%	0.06%	0.29%	719pF	629pF
X3	1.68%	1.57%	-0.09%	0.27%	681pF	624pF
X0	0.28%	0.28%	0.00%	0.28%	628pF	624pF





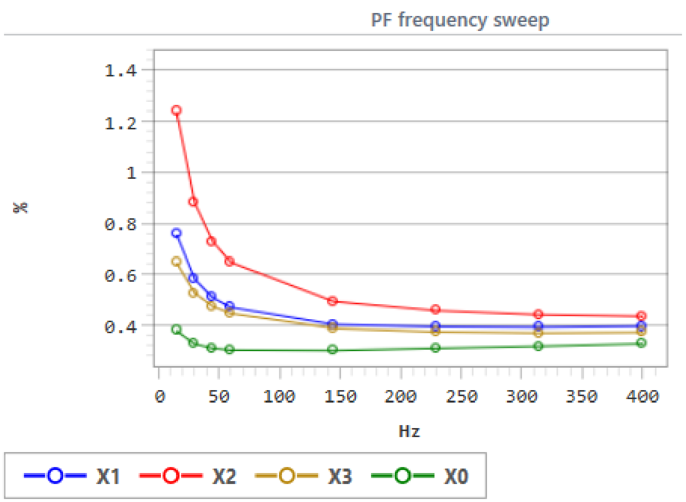
Questionable Bushing C1 Power Factor Measurements

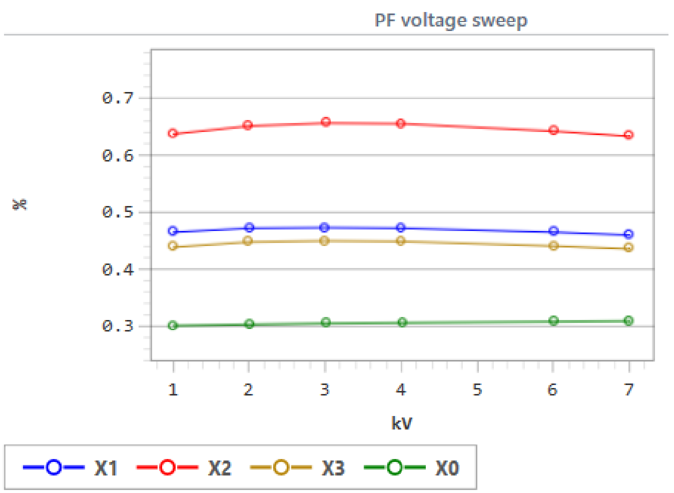
ABB O+C 69kV Bushings				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
H1	0.38%	0.41%	0.03%	-
H2	0.29%	0.31%	0.02%	-
H3	0.37%	0.43%	0.06%	-



Questionable Bushing C1 Power Factor Measurements

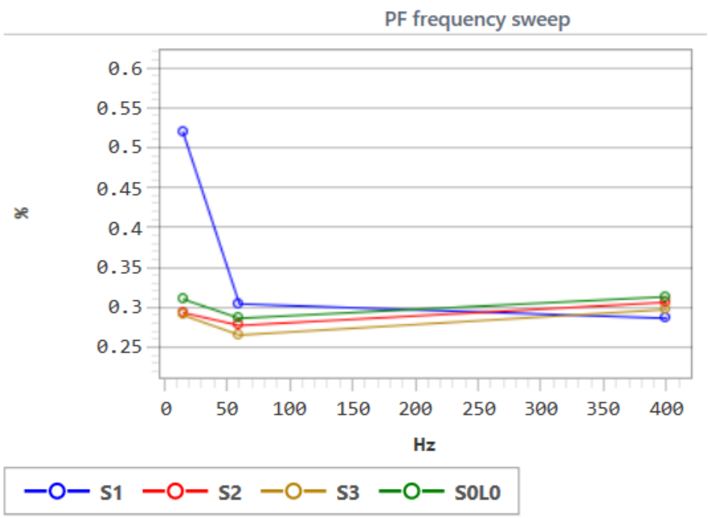
GE Type U, 25kV Bushings (1986)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
X1	0.47%	0.46%	-0.01%	0.29%
X2	0.65%	0.63%	-0.02%	0.30%
X3	0.45%	0.44%	-0.01%	0.30%
X0	0.31%	0.30%	-0.01%	0.28%





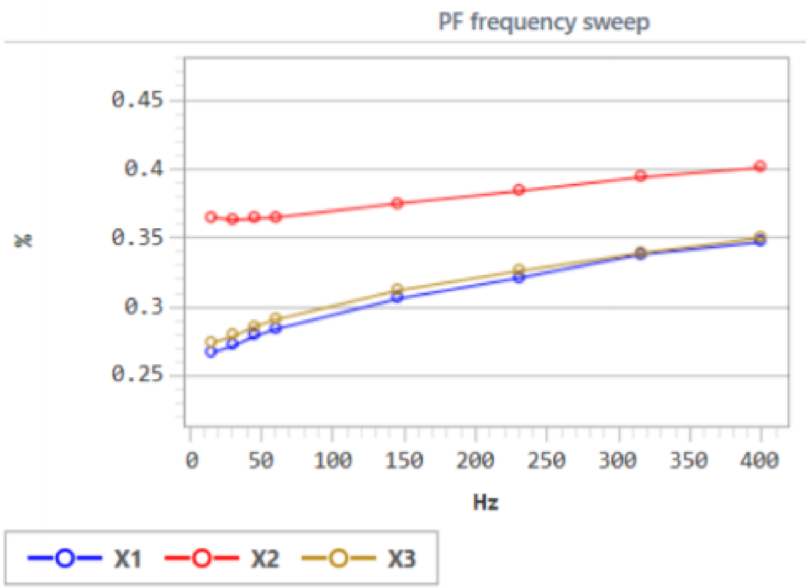
Questionable Bushing C1 Power Factor Measurements

GE Type U 27.5kV Bushings (1984)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
S1	0.30%	0.32%	0.02%	0.27%
S2	0.28%	0.28%	0.00%	0.31%
S3	0.27%	0.27%	0.00%	0.30%
S0L0	0.29%	0.29%	0.00%	0.33%



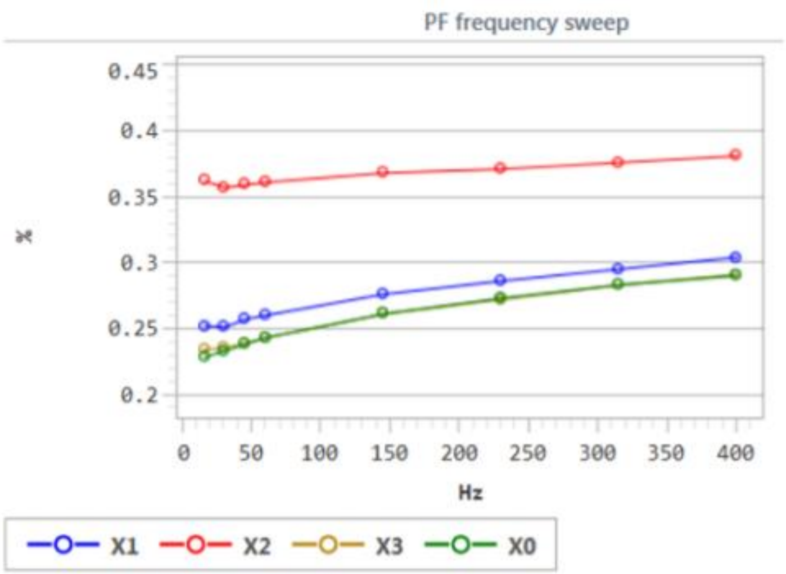
Questionable Bushing C1 Power Factor Measurements

ABB O+C 25kV Bushings (1992)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
X1	0.29%	0.31%	0.02%	0.31%
X2	0.36%	0.41%	0.05%	0.30%
X3	0.29%	0.31%	0.02%	0.31%



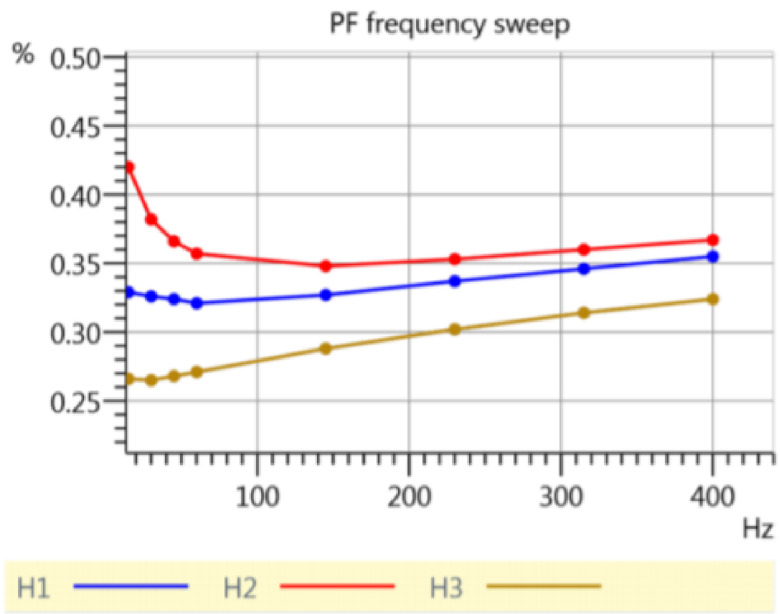
Questionable Bushing C1 Power Factor Measurements

ABB O+C 25kV Bushings (1992)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
X1	0.26%	0.29%	0.03%	0.29%
X2	0.36%	0.41%	0.05%	0.25%
X3	0.24%	0.26%	0.02%	0.28%
X0	0.24%	0.26%	0.02%	0.27%



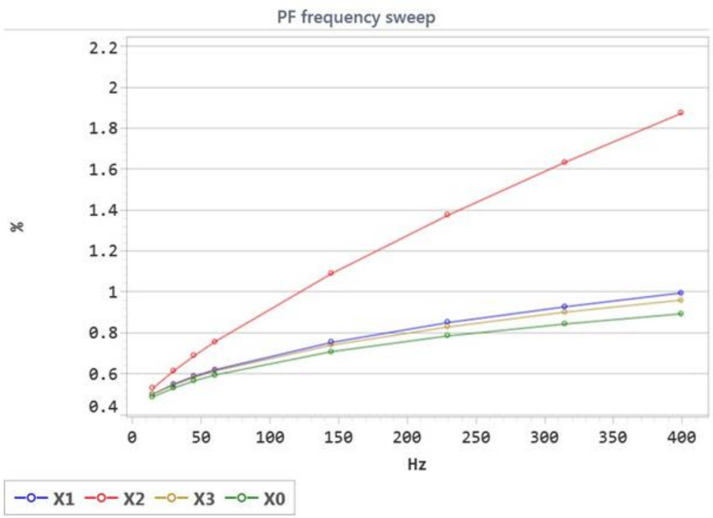
Questionable Bushing C1 Power Factor Measurements

VTC 69kV Bushings (2009) – Note, only H2 and H3 are similar unit bushings)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
H1	0.32%	0.32%	0.00%	0.31%
H2	0.36%	0.37%	0.01%	0.25%
H3	0.27%	0.27%	0.00%	0.25%



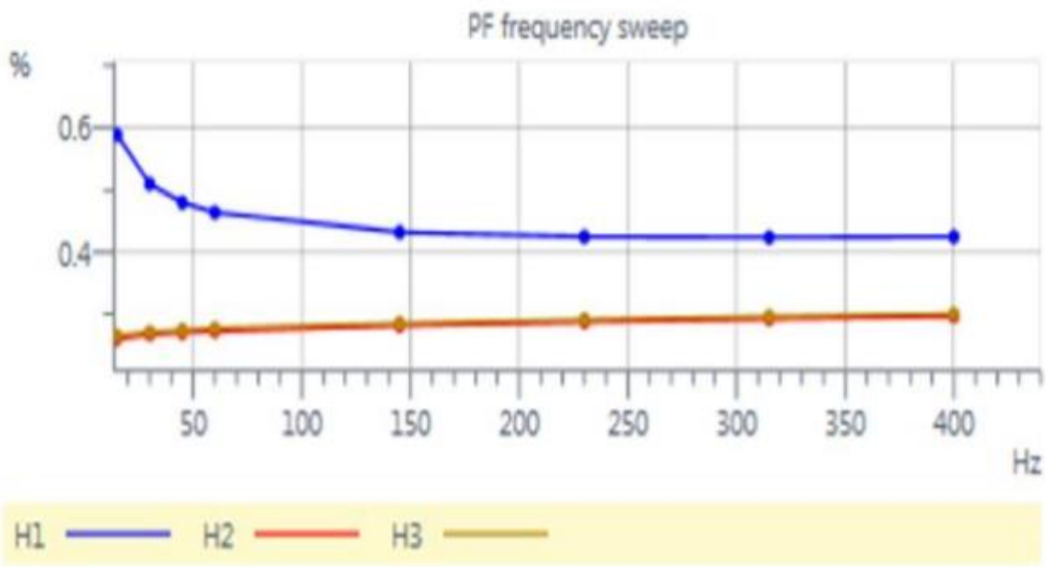
Questionable Bushing C1 Power Factor Measurements

PCORE 25kV Bushings (2017)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
X1	0.62%	0.62%	0.00%	0.66%
X2	0.76%	0.74%	-0.02%	0.65%
X3	0.61%	0.63%	0.02%	0.66%
X0	0.59%	0.60%	0.01%	0.65%



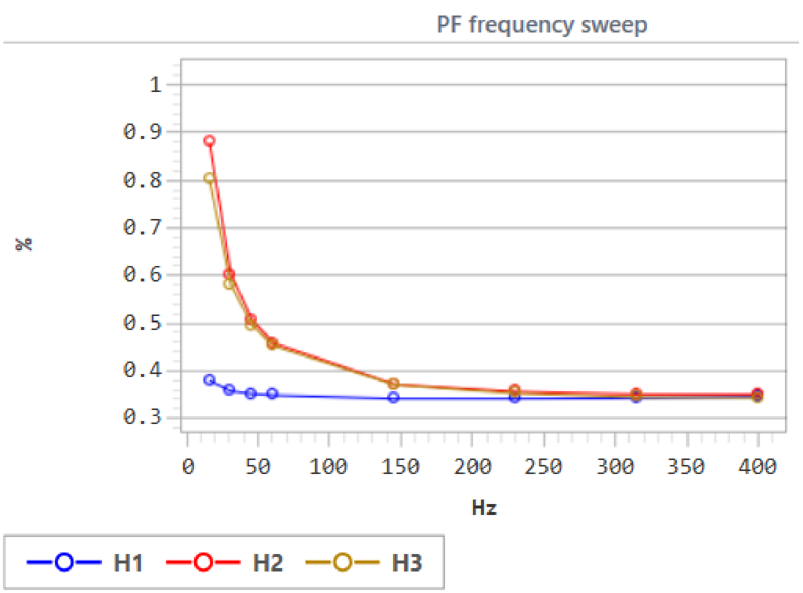
Questionable Bushing C1 Power Factor Measurements

ABB O+C 69kV Bushings (2000)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
H1	-	0.46%	-	0.30%
H2	-	0.27%	-	0.28%
H3	-	0.28%	-	0.29%



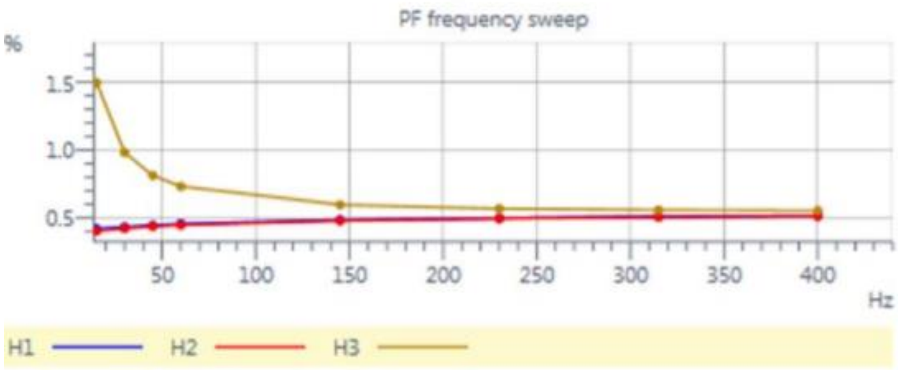
Questionable Bushing C1 Power Factor Measurements

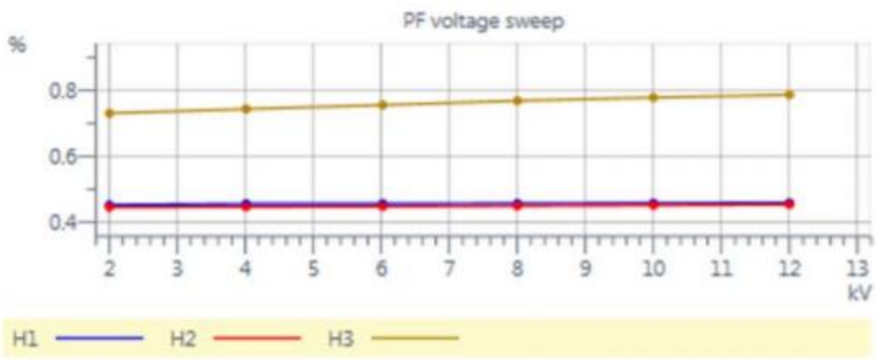
Lapp POC 230kV Bushings (2000)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
H1	0.34%	0.34%	0.00%	0.28%
H2	0.46%	0.47%	0.01%	0.24%
H3	0.45%	0.46%	0.01%	0.22%



Questionable Bushing C1 Power Factor Measurements

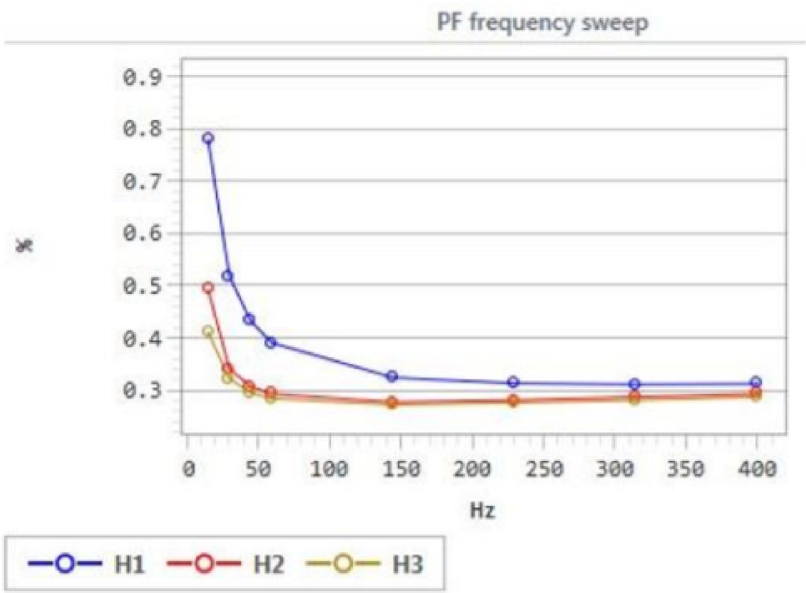
McGraw Edison 69kV Bushings (1979)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
H1	0.46%	0.46%	0.00%	0.51%
H2	0.45%	0.45%	0.00%	0.50%
H3	0.73%	0.78%	0.05%	0.50%





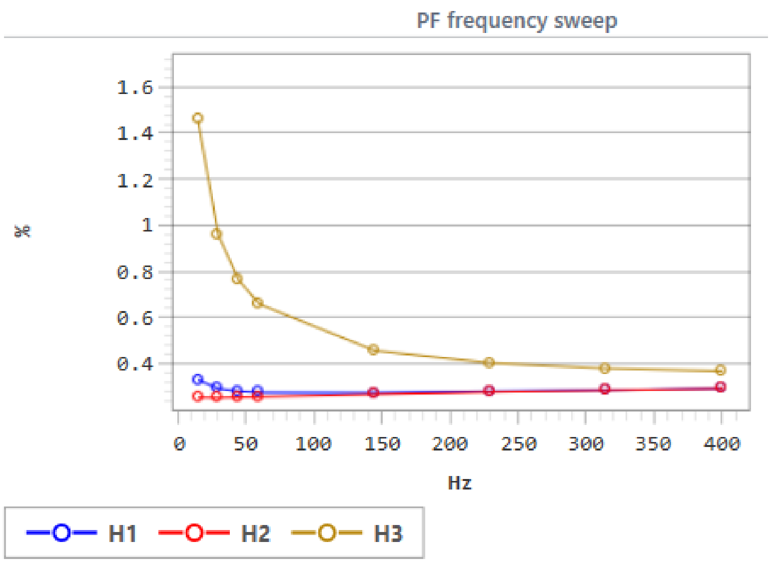
Questionable Bushing C1 Power Factor Measurements

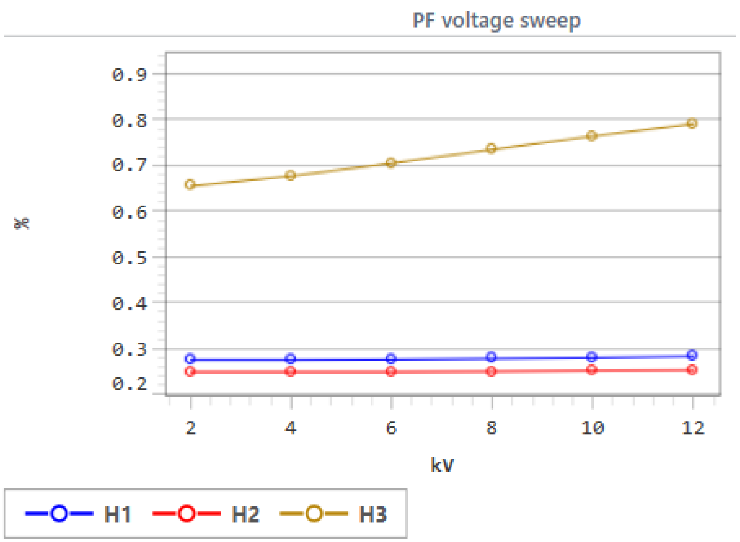
GE Type U 69kV Bushings (1985)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
H1	0.45%	0.55%	0.10%	0.28%
H2	0.34%	0.36%	0.02%	0.27%
H3	0.33%	0.35%	0.02%	0.27%



Questionable Bushing C1 Power Factor Measurements

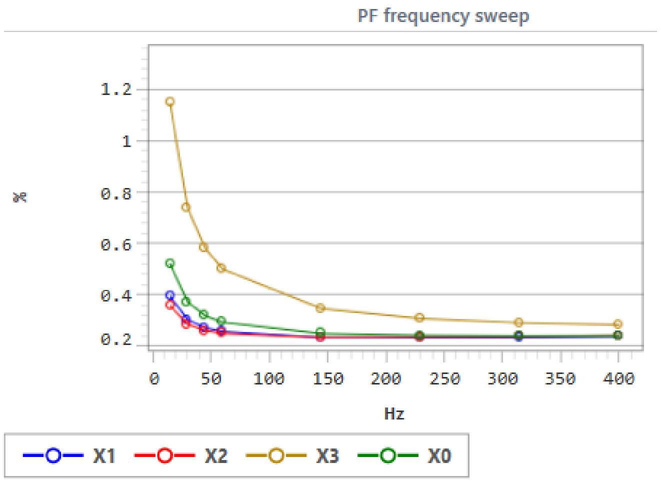
Lapp POC Series 2 115kV Bushings (1998)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
H1	0.27%	0.28%	0.01%	0.25%
H2	0.25%	0.25%	0.00%	0.25%
H3	0.66%	0.76%	0.10%	0.24%





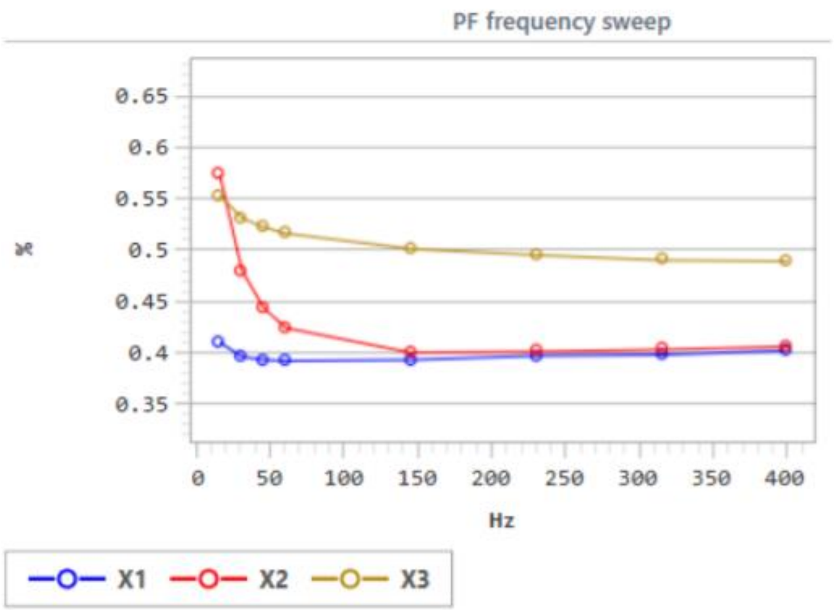
Questionable Bushing C1 Power Factor Measurements

PCORE OIP 24.9kV Bushings (2013)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
X1	0.26%	0.26%	0.00%	0.23%
X2	0.25%	0.25%	0.00%	0.23%
X3	0.50%	0.57%	0.07%	0.23%
X0	0.29%	0.29%	0.00%	0.23%



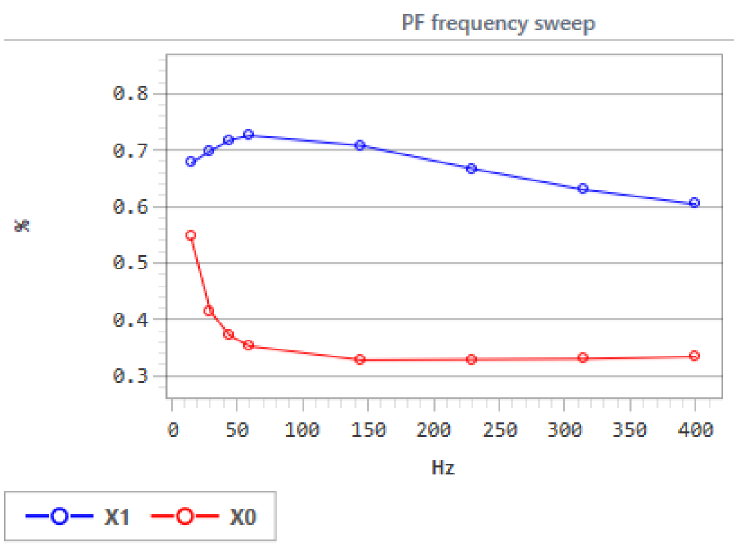
Questionable Bushing C1 Power Factor Measurements

ABB O+C 34.5kV Bushings (1998)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
X1	0.39%	0.42%	0.03%	0.25%
X2	0.42%	0.48%	0.06%	0.25%
X3	0.52%	0.61%	0.09%	0.31%



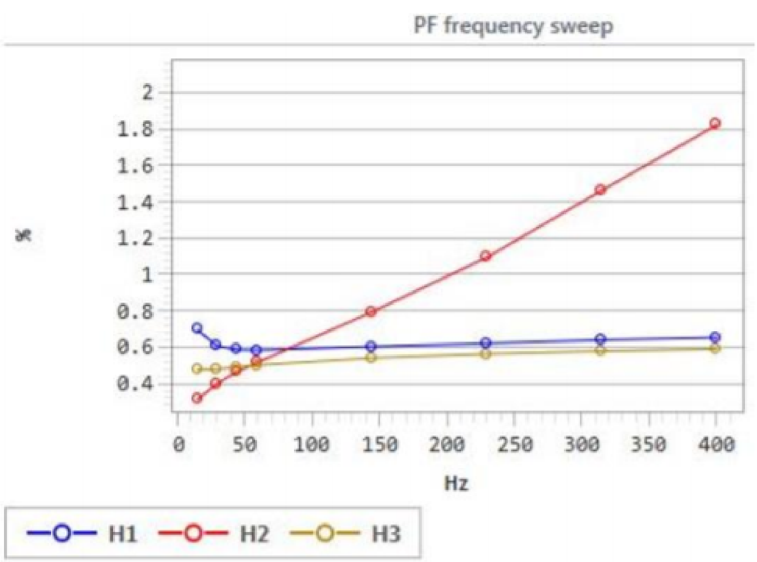
Questionable Bushing C1 Power Factor Measurements

GE Type-U 69kV Bushing (1984)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
X1	0.73%	0.71%	-0.02%	0.30%
X0	0.35%	0.36%	0.01%	0.30%



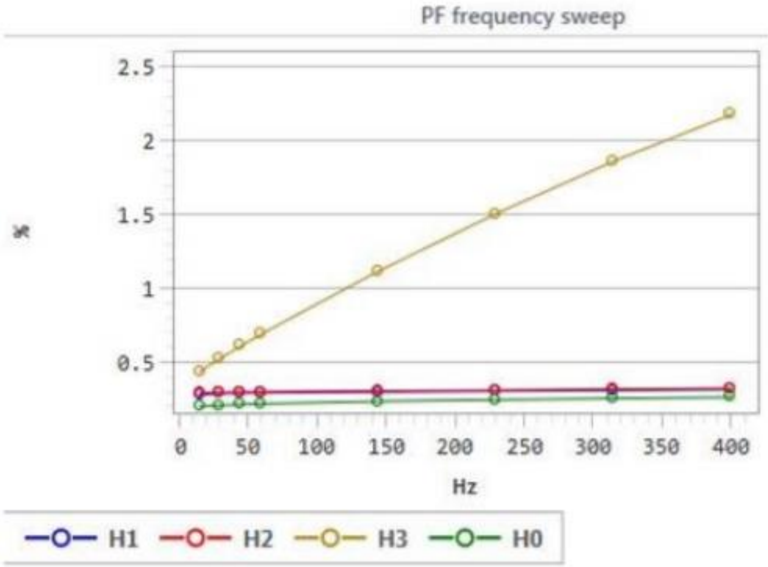
Questionable Bushing C1 Power Factor Measurements

McGraw Edison 69kV Bushings (1978)						
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor	Measured Capacitance	Nameplate Capacitance
H1	0.58%	0.59%	0.01%	0.52%	300pF	301pF
H2	0.52%	0.52%	0.00%	0.53%	248pF	298pF
H3	0.50%	0.50%	0.00%	0.51%	284pF	288pF



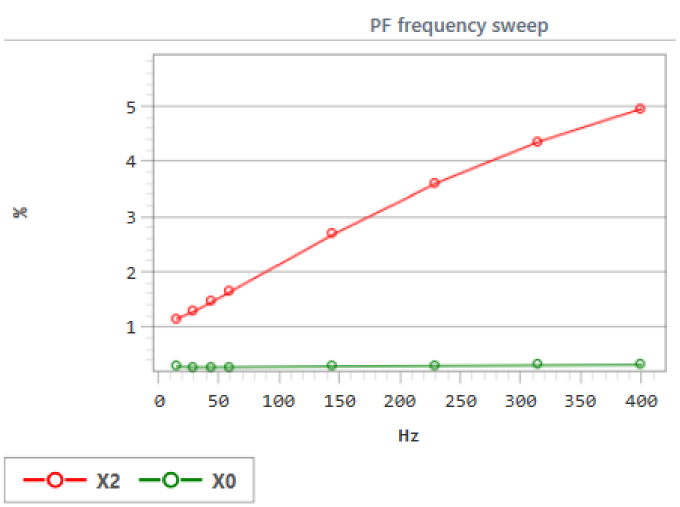
Questionable Bushing C1 Power Factor Measurements

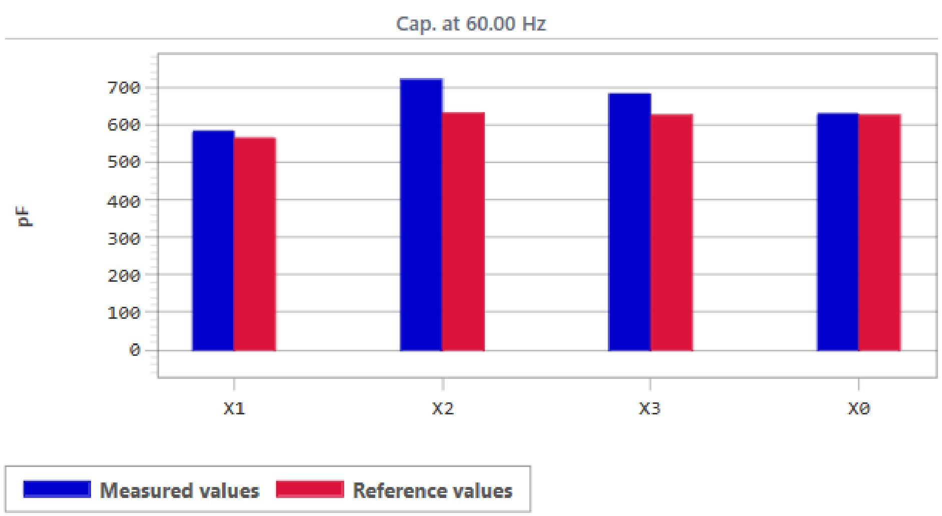
Westinghouse O+C 44kV Bushings (1988)						
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor	Measured Capacitance	Nameplate Capacitance
H1	0.29%	0.31%	0.02%	0.23%	267pF	270pF
H2	0.30%	0.32%	0.02%	0.21%	269pF	271pF
H3	0.69%	0.68%	-0.01%	0.23%	293pF	271pF
H0	0.22%	0.22%	0.00%	0.23%	269pF	274pF



Questionable Bushing C1 Power Factor Measurements

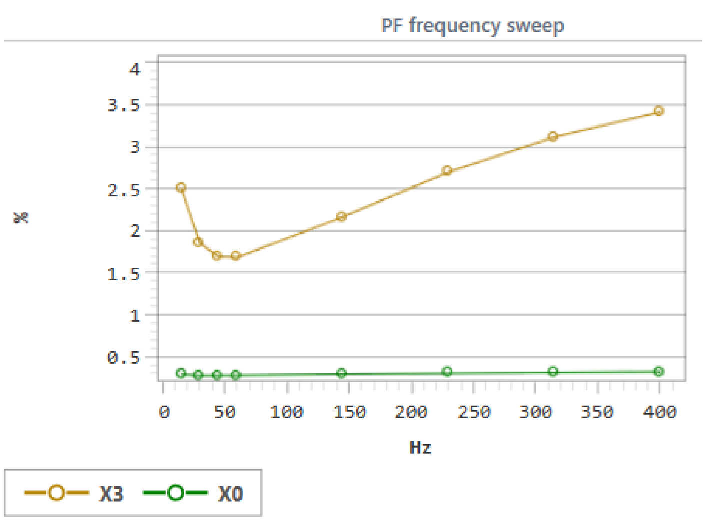
ABB O+C 25kV Bushings (1993)						
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor	Measured Capacitance	Nameplate Capacitance
X1	0.44%	0.46%	0.02%	0.28%	582pF	564pF
X2	1.64%	1.70%	0.06%	0.29%	719pF	629pF
X3	1.68%	1.57%	-0.09%	0.27%	681pF	624pF
X0	0.28%	0.28%	0.00%	0.28%	628pF	624pF

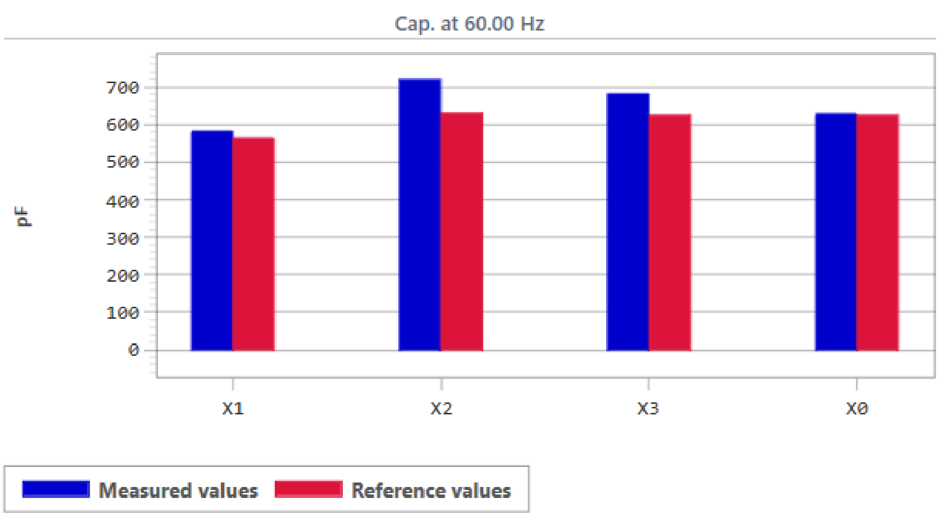




Questionable Bushing C1 Power Factor Measurements

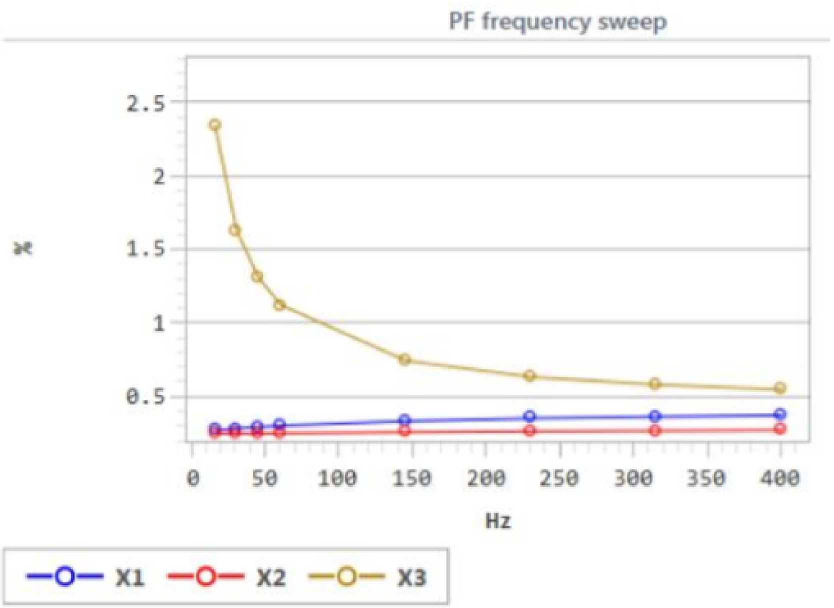
ABB O+C 25kV Bushings (1993)						
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor	Measured Capacitance	Nameplate Capacitance
X1	0.44%	0.46%	0.02%	0.28%	582pF	564pF
X2	1.64%	1.70%	0.06%	0.29%	719pF	629pF
X3	1.68%	1.57%	-0.09%	0.27%	681pF	624pF
X0	0.28%	0.28%	0.00%	0.28%	628pF	624pF





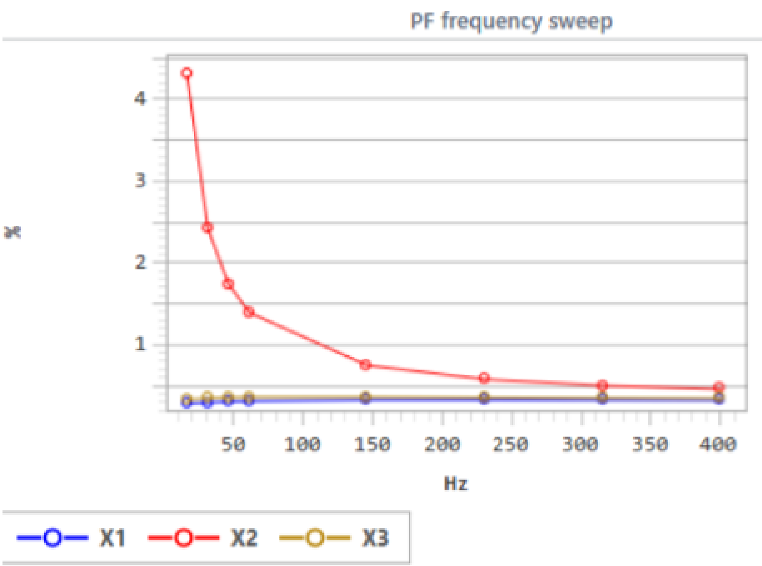
Questionable Bushing C1 Power Factor Measurements

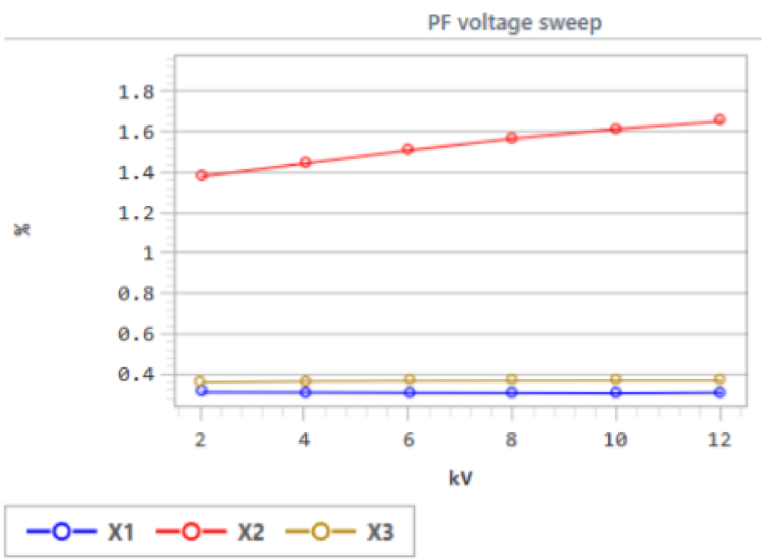
Ohio Brass 115kV Bushings (1975) – Note, only H1 and H3 are similar unit bushings				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
H1	0.30%	0.30%	0.00%	0.40%
H2	0.25%	0.25%	0.00%	0.31%
H3	1.12%	1.38%	0.26%	0.40%



Questionable Bushing C1 Power Factor Measurements

Lapp POC 72.5kV Bushings (1993)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
X1	0.38%	0.37%	-0.01%	0.19%
X2	1.21%	1.35%	0.14%	0.19%
X3	0.41%	0.43%	0.02%	0.18%

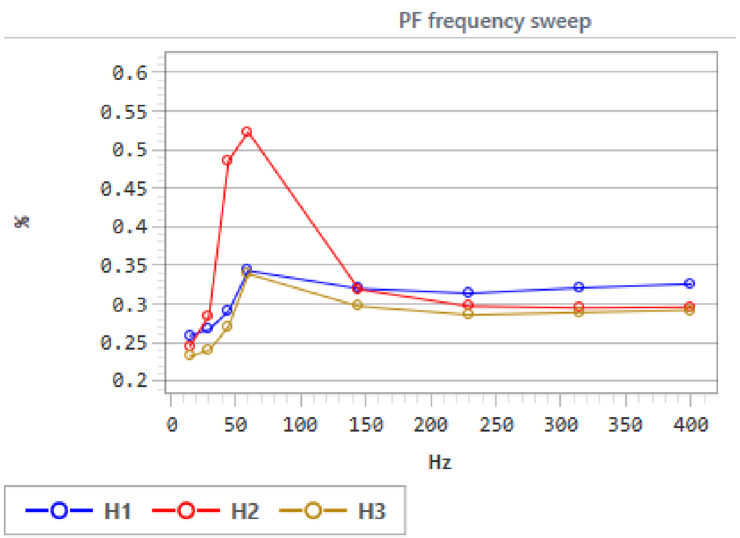




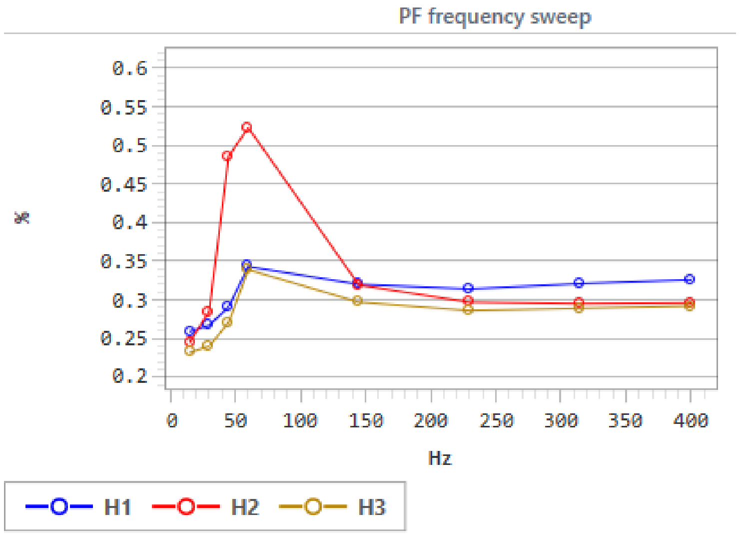
Using the Power Factor Sweep Tests to Identify Invalid Bushing Measurements

Questionable Bushing C1 Power Factor Sweep Measurements

Lapp POC 138kV Bushings (1998)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
H1	0.34%	0.36%	0.02%	0.29%
H2	0.52%	0.24%	-0.28%	0.23%
H3	0.34%	0.35%	0.01%	0.23%



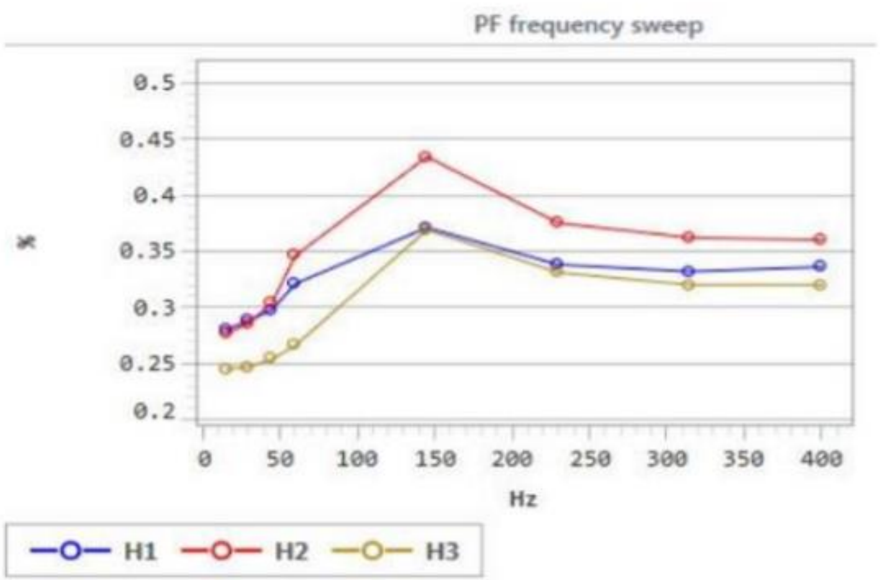
Questionable Bushing C1 Power Factor Sweep Measurements



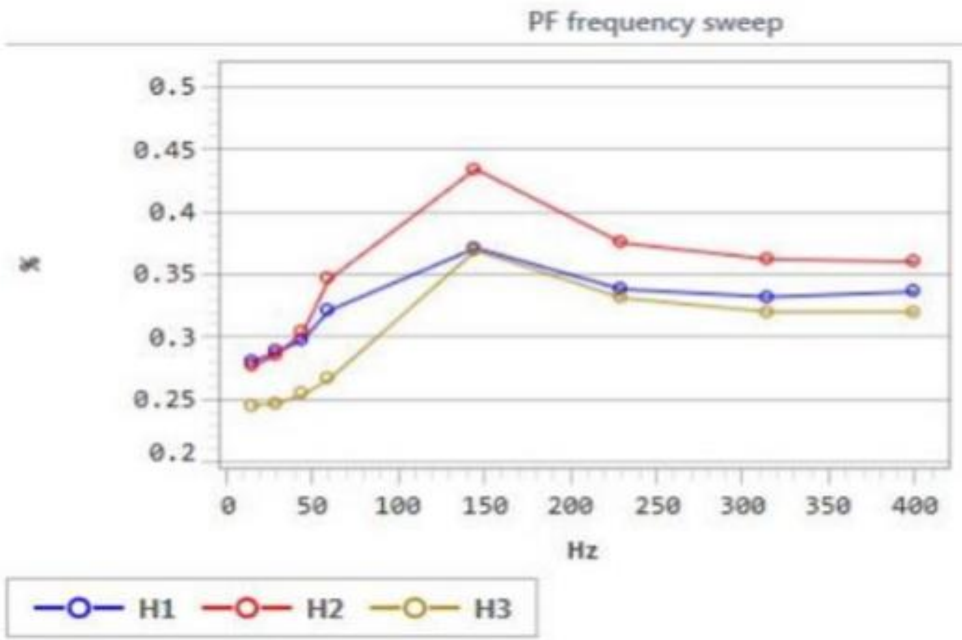
- Compromised insulation
- User-error – The customer did not short-circuit the primary side (H) bushings when the C1 Power Factor measurement was performed
- Test environment

Questionable Bushing C1 Power Factor Sweep Measurements

VTC 69kV Bushings (2009)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
H1	0.32%	0.36%	0.04%	0.31%
H2	0.36%	0.44%	0.08%	0.25%
H3	0.27%	0.30%	0.03%	0.25%



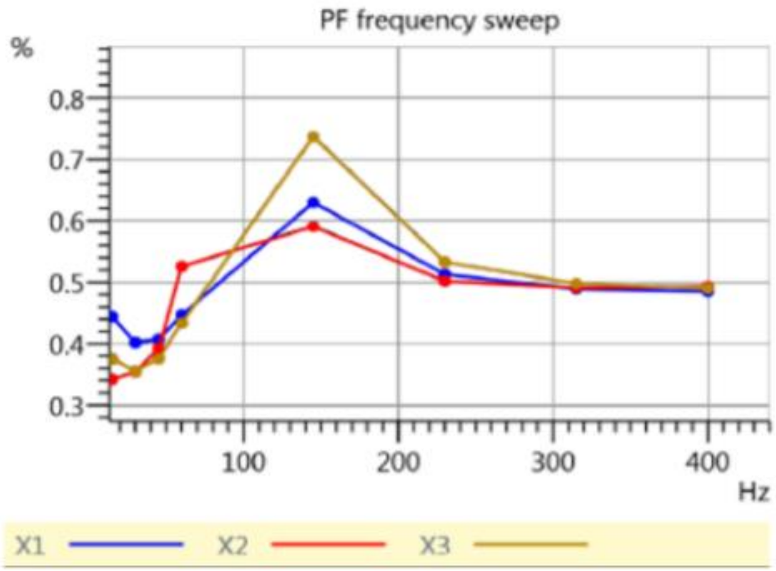
Questionable Bushing C1 Power Factor Sweep Measurements



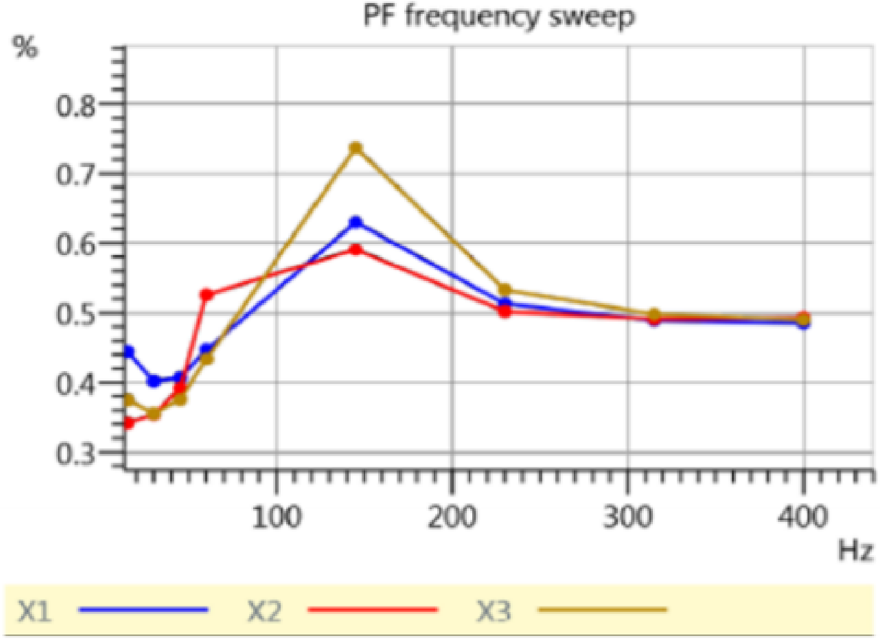
- Compromised insulation
- User-error
- Test environment

Questionable Bushing C1 Power Factor Sweep Measurements

McGraw Edison 69kV Bushings (1978)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
X1	0.45%	0.62%	0.17%	0.50%
X2	0.53%	0.76%	0.23%	0.50%
X3	0.43%	0.69%	0.26%	0.50%



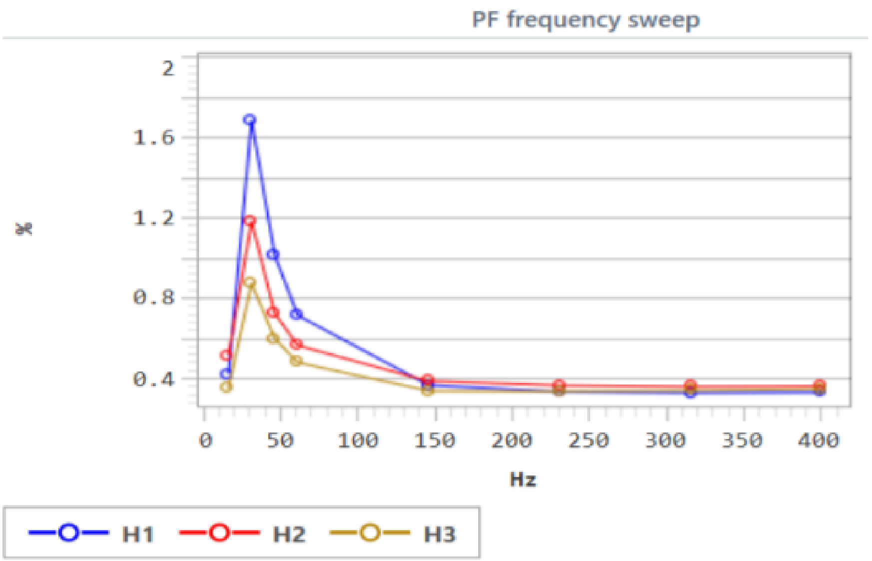
Questionable Bushing C1 Power Factor Sweep Measurements



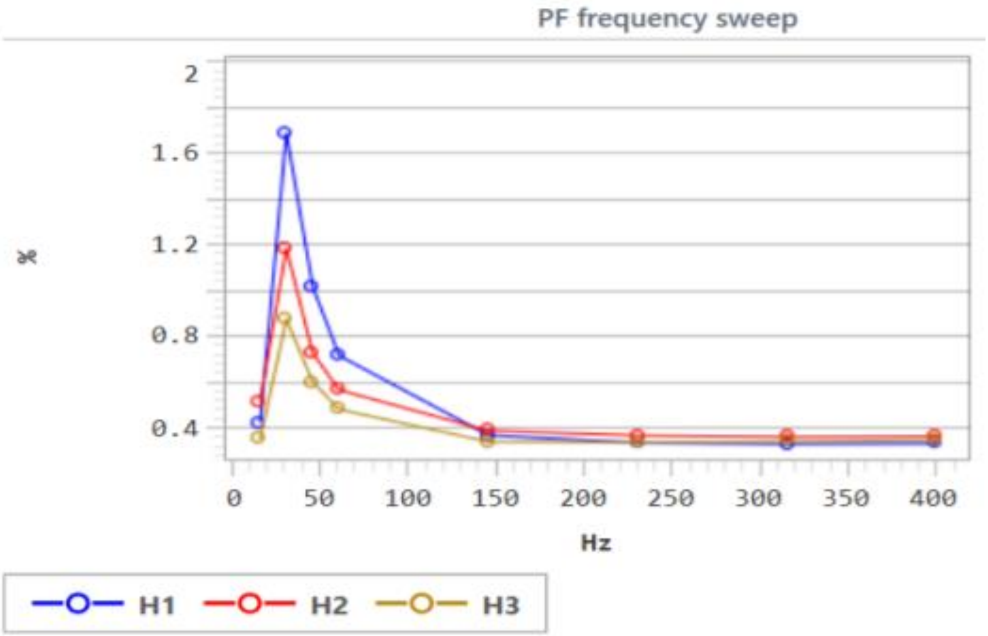
- Compromised insulation
- User-error
- Test environment

Questionable Bushing C1 Power Factor Sweep Measurements

GE Type U 230kV Bushings (1983)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
H1	0.72%	0.53%	-0.19%	0.27%
H2	0.57%	0.48%	-0.09%	0.29%
H3	0.48%	0.41%	-0.07%	0.28%



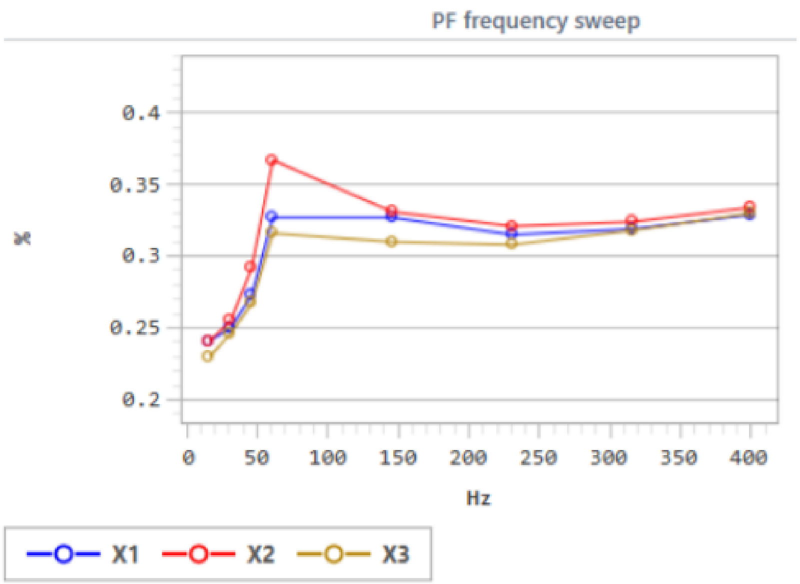
Questionable Bushing C1 Power Factor Sweep Measurements



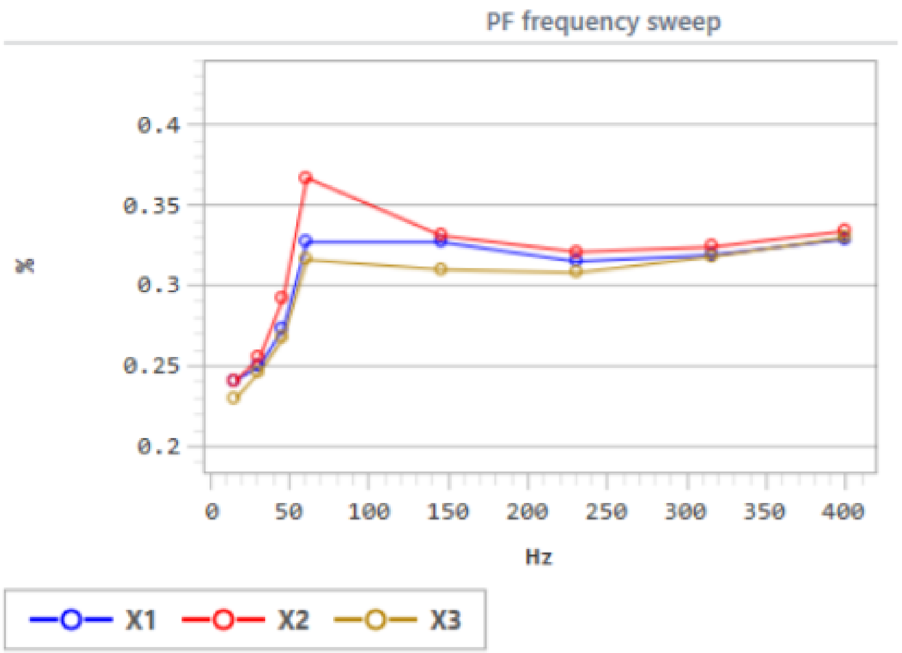
- Compromised insulation
- User-error
- Test environment

Questionable Bushing C1 Power Factor Sweep Measurements

GE Type U 150kV Bushings (1983)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
X1	0.32%	0.37%	0.05%	0.30%
X2	0.37%	0.37%	0.00%	0.29%
X3	0.32%	0.35%	0.03%	0.29%



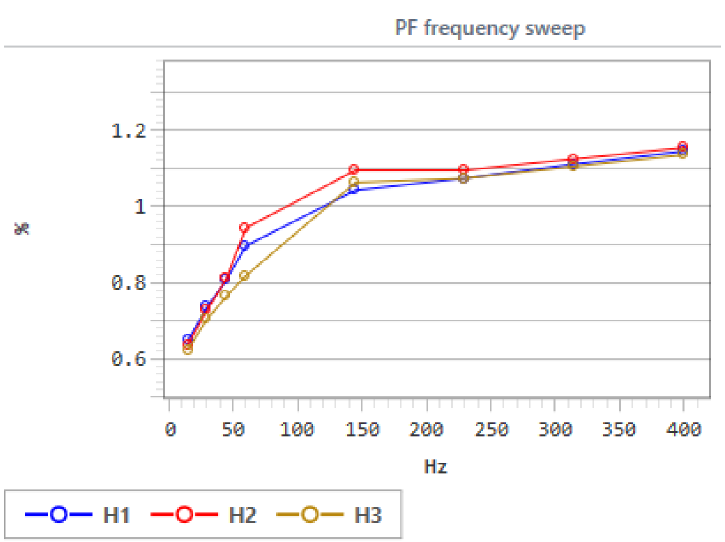
Questionable Bushing C1 Power Factor Sweep Measurements

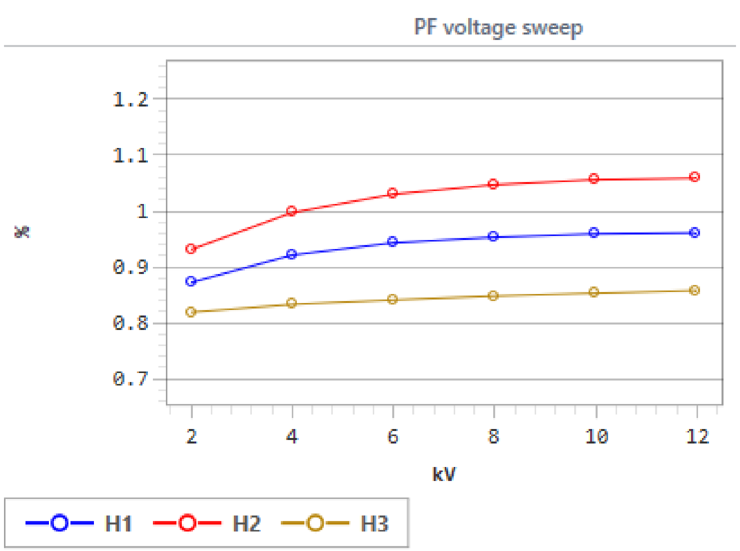


- Compromised insulation
- User-error
- Test environment

Questionable Bushing C1 Power Factor Sweep Measurements

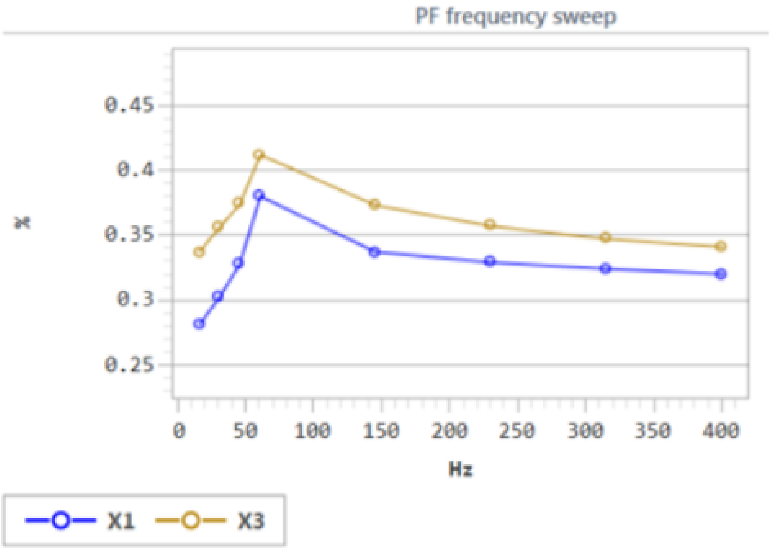
PCORE 69kV Bushings (2018)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
H1	0.90%	0.96%	0.06%	0.65%
H2	0.94%	1.06%	0.12%	0.64%
H3	0.82%	0.85%	0.03%	0.64%



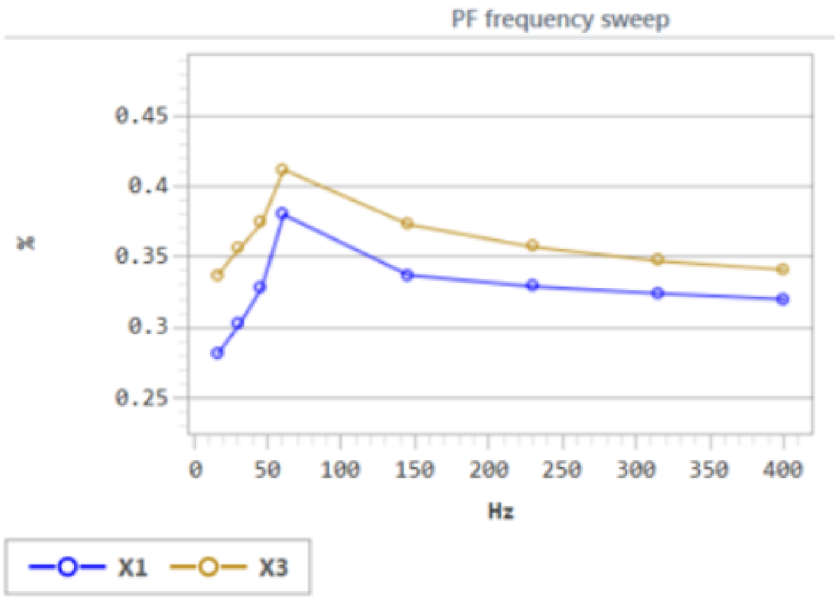


Questionable Bushing C1 Power Factor Sweep Measurements (with Emphasis on X1 and X3 Bushings)

Lapp POC 72.5kV Bushings (1993)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
X1	0.38%	0.37%	-0.01%	0.19%
X2	1.21%	1.35%	0.14%	0.19%
X3	0.41%	0.43%	0.02%	0.18%



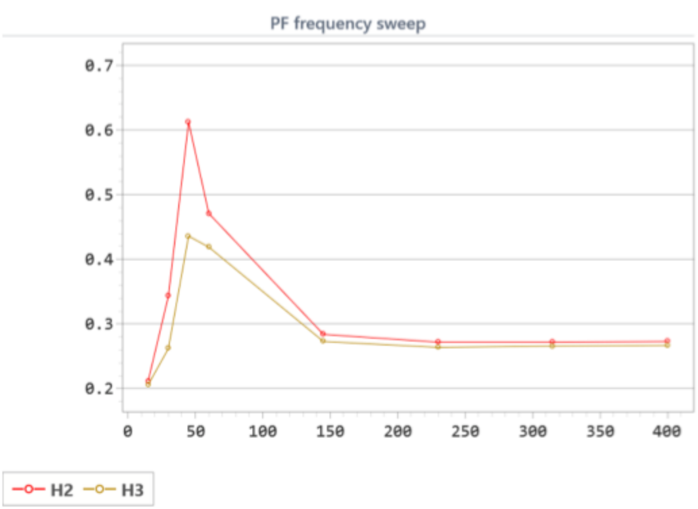
Questionable Bushing C1 Power Factor Sweep Measurements (with Emphasis on X1 and X3 Bushings)

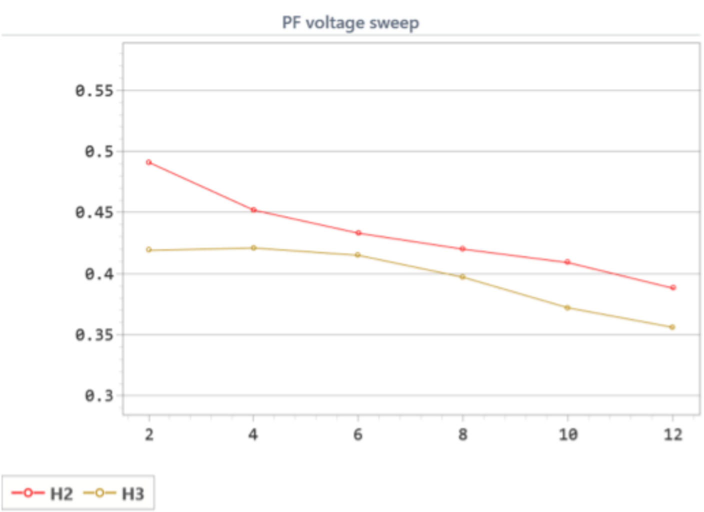


- Compromised insulation
- User-error
- Test environment

Questionable Bushing C1 Power Factor Sweep Measurements (with Emphasis on H2 and H3 Bushings)

ABB 115kV Bushings (2016)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
H1	-	-	-	0.25%
H2	0.47%	0.40%	-0.07%	0.25%
H3	0.42%	0.37%	-0.05%	0.25%





Bushing C2 Power Factor Test Examples

Questionable C2 Power Factor Measurement

McGraw-Edison 69kV Bushings (1978)					
	Test Voltage	Measured Power Factor	Measured Capacitance	Nameplate Power Factor	Nameplate Capacitance
H1	0.5kV	0.44%	432pF	-	-
H2	0.5kV	Overcurrent	Overcurrent	-	-
H3	0.5kV	0.24%	440pF	-	-

- The H2-C2 test could not be performed due to an overcurrent error (i.e. the test instrument "tripped" when the C2 measurement was performed)
- Assuming the test was performed correctly, there is clearly a defect involving the tap, the tap connection, and/or the tap insulation of the bushing

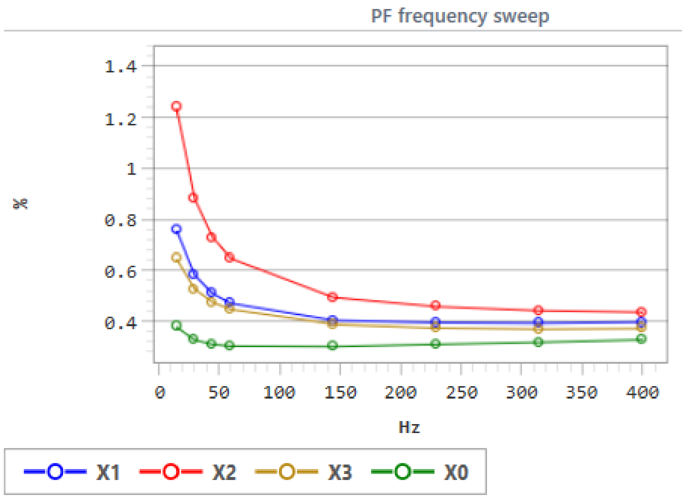
Case Study - GE Type U Bushings

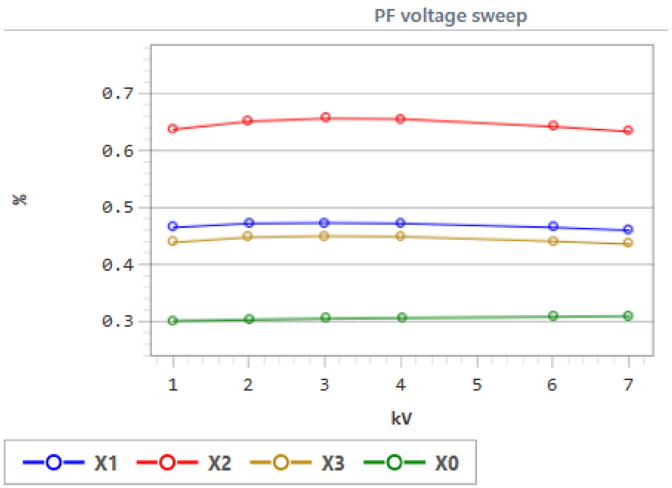
GE Type U 25kV Bushings (1986) – C2 Test					
	Test Voltage	Measured Power Factor	Measured Capacitance	Nameplate Power Factor	Nameplate Capacitance
X1	0.5kV	0.33%	769pF	-	-
X2	0.5kV	100%	67pF	-	-
X3	0.5kV	99.99%	596pF	-	-
X0	0.5kV	0.26%	791pF		

X2 C2 Investigation Test					
	Test Voltage	Measured Power Factor	Measured Capacitance	Nameplate Power Factor	Nameplate Capacitance
X2	0.1kV	99.97%	694pF	-	-
X2	0.25kV	99.99%	622pF	-	-
X2	0.5kV	99.99%	216pF	-	-

Case Study - GE Type U Bushings

GE Type U 25kV Bushings (1986)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
X1	0.47%	0.46%	-0.01%	0.29%
X2	0.65%	0.63%	-0.02%	0.30%
X3	0.45%	0.44%	-0.01%	0.30%
X0	0.31%	0.30%	-0.01%	0.28%





Case Study - GE Type U Bushings

GE Type U 25kV Bushings (1986)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
X1	0.47%	0.46%	-0.01%	0.29%
X2	0.65%	0.63%	-0.02%	0.30%
X3	0.45%	0.44%	-0.01%	0.30%
X0	0.31%	0.30%	-0.01%	0.28%

X2 Inverted C1 Investigation Test					
	Test Voltage	Measured Power Factor	Measured Capacitance	Nameplate Power Factor	Nameplate Capacitance
X2	0.1kV	0.52%	537pF	-	-
X2	0.25kV	0.59%	538pF	-	-
X2	0.5kV	0.45%	558pF	-	-

Questionable C2 Power Factor Measurement

GE Type-U 16kV Bushings					
	Test Voltage	**Measured Power Factor**	**Measured Capacitance**	**Nameplate Power Factor**	**Nameplate Capacitance**
X1	0.5kV	0.20%	749pF	-	-
X2	0.5kV	0.29%	718pF	-	-
X3	0.5kV	29.9%	845pF	-	-
X0	0.5kV	28.2%	883pF	-	-

- Compromised insulation – After performing a thorough investigation, the customer made the decision to replace the X3 and X0 bushings
- User-error
- Test environment

Questionable C2 Power Factor Measurement

PCORE POC 115kV Bushings					
	Test Voltage	**Measured Power Factor**	**Measured Capacitance**	**Nameplate Power Factor**	**Nameplate Capacitance**
H1	0.5kV	0.26%	3621pF	0.27%	3630pF
H2	0.5kV	-0.43%	3465pF	0.27%	3477pF
H3	0.5kV	0.34%	3502pF	0.29%	3506pF

- Compromised insulation
- User-error
- Test environment

Questionable C2 Power Factor Measurement

PCORE POC 115kV Bushings					
	Test Voltage	Measured Power Factor	Measured Capacitance	Nameplate Power Factor	Nameplate Capacitance
H1	0.5kV	0.26%	3621pF	0.27%	3630pF
H2	0.5kV	-0.43%	3465pF	0.27%	3477pF
H3	0.5kV	0.34%	3502pF	0.29%	3506pF

- **An "abnormally low" or negative Power Factor is typically caused by a high resistive path to ground**, which could be due to one of the following,
  - ❑ Compromised insulation
  - ❑ User error (e.g. a bad ground connection or a poor test connection)
  - ❑ Test environment – Moisture, high-humidity, rain, snow, cold temperatures, etc.
  - ❑ A test specimen that has a relatively low Capacitance value (typically defined as less than 80pF)
  - ❑ A loose or poorly connected bushing ground flange (typically only relevant when performing the C1 and C2 Power Factor measurements)

Questionable C2 Power Factor Measurement

ABB O+C 34.5kV Bushings					
	Test Voltage	Measured Power Factor	Measured Capacitance	Nameplate Power Factor	Nameplate Capacitance
X1	0.5kV	0.30%	309pF	0.19%	309pF
X2	0.5kV	1.9%	317pF	0.20%	308pF
X3	0.5kV	0.38%	309pF	0.19%	307pF

- Compromised insulation
- User-error
- Test environment

Unusually Low C2 Power Factor Measurements

ABB O+C 72.5kV Bushing (2013)					
	Test Voltage	Measured Power Factor	Measured Capacitance	Nameplate Power Factor	Nameplate Capacitance
H1	0.5kV	0.06%	484pF	0.18%	481pF
H2	0.5kV	0.001%	489pF	0.16%	481pF
H3	0.5kV	0.03%	481pF	0.17%	483pF

- Compromised insulation
- User-error
- Test environment

Unusually Low C2 Power Factor Measurements

ABB O+C 72.5kV Bushings (2009)					
	Test Voltage	Measured Power Factor	Measured Capacitance	Nameplate Power Factor	Nameplate Capacitance
H1	0.5kV	0.04%	507pF	0.15%	494pF
H2	0.5kV	0.06%	498pF	0.13%	503pF
H3	0.5kV	0.04%	493pF	0.14%	510pF

- Compromised insulation
- User-error
- Test environment

Unusually Low C2 Power Factor Measurements

- Was the transformer tank and test equipment solidly connected to earth ground potential, when the C2 Power Factor measurements were performed?
- Was the tap area of each bushing clean and dry, when the C2 Power Factor measurements were performed?
- Were the surfaces of the bushings clean and dry, when the C2 Power Factor measurements were performed?
- Were the bushing terminals short-circuited together, or not, when the C2 Power Factor measurements were performed?

Unusually Low C2 Power Factor Measurements

- Was the end of the high-voltage cable (i.e. the end of the cable that is connected to the bushing tap) “in the clear” when the measurement was performed?
- Were rubber blankets or insulator gloves used to keep the high-voltage cable off of the transformer tank, when the C2 Power Factor measurements were performed?
- To troubleshoot the C2 Power Factor measurement, apply a “jumper” from the bushing flange to the grounded transformer tank, and repeat the C2 measurement – This verifies the ground connection between the bushing’s flange and the transformer tank

Energized Collar (Hot Collar) Test Examples

Questionable Hot Collar Measurements

Bushing Manufacturer and Type not Provided			
	Test Voltage	**Measured Current**	**Measured Watt Losses**
H1	10kV	0.10mA	137mW
H2	10kV	0.09mA	270mW
H3	10kV	0.10mA	17mW

Acceptable Hot Collar Measurements

Bushing Manufacturer and Type not Provided			
	Test Voltage	**Measured Current**	**Measured Watt Losses**
X1	10kV	0.10mA	64mW
X2	10kV	0.10mA	65mW
X3	10kV	0.09mA	59mW
X0	10kV	0.10mA	47mW

Acceptable Hot Collar Measurements

Bushing Manufacturer and Type not Provided			
	Test Voltage	**Measured Current**	**Measured Watt Losses**
H1	10kV	0.11mA	31mW
H2	10kV	0.11mA	31mW
H3	10kV	0.11mA	31mW
H0	10kV	0.08mA	12mW

Acceptable Hot Collar Measurements

Bushing Manufacturer and Type not Provided			
	Test Voltage	**Measured Current**	**Measured Watt Losses**
X1	10kV	0.11mA	17mW
X2	10kV	0.11mA	17mW
X3	10kV	0.11mA	17mW
X0	10kV	0.09mA	20mW

OMICRON

A Bushing's Influence on the Overall Power Factor Test

Overall PF and Bushing Insulation

- The bushing insulation is “baked into” the Overall PF measurements,
  - ❑ The insulation of the primary side bushings is part of the CH measurement
  - ❑ The insulation of the secondary side bushings is part of the CL measurement
- The CHL measurement is not influenced by the insulation of the primary or secondary side bushings

Is the elevated CH due to the primary side bushings or not?

Measurement	Test mode	Sweep	V test	Freq.	V out	I out @10 kV	Watt losses @10 kV	PF meas
ICH+ICHL	GST	None	10.00 kV	60.00 Hz	10.00 kV	34.36 mA	1250.77 mW	0.3640 %
ICH (V)	GSTg-A	Voltage	10.00 kV	60.00 Hz	10.00 kV	12.38 mA	709.74 mW	0.5732 %
ICH (f)	GSTg-A	Frequency	2.00 kV	60.00 Hz	2.00 kV	12.39 mA	706.96 mW	0.5706 %
ICHL (V)	UST-A	Voltage	10.00 kV	60.00 Hz	10.00 kV	21.98 mA	542.34 mW	0.2467 %
ICHL (f)	UST-A	Frequency	2.00 kV	60.00 Hz	2.02 kV	21.99 mA	537.69 mW	0.2445 %

Bushing Insulation May...

- Negatively influence the Power Factor measurement – A bad bushing may cause an Overall Power Factor measurement to increase

- Positively influence the Power Factor measurement - Healthy bushings may cause an Overall Power Factor measurement to decrease (which may “mask” or hide a problem)

- Have no influence on the Overall Power Factor measurements

Overall Power Factor and Bushing Insulation

- If a transformer tests with an elevated CH or CL value, then we should first isolate and test the insulation of the bushings, to determine if the abnormally high measurement is due to a "bad" bushing or not
- Fortunately, if the C1 Power Factor measurement can be performed on the bushings, then we can subtract the contribution of the bushings from the Overall Power Factor measurement, to calculate the "true" CH and CL measurements
- To calculate the "true" CH measurement, the C1 Power Factor test must be performed on the primary side bushings
- To calculate the "true" CL measurement, the C1 Power Factor test must be performed on the secondary side bushings

Case Study #1: Bushings Worsening Overall Measurement

Overall Power Factor Measurement			
	Test Voltage	Power Factor	Capacitance
CH	10kV	0.54%	2323pF
CHL	10kV	0.24%	6163pF
CL	10kV	0.38%	11508pF

Case Study #1: Bushings Worsening Overall Measurement

Bushing H C1 Power Factor Measurement – PCORE PRC Bushing						
	Test Voltage	Current (mA)	Watts	Measured Power Factor	Nameplate Power Factor	Capacitance
H1	10kV	1.19	102.38	0.86%	0.6%	315pF
H2	10kV	1.21	111.01	0.92%	0.6%	320pF
H3	10kV	1.20	70.73	0.59%	0.6%	319pF

Case Study #1: Bushings Worsening Overall Measurement

	Current (mA)	Watts (mW)
H1	1.19	102
H2	1.21	111
H3	1.2	70.73
Total (H1+H2+H3)	3.6	283.73
CH	8.77	474
CH' (CH - Total)	5.17	190.27
CH' Power Factor	0.37%	
CH Power Factor	0.54%	

$$PF\ \% = \frac{Watts}{mA * 10kV} * 100\%$$

Case Study #2: Bushings Improving Overall Measurement

- Transformer Nameplate Information
  - Dyn1
  - 115kV – 12.47kV
  - 12MVA
  - Filled with Mineral Oil
  - Year of Manufacturing: 2012

Case Study #2: Bushings Improving Overall Measurement

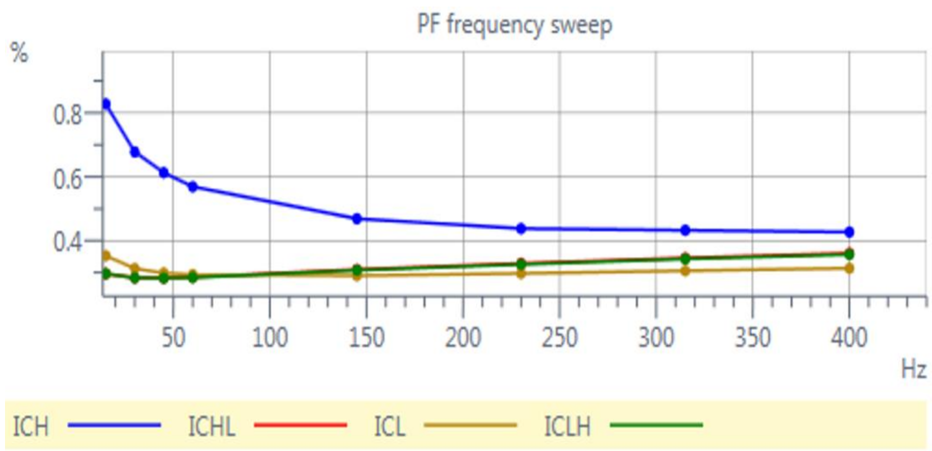
DISSOLVED GAS IN OIL ANALYSIS

Date:	07-Apr-16	03-Feb-15	
Temp:	30C	20C	
Hydrogen (H2)	2	2	ppm
Methane (CH4)	10	2	ppm
Ethane (C2H6)	33	0	ppm
Ethylene (C2H4)	118	0	ppm
Acetylene (C2H2)	20	0	ppm
Carbon Monoxide (CO)	37	36	ppm
Carbon Dioxide (CO2)	889	1924	ppm
Nitrogen (N2)	61283	80974	ppm
Oxygen (O2)	26002	4849	ppm
Total Gas	88394	87787	ppm
Total Combustible Gas	220	40	ppm
Equivalent TCG Reading	0.0556	0.0359	%

Comments: Increase in Acetylene may indicate arcing in oil

Case Study #2: Bushings Improving Overall Measurement

Overall Power Factor Measurement			
	Test Voltage	Power Factor	Capacitance
CH	10kV	0.58%	2180pF
CHL	10kV	0.29%	4802pF
CL	10kV	0.30%	9476pF



Case Study #2: Bushings Improving Overall Measurement

Overall Power Factor Measurement - 2013			
	Test Voltage	Power Factor	Capacitance
CH	10kV	0.27%	2174pF
CHL	10kV	0.26%	4779pF
CL	10kV	0.26%	9439pF

Overall Power Factor Measurement - 2016			
	Test Voltage	Power Factor	Capacitance
CH	10kV	0.58%	2180pF
CHL	10kV	0.29%	4802pF
CL	10kV	0.30%	9476pF

Case Study #2: Bushings Improving Overall Measurement

Bushing H C1 Power Factor Measurement					
	Test Voltage	Current (mA)	Watts	Power Factor	Capacitance
H1	10kV	1.29	34.28	0.27%	525pF
H2	10kV	1.31	48.67	0.37%	478pF
H3	10kV	1.30	37.57	0.29%	468pF

Case Study #2: Bushings Improving Overall Measurement

	Current (mA)	Watts (mW)
H1	1.29	34.3
H2	1.31	48.7
H3	1.30	37.7
Total (H1+H2+H3)	3.90	120.7
CH	8.23	476
CH' (CH - Total)	4.33	355
CH' Power Factor	**0.82%**	
CH Power Factor	0.57%	

$$PF\ \% = \frac{0.355\ Watts}{4.33\ mA * 10kV} * 100\% = 0.82\%$$

Case Study #3: Bushings Improving Overall Measurement

Overall Power Factor Measurement			
	Test Voltage	Power Factor	Capacitance
CH	10kV	0.62%	2507pF
CHL	10kV	0.55%	5039pF
CL	10kV	0.61%	12286pF

- Questionable CH – Perform the C1 Power Factor test on the primary side bushings and remove the contribution of the bushings from the Overall CH measurement
- Questionable CL – The secondary side bushings did not have test taps, so the secondary bushings could not be removed from the Overall CL measurement
- Questionable CHL – The insulation of the bushings do not influence the CHL measurement

Case Study #3: Bushings Improving Overall Measurement

Bushing H C1 Power Factor Measurement – ABB O+C Bushings					
	Test Voltage	Current (mA)	Watts	Power Factor	Capacitance
H1	10kV	1.20	0.029	0.24%	317pF
H2	10kV	1.20	0.031	0.26%	317pF
H3	10kV	1.18	0.029	0.25%	313pF

Case Study #3: Bushings Improving Overall Measurement

Bushing H C1 Power Factor Measurement – ABB O+C Bushings					
	Test Voltage	Current (mA)	Watts	Power Factor	Capacitance
H1	10kV	1.20	0.029	0.24%	317pF
H2	10kV	1.20	0.031	0.26%	317pF
H3	10kV	1.18	0.029	0.25%	313pF

$$\text{PF \%} = \frac{0.493\,Watts}{5.88\,mA * 10kV} * 100\% = 0.84\%$$

	Current (mA)	Watts (mW)
H1	1.20	0.029
H2	1.20	0.031
H3	1.18	0.029
Total (H1+H2+H3)	3.58	0.089
CH	9.45	0.582
CH' (CH - Total)	5.88	0.493
CH' Power Factor	**0.84%**	
CH Power Factor	0.62%	

Case Study #4: Bushings Worsening Overall Measurement

- Transformer Nameplate Information
  - Dyn1
  - 115kV – 12.47kV
  - 30MVA
  - Filled with Mineral Oil

Case Study #4: Bushings Worsening Overall Measurement

Overall Power Factor Measurement			
	Test Voltage	Power Factor	Capacitance
CH	10kV	1.36%	2971pF
CHL	10kV	0.18%	7323pF
CL	10kV	0.43%	21972pF

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Case Study #4: Bushings Worsening Overall Measurement

Bushing H C1 Power Factor Measurement – ABB O+C Bushings					
	Test Voltage	Current (mA)	Watts	Power Factor	Capacitance
H1	10kV	1.60	-0.09	-0.56%	424pF
H2	10kV	1.70	0.171	1.01%	451pF
H3	10kV	1.60	0.195	1.22%	425pF

- A Negative Power Factor typically indicates that there is a high resistive path to ground, which is most likely caused by one of the following,
  - ❑ Compromised insulation
  - ❑ External contamination on surface of bushings (clean and dry)
  - ❑ Loose ground flange on bushing (perform continuity test to investigate)

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Case Study #4: Bushings Worsening Overall Measurement

Overall Power Factor Measurement After all Primary (H) Bushings were Replaced			
	Test Voltage	Power Factor	Capacitance
CH	10kV	0.29%	3076pF
CHL	10kV	0.18%	7331pF
CL	10kV	0.31%	21997pF

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Case Study #5: Bushings Worsening Overall Measurement

Overall Power Factor Measurement					
	Test Voltage	Current	Watts	Power Factor	Capacitance
CH	10kV	9.2mA	0.269W	0.28%	2428pF
CHL	10kV	18.8mA	0.871W	0.45%	4994pF
CL	10kV	32.3mA	3.58W	1.08%	8554pF

Case Study #5: Bushings Worsening Overall Measurement

Bushing X C1 Power Factor Measurement					
	Test Voltage	Current	Watts	Power Factor	Capacitance
X1	10kV	1.992mA	2.293W	11.51%	525pF
X2	10kV	1.802mA	0.07W	0.39%	478pF
X3	10kV	1.763mA	0.063W	0.36%	468pF
X0	10kV	1.798mA	0.063W	0.35%	477pF

Case Study #5: Bushings Worsening Overall Measurement

Bushing X C1 Power Factor Measurement

	Test Voltage	Current (mA)	Watts	% PF	Cap. (pF)
X1	10kV	1.992	2.293	11.51	525
X2	10kV	1.802	0.070	0.39	478
X3	10kV	1.763	0.063	0.36	468
X0	10kV	1.798	0.063	0.35	477

$$PF = \frac{Watts}{kV * mA} * 100\%$$

$$PF\ \% = \frac{1.091\ Watts}{24.9\ mA * 10kV} * 100\% = 0.44\%$$

	Current (mA)	Watts
X1	1.992	2.293
X2	1.802	0.070
X3	1.763	0.063
X0	1.798	0.063
Total (X1+X2+X3+X0)	7.355	2.489
CL	32.35	3.58
CL' (CL - Total)	24.897	1.091
CL' Power Factor	0.44%	
CL Power Factor	1.08%	

Overall Power Factor Measurement

	Test Voltage	Current (mA)	Watts	% PF	Cap. (pF)
CH	10kV	9.156	0.269	0.28	2428
CHL	10kV	18.83	0.871	0.45	4994
CL	10kV	32.35	3.58	1.08	8554

Troubleshooting a Questionable Bushing Power Factor Test

Troubleshooting a Bushing Power Factor Test

- Were the surfaces of the bushings cleaned and dried before the measurement was performed?
    - ❑ Porcelain exterior – Use Windex or Collinite
    - ❑ Silicone exterior – Use a clean, dry rag
- If performing a C2 Power Factor measurement, clean and dry the tap area of the bushing (use a clean, dry rag), and then repeat the test
- Were the bushings short-circuited together when the measurement was performed? Did you use bare copper?

Troubleshooting a Bushing Power Factor Test

- Is both the transformer and the test equipment solidly grounded to earth potential?

- Is there a solid connection from the bushing flange to the ground plane of the transformer?

  - ❑ Perform a continuity test

  - ❑ Connect a jumper wire from the bushing flange to earth ground and retest the bushing to determine if the results improve

- Connect the test equipment ground directly to the ground flange of the bushing, and repeat the bushing Power Factor test

Troubleshooting a Bushing Power Factor Test

- Were the bushings tested in the transformer tank or out of the transformer tank? Is this a different test setup than the factory or previous measurement?

- Were the bushings tested in a wooden crate or on a wooden stand? Note, bushings should only be tested in a metal stand or in a web sling

- Was the bushing suspended while it was tested? Was it suspended upright or at an abnormal angle?

- Does the bushing require a bushing tap adapter? Was it properly applied?

Abnormally Low or Negative Power Factor

- **An "abnormally low" or negative Power Factor is typically caused by a high resistive path to ground**, which could be due to one of the following,
  - ❑ User error (e.g. a bad ground connection or a poor test connection)
  - ❑ Test environment – Moisture, high-humidity, rain, snow, cold temperatures, etc.
  - ❑ A test specimen that has a relatively low Capacitance value (typically defined as less than 80pF)
  - ❑ A loose or poorly connected bushing ground flange (typically only relevant when performing the C1 and C2 Power Factor measurements)
  - ❑ Compromised insulation

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Testing a Spare Bushing (Outside of a Transformer)

Testing a Spare Bushing (Outside of a Transformer)

- Do not test the bushing in a wooden crate or in a wooden stand
- Test the bushing in a metal stand, if possible
- A web sling may be used to suspend the bushing (upright)
  - ❑ The web sling must be clean and dry
  - ❑ Note, if suspended, ensure that the bushing does not tilt by more than approximately 15° from the upright position
- Ground the bushing flange to earth potential
- Ground the test equipment directly to the bushing flange

Testing a Spare Bushing (Outside of a Transformer)

- Clean and dry the exterior surface of the bushing before testing
  - ❑ Porcelain exterior – Use Windex or Collinite
  - ❑ Silicone exterior – Use a clean, dry rag
- If the bushing does not have a tap, then perform the Overall test
- If the bushing has a tap, then perform the Overall, C1, and C2 tests

Thank you!