Megger
Power on

TRANSFORMER LIFE MANAGEMENT (TLM) BULLETIN:

Power Factor/ Dissipation Factor and Capacitance

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I. INTRODUCTION

Insulation materials perform at a minimum one major function in all electrical equipment[1]. They must provide electrical isolation of an asset's energized parts from its other parts that are operating at different voltages or that are maintained at ground potential. A failure to do so has dire consequences, not least including the failure of the asset itself. Dielectric failures (as this would be called) have a reputation for their severity and for oil-filled assets, such as transformers, may result in fire, explosions, damage and destruction to surrounding equipment, and loss of life.

There are several offline electrical tests available to assess insulation health, including: DC insulation resistance testing; power factor/ dissipation factor (PF/DF) and capacitance; and dielectric response methods like dielectric frequency response (DFR). Each of these tests occupies a unique space with regard to transformer test needs so it is important to understand each. The subject of this bulletin is the power factor/ dissipation factor and capacitance test.

The electrical power industry has relied on power factor/ dissipation factor and capacitance testing for nearly a century as a screening tool to assess electrical insulation. Because of the test's touted ability to detect localized defects in multiple layer insulation systems, power factor/ dissipation factor and capacitance testing emerged and quickly gained in popularity in the early 1900's at a time when condenser[2] bushings, which are prime examples of multiple layer insulation systems, were coming into widespread use. Manufacturing problems with these type bushings were not being consistently identified using dc insulation resistance methods and manufacturers turned to power factor/ dissipation factor and capacitance tests as an alternative.

(1) Power factor/ dissipation factor and (2) capacitance are unique electrical test parameters "measured" simultaneously in a power factor/ dissipation factor and capacitance test. They each offer different information regarding the state of an insulation system. The subject is best framed starting with a review of capacitance…

1 Transformer oil also (1) provides sufficient cooling/heat transfer, (2) preserves the core and coil assembly by filling voids in the cellulose, and (3) minimizes the contact of oxygen with cellulose and other materials that are susceptible to oxidation. Meanwhile, the cellulose serves a mechanical function by supporting the windings and a thermal one by creating cooling ducts.

2 Better known as capacitance graded bushings

II. BACKGROUND

AN IDEAL INSULATION SYSTEM (CAPACITANCE)

An ideal (electrical) insulation system would effectively store 100% of the electrical energy placed across it (i.e., no losses). This behaviour is modelled by a capacitor. When a constant DC voltage is applied across a capacitor, once its plates are completely charged, a capacitor does not allow current to pass through it. In other words, a capacitor blocks DC (i.e., in-phase, real, resistive) current flow. Real current flow, I_R, is associated with losses, which are given by:

$$\text{Watts} = V \cdot I_R, \quad (1)$$

where V is voltage. Losses, given in Watts, in equation 1 above quantify the amount of applied electrical energy that is lost to heat. If resistive current, I_R, is zero, losses are zero, and all applied energy is stored.

When an AC voltage is applied across a capacitor, there is current flow through the capacitor as given by equation 2 but this is capacitive and represents the energy being stored on each half cycle.

$$I_C = C \cdot (dV/dt) \quad (2)$$

Therefore, a capacitor models the ideal behaviour of an insulation system – which is to store all electrical energy present.

CAPACITANCE

When a voltage is applied across reasonably spaced[3] electrodes of a capacitor (Figure 1), charge (Q) accumulates on the electrodes of the capacitor, as given by:

$$Q = V \cdot C \quad (3)$$

where V is voltage and C is capacitance. As the area, A, of a capacitor's electrodes (e.g., plates) becomes larger and/or the distance, d, between the plates, decreases, more charge accumulates on the electrodes and capacitance increases.

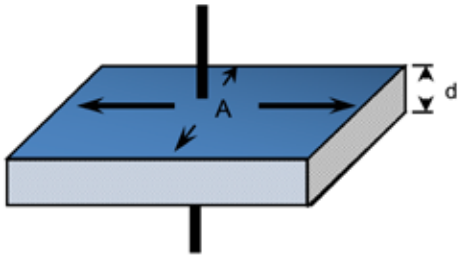


Figure 1: Parallel plate capacitor

If the electrodes of the capacitor are separated by a vacuum, the capacitance depends only on shape, or geometry. This is called geometric capacitance and is given by:

$$C = \frac{\varepsilon_0 \cdot A}{d} \quad (4)$$

where ε_0 is the vacuum permittivity, or the permittivity of free space (≈ 8.854 • 10-12 Fm-1), A is the area of the plates, and d is distance between the plates.

The vacuum that fills the space between the capacitor's electrodes is called a dielectric and as an electrical insulator, prevents charge from moving from one electrode to the other. More often, dielectrics other than a vacuum are used to fill the space between a capacitor's electrodes and include certain liquids, gases and solid materials. The source of the charge stored on a capacitor's electrodes is the voltage source applied across the capacitor and not a contribution from the dielectric. However, depending on the dielectric that fills the space, the amount of charge that collects on the plates can be enhanced. This material property is referred to as the material's relative permittivity, or dielectric constant, and is the measure of a material's capacitance relative to capacitance should that material be replaced with a vacuum [4]. Dielectric constant, ε, is an intrinsic material property discovered by Michael Faraday in 1836.

3 Not infinitely spaced apart

4 A vacuum does not enhance charge accumulation so is the standard to which all materials are compared.

All of the foregoing parameters, that is, area of a capacitor's electrodes (A), the distance between a capacitor's electrodes (d), and dielectric constant of the material(s) between the electrodes (ε), are all physical markers and contribute to the capacitance value as given by equation 4.

$$C = \frac{\varepsilon_r \bullet \varepsilon_0 \bullet A}{d} \qquad (4)$$

where C is capacitance, ε_r is relative static permittivity of the material between the plates, ε_0 is the permittivity of free space ($\approx 8.854 \bullet 10^{-12}$ Fm^{-1}), A is area of the plates, and d is distance between the plates.

CAPACITORS AND THE INSULATION SYSTEM ANALOGY

An insulation system should electrically isolate each of an asset's components from others that exist at different voltages when the asset is energized. Examples of components that operate at unique voltages in an energized transformer may be each winding of the transformer and a transformer's grounded core and tank. These components are analogous to a capacitor's electrodes while an asset's insulation material(s) is analogous to a capacitor's dielectric.

In order to access the capacitor's dielectric or the analogous insulation system for testing, the capacitor's electrodes (e.g., the asset's components such as a winding), must be accessible in order to apply voltage to them. Some windings, for example a stabilizing tertiary in a transformer, may not be brought out of the transformer tank and, in those cases, is not available as an electrode/ test connection point.

In the case of a transformer winding, the winding terminals must be short-circuited so that similar to a capacitor's electrodes, voltage at any point along the winding is the same when it is energized[5] . If the component is very large, just as with a capacitor's electrodes, more charge can accumulate and capacitance is large.

If the distance separating the asset's components (e.g., windings) were to decrease, the accumulated charge on the components, and therefore capacitance, increases. This is the principle by which capacitance can be used as one means to detect winding deformation in a transformer[6]. For example, if the distance between the HV and LV windings increases (due to forced or free buckling of the inner, concentric winding – usually the LV winding), the capacitance of the interwinding insulation system, C_{HL}, will decrease.

If the average dielectric constant of the material(s) present in the insulation system (e.g., the dielectric) changes, the amount of accumulated charge, and hence capacitance, changes. As an example, should a bulk oil-filled bushing develop a leak and lose an appreciable amount of oil that is subsequently replaced by air, the capacitance would change noticeably indicating that something is amiss. On the other hand, though, if the insulation material is oil-impregnated paper, as an example, and this becomes contaminated with a relatively small amount of moisture, even though water has a significantly higher dielectric constant than oil-impregnated paper, the average dielectric constant will not be notably affected in most power transformers, so capacitance is not expected to reflect the contamination.

In summary, capacitance reflects the physical attributes of the insulation being tested. A change in capacitance between tests suggests that either the physical system is not the same one that was previously tested or that a physical change has occurred within the system since the last time it was tested.

5 Otherwise an inductive component is introduced into the measurement that may distort the results; reference Figure 10

6 Capacitance is not acutely sensitive to winding deformation so it is not the preferred method to make a final determination if winding deformation exists. It is a convenient diagnostic since it is available any time a power factor/ dissipation factor test is performed so is suitable as a first level screening tool. Concerns that a winding has moved should be investigated with sweep frequency response analysis (SFRA) and/or leakage reactance testing.

REAL INSULATION SYSTEMS

Unlike an ideal capacitor, the insulation systems associated with most electrical assets have losses, even when brand new. They are still typically very efficient but do not store 100% of the electrical energy present across them.

When an AC voltage is placed across a typical insulation system, while most of the resulting current that flows through the insulation is capacitive (representing the energy being stored by the insulation), resistive current results as well. This resistive component, I_R, which is in-phase with the AC voltage, is associated with losses. The total resulting current that flows through the insulation when voltage is placed across it, I_T, is the vector sum of the capacitive current, I_C, and resistive current, I_R, as given in Figure 2.

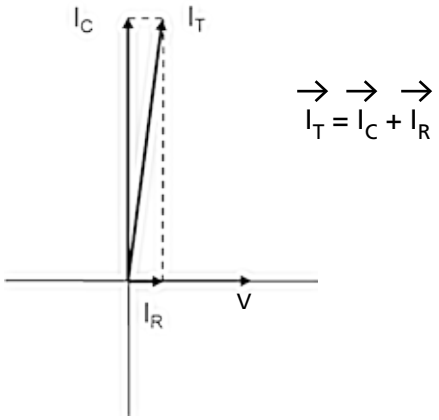


Figure 2: Total Current in a real insulation system

Dielectric loss is the energy lost/ released as heat when an electrostatic field is present across an insulation system. Losses can be broadly classified as conductive losses, arising from leakage current, or polarization losses[7] . The total losses ($I_R \cdot V$) in a dielectric are equal to the combined polarization losses and conductive losses present[8] . It is particularly desirable to identify changes in losses, which typically indicate the declining health of the dielectric. In general, a localized problem elicits far more concern than general, widespread degradation because a localized problem significantly raises risk of a dielectric failure.

Dielectrics perform best when they are clean, dry, relatively void-free, and utilized within a certain temperature range. Adversaries to a dielectric's continued good health are heat, moisture and oxygen.

A dielectric fails when the stresses across the materials meet or exceed the insulation system's dielectric withstand capabilities, which deteriorate with age and the worsening condition of the dielectric. Testing and maintenance are means by which an asset owner can influence the withstand capabilities of an insulation system; for example by determining when a transformer is wet and drying it, reconditioning the oil, repairing leaking gaskets, etc. An asset owner can influence the stresses present as well; for example, by reducing load on a transformer and therefore its operating temperature. This is particularly prudent in the case of a wet transformer for example, if the transformer cannot first and otherwise be restored to better condition [1].

7 Conductive and polarization losses are described in Megger's "DFR - narrowband application" TLM Bulletin

8 The ability to detect conductive losses is heightened as the test frequency is reduced (towards DC) from line frequency (50/60 Hz). Losses due to polarization processes occurring in the insulation system vary depending on the test frequency.

TRANSFORMER INSULATION SYSTEM

The insulation system of power transformers consists of oil and cellulose. Cellulose is solid insulation (paper and pressboard) that is typically processed using the Kraft method. These are organic materials so it is inevitable that they will age and reach end of life.

From a manufacturing and functional perspective, a transformer's insulation components are often classified as parts of the major and minor insulation. The major insulation structure of a power transformer refers to the oil gaps and multiple pressboard barriers between the windings, as conceptually illustrated in Figure 3.

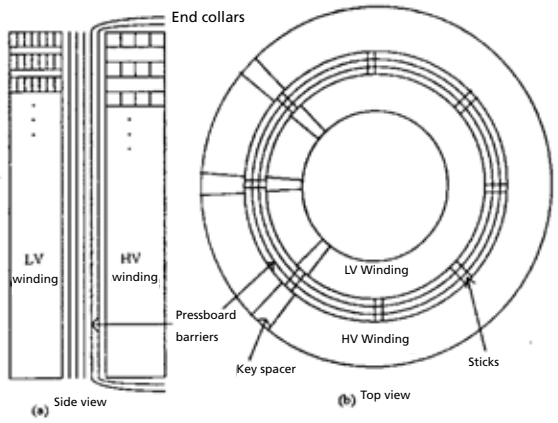


Figure 3: Major insulation structure in a power transformer [2]

"The minor insulation structure (Figure 4) consists of the smaller oil gaps separating the disks and maintained by the key spacers which are narrow insulators, usually made of pressboard, spaced radially around the disk's circumference. In addition, the turn to turn insulation, usually made of paper, can be considered as part of the minor insulation structure." [2]

From a dielectric test perspective, insulation is often thought of as systems that can be grouped and isolated for test; for example, the winding turn-to-turn insulation (tested in an exciting current test, turns ratio test, etc), and C_H, C_L and C_{HL} components in a two-winding transformer, described in the Dielectric Representation section on page 8.

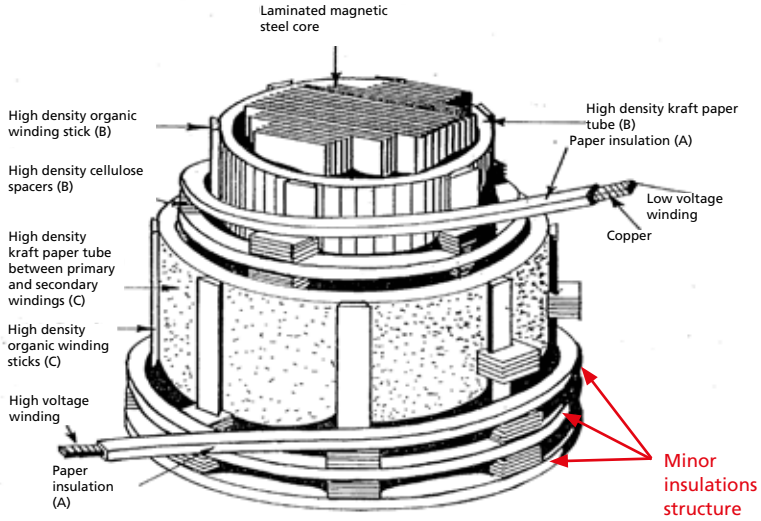


Figure 4: Minor Insulation Structure [3]

POWER FACTOR/DISSIPATION FACTOR

Power factor/ dissipation factor is an index (meaning that it has no units of measure) that provides a sense of the relative losses of an insulation system. In the case of power factor, relative losses means the amount of energy lost to heat compared to the total amount of electrical energy present across the insulation, as given by (I_R/I_T). Power factor is determined by the phase angle relationship of the ac waveforms of the voltage present across the insulation and the resulting current that flows through the insulation, as illustrated in Figure 5.

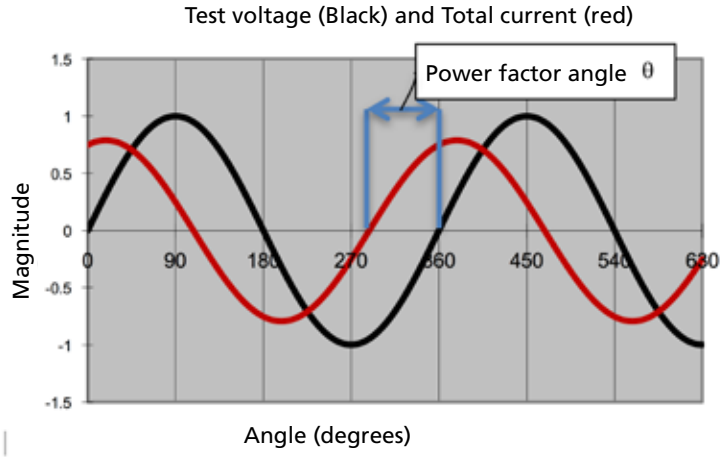


Figure 5: Determination of the Power Factor Angle θ (also called impedance angle)

For dissipation factor, relative losses means the amount of energy lost compared to the amount of electrical energy stored by the insulation, as given by (I_R/I_C). Dissipation factor is determined by the phase angle relationship of the ac waveforms of the capacitive current (which relates to reactive power/ energy stored by the insulation) and the total current that flows through the insulation when voltage is present across the insulation (Figure 6). This angle is appropriately known as the loss angle, δ. It is the complementary angle to the power factor angle, θ.

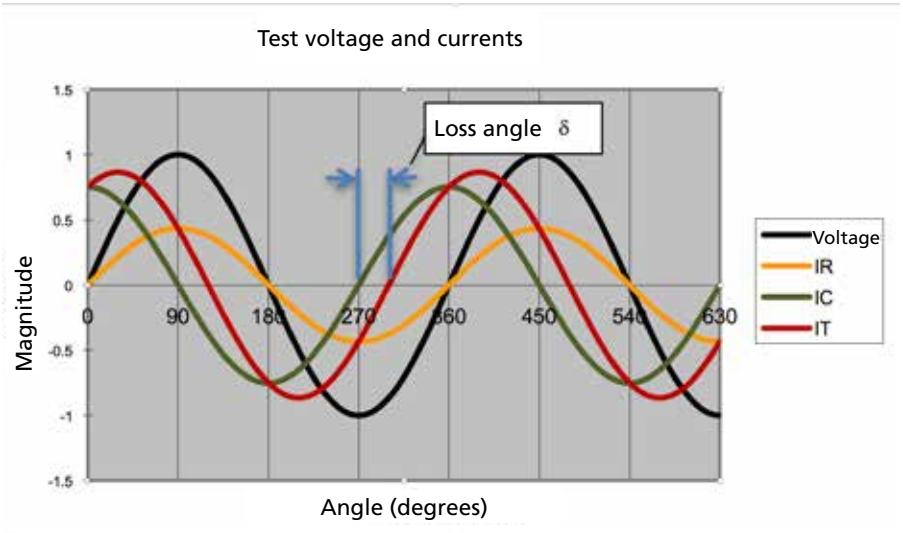


Figure 6: Determination of the Loss Angle δ

During a power factor/ dissipation factor and capacitance test, an AC test voltage is applied across the insulation system. This voltage signal is the reference waveform and is assigned a 0° phase angle. The phase angle of the resultant AC current measured through the insulation is evaluated. If the resultant current is completely capacitive, indicating that there are no losses, the power factor angle, θ, will be 90° and the loss angle, δ, will be 0°. However, since there are inherent losses present with most insulation systems, the power factor angle, θ, of the resultant total current through the insulation system will be less than 90° while the loss angle, δ, will be greater than 0°. Power Factor is the cosine of θ (the complementary angle of the "loss angle") while Dissipation Factor is the tangent of δ, or the loss angle (Figure 7).

Power Factor/ Dissipation Factor and Capacitance

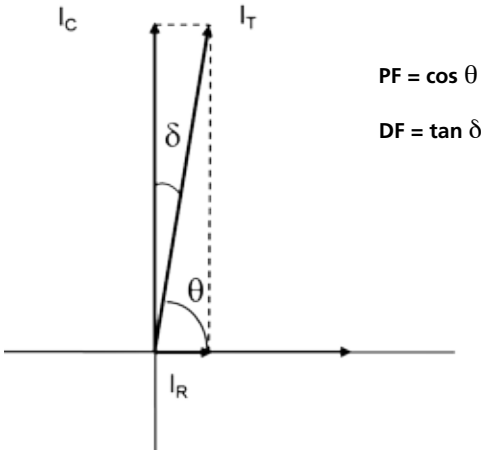


Figure 7: Power Factor and Dissipation Factor

The cosine of an angle (θ) close to 90° and the tangent of an angle (δ) close to 0° is a very small number – close to zero. This is why power factor/ dissipation factor is multiplied by 100 and reported as a percentage. Even then, typical values of power factor/ dissipation factor for oil-filled power transformers are less than 1%.

Losses, given in units Watts, are normally provided in the test results as well. Losses are dependent on the insulation size. An insulation system that is twice as large and in the same condition as another insulation system of the same type will have twice the losses as the comparatively smaller one. Losses cannot be compared directly between same type insulation systems of different sizes as a means to determine which system is in better condition unless the size of each is known to determine relative losses. Since it is not practical to quantify the sizes of insulation systems inside electrical assets, losses are not commonly compared between similar assets. However, losses may be compared to previous test results. The convenience of power factor/ dissipation factor as a loss index is that the insulation size (through its direct correlation to capacitance) and losses determine the power factor/ loss angle and are reflected by the power factor/ dissipation factor value. Power factor/ dissipation factor indicates the dielectric's relative losses, which is necessary to compare insulation systems of same type. This is a strength of power factor/ dissipation factor. Unfortunately, it is often touted to the point that an important caveat is overlooked. Power factor/ dissipation factor is more revealing on a smaller insulation system than a larger one. So, low and identical power factor/ dissipation factor test results for a large insulation system and a small insulation system may not carry the same meaning and may not be indicating insulation systems in identical condition. In such a case, the low and equal power factor/ dissipation factor is more reassuring on the smaller insulation system.

- **It is important to note that a power factor/ dissipation factor and capacitance test is performed at line, or mains, frequency[9]. Power factor/ dissipation factor and capacitance values are frequency dependent. Dielectric response methods like dielectric frequency response (DFR) entail making power factor/ dissipation factor measurements at multiple frequencies and considering how power factor/ dissipation factor and capacitance change with frequency. All observations made about power factor/ dissipation factor in this bulletin refer specifically to the line frequency measurement of power factor/ dissipation factor.**

NOMENCLATURE

Power factor and dissipation factor, though determined differently, are very similar and serve the same purpose. Conveniently, both give nearly identical indications within the realm of where most insulation systems will test (up to approximately 10% power factor/ dissipation factor), so which to use becomes largely a matter of preference.

The use of power factor spans various applications in the industry and, in fact, is often more readily associated with other uses like characterizing distribution feeder efficiency and in performing generator/load power system studies, etc. Some feel that its additional use to describe insulation efficiency causes confusion. Many power plant personnel, as one example, are less than enthused about the use of power factor in insulation assessment. Meanwhile, it can be argued that dissipation factor is a more descriptive name for what is being assessed. Dissipate means to use something wastefully. So, as a reporting index of the relative amount of energy that is lost to heat, dissipation factor conveys its reason for use practically through its name alone.

Slang names for a power factor/ dissipation factor and capacitance test may be encountered as well, and include "tan δ" when referring to a dissipation factor measurement and a "Doble test" when referring to a power factor measurement.

9 As a means to filter electrostatic interference, measurements are typically made at frequencies just above and below line frequency and averaged.

Another point of clarification regards the use of the terms "dielectric" and "insulation". These are often used interchangeably since a dielectric is an insulator. The term dielectric specifically conveys that the material(s) will efficiently support an electrostatic field while prohibiting conduction. Insulation has many applications (electrical, thermal, acoustic, etc.) and when used without context may be referring to any one of them.

III. TESTING

DIELECTRIC REPRESENTATION – a testing guidepost

An asset may have a large amount of insulation material(s). For diagnostic purposes, it is imperative that the amount of insulation evaluated in a single power factor/ dissipation factor and capacitance test be held to the smallest quantity possible. Otherwise, problems may become difficult, if not impossible, to notice. The tester won't have control over how far an insulation system may be segmented for testing beyond a point. A "dielectric representation" serves as a guidepost to the tester showing how segmentation may be done.

A dielectric representation is a diagram that identifies each (group of) component(s) in the asset that will exist at a unique voltage when the asset is energized. It is left to the tester to identify whether or not the component is accessible so that a test lead may be connected. The number of unique voltages/component groups present will determine the number of necessary insulation systems. Any area where a difference in potentials will exist when the asset is energized will require insulation to store the energy from the resulting electrical field that will be created. For example, each turn of a transformer winding will have a voltage across it, necessitating insulation between each turn. The voltage difference between the transformer winding and the grounded core or grounded tank will also require insulation. If a transformer has more than one transformer winding, insulation will be required between the transformer windings to support the difference in the voltages present on each winding[10].

In a dielectric representation, insulation between components is depicted by a single capacitor. This is adequate since a dielectric representation is simply a guidepost to testing. A dielectric model, on the other hand, serves to predict the electrical behaviour of an insulation system so a single capacitor for this type of diagram would not be adequate.

An example of a dielectric representation is given in Figure 8 for a two-winding transformer. It identifies three (3) components of the transformer that will exist at unique voltages when the transformer is energized: the high-voltage winding, the low-voltage winding, and the grounded tank and core.

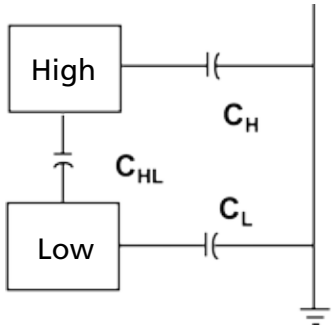


Figure 8: Dielectric representation of a 2-winding transformer

The insulation systems are identified as C_H, C_{HL}, and C_L:

- C_H is the system of materials that provides electrical isolation between the energized high-voltage winding and transformer components at ground potential such as the tank and core. C_H includes the active insulation of the high-voltage bushings, the high-voltage winding insulation, structural insulating components and oil.
- C_{HL} is the system of materials that provides electrical isolation between the energized high-voltage winding and the energized low-voltage winding; also called the interwinding insulation system. C_{HL} includes insulation of the high-voltage and low-voltage windings, the barriers and oil (i.e., the major insulation structure). C_{HL} is comprised predominantly by paper insulation.
- C_L is the system of materials that isolates the energized low-voltage winding from ground potential components. This includes the active insulation of the low-voltage bushings, low-voltage winding insulation, structural insulating components and oil.

10 Assuming that the windings operate at different voltages, which is typically the case.

To determine how to test a transformer, a helpful approach is to count the number of separable[11], accessible windings. For example, consider the case of a 4-winding transformer with a winding configuration of Δ-Y-Y-Y whereby all winding terminals are accessible except for the 3 secondary neutral terminals which are all connected and grounded internally. The number of practically separable windings is two – (1) the delta winding and (2) the three wye-connected secondary windings, which will be treated as one winding/electrode since they cannot be conveniently separated. As for accessibility, while the delta winding is fully accessible, the neutral terminals of the secondary group (Y-Y-Y) are not, making it impractical to disconnect from ground. In this case, this 4-winding transformer will be tested using a 2-winding transformer test procedure but with the expectation that all of the results will not be entirely meaningful (reference negative power factor/ dissipation factor on page 16).

TEST PREPARATION

Improper test preparation may impact results. To maximize the likelihood that the results are representative, the following preparations must be made before performing a power factor/ dissipation factor and capacitance test on a transformer.

1. *Check that the transformer tank is grounded well.* In instances whereby test results are truly perplexing, often a poorly grounded test specimen will ultimately be discovered to have been the culprit. If uncertain, provide a known good ground to the tank and repeat the test.

2. *Physically and electrically isolate each winding's terminals (bushings).* The best practice is to leave nothing physically connected to the bushing terminals. Do not rely upon rubber blankets to achieve clearance from nearby bus; otherwise, these blankets become part of the insulation test circuit and may lead to non-representative test results. If it is truly impractical to disconnect bus that is attached to a winding's terminals, the consequences are:
    a. The insulation system between the winding, which is not physically isolated, and ground cannot be tested independently. Assuming that the subject winding is the transformer's low voltage winding, as an example, the bus left attached to the low voltage winding introduces an additional capacitance, C_{bus}, into the measurement. This capacitance is in parallel to the C_L capacitance, and so the C_L and C_{bus} capacitance values add, resulting in a higher measured "C_L" capacitance result.

    b. Insulators along the attached bus frame will be included in the measurement. Since power factor/ dissipation factor is an average measurement, the condition of the insulation between the attached bus and ground may influence the C_L power factor (in this example) for better or worse. Bottom line is that the measured "C_L" power factor/ dissipation factor cannot be presumed to be representative of the low-voltage winding to ground insulation only.

    c. Because the insulation included in the C_L measurement is greater than what it would be had the winding terminals been isolated, a problem will become more difficult to see (remember that smaller = better).

    d. Winding to ground measurements can already be influenced by excessive surface leakage on that winding's bushing terminals. If a bus frame and all of its support is included in the measurement as well, the 'exposed' surface area of insulation included in the measurement notably increases and surface leakage may especially influence the measurement such that the electrical results are not representative of the condition of the insulation.

3. *Short circuit each separable winding by connecting each respective winding's terminals/bushings together.* If a winding has a neutral terminal, connect this to the winding's other terminals as well (Figure 9). If the neutral terminal is normally grounded in service, disconnect the ground connection for test. Once the test is complete, the ground connection to the neutral terminal should be reconnected.

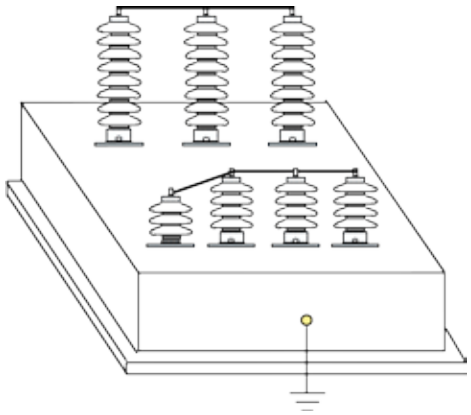


Figure 9: Transformer prepared properly for a power factor/ dissipation factor test

11 Separable from a practical perspective – a tester should not be draining oil to make test preparations for routine measurements

Failing to short circuit each winding may or may not, depending on the transformer, notably affect test results. This is what happens:

A winding is an inductor. If not short-circuited during the test, an inductive component of current will be introduced into the measurement. Inductive current, I_L, is 180° out of phase with capacitive current, I_C, and will cancel an indeterminate portion of I_C so that it appears that the insulation is storing less electrical energy than it actually is. I_R is unaffected in this scenario. The net effect is that the loss angle, δ, increases to δ' (and the power factor angle decreases), resulting in a higher dissipation factor/ power factor result – to what degree this influence is wielded is largely variable. Figure 10 illustrates this influence.

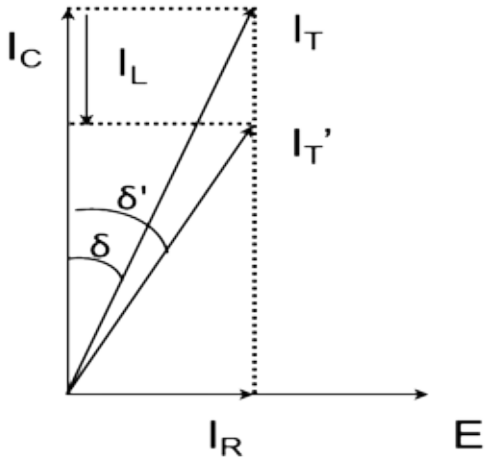


Figure 10: Inductive Influence when Transformer Windings are not Short-Circuited in Preparation for a Power Factor/ Dissipation Factor and Capacitance Test

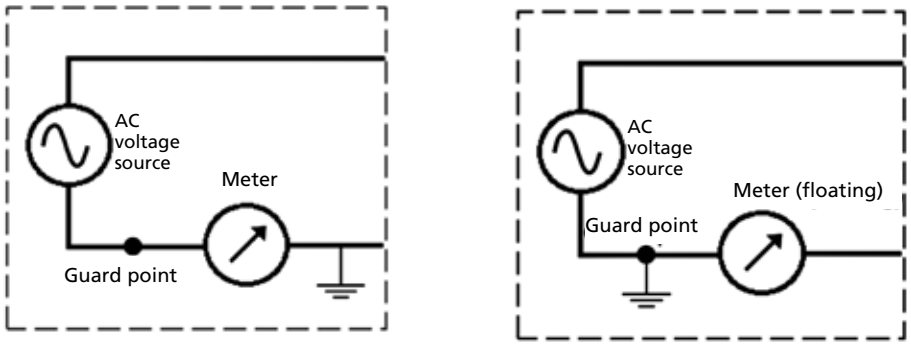
- Shorting jumpers used to short-circuit winding terminals must have adequate clearances from grounded surfaces. Otherwise, coupling to ground may occur and introduce error into the measurement. In these instances, ironically, the efforts taken (shorting the windings) to minimize the chance of a non-representative measurement cause the results to be less representative. There are some instances wherein short-circuiting the low-voltage winding, in particular, is challenging; for example, when metal enclosures[12] separate the winding terminals from each other. Here, a tester may find that it is better to not short-circuit the winding. It is advisable when dealing with such a situation to test using both set-up configurations (winding short-circuited and then not) to better understand the influences on the test results in each case.
- Only bare copper/ aluminum wire should be used for shorting jumpers. Insulated conductors are not recommended.
- **Note** that since the windings are short-circuited in preparation for a power factor/ dissipation factor and capacitance test, the winding(s) turn-to-turn insulation is not stressed/assessed in this test. Turn-to-turn insulation is assessed in other off-line electrical tests such as exciting current and transformer turns ratio.

12 Sometimes referred to as a "dog-house"

TEST MODES

When a winding is energized, an electrical field is created and surrounding insulation is charged. Test modes provide the user with a means to segment charged insulation and test the smallest components of insulation possible.

The enabling feature of a power factor/ dissipation factor test instrument that supports test modes is a so-called "guard circuit". The guard point is located between the test instrument's AC voltage source and its current meter (Figure 11). All current resulting from the application of the instrument's test voltage will seek to return to the guard point. Return paths to the power factor/dissipation factor test instrument are typically provided by up to three (3) measuring leads: a "ground" lead and two (2) low voltage leads that are connected between the instrument and the asset under test.



a) GST mode **b) UST mode**

Figure 11: Power Factor/ Dissipation Factor Test Instrument: Internal Test Circuit Configuration

Test modes include:

- GST – Ground
- GST – Guard
- UST

GST is an acronym for "grounded specimen test". In these tests, the meter is grounded as shown in Figure 11(a). The appended "- ground" or "- guard" designation indicates whether the test instrument will internally connect the low voltage lead(s) to ground or to the "guard point" (assuming that the low voltage lead(s), which is optional in use, is plugged into the test instrument panel). When in the GST – Ground mode, the low voltage lead(s) is a measuring lead. When in the GST – Guard mode, the low voltage lead(s) diverts current flow around the meter.

UST is an acronym for "ungrounded specimen test". In UST mode, the guard point is grounded and the meter "floats" as illustrated in Figure 11(b). Current flow on the low voltage lead(s) will pass through the floating meter to return to the guard point and will be measured.

The ground lead is always used in a power factor/ dissipation factor test and is connected between the test instrument and the ground of the asset under test. Although it is referred to as the ground lead because it connects to the test specimen's ground and serves to compare the specimen ground to the voltage supply ground, it is also a current carrying lead used to measure or guard. When the meter is grounded as in the GST mode (Figure 11a), all current flow along the ground lead passes through the meter to return to the guard point and is included in the measurement. When in the UST mode (Figure 11b), the guard point is grounded, and all current flow along the ground lead bypasses the meter to return to the (grounded) guard point. In UST mode, the ground lead serves as a guard mechanism to divert current from being measured.

With a solid understanding of test modes and a dielectric representation of an asset in hand, a tester should be able to determine how to perform power factor/ dissipation factor and capacitance tests on just about anything (although test procedures for most electrical assets are readily available through software and literature – ref Megger software and test guides).

TEST VOLTAGE

A power factor/ dissipation factor and capacitance test, properly executed, is a non-destructive test. The line-to-ground (L-G) single phase test voltage delivered by the instrument should not exceed the line-to-line (L-L) voltage rating of the winding being energized. Additional precaution is advised when testing a distribution transformer with a grounded wye-winding or a single-phase distribution transformer with a neutral. These transformers may have a graded insulation system[13], so the test voltage should be kept less than the voltage rating of the neutral terminal.

Recommended, industry standard test voltages are usually automatically provided in test software once the winding rating(s) and configuration of the transformer to be tested are provided by the tester.

On ideal oil-paper insulation systems, power factor/ dissipation factor and capacitance tests performed at all test voltages less than the maximum, recommended test voltage are expected to yield the same power factor/ dissipation factor. An unexpected voltage dependence (i.e., when power factor/ dissipation factor changes with test voltage) often indicates that the insulation is degraded or may be indicating a problem in the test circuit. Tip-up testing (step voltage) is recommended for investigating power factor/ dissipation factor voltage dependence in insulation materials.

Traditionally, in order to determine if voltage dependence exists, an additional power factor/ dissipation factor measurement is made with a different test voltage and the power factor/ dissipation factor results are compared. Megger's power factor/ dissipation factor test instruments come equipped with Megger's unique automatic voltage dependence detection (VDD) capability, which eliminates this need for extra testing. The feature capitalizes on a noted correlation of an asset with a voltage dependent problem and the harmonics generated in its dielectric response. VDD estimates the harmonic content in the measured response and determines the harmonics created by the test specimen. If the harmonic content is too high, the tester is alerted to perform tip-up testing to confirm that a voltage sensitive issue is present.

Power factor/ dissipation factor and capacitance tests have been performed on (oil-filled) transformers in the absence of insulating fluids as a means to assess moisture and the success of a dry out. This necessitates significantly reduced test voltages. Because of the relative insensitivity of (line frequency) power factor/ dissipation factor to moisture at low levels (reference Figure 12) and the inherent dangers of performing traditional power factor/ dissipation factor testing on transformers in the absence of insulating fluid, this practice is not recommended. The reader is directed to the Megger TLM Bulletin describing the use of the Megger IDAX – DFR technology to monitor the dry out process of a transformer.

IV. ANALYSIS

CAPACITANCE – THE SANITY CHECK

Often, testers look immediately to the power factor/ dissipation factor result upon completion of a power factor/ dissipation factor and capacitance test and begin drawing conclusions about insulation health while forgetting entirely about capacitance. Upon completion of a power factor/ dissipation factor and capacitance test, best practice is to assess capacitance/ total current first. The assessment of capacitance/ current requires that the insulation system has been tested previously and the capacitance/ current results from factory tests or previous field tests are available (e.g., via a report, a file or, as is the case with bushings, stamped on the nameplate).

Without a benchmark value with which to compare, capacitance generally cannot be evaluated to any great extent. A tester should, however, be on the lookout for abnormally low current/ capacitance test results[14] , such as 1 – 2 mA or less (approximately 365 pF – 700 pF, or less), which would be particularly unusual for power transformer winding-to-ground insulation systems such as C_H or C_L. Such low current/ capacitance might be the cause of poor grounding, substandard test connections or an improperly designated test mode. However, if such a low current/ capacitance were encountered for a transformer's interwinding insulation system such as C_{HL} or C_{HT}, although atypical, this may not be cause for immediate concern. Rather, the low C_{HL} current/ capacitance measurement may be indicating the presence of a grounded shield between the high voltage and low voltage windings, in which case a low current/ capacitance result is expected. Similarly, in some multi-winding transformers, a winding may look like a grounded shield to the test circuit (e.g., the low voltage (LV) winding is sandwiched between the high voltage (HV) and tertiary voltage (TV) windings) and result in a low current/ capacitance measurement (e.g., for C_{HT}).

When a comparison is possible, capacitance/ total current measurements should not change from previous results. Confirmation that this is the case validates that one is in fact testing what he/she believes that he/she is testing (no more/ no less) and that the overall physical attributes of the insulation system have not changed grossly[15] .

For a power transformer, capacitance/ total current should not change by more than ±1% of the previous measurement[16] . If greater change occurs, the cause should be investigated before focus shifts to assessment of power factor/dissipation factor.

13 Less insulation around the neutral end of the winding

14 As a general rule for any power asset, if the total measured current is less than 300 μA, the (10 kV or 10 kV equivalent, line frequency) power factor/dissipation factor is ignored because, in these cases, power factor/dissipation factor fluctuates notably with small and insignificant changes in current.

15 Capacitance is not acutely sensitive to winding deformation. There are cases wherein a winding has moved and capacitance did not change.

16 Over the life of a transformer, it is not atypical for capacitance to change but this should not be more than 2% over, for example, 40 plus years.

Power Factor/ Dissipation Factor and Capacitance

Table 1 lists reasons why capacitance may change from expected values for C_H, C_{HL} and C_L insulation systems of a two-winding transformer.

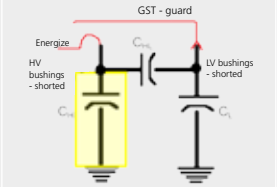
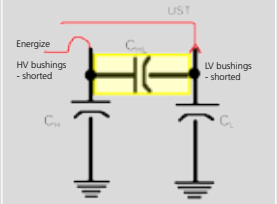
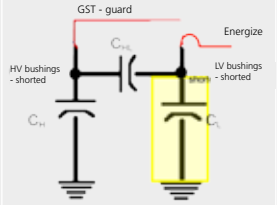
C_H		■ HV bus has not been disconnected ■ HV winding deformation ■ HV bushings have been changed ■ Ungrounded tank ■ Incorrect test mode ■ Drained tank versus oil-filled
C_{HL}		■ HV or LV winding deformation ■ Drained tank versus oil-filled ■ Incorrect test mode ■ Normally grounded shield between the HV or LV windings, if present (fairly uncommon), becomes ungrounded ■ Ungrounded tank
C_L		■ LV bus has not been disconnected ■ LV winding deformation ■ Core ground connection is bad resulting in a decrease in capacitance ■ LV bushings have been changed ■ Ungrounded tank ■ Incorrect test mode ■ Drained tank versus oil-filled

TABLE 1: Reasons capacitance may change from previous

- As noted in Table 1, one reason for a decrease in C_L capacitance may be a change in core ground connection integrity. A transformer's core is insulated from ground (with an insulation system that can be labelled, C_{core}) and then the manufacturer provides a ground reference to the core in at least one location of the core (effectively shorting C_{core}). If the core ground is lost or seriously compromised (e.g., nearly burns open), the C_L capacitance on a core-form transformer will notably decrease. This is why:

  The low-voltage winding on a two-winding transformer is typically the innermost concentric winding, nearest the core leg. A test of C_L includes the insulation between the low-voltage winding and ground potential components, such as the transformer core. If the core ground is removed, then C_L is placed in series with the C_{core} insulation in the test circuit and cannot be isolated for measurement.

  It is known that the equivalent capacitance of two capacitors in series is less than either of the two individual capacitance values (e.g., C_L or C_{core}). Therefore, if C_L capacitance is known from a previous test, even though the capacitance of C_{core} is presumably unknown, it is recognized that the capacitance of C_L apparent (C_L') will still be less than C_L.

POWER FACTOR/ DISSIPATION FACTOR

Power factor/ dissipation factor generally reflects how efficiently the insulation system is fulfilling its purpose of maintaining electrical isolation between points of different potential within an energized electrical apparatus. With few exceptions[17], a power factor/ dissipation factor of 0% indicates a system with zero losses, and a lower power factor/ dissipation factor test result indicates an insulation system in better condition than one with a higher power factor/ dissipation factor.

Insulation systems typically have losses, even when brand new. As an insulation ages or becomes contaminated, the power factor/ dissipation factor will often increase. But here one must be careful for the following reasons:

- Power factor/ dissipation factor represents the average condition[18] of the total insulation system under test. If the system is big enough, some localized contamination may be impossible to see. Take a look at the size of the specimen you are testing. This should help shape expectations of the diagnostic capabilities of this test. One example is a large

17 See excerpt about negative power factor/dissipation factor

18 Take a look at any averaging index – the smaller the sample size (or set), the greater the influence that a change in one element makes on the whole. If the set is very large, changes in one element may not even be noticeable.

single phase autotransformer with an inaccessible tertiary that had severe tracking on the collar around the lower insulator of one of the bushings. Only one (1) power factor/dissipation factor and capacitance measurement can be performed on such a transformer (all the winding terminals are connected together and energized for a winding to ground insulation measurement). The localized contamination did not result in any change in power factor/ dissipation factor (before and after).

- Increasing levels of some contaminants, particularly moisture, do not result in notable change in power factor/ dissipation factor until the level of contamination reaches a certain level. Figure 12 illustrates this point. Here dissipation factor (tan δ) at 50 Hz is plotted (on a logarithmic scale) for a new transformer and a service aged transformer as they become increasingly contaminated with moisture. The slopes of both responses are relatively flat at low moisture levels; in this region, dissipation factor/ power factor does not increase noticeably as moisture is increasing so someone relying on this as an indicator will be unaware that moisture contamination is present and trending upwards. It is not until moisture in paper is at least 2.5% that the slopes marginally increase and 3.5% moisture when the slopes notably increase – at which point it could be said that dissipation factor/ power factor has heightened sensitivity to moisture. In spite of its eventual sensitivity to moisture that occurs somewhere, on average around 3%, dissipation factor is still only 0.5% when the moisture content approaches 3%! For perspective, operators become weary when percent water content exceeds 1.7% and by 2.5% are typically scheduling a processing unit to dry the transformer.

  Of additional note is the divergence or separation of the two curves at low moisture levels, indicating that a single dissipation factor value may represent a wide range of moisture contamination levels that is largely dependent on how aged the insulation system is. For example, a dissipation factor (tan δ) of 0.3% is obtained for moisture contents ranging from 0.5% (for the service-aged transformer) to 2% (for the new transformer). This presents a challenge since it is not a straightforward task to quantify aging of a transformer. Service life (years in service) is not a reliable indicator of how aged an insulation system is as environmental and system variables, maintenance, and several other factors all have a role in how insulation will age.

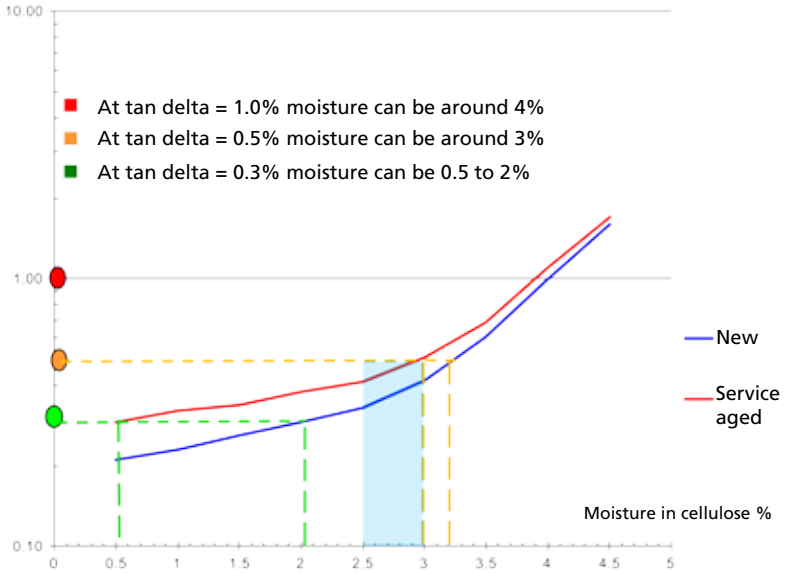


FIGURE 12: Sensitivity of (line frequency) Dissipation Factor (tan δ) to Changing Moisture in Transformers [4]

Assigning significance to a change in power factor/ dissipation factor is challenging. This is also rooted in the fact that power factor/ dissipation factor is an average representation. When power factor/ dissipation factor changes, it is impossible to know whether this is due to general, widespread contamination or aging, or due to a localized problem; all of which are approached differently. To emphasize this point, consider the case whereby a class average on a test is a 75 and there are 2 students in the class; it is impossible to know from this averaging index, whether both students scored a 75 or if one student scored a 100 while the other scored a 50, or some variation between.

A localized problem significantly raises risk of a dielectric failure so it is of utmost importance to identify these occurrences. Not only is it impossible to characterize the nature of increasing losses and determine when a localized problem exists from the power factor/ dissipation factor alone, when

Power Factor/ Dissipation Factor and Capacitance

there is a localized problem, power factor/ dissipation factor might not change appreciably because of the averaging influence of surrounding healthy insulation, belying the severity of the problem at hand. A very small increase in power factor/ dissipation factor could be the manifestation of a very serious problem. Meanwhile, if a power factor/ dissipation factor change is due to aging, aging is expected and an appropriate course of action here may be increasing vigilance through more frequent testing, in contrast to a localized problem that requires immediate attention. A small change in power factor/dissipation factor due to aging might require nothing more than taking note and repeating the test again in several years. Widespread contamination that results in a change might require remediation but it might not be immediate or urgent; rather, it might be completely reasonable to schedule during some more suitable and upcoming maintenance period. On the other hand, if the contaminant is moisture, by the time its presence results in a change in power factor/ dissipation factor, one might have far exceeded the point in time at which it would have been most prudent to schedule processing/ dry-out of the transformer. If it were possible to discern the cause of a change in power factor/ dissipation factor, more practical guidelines could be developed.

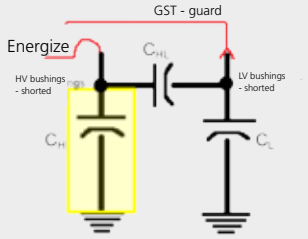
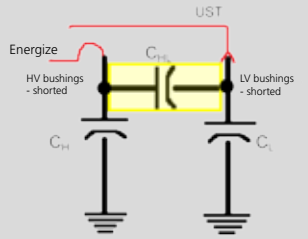
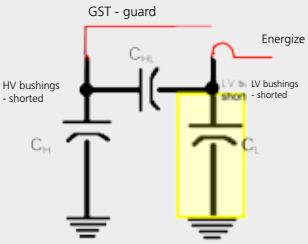
C_H		■ HV bus has not been disconnected ■ One or more HV bushings are in poor or changing condition ■ Excessive surface leakage across the HV bushings (rain, snow, salt, dust, etc.) ■ Use of rubber blankets to achieve electrical clearances ■ Ungrounded tank (negative power factor) ■ Temperature (if an accurate correction factor isn't used) ■ Moisture or other contaminant ■ Aging ■ Partial Discharge ■ Internal tracking or unintentional resistive path to ground
C_{HL}		■ Interwinding grounded shield (negative power factor) ■ Ungrounded tank (negative power factor) ■ Temperature (if an accurate correction factor isn't used) ■ Moisture or other contaminant ■ Aging ■ Partial Discharge ■ Internal traching or unintentional resistive path to ground
C_L		■ LV bus has not been disconnected ■ One or more LV bushings are in poor or changing condition ■ Excessive surface leakage across the LV bushings (rain, snow, salt, dust, etc.) ■ Use of rubber blankets to achieve electrical clearances ■ Ungrounded tank (negative power factor) ■ Temperature (if an accurate correction factor isn't used) ■ Moisture or other contaminant ■ Aging ■ Partial Discharge ■ Internal tracking or unintentional resistive path to ground

TABLE 2: Reasons power factor/dissipation factor may change from previous

Given these uncertainties, when comparing to previous test results, any observed change in power factor/ dissipation factor deserves attention. Table 2 lists reasons why power factor/ dissipation factor may change from previous results for C_H, C_{HL} and C_L insulation systems of a two-winding transformer..

Table 2 notes:

- The active insulation of high/ low / tertiary bushings is included in the measure of C_H/ C_L/ C_T, respectively. As noted in Table 2, it is possible that the condition of a winding's bushings is influencing the respective measurement, for better or worse, but in either case, such that the power factor/ dissipation factor is not representative of the actual condition of the C_H/ C_L/ C_T insulation materials inside the transformer tank. There is also the possibility that a winding's collective bushing insulation systems make up only a small percentage of the total insulation included in the measurement of C_H/ C_L/ C_T and, therefore, does not cause any noticeable change in the C_H/ C_L/ C_T power factor/ dissipation factor when the condition of the bushing insulation system(s) changes. It is useful to know if and how the winding's bushings are influencing the measure of C_H/ C_L/ C_T so if bushings have potential or test tap electrodes, the active insulation of the bushings should be tested separately via C1 tests to facilitate a calculation that

effectively subtracts their contribution from the C_H/ C_L/ C_T measurement.

- Also referenced in Table 2 is that power factor/ dissipation factor is temperature sensitive. For example, as a transformer cools after it has been removed from service for test, the power factor/ dissipation factor test result will change if the test is simply repeated at different insulation temperatures. Therefore, for a meaningful comparison between tests, all power factor/ dissipation factor test results need to be normalized (or corrected) to equivalent 20°C power factor/ dissipation factor values that adjust for the influence of temperature. The challenge here is that no single temperature correction curve will fit all cases because the dielectric thermal response is not a single curve for all conditions; aging, moisture and contamination all have an effect. Temperature correction curves in use for decades are invalid and may introduce error, which then complicates analyses. In fact, some standards recommend discontinuing the use of these correction tables/ curves all together [5]. A more complete solution and a transformer testing best practice is to apply DFR's algorithm for Individual Temperature Correction; this provides a reliable and consistent correction for a normalized power factor/ dissipation factor value that can be compared between test dates. The reader is directed to Megger's "Individual Temperature Correction (ITC)" TLM bulletin for more information.

- Negative power factor/ dissipation factor: As noted in Table 2, it is possible, though not common, to obtain a negative power factor/ dissipation factor when performing power factor/ dissipation factor and capacitance tests on a transformer. A negative C_{HL} power factor/ dissipation factor can be obtained if there is a grounded shield between the windings, which would result in a corresponding unusually low current/ capacitance measurement. As long as the power factor/ dissipation factor has not changed from previous test results, this is not a cause for concern. Similarly, a negative C_{HT} power factor/ dissipation factor can be obtained on a multi-winding transformer where the low-voltage winding is sandwiched between the high voltage and tertiary voltage windings and, therefore, presents as a grounded shield to the test circuit.
  Another cause for a negative power factor/ dissipation factor test value for an interwinding insulation system, such as C_{HL}, is if the neutral of a Y-connected low voltage winding is left connected to ground, either by mistake or because it is grounded internally and cannot be practically accessed.
  Negative power factor/ dissipation factor test results are not expected under any circumstances for a winding to ground insulation system, such as C_H, C_L or C_T. In such cases, grounding of the transformer or test connections should be checked.

If more than one set of previous power factor/ dissipation factor test results are available, trending can be performed. Trending is the preferred assessment approach. When many test points are available, it is possible to filter outliers/ erroneous data points that are a reflection of poor test preparation, incorrect compensation for temperature influences on power factor/ dissipation factor, or undesirable test conditions.

If there are no previous test results with which to compare, general guidelines exist to indicate approximately what a healthy power factor/ dissipation factor for an asset should be (Table 3). A transformer constructed with relatively low loss materials and that is subject to much care in handling during manufacturing and assembly in the field, should meet these limits. Beyond its use for these purposes, however, comparing to limits or to sister transformers/ similarly constructed transformers as a tool to analyse power factor/ dissipation factor results throughout a transformer's life is not recommended. Rather, power factor/ dissipation factor and capacitance values must be compared to previous results.

Insulating Liquid	kV rating	Nominal/New PF limit	Serviceability aged limit
Mineral Oil	< 230 kV	0.5 %	1.0 %
Mineral Oil	≥ 230 kV	0.4 %	1.0 %
Natural Ester[19]	All	1.0 %	1.0 %

TABLE 3: Power Factor recommended limits for power transformers as per IEEE C57.152-2013

DIELECTRIC FREQUENCY RESPONSE (DFR)

Power factor/ dissipation factor and capacitance testing is an insulation screening tool in wide use but it is certainly not fail-proof and, particularly in terms of moisture detection, does not always result in best decisions for promoting asset longevity. The test was popularized through its successes with capacitance-graded bushings and spread in use. Power factor/ dissipation factor and capacitance testing has also been promoted in the past for its ability to detect water contamination early. It is now known that power factor/ dissipation factor and capacitance testing (performed at line frequency) is not as sensitive to low levels (albeit actionable levels) of water contamination as once thought. The measurement's far greater potential is through the information that power factor/ dissipation factor (and capacitance) provides when considering its behaviour across a range of frequencies – testing that is known as DFR, or dielectric frequency response. The reader is directed to Megger's DFR TLM bulletins for further understanding.

19 "The numbers shown here for natural esters are only provisional as there are no correction curves established by the industry yet".

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[5] Megger Transformer Life Management (TLM) Bulletin: Individual Temperature Correction, Dec 2016.

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