Power Factor Insulation Diagnosis

Demystifying Standard Practices

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MEGGER
Agenda

- Power Factor Fundamentals
- Power Factor (PF) vs. Voltage
- Negative Power Factor Values
- Excitation Current vs. Voltage
- Temperature Correction Factors for PF Readings
Power Factor Testing

What is it?

- A form of AC testing that applies voltage and measures the leakage/loss current of electrical insulation. It is a type of insulation testing used to evaluate the integrity of electrical insulation.

![Diagram showing insulation testing](image-url)
Facts about Insulation

- Power factor is defined as Cosine of phase angle between voltage and current.

- For an ideal insulation phase angle is 90°.

- \( \cos (90) = 0 \)

Power Factor is ZERO for an ideal insulation !!
Facts about Insulation

■ No Insulation is ideal. A small amount of current flows through all insulation called as leakage current.

■ Leakage current comprises of two components.
  • Resistive current
  • Capacitive current

■ In real life insulating conditions, in addition to the capacitance current there appears a resistive (or loss) current in-phase with the voltage.
Facts about Insulation

In practice no insulation is perfect, but has a certain amount of loss and the total current leads the voltage by a phase angle less than 90°
Power Factor Testing

**Power factor**

\[ \cos \Theta = \frac{I_r}{I_T} \]

**Dissipation factor**

\[ \tan \delta = \frac{I_r}{I_c} \]
Power Factor Testing
Power Factor Testing

- UST
- GST
- GST with Guard

Guard
POWER FACTOR vs. VOLTAGE
Power Factor vs. Voltage

- PF test is typically performed at 10 kV or values equivalent to 10 kV are obtained

- Why not 25 V or 25 kV?

- What test voltage is “good enough”? 

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Power Factor vs. Voltage

- Oil-paper type insulation system

![Power Factor vs. Voltage graph]

Three Phase two winding Oil filled Transformer
Delta-Delta
13.8/2.4 kV, 3.75 MVA

\[ C_{HL} + C_{HG} \]

- PF shows a flat response as a function of test voltage
Power Factor vs. Voltage

- Solid or dry type insulation

The amount of increase in PF value as a function of voltage corresponds to the degree of ionization taking place in voids.

2000 HP, 4000V 3-Φ induction motor
Power Factor vs. Voltage

Dielectric losses as a function of applied test voltage
[Reference IEEE Std. 286-2000]

Tip up test helps in estimating the presence of voids in dry type insulations.
Power Factor vs. Voltage

- 10 kV test voltage provides immunization against electrostatic interference and electrical noise in HV substations.

<table>
<thead>
<tr>
<th>Test</th>
<th>Mode</th>
<th>Freq</th>
<th>V (kV)</th>
<th>Noise (mA)</th>
<th>I (mA)</th>
<th>PF (%)</th>
<th>Cap (µF)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>UST-R</td>
<td>50</td>
<td>4.01</td>
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<td>UST-R</td>
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<td>1998.97</td>
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</table>

Four repeat UST measurements on a grading capacitor in a 765 kV Substation

- A HV test signal provides better signal to noise ratio (SNR) for precise and accurate measurements.
NEGATIVE POWER FACTOR VALUES
Negative Power Factor Values

- Specimens like bushings, three winding transformers, interphase insulation of rotating machinery sometimes exhibits negative PF values.

- PF values cannot be negative. It is a phantom value.

- It is caused when phase angle of measuring current exceeds reference voltage by more than 90 deg.

- This happens typically because of introduction of surface leakage current.
Negative Power Factor Values

\[ I_{\text{NET}} = \text{Total Current} \]
\[ I_T = \text{Test Current} \]
\[ I_s = \text{Surface Loss Current} \]
Negative Power Factor Values

Specimens with low capacitance values (smaller current) are more susceptible to this surface loss current and can lead to negative PF values.

Vector diagram with different magnitude of current $I_{NET}$ and purely resistive loss current $I_s$
Negative Power Factor Values

- Important to understand the source of negative PF values

- Some specimens exhibit negative values by virtue of their design

- Following best testing practices, one should eliminate all external effects

- Repeated negative values after following best testing practices may point towards some contamination/moisture or a bad insulation system
EXCITATION CURRENT vs. VOLTAGE
Excitation Current vs. Voltage

- Excitation current test is a voltage dependant test.

*Typical magnetization curve of a power transformer*

- Test is either performed at 10 kV or values equivalent to 10 kV are determined using a linear relation.
Excitation Current Test

Three Phase High Side “Y”

<table>
<thead>
<tr>
<th>Measures</th>
<th>Test Lead Connections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terminal Symbol</td>
<td>Black</td>
</tr>
<tr>
<td>H1-H0</td>
<td>H1</td>
</tr>
<tr>
<td>H2-H0</td>
<td>H2</td>
</tr>
<tr>
<td>H3-H0</td>
<td>H3</td>
</tr>
</tbody>
</table>

Three Phase High Side “Δ”

<table>
<thead>
<tr>
<th>Measures</th>
<th>Test Lead Connections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terminal Symbol</td>
<td>Black</td>
</tr>
<tr>
<td>H1-H2</td>
<td>H1</td>
</tr>
<tr>
<td>H2-H3</td>
<td>H2</td>
</tr>
<tr>
<td>H3-H1</td>
<td>H3</td>
</tr>
</tbody>
</table>
Excitation Current vs. Voltage

- A linear approximation is used to determine the equivalent excitation current values at 10kV

20 mA @ 5kV is 40 mA @ 10 kV equivalent

<table>
<thead>
<tr>
<th>Voltage (kV)</th>
<th>Excitation Current (mA)</th>
<th>10 kV Equivalent (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.22</td>
<td>12.20</td>
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<tr>
<td>2</td>
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<td>10.00</td>
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<tr>
<td>3</td>
<td>2.68</td>
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<td>4.38</td>
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<td>4.88</td>
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<tr>
<td>8</td>
<td>5.36</td>
<td>6.70</td>
</tr>
<tr>
<td>9</td>
<td>5.84</td>
<td>6.49</td>
</tr>
<tr>
<td>10</td>
<td>6.3</td>
<td>6.30</td>
</tr>
</tbody>
</table>

Voltage and Current exhibits non-linear relation!!

Linear approximation will only give approximate values and can introduce significant errors.

Excitation current test performed at different voltages on a single phase Transformer
Excitation Current on Delta Windings

- Third leg of Delta winding should always be grounded for accurate measurements.

Pending the inductance and resistance of each winding, if third leg is not grounded, the results would be approximately 30 to 50% higher than true readings.
Excitation Current & Residual Magnetism

- A transformer core with residual magnetism can cause erroneous readings in excitation current measurements.

- IEEE C57.152 section 7.211.1 states that “The transformer core may have residual magnetism present as a result of being disconnected from the power line or, as is frequently the case, as a result of dc measurements of winding resistance. The residual magnetism results in the measurement of higher-than-normal excitation current.”

If a significant change in the test results is observed, the only known reliable method of excluding the effect of residual magnetism is to demagnetize the transformer core.
Temperature Correction Factor for PF Readings
Temperature Correction Factors

- Temperature correction factors (TCF) are based only on nameplate information.

- TCF does not take into account critical information such as the aging of insulation, the quality and type of oil and paper insulation, operating conditions or the history of the transformer.

- Insulation temperature dependence would be different based upon it’s condition and age.

- It can lead to incorrect temperature compensation and false trending of results.
TCF for Any Oil Filled Power Transformer Above \( \frac{1}{2} \) MVA

1970, 500 MVA and 2012, 5 MVA oil filled transformers use the same correction factor

Insulation used in power transformers (type of oil and paper) is not taken into account
IEEE C57.12.90 section 10.10.4 Note 3 (b) states that “Experience has shown that the variation in power factor with temperature is substantial and erratic so that no single correction curve will fit all cases.”

“When the insulation power factor is measured at a relatively high temperature and the corrected values are unusually high, the transformer should be allowed to cool and the measurements should be repeated at or near 20 °C.”

It is imperative to only compare a specimen’s PF values that are either taken at a similar temperature or corrected to the same temperature accurately.
Temperature Correction Factors

Temperature dependence of different transformers with different levels of ageing
Temperature Correction Factors

- Each specimen is unique in its construction, design and ratings. They are each subjected to different kinds of stresses, loading and environmental conditions.

- Temperature correction factor values are highly dependent on insulating material, their structure, ageing, presence of moisture or contamination and various other factors.

- The available temperature correction factor data is based upon the average value.
Temperature Correction Factors

- The average correction would introduce some error into the corrected value, as each specimen is unique.

- New transformers have relatively weak temperature dependence and use of TCF tables would overcompensate.

- An aged transformer, becomes highly temperature dependent.

- Average TCF values to 20°C lie somewhere between these two extremes.
Dielectric Frequency Response (DFR)

- Also known as Frequency Domain Spectroscopy

- DFR is a test technique used to determine the moisture concentration in the solid insulation (oil impregnated paper) of liquid-filled power transformers

- PF measurements are performed in a frequency range of 1 mHz – 1000 Hz.

- PF vs. Frequency plot is generated
Dielectric Frequency Response

Each point is a Power Factor value!
DFR Measurement

- Measures Capacitance
- Measures Power Factor
- Measures MOISTURE % in cellulose

Conductor

Insulation Material

Conductor or Ground

Determines Individual Temperature Correction factors (ITC)

Insulation parameters:

\[ Z = R + jX \]

- Capacitive charging current
- Resistive watts lost current (heat)
Temperature Correction Factors

- The determination of temperature correction factors using DFR method is based on the fact that a power factor measurement at a certain temperature and frequency corresponds to a measurement made at different temperature and frequency.

- With DFR technique, individual temperature correction factors can be determined and values can be accurately corrected to 20 °C.

- The big advantage of this technique is that PF values can now be measured at any insulation temperature ranging from 5-50 °C and still can be corrected to 20 °C accurately.
Case Study to COMPARE
Table based
Temperature Correction Factors (TCF)
Vs.
DFR based Individual
Temperature Correction Factors (ITC)
ITC and TCF Field Results

- ITC method using DFR technique was verified and implemented on a new 40 MVA core type three-phase delta wye transformer.

- Transformer was tested in a controlled environment at an EFACEC manufacturing plant.

- The goal was to perform PF test at different temperatures and compare ITC and TCF against real Measured Correction Factors (MCF).
Test Setup

- Windings were heated using short circuit method and temperature was raised to 75º C

- The transformer was allowed to cool for hours to bring the oil and windings temperature closer

- Winding resistance test was performed to determine the high and low side temperatures

- Top oil temperature, top and bottom radiator and ambient temperature were monitored through out the test duration
Test Object
Short Circuit Test
Temperature Measurements
Transformer Temperature

- The average temperature of the transformer oil was estimated using the formula mentioned in IEEE C57.12.90
  \[ \text{Avg oil temp} = \text{Top oil} - \frac{\text{(Top Rad.} - \text{Bottom Rad.})}{2} \]

- Transformer insulation temperature was determined by taking average of high side, low side and average oil temperature

- Temperatures were measured at the start and end of each test to get a more accurate overall transformer insulation temperature
Test Details

- PF was measured at different temperatures as the transformer was cooling down from 50° C to 20° C

- Two different test instruments (IDAX 300 and Delta 4000) were used to perform the PF measurement at different temperatures

- All three insulations ($C_{HL}$, $C_{HG}$ and $C_{LG}$) were measured for this analysis

- DFR from 1- 500 Hz was run for each measurement
Test Setup
ITC Analysis

- Three different types of correction factors were used in the case study

1) **TCF**, traditional temperature correction factors obtained from standard tables

2) **Measured (real) Correction Factors**

   \[
   MCF \ @ \ Temp \ X = \frac{\text{Measured PF @ 20C}}{\text{Measured PF @ Temp X}}
   \]

3) **ITC** by using DFR
Comparison of ITC & TCF against MCF
Observation # 1

Comparison of ITC and TCF with respect to Measured Correction Factors (MCF) for $C_{HL}$ insulation
Observation # 1

ITC and TCF percent error with respect to Measured Correction Factors (MCF) for $C_{HL}$ insulation
Observation # 2

Comparison of ITC and TCF with respect to Measured Correction Factors (MCF) for $C_{HG}$ insulation
Observation # 2

ITC and TCF percent error with respect to Measured Correction Factors (MCF) for \( C_{HG} \) insulation.
Observation # 3

Comparison of MCF and TCF for \( C_{LG} \) insulation
Observation # 4

Comparison of ITC and TCF corrected values to 20° C with respect to measured PF readings at different temperatures and 20° C for CHL insulation

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DFR  ITC Summary

- The tests performed and analysis of results indicates that TCF being average correction values can introduce error varying from as little as 2% to as high as 92% on the specimen tested.

- The analysis was performed on three different insulations of a single transformer only. Other transformers with different aging and operating conditions can have varying percent errors in measurements when TCF is applied for temperature correction.

- ITC results were very comparable to MCF and worst case error was 10%.

- With same PF connections and little extra time ITC can be obtained via DFR technology that can better compensate for temperature and correct values to 20 ºC.
Temperature Correction Factors

- With the help of Power Factor vs. frequency, Power Factor vs. temperature can be plotted.

- With DFR technique, individual temperature correction factors can be determined and values can be accurately corrected to 20 °C.

- The big advantage of this technique is that PF values can now be measured at any insulation temperature ranging from 5-50 °C and still can be corrected to 20 °C accurately and precisely.
Conclusions

- Electric apparatus have failed and will continue to fail because of insulation deterioration.

- Power factor readings are dependent on various different factors and it is very important to understand the effect of these factors.

- Test voltage, electrostatic interference, temperature, humidity, surface losses and various other parameters can greatly influence the PF readings.

- A better understanding of the impact of these varying parameters would help in obtaining accurate PF measurements.
Thank You!!

QUESTIONS ??