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Predictive diagnostic testing of electrical apparatus including transformers

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Title	Predictive diagnostic testing of electrical apparatus including transformers
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Abstract	Electric apparatus sometimes fails because of insulation deterioration. A proactive approach using Tan delta/power factor diagnostic testing is the key to monitoring the integrity of the insulation system and preventing or at least anticipating such failures. Understanding the impact of these parameters will help in obtaining accurate measurements that can be relied upon in the decision making process.

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With an increasing failure rate of substation electrical equipment, utilities and heavy industry must focus on preventive and predictive maintenance to ensure power system integrity and reliability. Electrical insulation is a common reason for electrical equipment failures and tan delta/dissipation/power factor (PF) testing is a popular way of diagnosing and estimating the condition of insulation as it ages. There are, however, a number of issues relating to PF testing that are not nearly as widely understood as they should be. PF testing is widely used on electrical equipment such as power transformers, circuit breakers, generators and cables. PF values, trended over time, can help in detecting problems like contamination, high moisture content and the presence of voids in insulation. Excitation current tests, along with PF tests, performed on power transformers, can also help in detecting turn-to-turn insulation failure. Dissipation factor tests are usually performed at 10 kV or the readings are converted to 10 kV equivalent. The best voltage for PF tests is a frequently debated topic as instruments are now available that allow the tests to be performed at voltages from 27 V to 12 kV.

What test voltage is “good enough” for accurate and reliable measurements? The answer depends on the type of test specimen and the test conditions. Most power transformers have oil-paper type insulating systems that exhibit a flat response when PF is measured as a function of test voltage. However, motors and generators typically have dry or solid insulation whose PF values may vary with test voltage.

Values increase with increasing test voltage due to the voids that are almost invariably present in solid insulation. The increase in PF value as a function of voltage corresponds to increasing ionization in the voids.

One reason that industry has standardized on a 10 kV test voltage is for immunity against electrostatic interference; power transformers operating in HV substations are subject to a lot of electrical noise and interference. An HV test signal provides better signal to noise ratio, giving more accurate measurements. Test instruments with very high noise suppression capability are required for measurements in HV substations as the test current is very low in insulation tests and noise levels can be as high as 20 times the test current.

For perfect insulation, the PF should be zero. In practice, any value close to zero is considered to indicate a good insulation system. PF test sets always try to measure a single capacitor, but if the test object has some phantom circuits along with that single capacitance, the results look strange. For example, when performing tests on bushings, three-winding transformers or inter-phase insulation of rotating machinery, the PF values will sometimes be negative. Negative PF therefore corresponds to watts generation. Obviously, insulation cannot generate power, which shows that negative PF values are not real but instead tell us that the insulation does not behave as an expected capacitance.

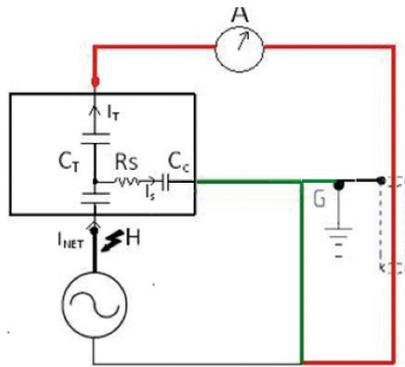


Fig 1: Specimen in UST mode with surface loss components

Negative values also appear with some specimens that have high surface leakage. As shown in Fig 1, phantom circuits introduce a current (I_s) which changes the phase angle of the measured test current (I_T). The surface loss current (I_s) is predominantly resistive (R_s) and has a very small phase angle with respect to the applied voltage. Capacitive coupling (C_c) may be present as a result of this parallel path of R_s to main insulation under test.

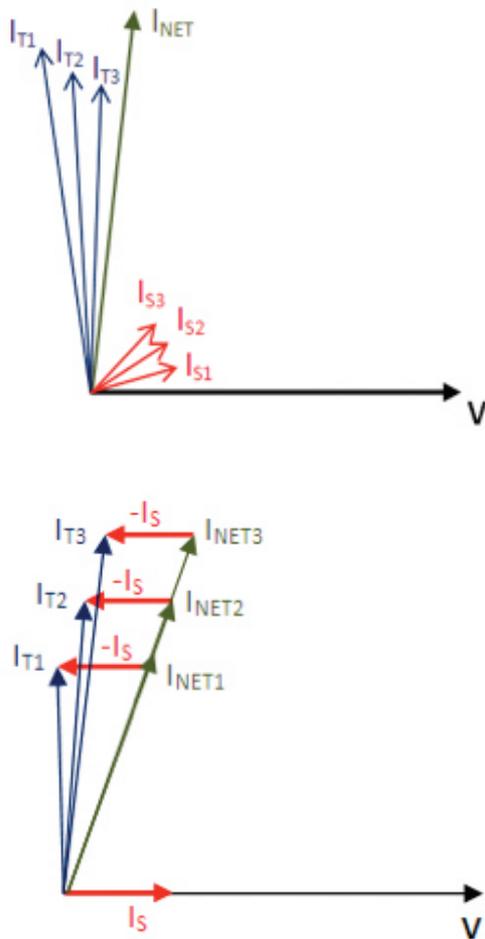


Fig 2: Vector diagrams with different I_s phase angles and different magnitude of I_{NET}

Smaller phase angles for surface loss current (I_s) can lead to negative PF values. Measured test current (I_T) is the vector difference of total current (I_{NET}) and surface loss current (I_s). In UST or GST configurations, this surface loss makes the measured test current (I_T) phase angle greater than 90° , and this results in negative PF values. It is important to understand where negative PF values come from. For some specimens it is just a result of design – for example, the presence of electrostatic grounded shield between the inter-windings of a transformer. In other cases, where negative values are encountered users should consider eliminating all external effects by following best testing practices such as verifying proper grounding circuits, cleaning external bushing surfaces, avoiding unfavorable weather conditions and using guard circuits effectively. Repeated negative values after taking these precautions could point toward contamination or a bad insulation system. Excitation current testing is commonly performed along with PF testing. It is a voltage dependent test and is always performed in UST mode. Like PF tests, the excitation current readings are normalized to 10 kV equivalent values, using a linear approximation. When dealing with specimens that are highly inductive, such as power transformers, the relationship between voltage and current is, however, not linear. Assuming a linear relation to determine 10 kV equivalent excitation gives only approximate values. It is, therefore, important to perform tests at the same voltage if excitation current historical data needs to be trended. Tests performed at different voltages and then corrected to 10 kV may not be comparable. This is important as trending data is critical when evaluating problems with turn-to-turn insulation.

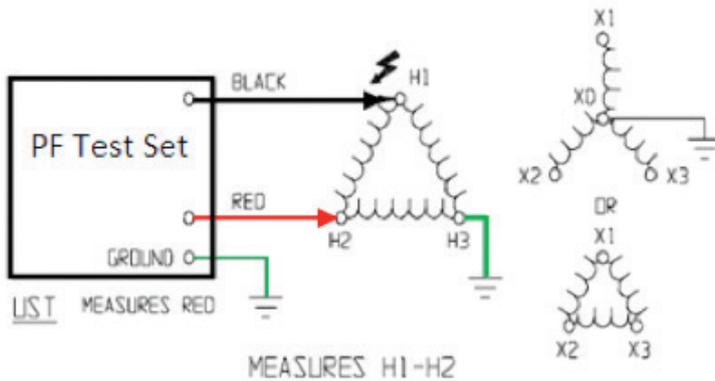


Fig 3: Excitation current measurement on a Delta winding with third leg grounded

When performing excitation current measurements on delta windings, it is important to ground the third leg of the delta configuration as shown in Fig 3. Since excitation current is a UST test, grounding the third leg eliminates the current flowing in the other two windings from the measurement circuit. Depending on 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.

A transformer with magnetized core can exhibit higher excitation current measurements than normal. IEEE 62-1995 section 6.1.3.4 states, "If a significant change in the test results is observed, the only reliable method of excluding the effect of residual magnetism is to demagnetize the transformer core." The factors discussed here that affect excitation current measurements should be borne in mind before performing the test. The dissipation factor values are highly dependent on temperature. 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." Nevertheless, correction factor tables have traditionally been used to bring all data to a common base of 20 °C. It is imperative only to compare a specimen's PF values that are taken at a similar temperature or corrected to the same temperature accurately. For different specimens, changes in temperature affect PF values in different ways. And even the same specimen will become more temperature dependent as it ages. Temperature correction factors are highly dependent on insulating material, its structure, ageing, presence of moisture or contamination and other influences. However, temperature correction data is based upon the average values. Since each test object is unique, using these average corrections introduces errors.

New transformers have relatively weak temperature dependence and the use of standard tables overcompensates. As the object ages, same average correction factors would under compensate and error pre-dominates in the other direction. Trending of PF values becomes more critical in the second half of the life cycle. In this second half, correction factors should be larger because of the increased effect of temperature on the insulation. Using average factors can lead to incorrect trending and inaccurate estimation of the remaining healthy life of the object.

IEEE Standard 62-1995 states, "Testing at temperatures below freezing should be avoided, since this could significantly affect the measurement. Among the primary reasons for performing this test is the capability of detecting moisture in insulation. The electrical characteristics of ice and water are quite different and it is much more difficult to detect the presence of ice than it is to detect water; sometimes it is impossible." Measuring PF at too high or too low a temperature can introduce errors, and the IEEE recommends performing PF tests at or near 20 °C. However, it's not always practical to cool down or heat up the test specimen to 20 °C.

Fortunately, new technology makes it possible to accurately correct PF values to 20 °C without resorting to correction factor tables based on averages. Using dielectric frequency response (DFR), the unique temperature correction factor of each test object can be determined. This is possible because a PF measurement at a certain temperature and frequency corresponds to a PF measurement made at different temperature and frequency. Therefore by measuring PF at different frequencies, it is possible to determine the temperature dependence of the specific test object. With this technique, PF can be measured at any insulation temperature [5 °C-50 °C] and then corrected to 20 °C accurately and precisely.

Electric apparatus has failed and will continue to fail because of insulation deterioration. A proactive approach is the key to monitoring the integrity of the insulation system and preventing or at least anticipating such failures. Tan delta/power factor diagnostic testing is an important tool in determining the quality of the insulation and estimating its remaining healthy life.

Dissipation factor readings are dependent on various factors and it is important to be aware of these. Test voltage, electrostatic interference, temperature, humidity, surface losses and other parameters can greatly influence PF measurements. A better understanding of the impact of these parameters will help in obtaining accurate measurements that can be relied upon in the decision making process.



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