Transformer Assessment and Case Studies

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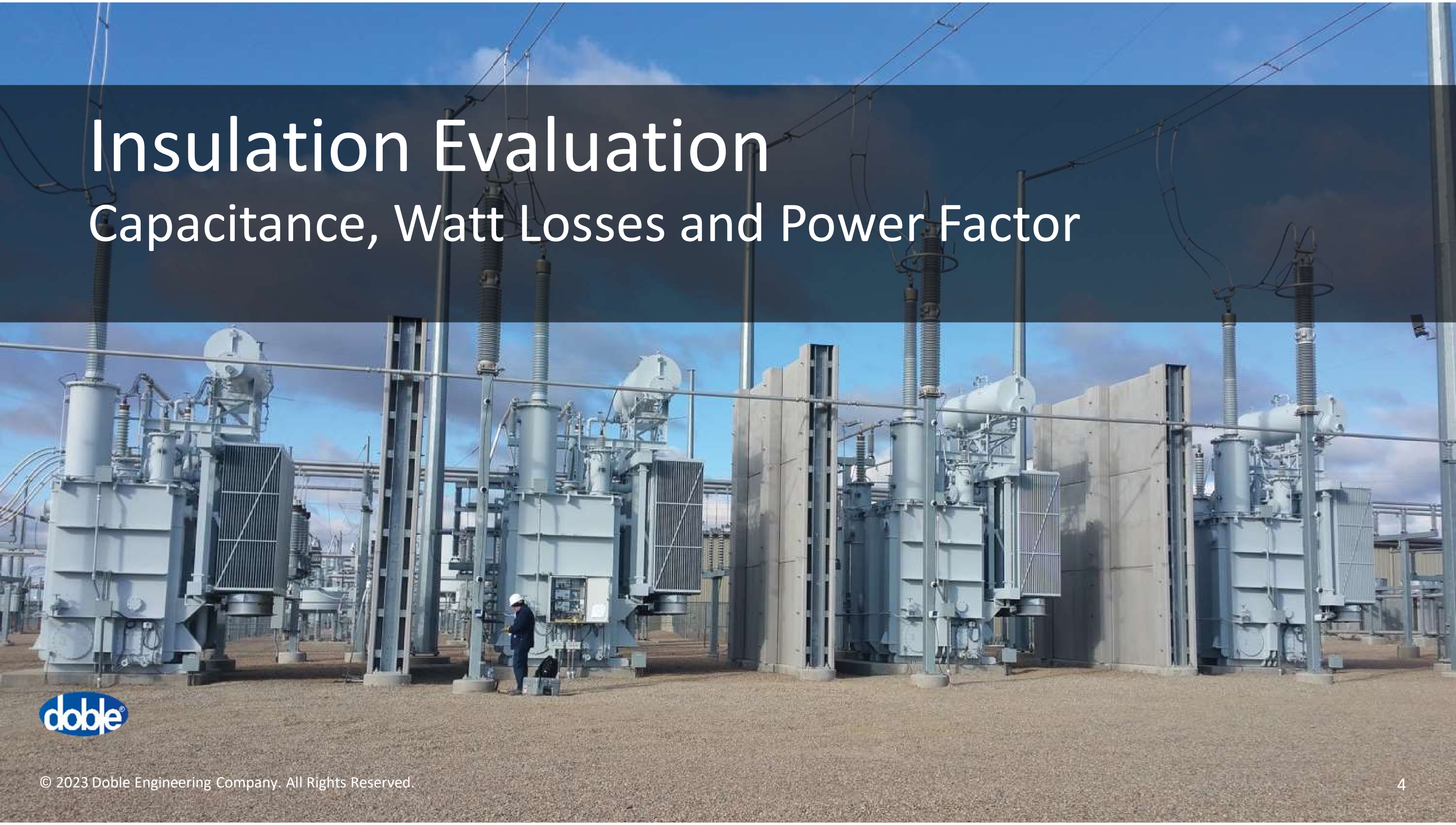
Senior Principal Engineer

- Founded in 1920 by Frank Doble
- First Doble Conference held in 1934
- Headquarters in Marlborough, MA
- 300 Employees in 15 Countries
- 85 Representatives & Distributors Worldwide
- Acquired in 2007 by ESCO Technologies based in St. Louis, MO
- Doble Products & Services used by over 90% of US & Canada Power Utilities, over 500 client companies

- Members of an Extensive Global Power Community
- Over 500 Doble Client Companies Worldwide
- Thousands of Power Industry Professionals
- Two annual meetings
  - Fall Committee meetings
  - Spring International Client Conference

Insulation Evaluation

Capacitance, Watt Losses and Power Factor

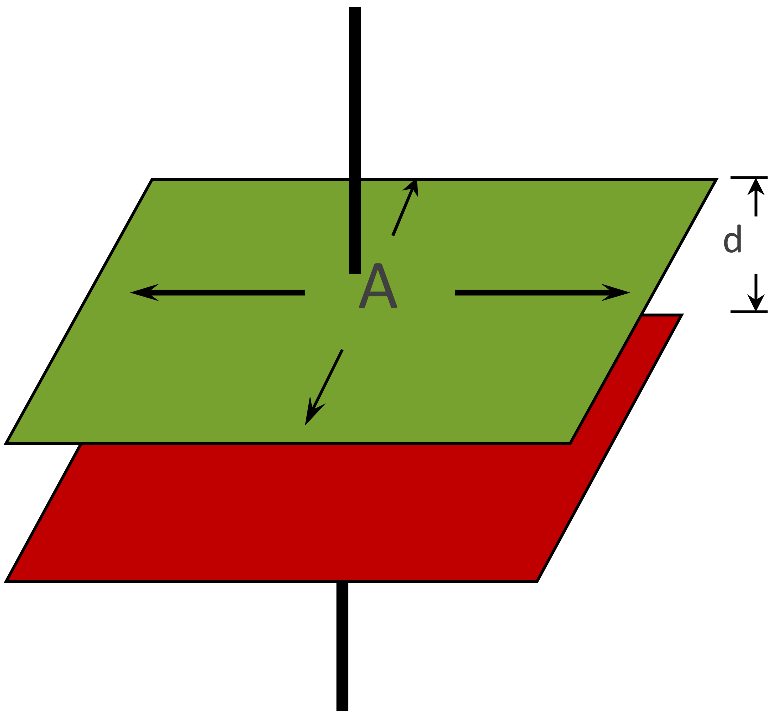


Insulation Capacitance

Insulation Evaluation – Capacitance Modeling

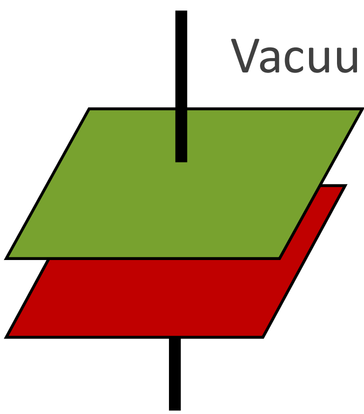
- By controlling a few physical features of these two conducting plates, size, space between them the dielectric filling the space we can dictate or design a capacitance measured in Farads
- Changes in the area of the plates and the distance and dielectric between the plates results in a capacitance change

$$\frac{\epsilon A}{D}$$



Insulation Evaluation – Capacitor Dielectric

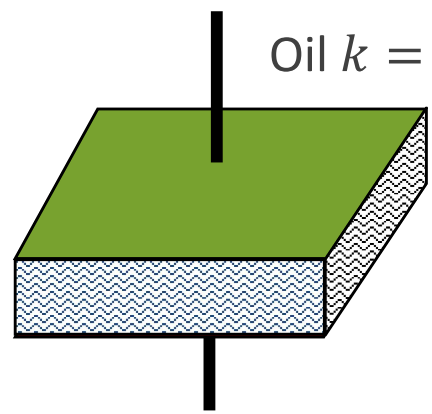
- The dielectric materials filling the void between the plates also changes the capacitance
- This medium filling the void will increase the capacitance by a factor which we call the mediums Dielectric Constant(k).



Vacuum

$C_{vacuum} = 10pF$

$$\frac{k\epsilon A}{D}$$



Oil $k = 2.1$

$C_{oil} = 21pF$

Capacitor and Dielectrics

- Change in capacitance is always going to be a physical change
- Change in Area
- Change in Orientation or Distance
- Change in Dielectric Material

Material	Dielectric Constant
• Vacuum	1.0
• Air	1.000549
• SF6 Gas	2.5
• Mica	5.4
• Dry Paper	2
• Porcelain	7
• Oil	2.2
• Silicone Fluid	2.75
• Water (20° C)	80

Dielectric Losses

Dielectric Losses - Terminology

- Insulation vs. Dielectric
  - Insulation
    - Insulation is a generic term stating the material or combination of materials which resist the flow of electricity (very low current).
  - Dielectric
    - A Dielectric while resisting the flow of electricity it also provides the environment for the creation of an electric field
    - The measurable properties include; Capacitance, Dielectric Constant, Loss (heat), Absorption Rate and Dielectric Strength or Breakdown.

Dielectric Losses – Attributes

- In general, a low loss or a lower loss dielectric is a better insulation system.
- A large insulation system will have higher losses than a smaller insulation system in the same condition, due to a larger volume of insulation
- As the insulation deteriorates, the resistance decreases allowing the resistive current to increase, resulting in a watts increase.
- Without previous test data from that equipment or identical equipment it is difficult to make an accurate diagnosis

Dielectric Losses – Insulating/Dielectric Materials

Gaseous:	Liquid:	Solid:
High Vacuum	Mineral Oil	Cellulose
Air	Silicone Oil	Porcelain
Sulfur Hexafluoride (SF_6)	Distilled Water	Polymers
		Resins

Power Factor

Power Factor Definition

- What is a Power Factor/Dissipation Factor/Tangent Delta Test?
  - IEEE Definition of Power Factor is the cosine of the phase angle between a sinusoidal voltage applied across a dielectric (or combination of dielectrics) and the resulting current through the dielectric system.
  - Overall assessment of the condition and efficiency of the insulation
  - AC high voltage low current measurement

Power Factor Calculation

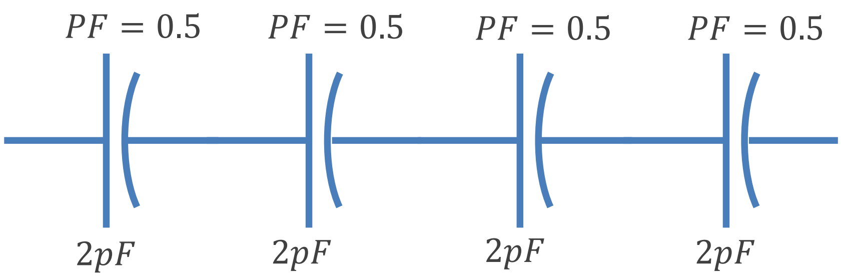
- How do we calculate Power Factor in the field? (10kV equivalent)
- $Power\ Factor = \frac{Watts}{E * I_T} * 100 = \frac{W}{10{,}000 * 0.001\text{A}} * 100 = \frac{\text{W} * 100}{10\text{mA}} = \frac{\mathbf{W*10}}{\mathbf{mA}}$
- Power Factor = $\left(\frac{.301 * 10}{7.011}\right) = .429\%$
- 60Hz Capacitance = $265 * I(mA) = 265 * 7.011 = 1857.9$

Results						
V [kV]	I [mA]	Loss [W]	TCF [#]	PF [%]	PF*TCF [%]	Capacitance [pF]
10.000	7.011	0.301	1.00	0.429	0.429	1857.9

Power Factor Attributes

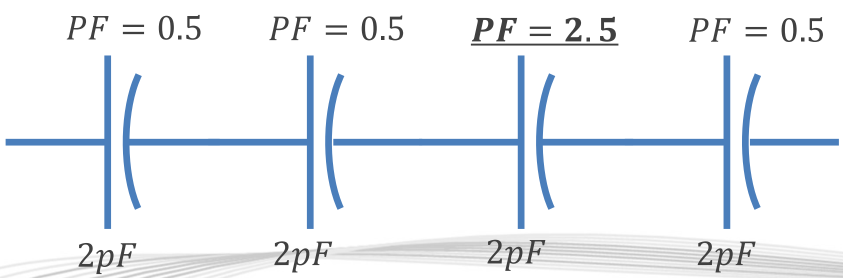
- Independent of voltage
- Independent of specimen size
- Temperature sensitive
  - Why correction factor applied to the measured power factor recorded for some types of apparatus.
- Performed at/near apparatus frequency
- Non-Destructive
- Not time dependent
- Power Factor results allow us to evaluate a piece equipment without prior test data

Power Factor – Detecting Defective Insulation



$$Average\ PF = \frac{0.5 + 0.5 + 0.5 + 0.5}{4} = 0.5\% PF$$

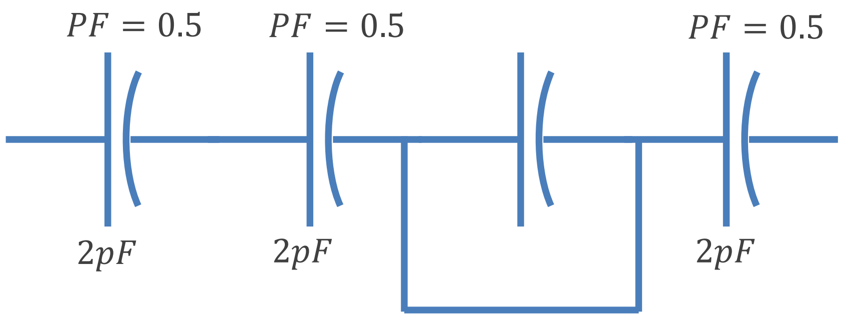
$$Capacitance = \frac{1}{\frac{1}{2} + \frac{1}{2} + \frac{1}{2} + \frac{1}{2}} = \frac{1}{2} pF$$



$$Average\ PF = \frac{0.5 + 0.5 + 2.5 + 0.5}{4} = \mathbf{1.0\% PF}$$

$$Capacitance = \frac{1}{\frac{1}{2} + \frac{1}{2} + \frac{1}{2} + \frac{1}{2}} = \frac{1}{2} pF$$

Power Factor – Detecting Capacitance Change



$$Average\ PF = \frac{0.5 + 0.5 + 0.5}{3} = 0.5\ \text{PF\%}\ (ok)$$

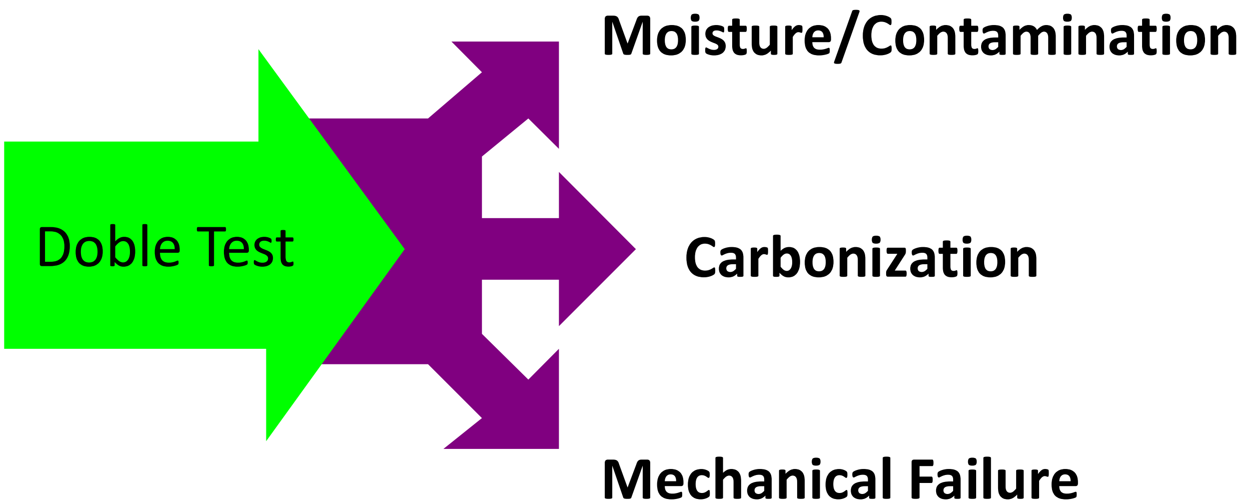
$$Capacitance = \frac{1}{\frac{1}{2}+\frac{1}{2}+\frac{1}{2}} = \mathbf{0.667\ pFarad}$$ **(133% increase from 0.5pF)**

Capacitance, Watt Loss and %PF Summary

- Why do we test?
  - We test to identify contamination/degradation or physical change of insulating components before they lead to an electrical outage or failure!
- What can cause a change in Capacitance?
  - To have a change in Capacitance we must have a physical change occur which may or may not change our Power Factor
- What can cause a change in Power Factor?
  - A change in Power Factor is usually (not always) associated with some type of increase in resistive losses

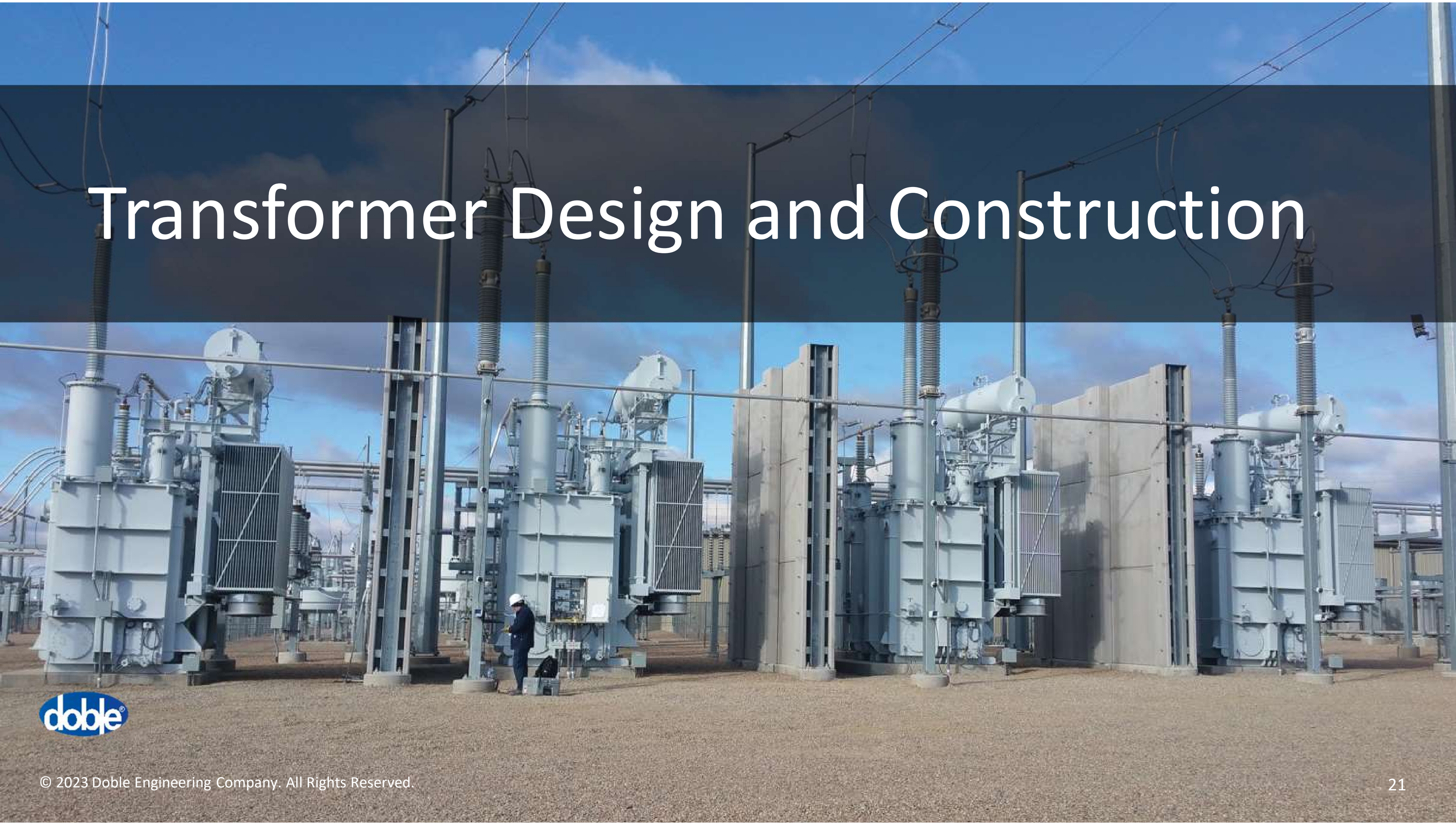
Power and Distribution Transformers

The Doble dielectric-loss and power factor test as applied to transformers are the most comprehensive tests for insulation assessment.



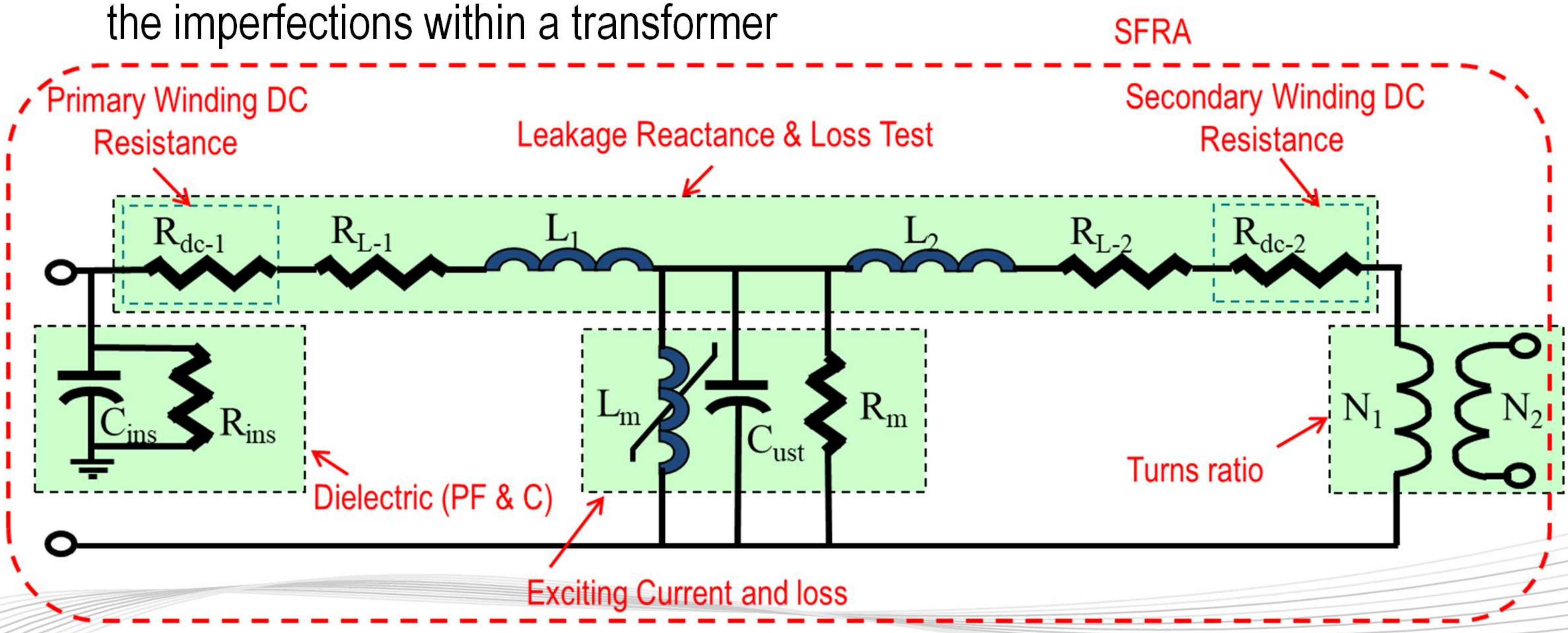
The test technique makes it possible to segregate the specimen into major components
for more effective analysis of test results.

Transformer Design and Construction

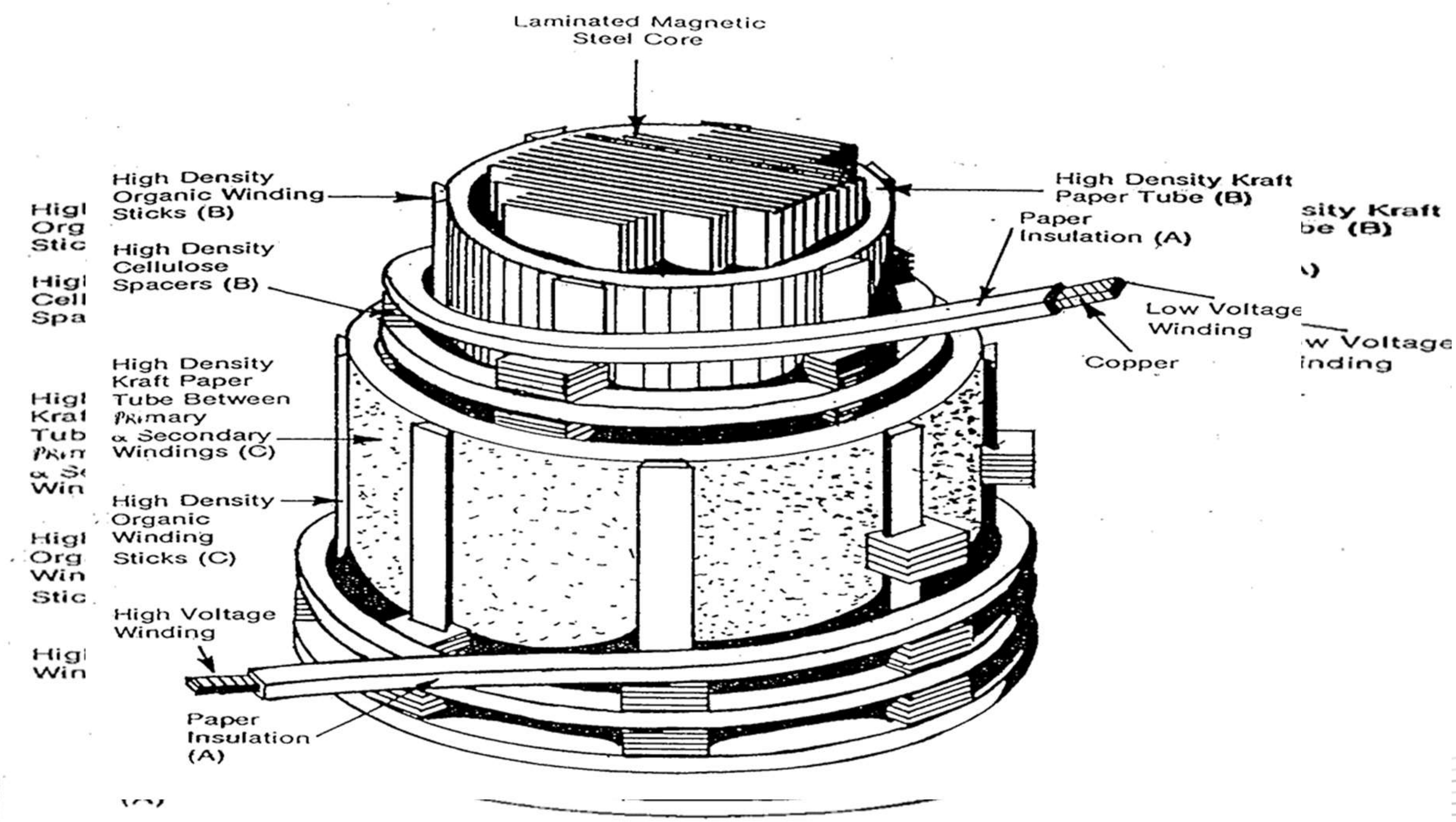


Practical Transformer Model

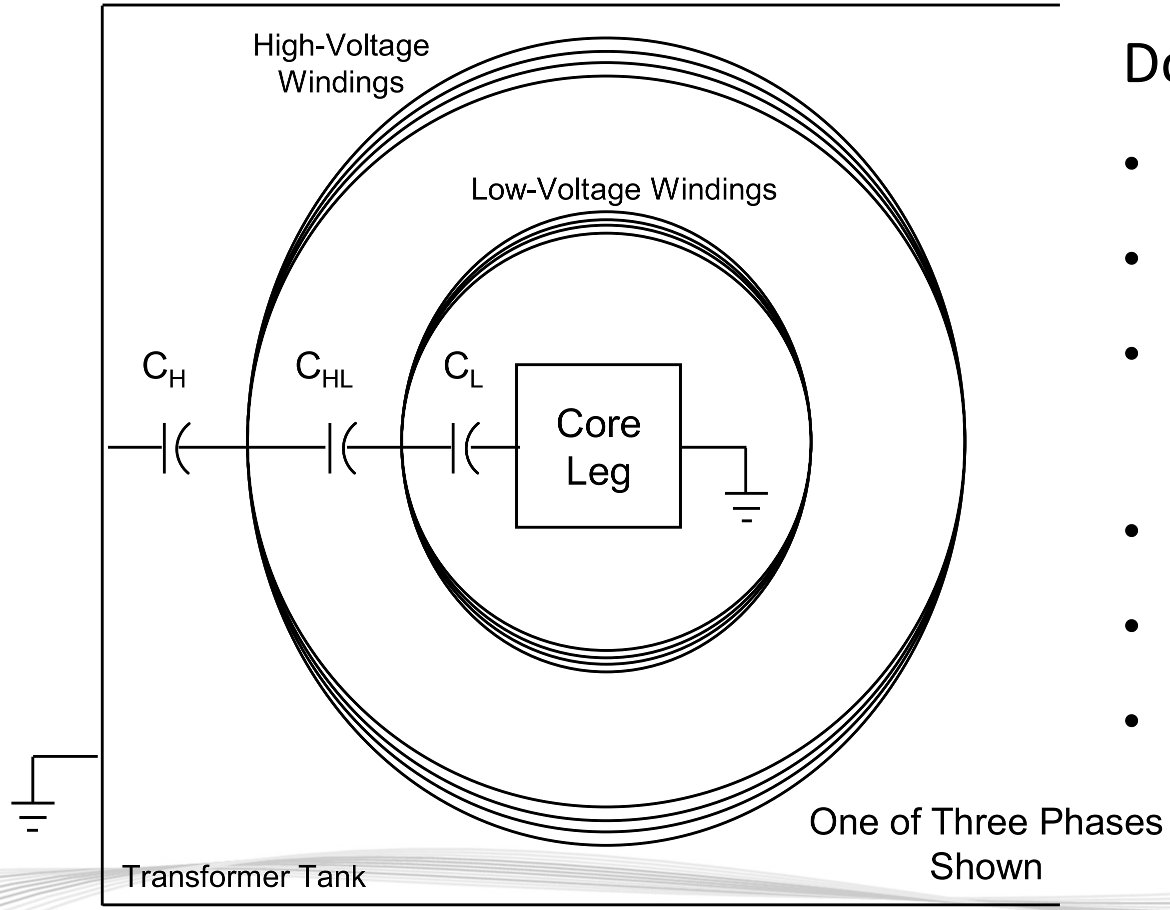
- From an energy transfer perspective, the elements in this circuit represent the imperfections within a transformer



Two-Winding Transformer Construction



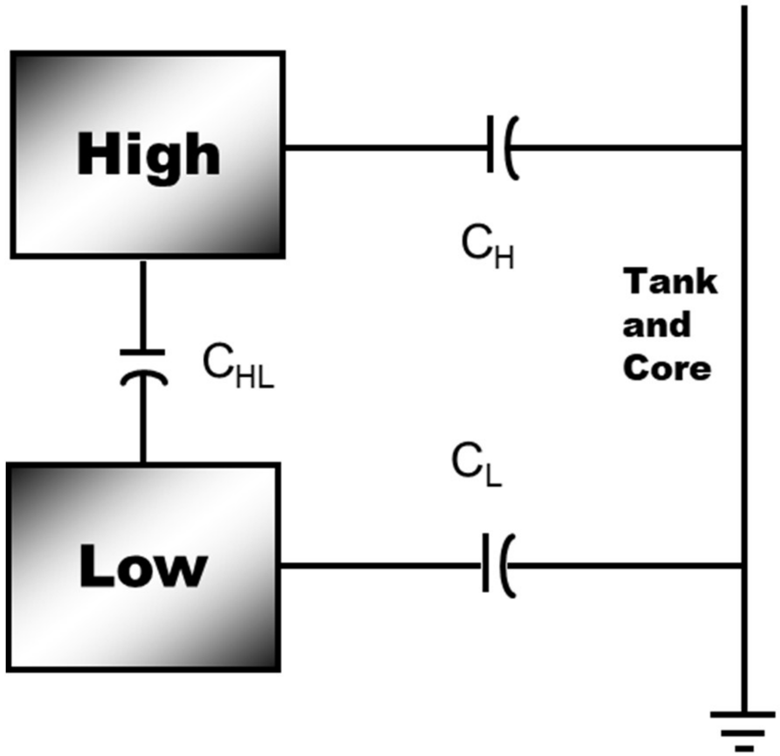
Physical Representation of Three-Phase Two-Winding Transformer



Doble testing yields:

- Overall (C_H, C_L, C_{HL})
- Bushings (C_1, C_2, Hot Collar)
- Oil (Field Power Factor, Laboratory DGA, etc.)
- Excitation Current Test
- Doble Turns Ratio Test
- Leakage Reactance

Dielectric Circuit: Two-Winding Transformer



C_H - Insulation between High-Voltage conductors and grounded Tank & Core (H Bushings-Winding Insulation-Structural Insulating Members-Oil)

C_L - Insulation between Low-Voltage conductors and grounded Tank & Core (X Bushings - Winding Insulation-Structural Insulating Members-Oil)

C_{HL} - Insulation between High- and Low-Voltage Windings (Winding Insulation-Barriers-Oil)

Case Studies

Elevated CH Capacitance

CH Capacitance Change

The CH capacitance increased by 8.5%.

In 2017 the initial capacitance was 2878 pf and in 2021 it's 3140 pf.

Display History for Test Row:									2	
	Setup	Results							Ratin	
Date	Test kV	V [kV]	I [mA]	Loss [W]	TCF [#]	PF [%]	PF*TCF [%]	Capacitance [pF]	Ask FRANK™	
3/4/2021	10.000	10.000	11.838	0.315	0.99	0.267	0.265	3140.2	D Deteriorated	...
2/9/2017	10.000	10.003	10.851	0.348	1.00	0.320	0.319	2878.4	! Investigate	...

CH Capacitance Change

- CL, CHL- no issues
- Bushings, Excitation, Winding Resistance, Insulation Resistance, TTR- no issue
- The initial test was performed in 2017 and allowed the C1 and C2 to be tested on the H0 bushing.
- In 2021 the test tap was covered by the CT's and only a hot collar was performed on the H0 bushing.

CH Capacitance Change

- In this case a picture is worth a thousand words.

CH Capacitance Increase

- The external CT's encircling the H0 bushing will affect the capacitance in this case by 262 pf.
- So now a value is available with and without the CT in place for future testing evaluations.
  - Initial tests and factory results should compare

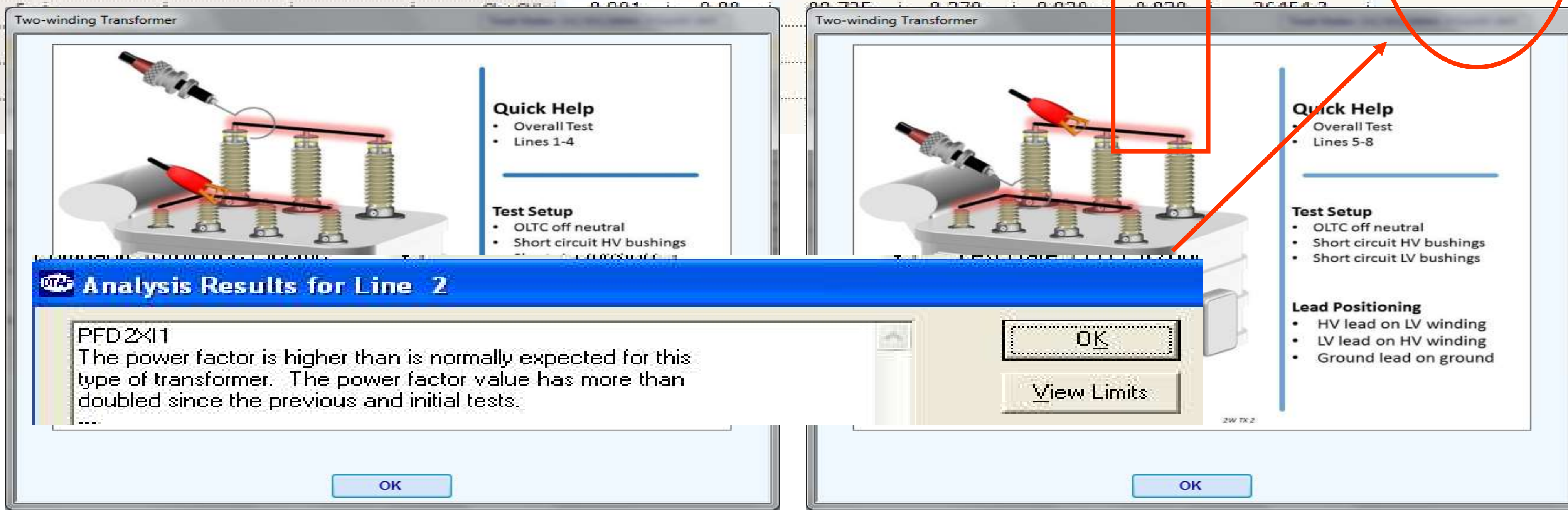
Elevated %PF

Overall PF% November 2006

Connections					Inputs		Test Results				
#	HV Lead	Red Measure Lead	Blue Measure Lead	Insulation	Test kV	Corr. Factor	mA	Watts	%PF Meas.	%PF Corr.	Capacitance (pF)
1	HV Winding	LV Winding	Unused	CH+CHL	10.004	0.89	51.192	4.234	0.830	0.740	13578.5
2				CH	10.002	0.89	14.034	1.011	0.720	0.640	3722.4
3				CHL(UST)	10.002	0.89	37.152	3.220	0.870	0.770	9854.5
4	Test 1 - Test 2 (calculated)			CHL		0.89	37.158	3.223	0.870	0.770	9856.1
5	LV Winding	HV Winding	Unused	CL+CHL	8.001	0.89	99.735	9.270	0.930	0.830	26454.3
6				CL	8.001	0.89	62.570	6.080	0.970	0.860	16596.3
7				CHL(UST)	8.001	0.89	37.154	3.179	0.860	0.770	9854.9
8	Test 5 - Test 6 (calculated)			CHL		0.89	37.165	3.190	0.860	0.770	9858.0

Capacitance PF% November 2006

	Connections				Inputs		Test Results					
#	HV Lead	Red Measure Lead	Blue Measure Lead	Insulation	Test kV	Corr. Factor	mA	Watts	%PF Meas.	%PF Corr.	Capacitance (pF)	Doble eXpert System
1	HV Winding	LV Winding	Unused	CH+CHL	10.004	0.89	51.192	4.234	0.830	0.740	13578.5	
2				CH	10.002	0.89	14.034	1.011	0.720	0.640	3722.4	Deteriorated
3				CHL(UST)	10.002	0.89	37.152	3.220	0.870	0.770	9854.5	Investigate
4	Test 1 - Test 2 (calculated)			CHL		0.89	37.158	3.223	0.870	0.770	9856.1	



History of C_H, C_{HL} and C_L

Display History for Test Row: Ch

C_H

Date	Inputs		Results					Ratin	
	Test kV	Corr. Factor	mA	Watts	% PF Meas.	% PF Corr.	Capacitance (pF)	Doble eXpert System	
11/15/2006	10.002	0.89	14.034	1.011	0.720	0.640	3722.4	Deteriorated	...
4/27/1998	10.000	0.99	13.960	0.600	0.430	0.430	3699.4	Good	...
9/10/1986	10.000	0.96	13.600	0.700	0.510	0.490	3604.0	Good	...

Display History for Test Row: Chl

C_{HL}

Date	Inputs		Results					Ratin	
	Test kV	Corr. Factor	mA	Watts	% PF Meas.	% PF Corr.	Capacitance (pF)	Doble eXpert System	
11/15/2006	10.002	0.89	37.152	3.220	0.870	0.770	9854.5	Investigate	...
4/27/1998	10.000	0.99	36.900	1.520	0.410	0.410	9778.0	Good	...
9/10/1986	10.000	0.96	36.000	1.400	0.390	0.370	9594.0	Good	...

Display History for Test Row: Cl

C_L

Date	Inputs		Results					Ratin	
	Test kV	Corr. Factor	mA	Watts	% PF Meas.	% PF Corr.	Capacitance (pF)	Doble eXpert System	
11/15/2006	8.001	0.89	62.570	6.080	0.970	0.860	16596.3	Investigate	...
4/27/1998	8.000	0.99	61.700	3.700	0.600	0.590	16350.0	Deteriorated	...
9/10/1986	8.000	0.96	60.000	4.000	0.670	0.640	15900.0	Deteriorated	...
12/8/1982	8.000	0.99	61.000	2.800	0.460	0.460	16165.0	Good	...

Water Content

- The water content is difficult to assess without oil temperatures at time of sampling
- Latest sample indicated transformer very wet

Date Sampled	Top Oil Temp, °C	Moisture Content, ppm	% Relative Saturation
11/15/2006	30	29	35 (≤10%)
9/14/2005	Not given	36	-
11/16/2004	Not given	17	-
8/13/2004	Not given	26	-
10/29/1997	Not given	19	-

Oil Quality

- Some values indicate end of life for service aged, IEEE C57.106

Dielectric Breakdown	D877	43 (N/A)
Dielectric Breakdown	D1816	28 (>40kV)
Interfacial Tension	D971	24 (>25 dynes)
Neutralization No.	D974	0.16 (<0.1)
Power Factor 25C	D924	0.336 (0.5% max)
Power Factor 100C	D924	13.00 (5% max)
Specific Gravity	D1298	0.896 (N/A)

Field Test – December 2006

- After reclaiming oil and vacuum fill of transformer

Overall Test Setup

Connections					Inputs		Test Results					
#	HV Lead	Red Measure Lead	Blue Measure Lead	Insulation	Test kV	Corr. Factor	mA	Watts	%PF Meas.	%PF Corr.	Capacitance (pF)	Doble eXpert System
1	HV Winding	LV Winding	Unused	CH+CHL	10.000	0.98	51.234	1.713	0.330	0.320	13590.0	
2				CH	10.000	0.98	14.061	0.505	0.360	0.350	3729.7	Good
3				CHL(UST)	10.000	0.98	37.152	1.215	0.330	0.320	9854.7	Good
4	Test 1 - Test 2 (calculated)			CHL		0.98	37.173	1.208	0.320	0.310	9860.3	
5	LV Winding	HV Winding	Unused	CL+CHL	8.001	0.98	99.075	4.413	0.450	0.440	26280.0	
6				CL	8.001	0.98	61.912	3.222	0.520	0.510	16422.0	Investigate
7								1.193	0.320	0.310	9854.6	
8								1.191	0.320	0.310	9858.0	Good

DXS - Doble Expert System

#	Ratings, Details
2	%PFG<2XP The power factor value does not compare to the previous test result, however it does compare with the initial test result and is good compared to the limit. This may reflect recent repair or maintenance, or an error in the test procedures of the previous test. If not, retest in one year. G All values are acceptable. Limit 1 For 230 kV and below, the power factor limits are .5% for a "G" and .7% for a "D". Above 230 kV, the power factor limits are .4% for a "G" and .6% for a "D".
3	%PFG<2XP The power factor value does not compare to the previous test result, however it does compare with the initial test result and is good compared to the limit. This may reflect recent repair or maintenance, or an error in the test procedures of the previous test. If not, retest in one year. G

Capacitance Change

Test History

History for Overall Test

C_H History

Display History for Test Row: 2

Date	Inputs		Results					Ratings		Notes
	Test kV	Corr. Factor	mA	Watts	PF (%)	PF Corr. (%)	Capacitance (pF)	Ask FRANK™	Manual	
4/17/2015	10.000	1.00	10.492	0.597	0.569	0.568	2783.1	Deteriorated	Unrated	
4/6/2015	10.000	0.99	10.461	0.511	0.490	0.490	2774.7	Good	Unrated	
10/6/2005	10.000	0.99	10.550	0.527	0.500	0.500	2800.0	Good	Unrated	

C_{HL} History

Display History for Test Row: 3

Date	Inputs		Results					Ratings		Notes
	Test kV	Corr. Factor	mA	Watts	PF (%)	PF Corr. (%)	Capacitance (pF)	Ask FRANK™	Manual	
4/17/2015	10.000	1.00	9.121	0.233	0.255	0.255	2419.3	Good	Unrated	
4/6/2015	10.000	0.99	9.122	0.230	0.250	0.250	2419.7	Good	Unrated	
10/6/2005	10.000	0.99	9.269	0.267	0.290	0.290	2458.0	Good	Unrated	

C_L History

Date	Inputs		Results					Ratings		Notes
	Test kV	Corr. Factor	mA	Watts	PF (%)	PF Corr. (%)	Capacitance (pF)	Ask FRANK™	Manual	
4/17/2015	10.000	1.00	31.701	1.199	0.378	0.378	8408.9	Deteriorated	Unrated	
4/6/2015	10.000	0.99	31.699	1.145	0.360	0.360	8408.3	Deteriorated	Unrated	
10/6/2005	10.000	0.99	35.440	1.514	0.430	0.430	9401.0	Good	Unrated	

CL Capacitance decrease

- Overall winding capacitance C_L changed by **over 10%**
- This is extremely significant – **A show stopper**
- But wait a historic review of the bushings yielded…

Capacitance Change Due to Bushings Replacement

Bushing Detail - Replaced

Designation	Replaced	Winding	Low	Serial#	6s00288528

Required for Expert System and Temperature Correction

Manufacturer	Type	Rated kV	% Power Factor		Capacitance (pF)	
			C1	C2	C1	C2
ABB (ASEA-Brown Boveri)	O+C	25.0 kV	0.290 %	0.290 %	600.0 pF	*

Bushing Detail - X1

Designation	X1	Winding	Low	Serial#	05F0215-103

Required for Expert System and Temperature Correction

Manufacturer	Type	Rated kV	% Power Factor		Capacitance (pF)	
			C1	C2	C1	C2
Haefely	COTA	25.0 kV	0.270 %	*	383.0 pF	*

- Thank you for your opportunity..
- Questions?