

Variable Frequency Power Factor and Voltage Tip-Up Tests (In-Depth)

***For more information regarding this topic, please refer to my “Value of Performing Power Factor Sweep Measurements on Bushings” paper**



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includes both presentations and hands-on training. Brandon is an active member of the IEEE/PES Transformers Committee.

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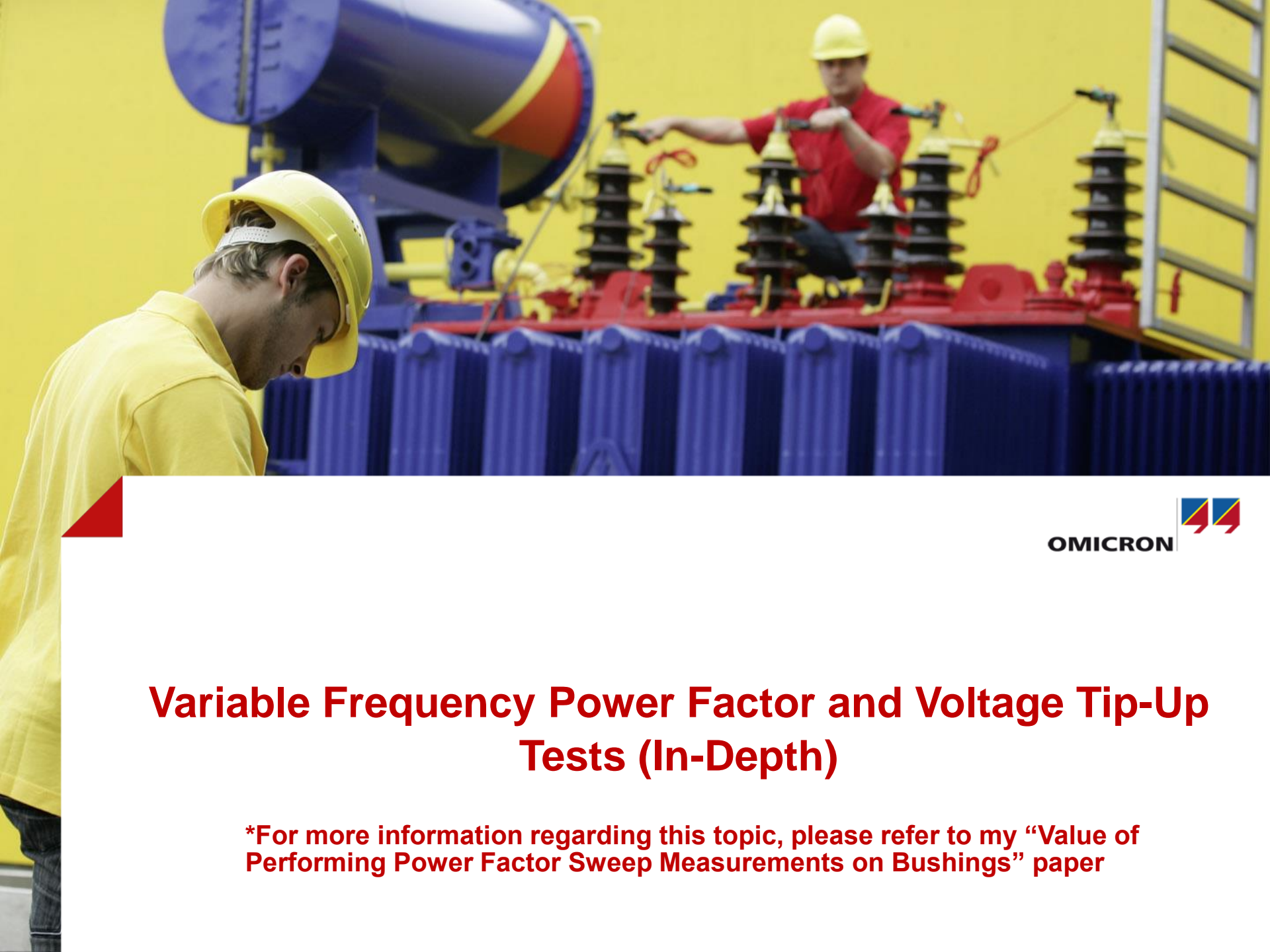
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Variable Frequency Power Factor and Voltage Tip-Up Tests (In-Depth)

***For more information regarding this topic, please refer to my “Value of Performing Power Factor Sweep Measurements on Bushings” paper**

The Power Factor Test

- The Power Factor Test is used to test the integrity of the **insulation system** of a transformer
- The Power Factor Test can identify the following **insulation** defects,
 - ☐ **Naturally aged, deteriorated, and/or contaminated insulation**
 - ☐ **Overheated insulation**
 - ☐ **Moisture ingress**, which is one of the main “transformer killers”
 - ☐ **Localized insulation failures**, such as a partial or full short-circuit to ground, or between the windings

The “Big Three” of Power Factor Testing

- In nearly all cases, a “questionable” or “abnormal” Power Factor measurement is caused by one of the following three things,
 1. **User-error**
 2. **The test-environment**
 3. **Compromised insulation**
- Most of the time, a “questionable” or “abnormal” Power Factor measurement is caused by one of the first two items listed above
- The test-equipment operator must troubleshoot, and retest, to determine which of the three items listed above is causing a “questionable” or “abnormal” Power Factor measurement

The Value of Performing Power Factor Sweep Tests

- The **voltage sweep test** involves performing Power Factor measurements at different test voltages (e.g. 2kV, 4kV, 6kV, 8kV, and 10kV)
- The **frequency sweep test** involves performing Power Factor measurements at different test frequencies (e.g. at 15Hz, 30Hz, 60Hz, 200Hz, and 400Hz)
- In its simplest terms, the Power Factor voltage sweep and frequency sweep tests can be used to,
 1. Better identify “bad” Power Factor measurements
 2. Better assess the condition of an insulation system

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

- The **voltage sweep** test involves performing Power Factor measurements at 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 test voltages (e.g. at 2kV and at 10kV)
- In most cases, the Power Factor measurement performed on an oil-and-paper insulation system should not be voltage sensitive
- If a Power Factor measurement is not reasonably similar at two different test voltages, then the measurement should be investigated

The Power Factor Frequency Sweep Test

- The **frequency sweep** test involves performing Power Factor measurements at different test frequencies (e.g. at 15Hz, 30Hz, 60Hz, 200Hz, and 400Hz)
- The Power Factor measurement is plotted versus the applied test-frequency, and is analyzed based on the shape of the frequency sweep “trace”
- Emphasis is typically placed on the Power Factor measurements at frequencies below 60Hz (i.e. at the “lower frequencies”)
- A Power Factor measurement at a frequency below 60Hz, is more sensitive than a Power Factor measurement at 60Hz

Who Can Benefit from Performing Power Factor Sweep Tests?

The Test-Equipment Operator

- Unfortunately, the Power Factor Measurement is highly sensitive, and is one of the hardest measurements to “get right”
- With a Power Factor measurement at one test-voltage and at one test-frequency, it is difficult to determine whether or not a measurement is even valid
- **Invalid measurements often become obvious when the Power Factor sweep measurements are performed and analyzed**
- **The test-equipment operator should use the Power Factor sweep measurements as a tool, to identify and correct “bad” measurements, before leaving the job-site**

Who Can Benefit from Performing Power Factor Sweep Tests?

The Engineer

- The engineer is responsible for assessing the condition of the insulation system, to determine the best “course of action”
- Typically, the engineer is not on-site when the Power Factor measurements are performed; therefore, it is difficult for the engineer to be confident that the measurements are even valid
- If the engineer has the Power Factor frequency and voltage sweep test results in-hand, then they can better identify invalid measurements, which helps to prevent an incorrect condition assessment
- The Power Factor frequency and voltage sweep tests 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

Power Factor Frequency Sweep - Analysis Guidelines

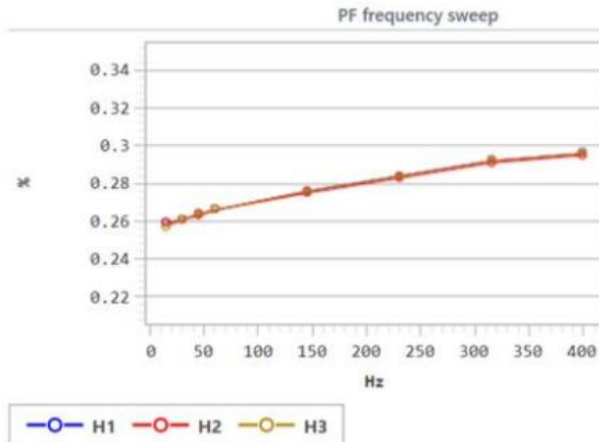
- The analysis of the Power Factor frequency sweep measurement is performed visually
- The condition of the insulation system is assessed based on the shape of the frequency sweep traces
- In general, the analysis involves determining whether or not the shape of a trace is “normal” or “abnormal”

Power Factor Frequency Sweep - Analysis Guidelines

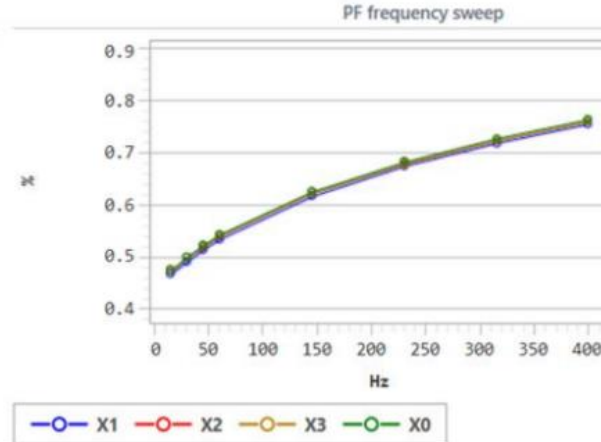
- In general, if the insulation system under test is healthy, then the Power Factor value will **increase** (from left-to-right) versus frequency for the majority of the sweep
- In general, if the insulation system is compromised, then the Power Factor value will **decrease** (from left-to-right) versus 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)
- **The guidelines states above are valid for fluid-filled power transformers and fluid-filled bushings**
- **When comparing sister unit bushings, the shape of the frequency sweep traces should be reasonably similar**

Four Examples of “Typical”, Acceptable Bushing C1 Power Factor Frequency Sweep Results

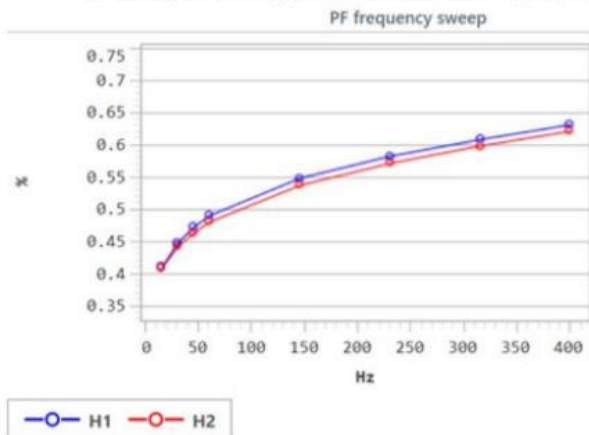
ABB O+C II - 115kV Bushings (2015)



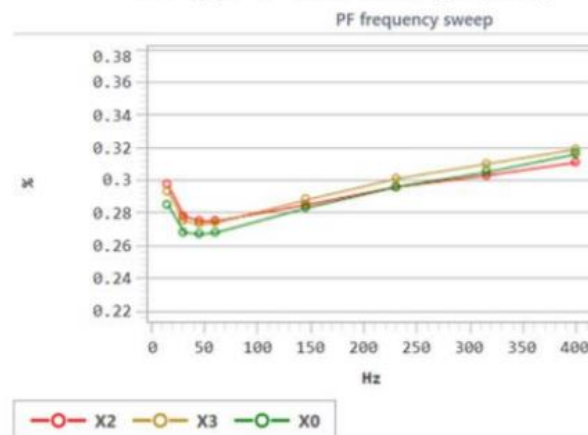
Hubbell PCORE PRC - 15kV Bushings (2014)



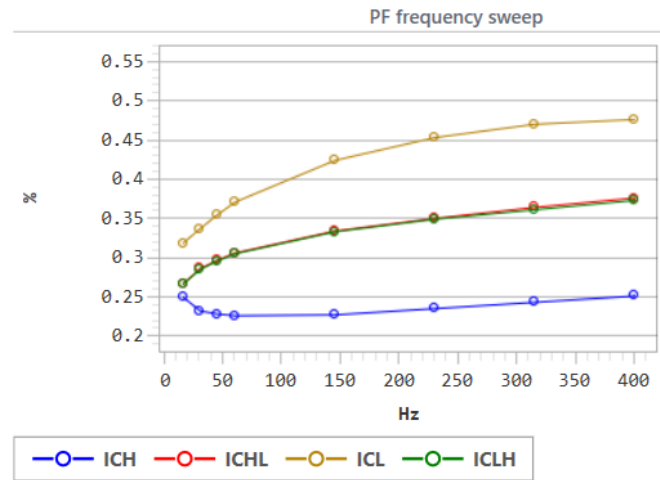
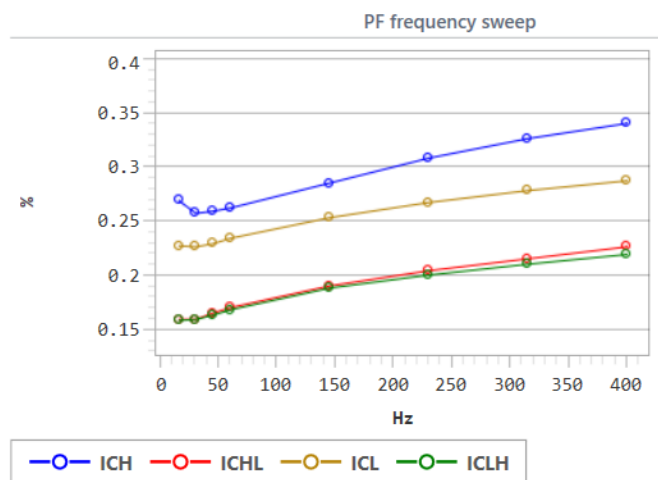
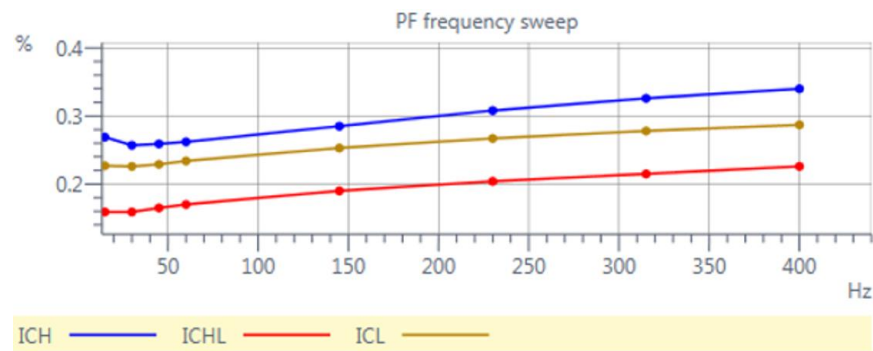
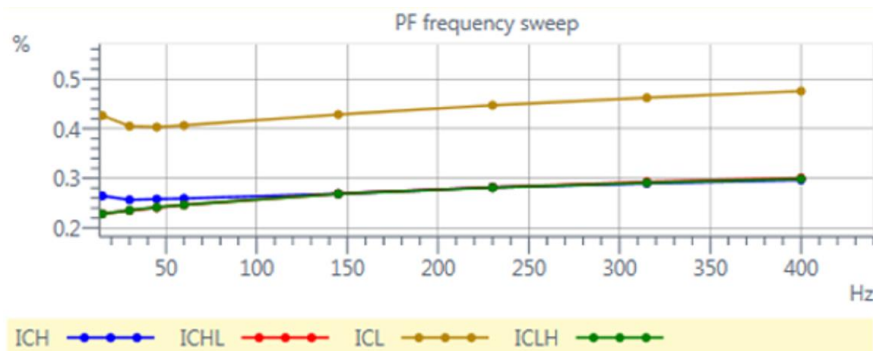
Westinghouse Type O - 69kV Bushings (1969)



GE Type U - 16kV Bushings (1978)



Four Examples of “Typical”, Acceptable Overall Power Factor Frequency Sweep Results (for fluid-filled power transformers)

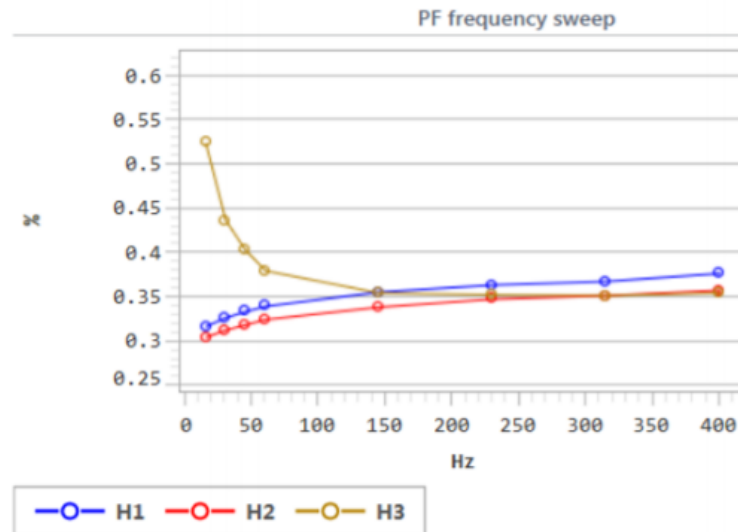




Examples of Suspect Insulation, Identified by Utilizing the Power Factor Sweep Tests

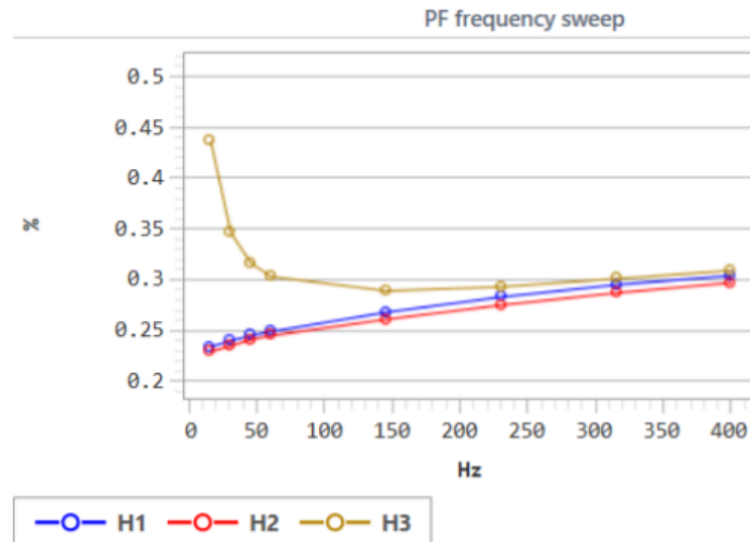
Example: Bushing C1 Power Factor Test

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%



Example: Bushing C1 Power Factor Test

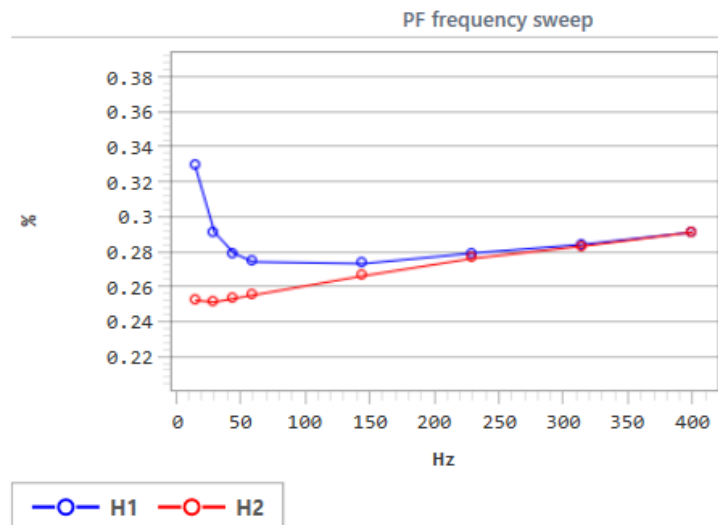
ABB O+C 115kV Bushings (1992)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
H1	0.25%	0.25%	0.00%	0.26%
H2	0.24%	0.24%	0.00%	0.24%
H3	0.30%	0.31%	0.01%	0.25%



Example: Bushing C1 Power Factor Test

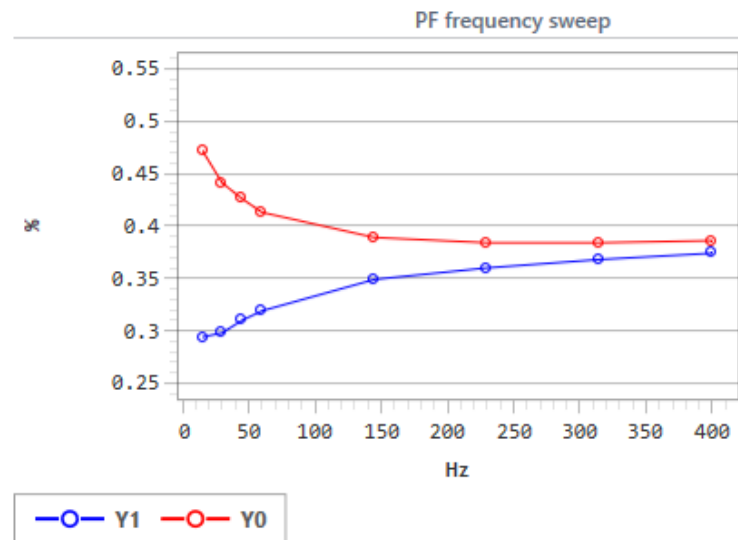
Lapp POC Series 2 115kV Bushings (1998)

	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%



Example: Bushing C1 Power Factor Test

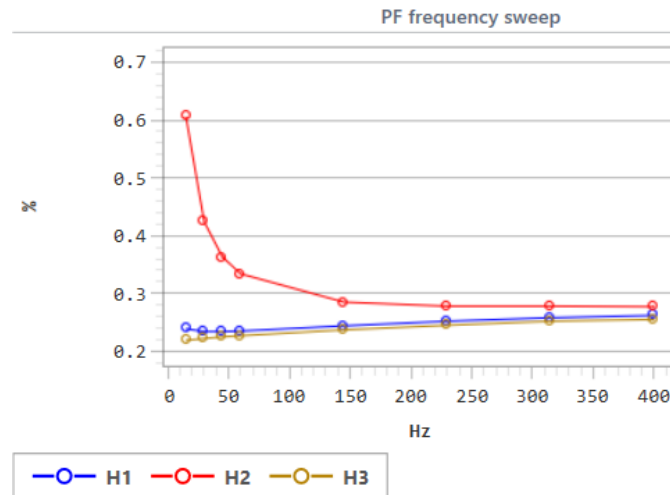
GE Type-U 16kV Bushing (1964)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
Y1	0.32%	0.32%	0.00%	-
Y0	0.41%	0.44%	0.03%	-



Example: Bushing C1 Power Factor Test

ABB O+C 142kV Bushings (2010)

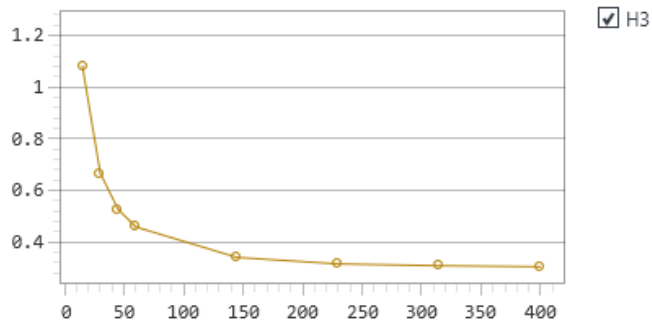
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
H1	0.24%	0.24%	0.00%	0.26%
H2	0.33%	0.36%	0.03%	0.26%
H3	0.23%	0.23%	0.00%	0.24%



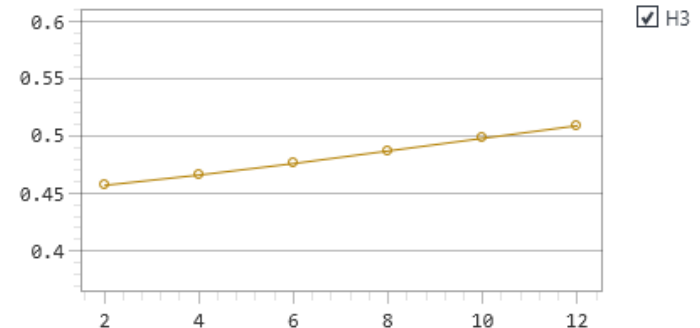
Example: Bushing C1 Power Factor Test (note, the VFPP and Tip-Up Tests were only performed on the H3 bushing)

ABB O+C 115kV Bushings (1999)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
H1	-	0.25%	-	0.23%
H2	-	0.29%	-	0.23%
H3	0.46%	0.50%	0.04%	0.23%

PF frequency sweep

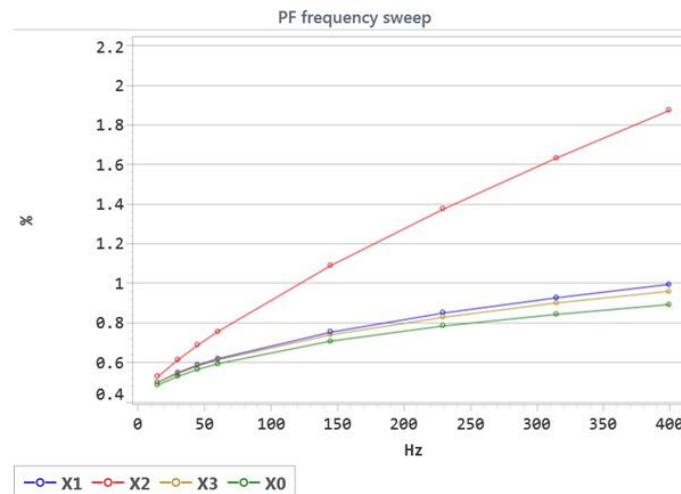


PF voltage sweep



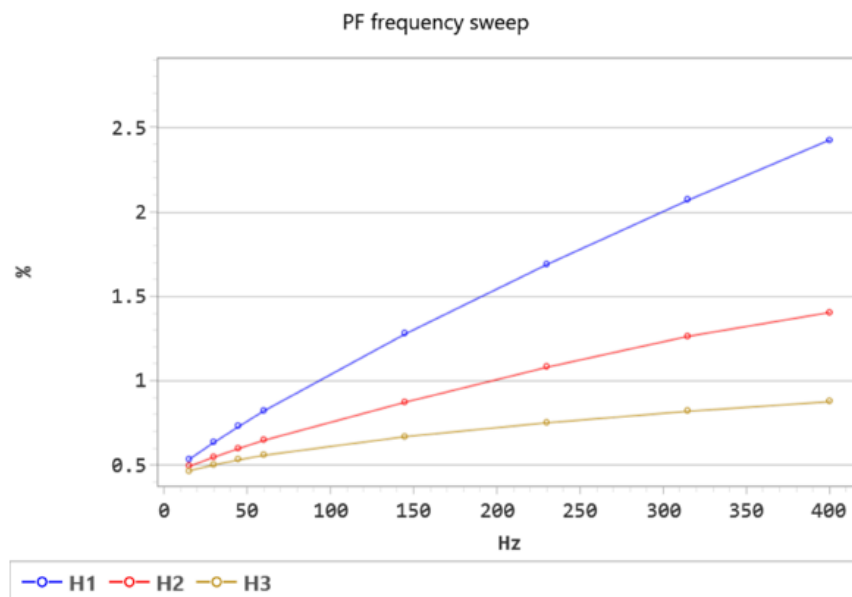
Example: Bushing C1 Power Factor Test

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%



Example: Bushing C1 Power Factor Test

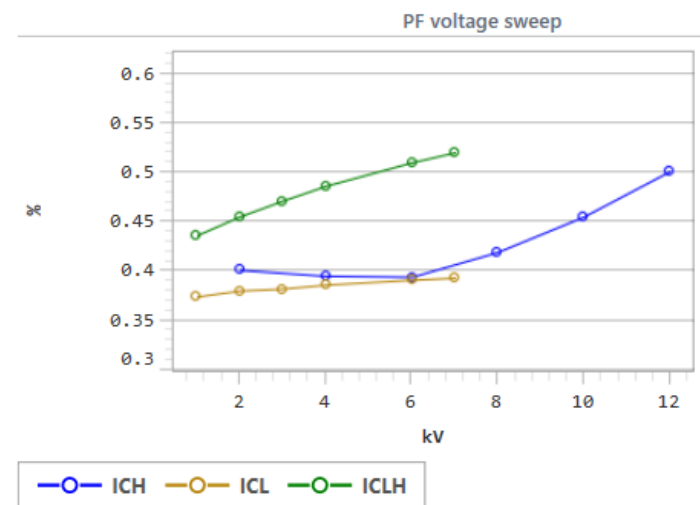
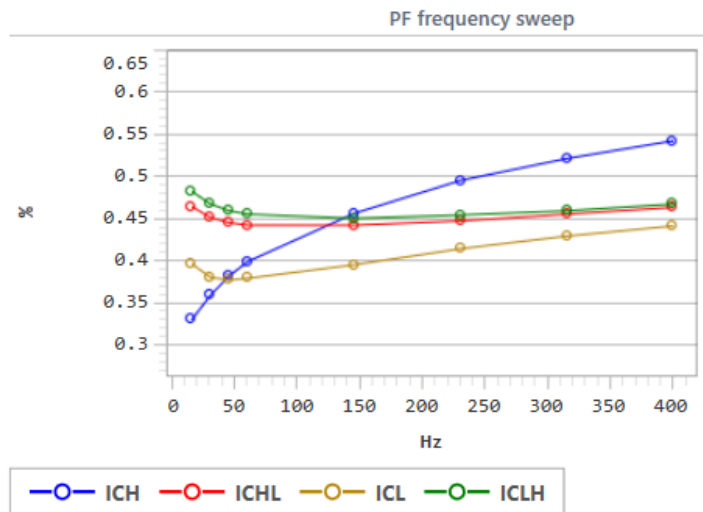
PCORE 69kV Bushings (2019)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
H1	0.81%	0.81%	0.00%	0.64%
H2	0.66%	0.66%	0.00%	0.65%
H3	0.56%	0.56%	0.00%	0.64%



Example: The Overall Power Factor Test

Serial number	Mfg. Year	Rated Power	Voltage (Prim.)	Voltage (Sec.)
		12MVA	68.8kV	13.09kV

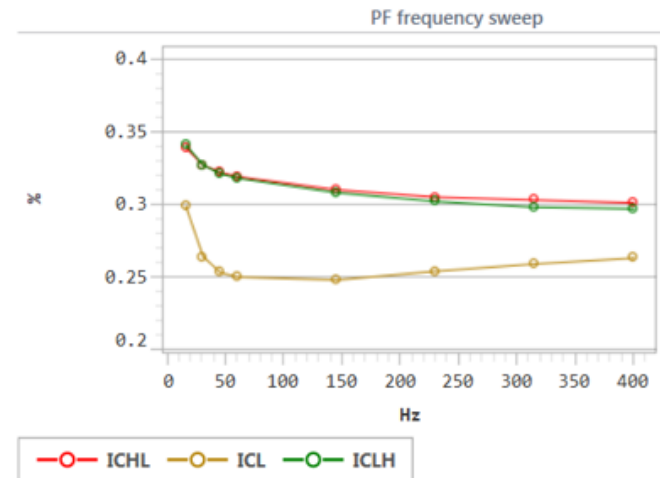
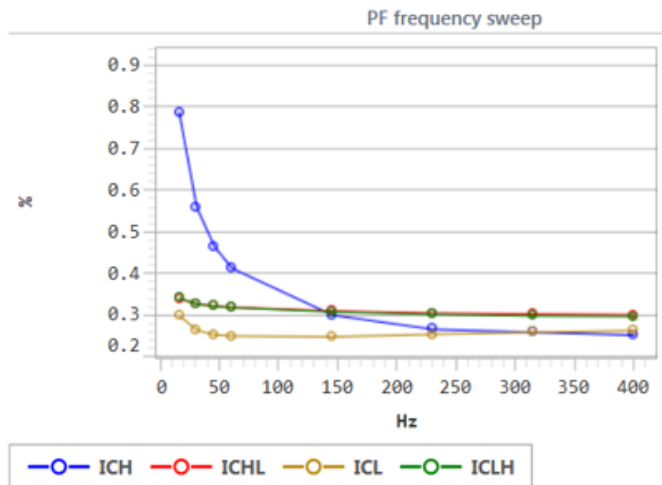
Measurement	2kV PF	10kV PF	10kV PF – 2kV PF
CH	0.40%	0.45%	0.05%
CL	0.38%	0.39%	0.01%
CHL	0.44%	0.52%	0.08%



Example: The Overall Power Factor Test

Serial number	Mfg. Year	Rated Power	Voltage (Prim.)	Voltage (Sec.)
	2004	56MVA	69kV	14.4kV

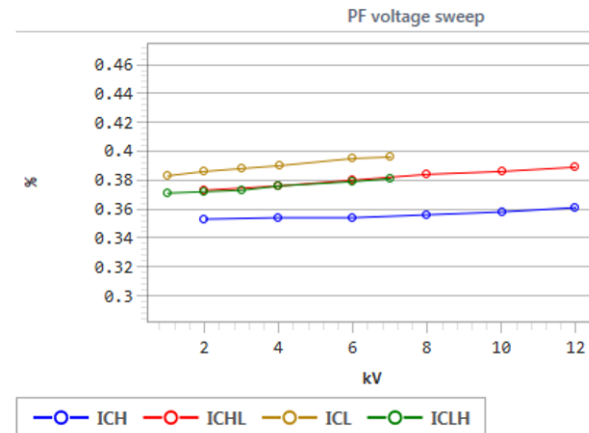
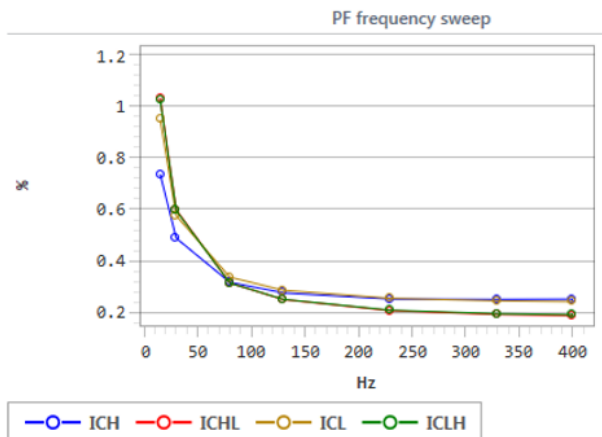
Measurement	2kV PF	10kV PF	10kV PF – 2kV PF
CH	0.41%	0.41%	0.00%
CL	0.25%	0.26%	0.01%
CHL	0.32%	0.36%	0.04%



Example: The Overall Power Factor Test

Serial number	Mfg. Year	Rated Power	Voltage (Prim.)	Voltage (Sec.)
	2005	20MVA	115kV	13.2kV

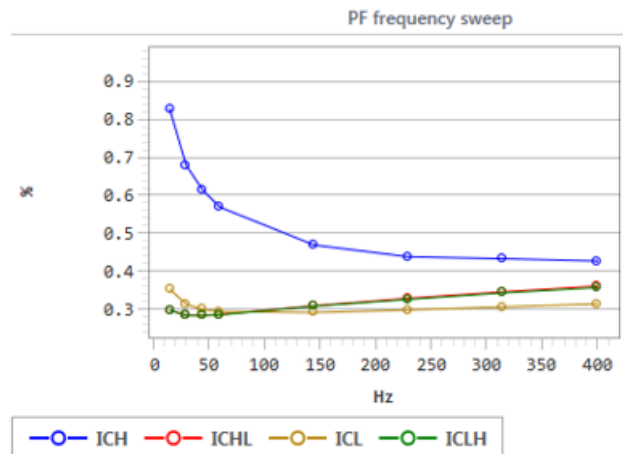
Measurement	2kV PF	10kV PF	10kV PF – 2kV PF
CH	0.40%	0.45%	0.05%
CL	0.42%	0.50%	0.08%
CHL	0.39%	0.48%	0.07%



Example: The Overall Power Factor Test

Serial number	Mfg. Year	Rated Power	Voltage (Prim.)	Voltage (Sec.)
	2012	12MVA	115kV	12.47kV

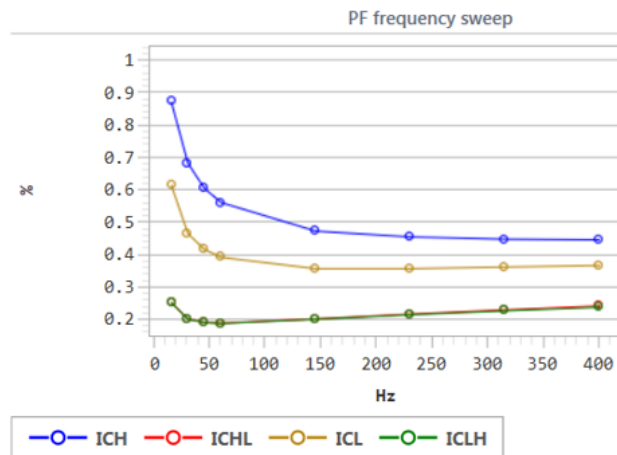
Measurement	2kV PF	10kV PF	10kV PF – 2kV PF
CH	0.57%	0.58%	0.01%
CL	0.29%	0.30%	0.01%
CHL	0.29%	0.29%	0.00%



Example: The Overall Power Factor Test

Serial number	Mfg. Year	Rated Power	Voltage (Prim.)	Voltage (Sec.)
	1981	30MVA	161kV	13.8kV

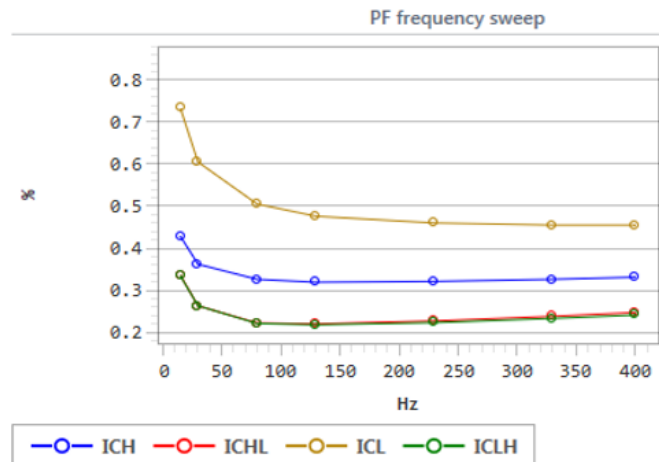
Measurement	2kV PF	10kV PF	10kV PF – 2kV PF
CH	0.56%	0.56%	0.00%
CL	0.39%	0.40%	0.01%
CHL	0.19%	0.19%	0.00%



Example: The Overall Power Factor Test

Serial number	Mfg. Year	Rated Power	Voltage (Prim.)	Voltage (Sec.)
	1984	20MVA	115kV	13.2kV

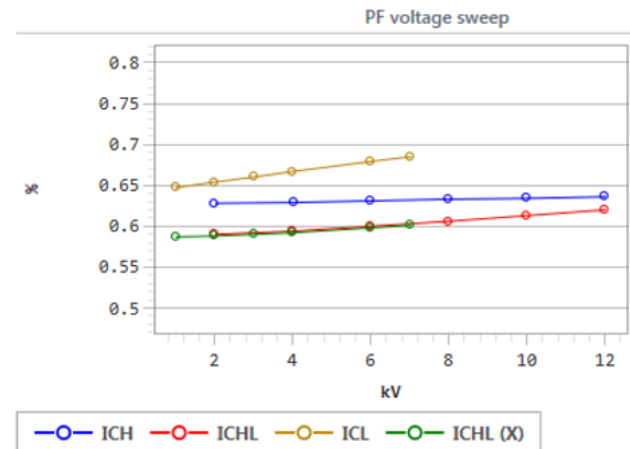
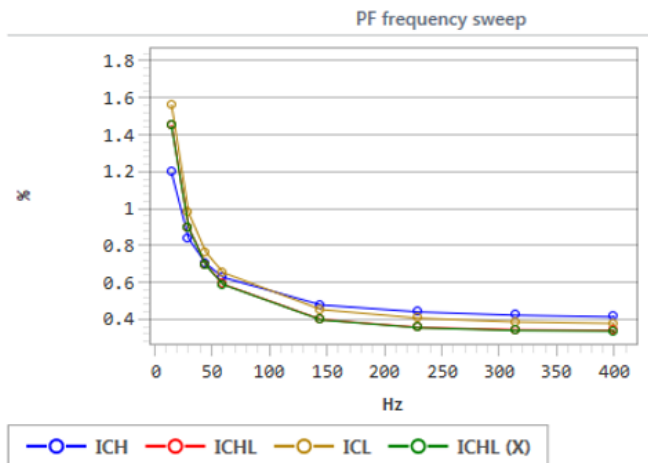
Measurement	2kV PF	10kV PF	10kV PF – 2kV PF
CH	0.33%	0.34%	0.01%
CL	0.50%	0.54%	0.04%
CHL	0.22%	0.23%	0.01%



Example: The Overall Power Factor Test

Serial number	Mfg. Year	Rated Power	Voltage (Prim.)	Voltage (Sec.)
	2000	20MVA	115kV	13.2kV

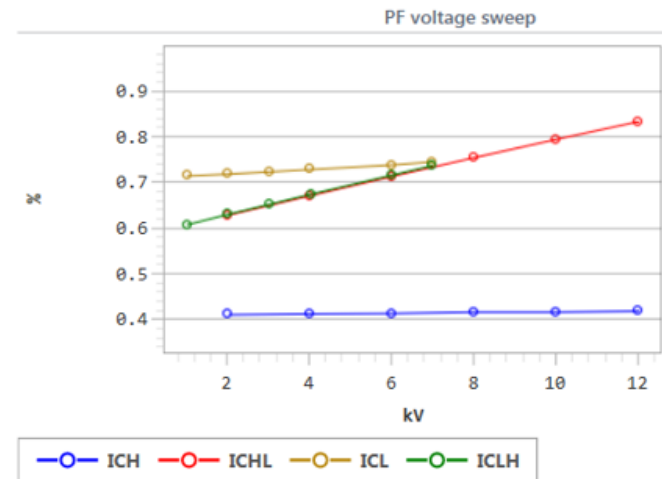
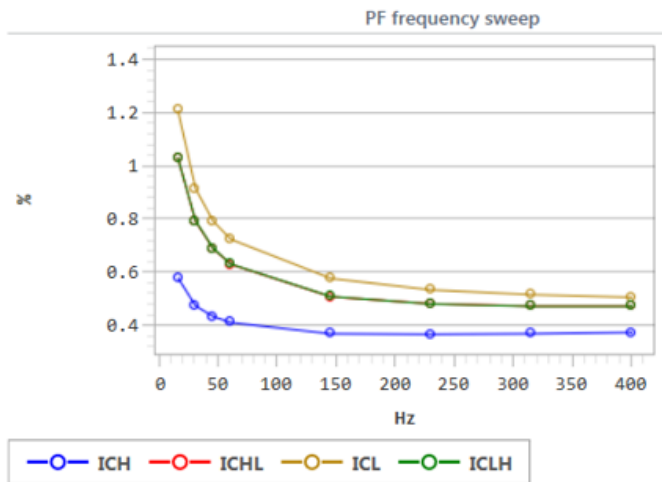
Measurement	2kV PF	10kV PF	10kV PF – 2kV PF
CH	0.63%	0.63%	0.00%
CL	0.65%	0.69%	0.04%
CHL	0.59%	0.60%	0.01%



Example: The Overall Power Factor Test

Serial number	Mfg. Year	Rated Power	Voltage (Prim.)	Voltage (Sec.)
	-	-	115kV	12.47kV

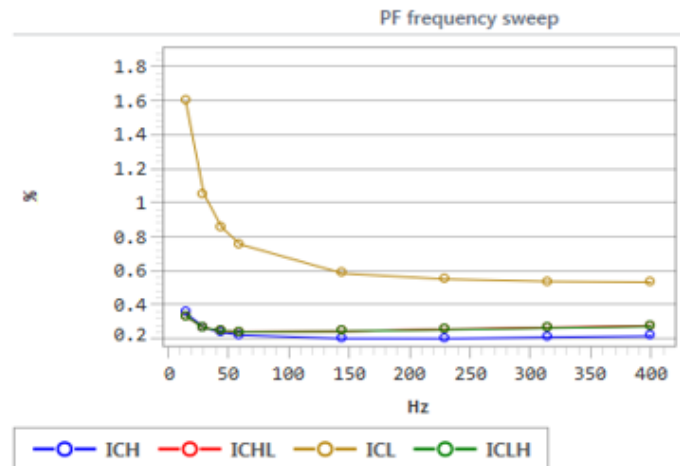
Measurement	2kV PF	10kV PF	10kV PF – 2kV PF
CH	0.41%	0.41%	0.00%
CL	0.72%	0.75%	0.03%
CHL	0.63%	0.74%	0.11%



Example: The Overall Power Factor Test

Serial number	Mfg. Year	Rated Power	Voltage (Prim.)	Voltage (Sec.)
	1980	20MVA	67kV	13.8kV

Measurement	2kV PF	10kV PF	10kV PF – 2kV PF
CH	0.22%	0.23%	0.01%
CL	0.75%	0.76%	0.01%
CHL	0.24%	0.24%	0.00%

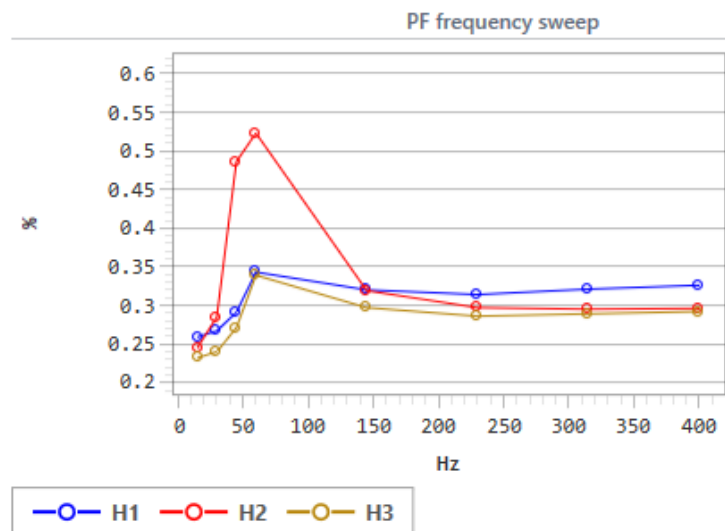




Examples of Invalid Power Factor Measurements, Identified by Utilizing the Power Factor Sweep Tests

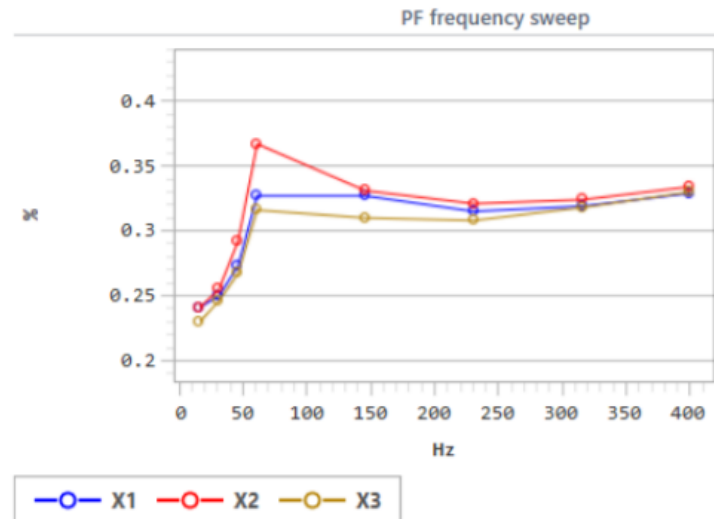
Example: Invalid Bushing C1 Power Factor Test

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%



Example: Invalid Bushing C1 Power Factor Test

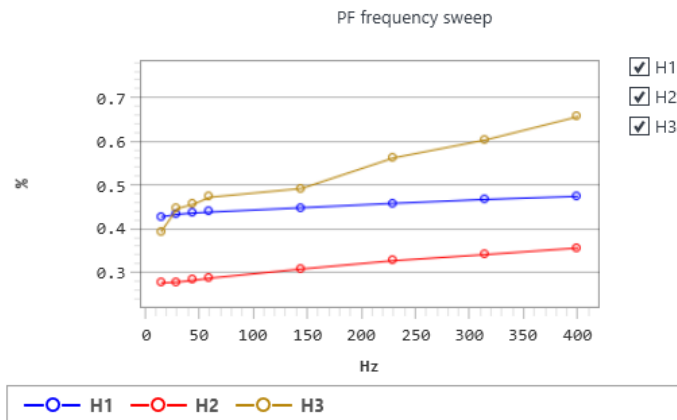
GE Type U 150kV Bushings (1983)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
X1	0.32%	0.37%	0.05%	0.30%
X2	0.37%	0.37%	0.00%	0.29%
X3	0.32%	0.35%	0.03%	0.29%



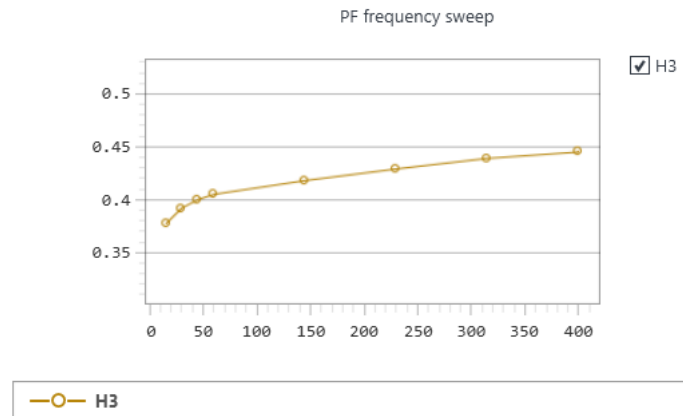
Example: Invalid Bushing C1 Power Factor Test

115kV Bushings (Manufacturer and Type is Unknown)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
H1	0.44%	0.44%	0.00%	0.38%
H2	0.29%	0.29%	0.00%	0.30%
H3	0.47%	0.43%	-0.04%	0.36%

Initial Test

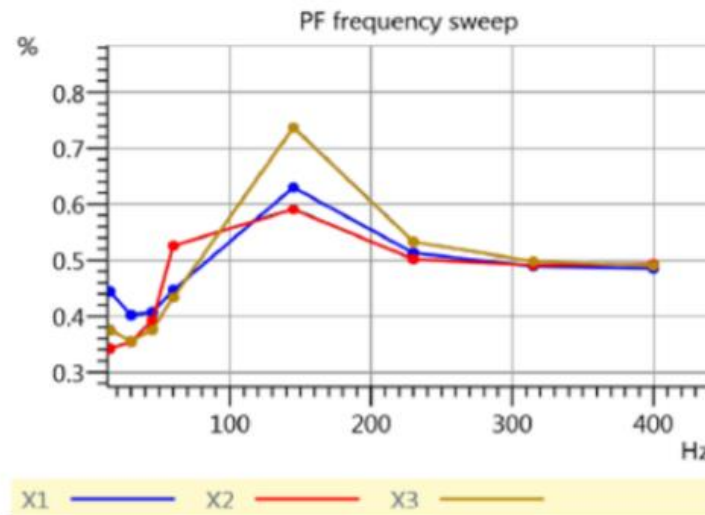


H3 Retest



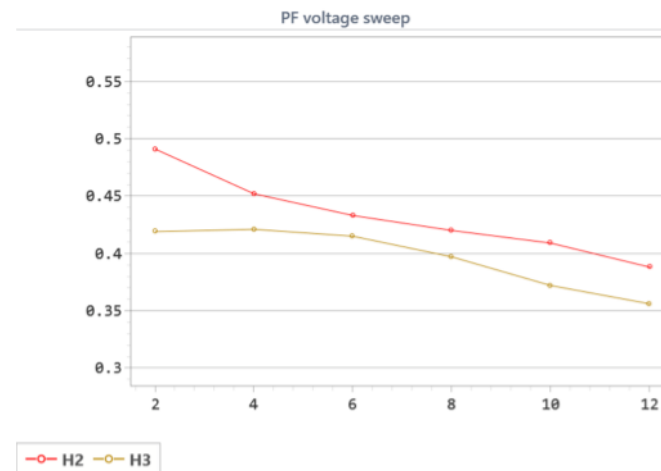
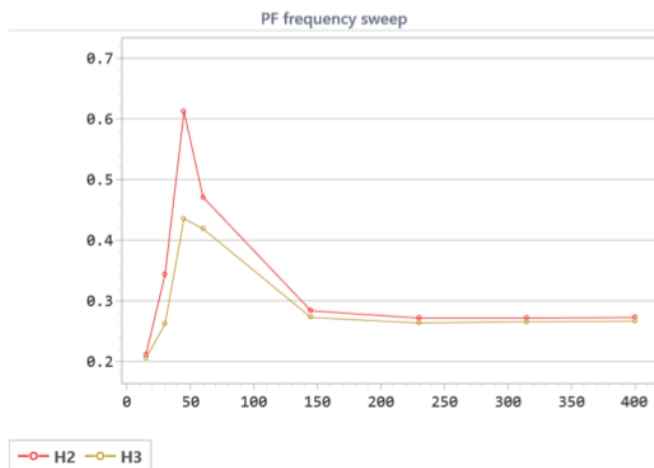
Example: Invalid Bushing C1 Power Factor Test

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%



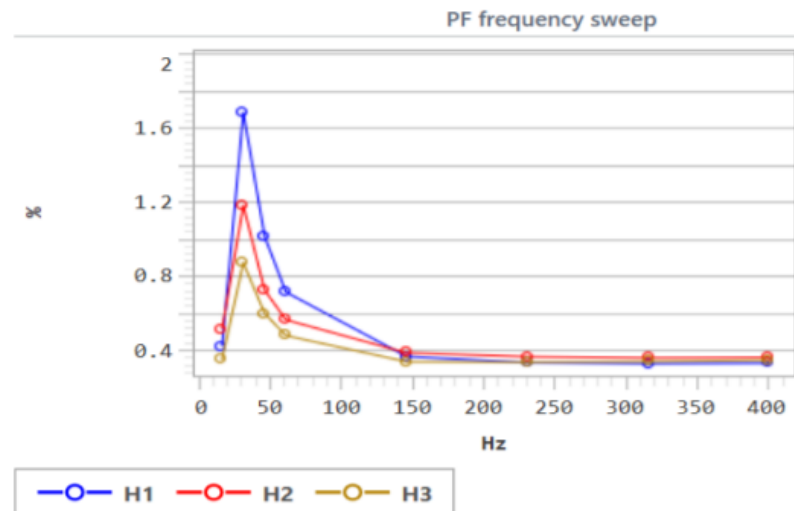
Example: Invalid Bushing C1 Power Factor Test

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%



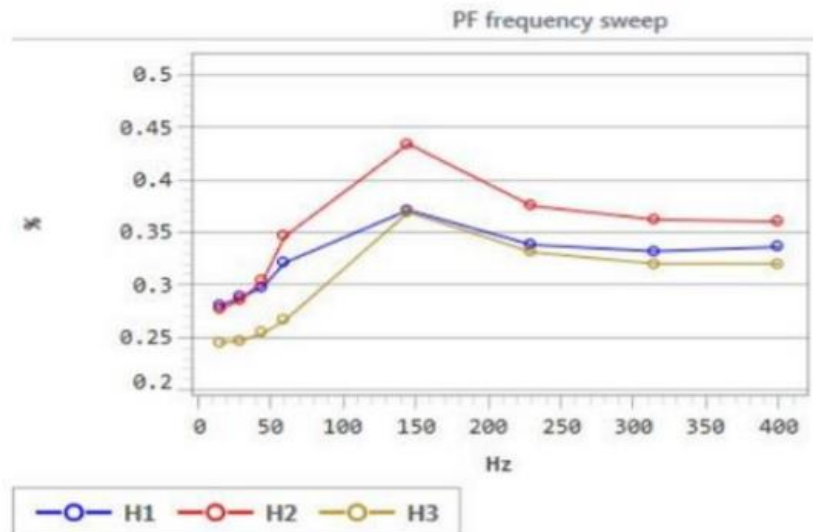
Example: Invalid Bushing C1 Power Factor Test

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%



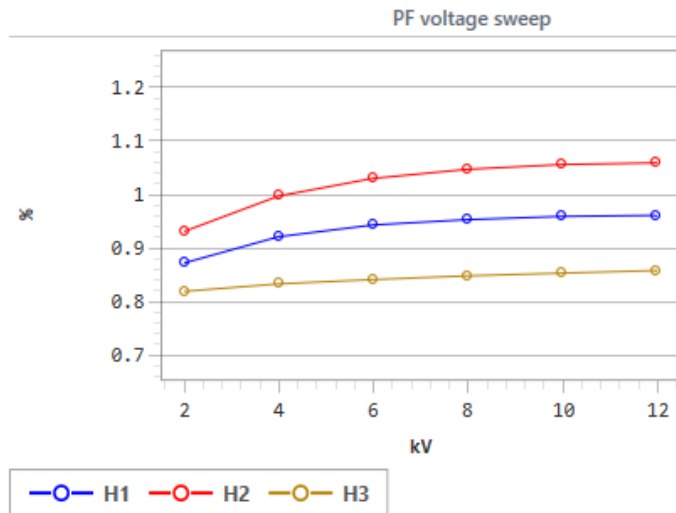
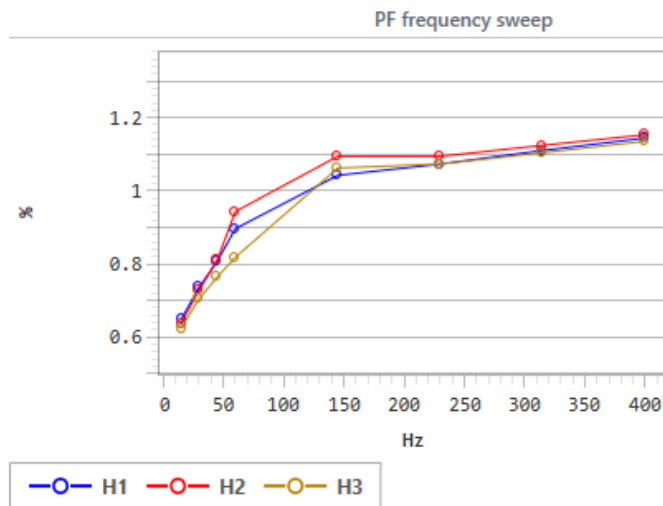
Example: Invalid Bushing C1 Power Factor Test

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%



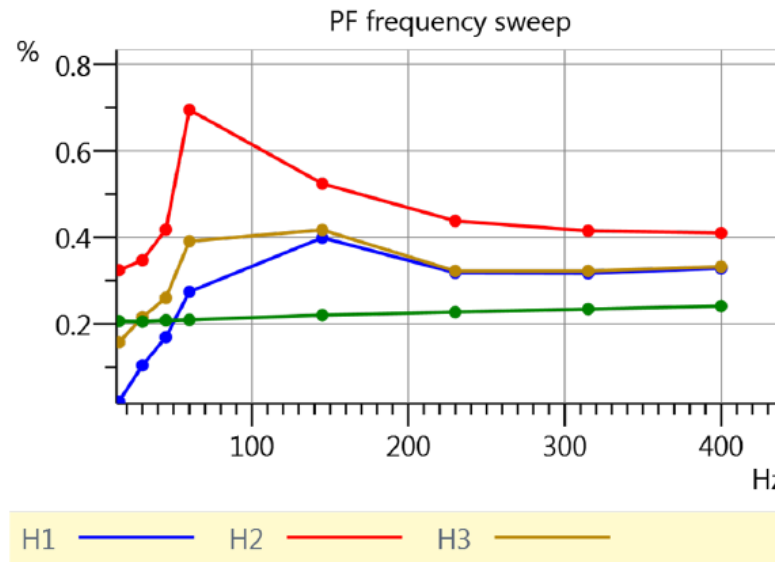
Example: Invalid Bushing C1 Power Factor Test

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%



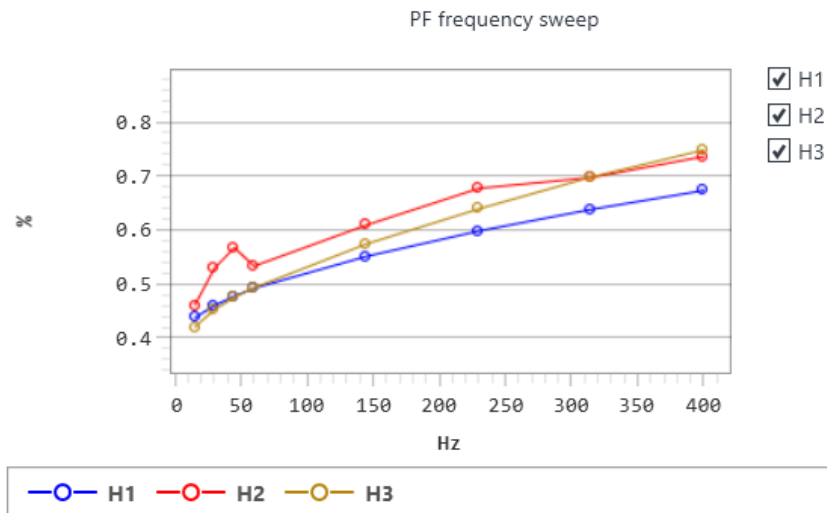
Example: Invalid Bushing C1 Power Factor Test

ABB O+C 362kV Bushings (2006)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
H1	0.28%	0.44%	0.16%	0.34%
H2	0.70%	0.68%	-0.02%	0.33%
H3	0.39%	0.48%	0.09%	0.33%



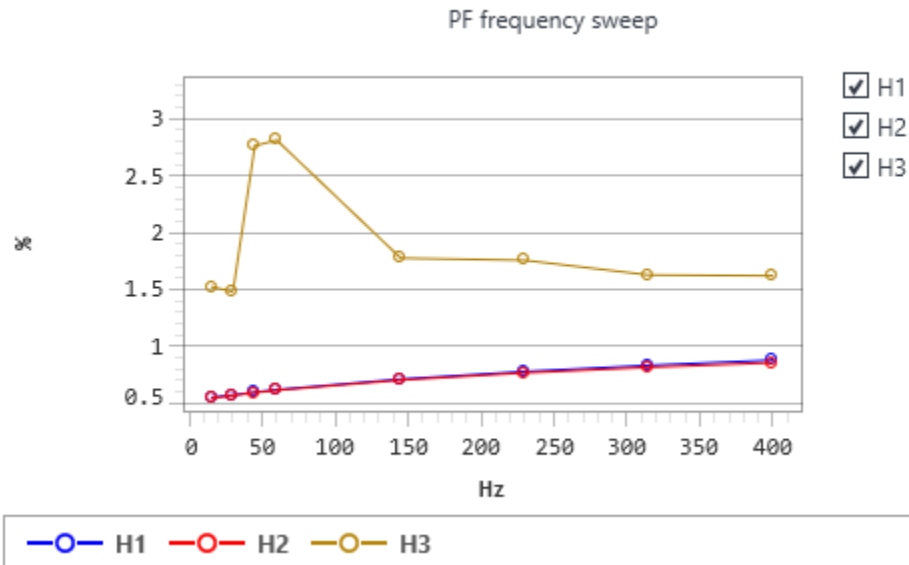
Example: Invalid Bushing C1 Power Factor Test

Westinghouse RDP 115kV Bushings (1975)				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
H1	0.49%	0.49%	0.00%	0.48%
H2	0.53%	0.48%	-0.05%	0.40%
H3	0.49%	0.49%	0.00%	0.40%



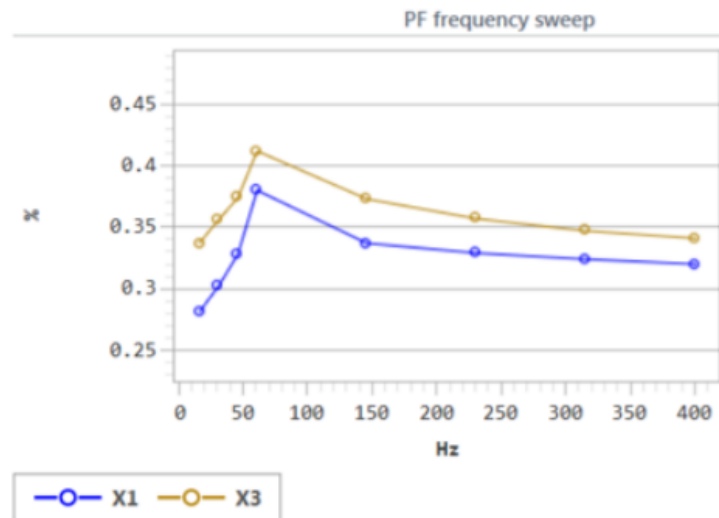
Example: Invalid Bushing C1 Power Factor Test

43.8kV Bushings				
	2kV Power Factor	10kV Power Factor	10kV PF – 2kV PF	Nameplate Power Factor
H1	0.62%	0.77%	0.15%	0.76%
H2	0.61%	0.74%	0.13%	0.76%
H3	2.81%	0.81%	-2.00%	0.68%



Example: Invalid Bushing C1 Power Factor Test

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%



Example: Invalid Overall Power Factor Test

- User-error – The customer used 600V rated insulated leads to short-circuit the primary bushing terminals together, and the insulated leads were lying on the grounded transformer tank

Serial number	Mfg. Year	Rated Power	Voltage (Prim.)	Voltage (Sec.)
	2010	7.5MVA	69kV	12.47kV

Measurement	2kV PF	10kV PF	10kV PF – 2kV PF
CH	0.27%	1.63%	1.36%
CL	0.26%	0.28%	0.02%
CHL	0.28%	0.28%	0.00%

Example: Invalid Overall Power Factor Test

- User-error – The customer used wooden blocks to isolate the primary bushing terminals from the bus connection (i.e. the wooden blocks were used as insulators)

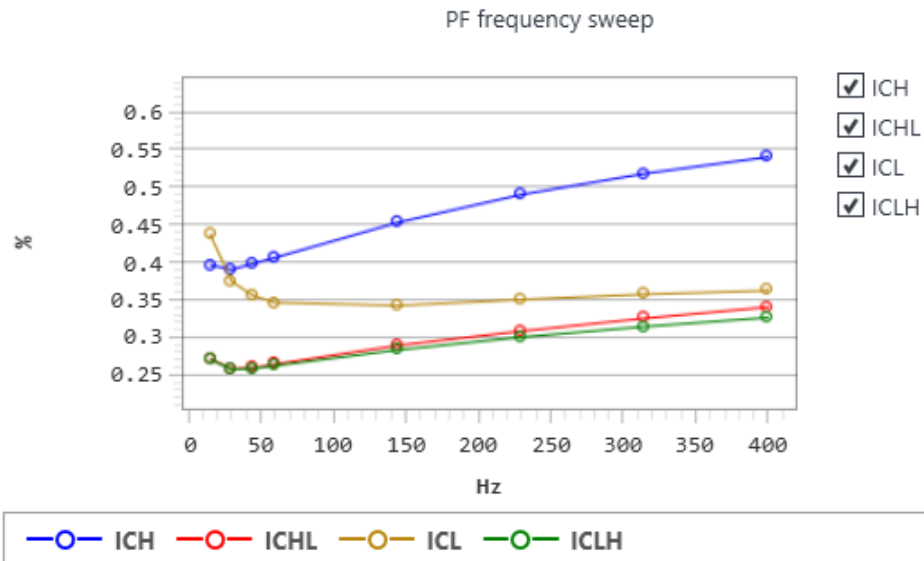
Serial number	Mfg. Year	Rated Power	Voltage (Prim.)	Voltage (Sec.)
	-	31MVA	34.5kV	11.5kV

Measurement	2kV PF	10kV PF	10kV PF – 2kV PF
CH	0.54%	0.90%	0.36%
CL	0.34%	0.34%	0.00%
CHL	0.27%	0.27%	0.00%

Example: Invalid Overall Power Factor Test

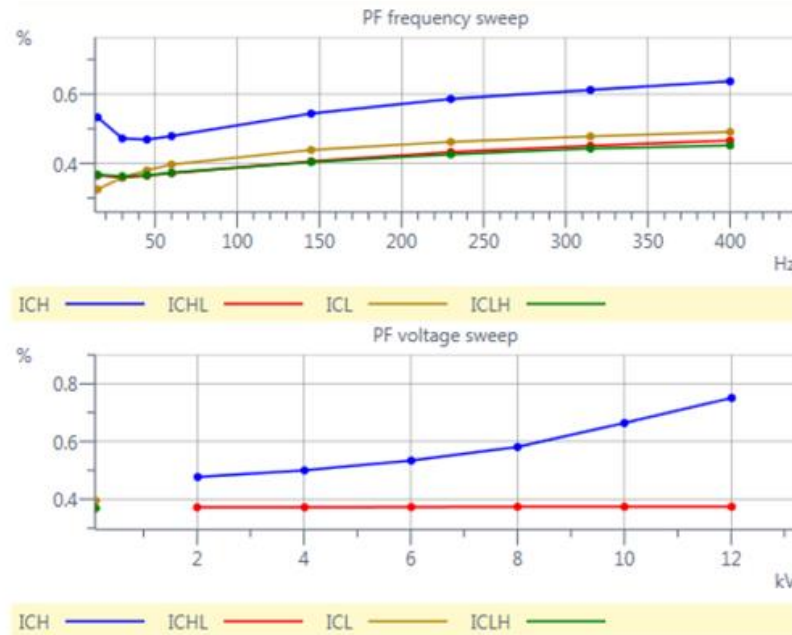
Serial number	Mfg. Year	Rated Power	Voltage (Prim.)	Voltage (Sec.)
	2001	12MVA	67kV	13.8kV

Measurement	2kV PF	10kV PF	10kV PF – 2kV PF
CH	0.41%	0.53%	0.12%
CL	0.35%	0.35%	0.00%
CHL	0.26%	0.26%	0.00%



Example: Invalid Overall Power Factor Test

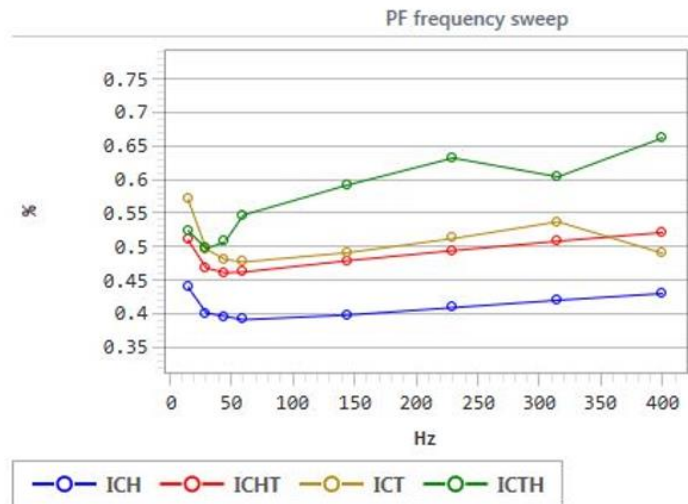
Measurement	2kV PF	10kV PF	10kV PF – 2kV PF
CH	0.48%	0.66%	0.18%
CL	0.40%	0.40%	0.00%
CHL	0.37%	0.37%	0.00%



Example: Invalid Overall Power Factor Test

Serial number	Mfg. Year	Rated Power	Voltage (Prim.)	Voltage (Sec.)	Voltage (Tert.)
	1974	224MVA	230kV	115kV	13kV

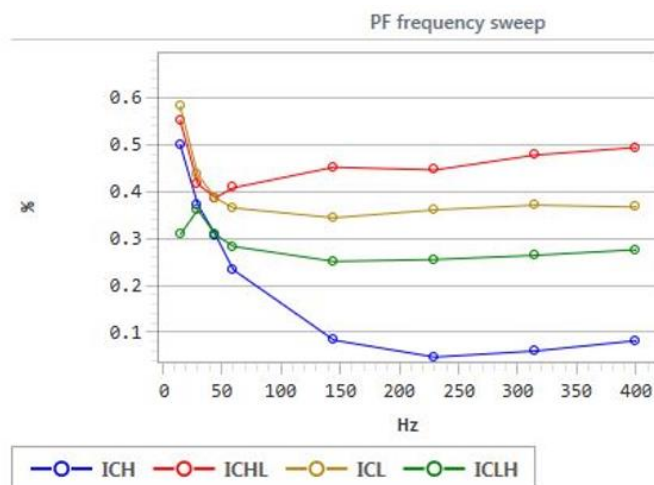
Measurement	2kV PF	10kV PF	10kV PF – 2kV PF
CH	0.39%	0.39%	0.00%
CT	0.48%	0.48%	0.00%
CHT	0.55%	0.49%	-0.06%



Example: Invalid Overall Power Factor Test

Serial number	Mfg. Year	Rated Power	Voltage (Prim.)	Voltage (Sec.)
	2000	17MVA	92kV	13.2kV

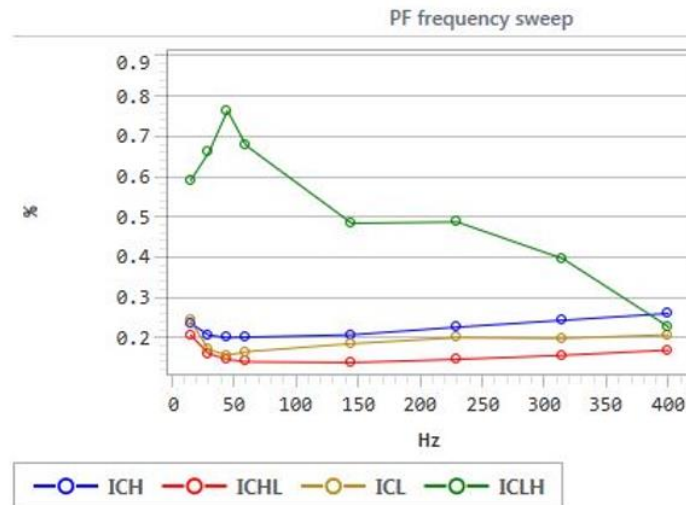
Measurement	2kV PF	10kV PF	10kV PF – 2kV PF
CH	0.23%	0.30%	0.07%
CL	0.28%	0.28%	0.00%
CHL	0.41%	0.35%	-0.06%



Example: Invalid Overall Power Factor Test

Serial number	Mfg. Year	Rated Power	Voltage (Prim.)	Voltage (Sec.)
	1981	20MVA	115kV	12kV

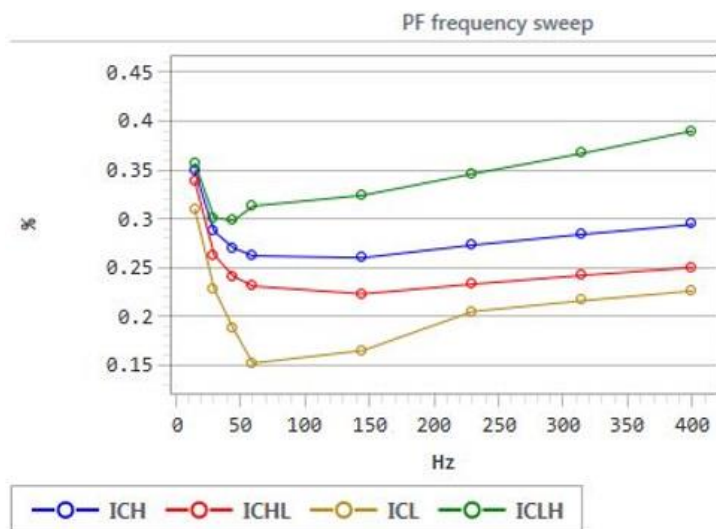
Measurement	2kV PF	10kV PF	10kV PF – 2kV PF
CH	0.30%	0.30%	0.00%
CL	0.25%	0.33%	0.08%
CHL	0.21%	0.21%	0.00%



Example: Invalid Overall Power Factor Test

Serial number	Mfg. Year	Rated Power	Voltage (Prim.)	Voltage (Sec.)
	-	5MVA	67kV	4.16kV

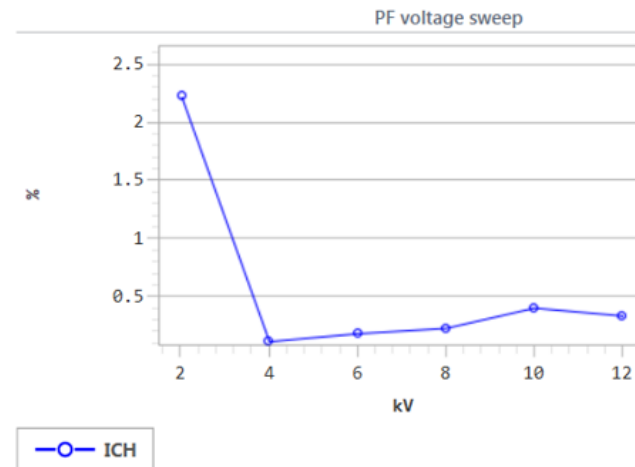
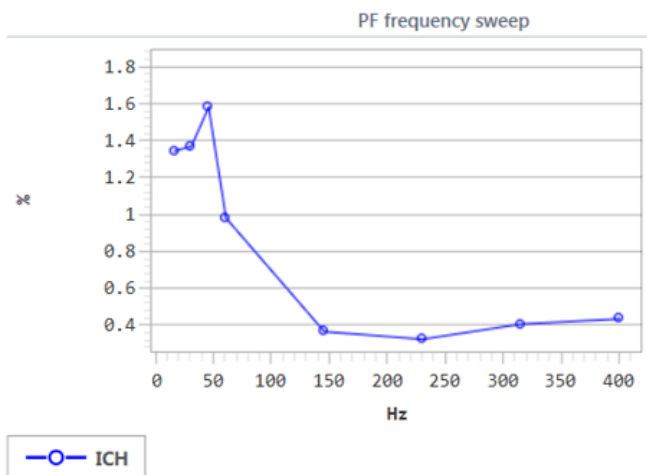
Measurement	2kV PF	10kV PF	10kV PF – 2kV PF
CH	0.29%	0.29%	0.00%
CL	0.17%	0.26%	0.09%
CHL	0.25%	0.25%	0.00%



Example: Invalid Overall Power Factor Test

Serial number	Mfg. Year	Rated Power	Voltage (Prim.)	Voltage (Sec.)
	1976	112MVA	230kV	115kV

Measurement	2kV PF	10kV PF	10kV PF – 2kV PF
CH	1.00%	0.40%	-0.60%





Thank you!