Dielectric Response Analysis of Transformers


Will Knapek *Jeff Foley*
OMICRON electronics Corp. USA

You have just come from your annual physical checkup. The doctor has ordered a blood test, and a few of the results have come back out of the normal range. He scheduled you for a few more diagnostic tests such as x-ray, treadmill, and EKG. Those test results are inconclusive. Further tests are required to provide a complete diagnosis. Due to advances in the medical field, tests such as CAT scan and MRI are available. In the power industry there are advanced tests available for transformers when the blood test result (oil test) comes back out of the normal range. In the past, you could do a power-factor test, turns-ratio test, and a winding-resistance test to try to diagnose a problem in the transformer. There are new tests available to the power industry where more complete diagnosis can be performed. Tests such as sweep frequency response analysis and dielectric response analysis make the high-end diagnosis possible for transformers, motors, generators, and cables. Let us explore the dielectric response analyzer as diagnostic tool for transformers.

During the service life of high-voltage equipment such as power transformers, rotating machines, and cables, insulation systems are subjected to numerous stresses. As a result, a gradual loss in mechanical and dielectric properties will eventually compromise the equipment's reliability. Moisture is particularly detrimental to paper insulation and is a good indicator of aging.

Moisture in transformer insulation can affect transformer performance in several ways. First, it can trigger partial discharge (PD). PD is a discharge of energy in a void or gas bubble. Second, it can generate bubbles in the oil. As the transformer heats, the cellulose will release the moisture that is contained inside. The moisture trapped inside the cellulose will also decrease the dielectric strength of the paper and the oil. This third problem can be seen by performing dielectric strength or breakdown voltage test. Lastly, it can cause the insulation to age prematurely. The first three effects can lead to the premature failure of otherwise healthy transformers. The last issue decreases the life expectancy.

Even the best efforts to install a transformer properly provide opportunities where the moisture level can increase in several ways. Faulty seals can allow moisture in the vessel. Exposure during maintenance or repairs is another avenue for water to find its way into the transformer. In addition, normal aging of cellulose produces water. This is caused by the molecular breakdown of the cellulose which is high in hydrogen and oxygen molecules. The original bonds are broken by what is call depolymerization and the loose hydrogen and oxygen molecules reunite to form H_2O, hence water.

Moisture Estimation in Insulation

The only direct method to determine the moisture content in the cellulose is to take paper samples from the transformer and test for moisture content. This is possible only during the repair or tear down of a unit; hence, it is of limited use. There are several indirect methods to determine the moisture content. We can determine the moisture content by measurement of properties that can be related to moisture in the insulation. The first of these indirect methods can be done by moisture in oil measurements. They are easy to conduct, (however, temperature is critical and equilibrium curves must be applied) but often the results have large errors.

A traditional method for determining mositure content in a transformer has been an oil sample. Oil samples are easily taken from transformers while they are on-line. This sample is then analyzed by what is called a Karl Fisher titration test (ASTM D1533-A). The moisture content measured at the lab temperature would give an indication of the dryness/wetness of the oil. Titration is a chemical reaction where oil is injected into a reaction vessel. The water inside the oil chemically reacts and this is measured. Moisture in paper is then estimated using equilibrium curves or relationships that link moisture in oil to moisture in paper.

It is also very important to understand that the cellulose insulation acts like a sponge for moisture. When the transformer is loaded and the winding temperature rises, the moisture is driven from the insulation to the oil. When the transformer cools, the moisture is absorbed back into the cellulose. Since the loading of transformers often varies and the rate that moisture is driven out versus absorbed back in occurs at different rates, it makes oil samples and equilibrium curves problematic. As can be seen from the equilibrium curve in figure 1, the temperature of the oil is an important consideration in applying the curves. Often times, the oil temperature of the transformer is not known, or is recorded arbitrarily at the time of sampling. Further, moisture relationships and curves have limitations to application and accuracy.

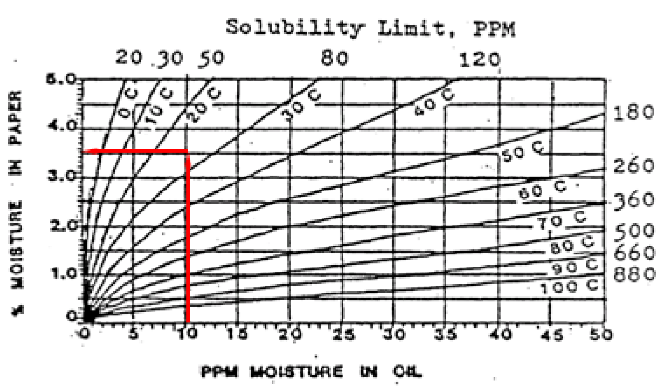

Figure 1 — Moisture Equilibrium Curves

It should be noted that moisture in oil is not necessarily an indicator of moisture in paper. The oil moisture content can change quickly during warm up and cool down of a transformer. The volume of water in the cellulose can be as much as 200 percent more than in the oil at the point of equilibrium. That is why it is much more important to know the moisture content of the cellulose than the moisture content of the oil. Another issue with applying the equilibrium diagrams is that these are based on new oil and do not take into account the effects of aging byproducts that are found in older transformer oil.

Dielectric Response

Let us look at the advanced techniques of moisture analysis. The dielectric response is a unique characteristic of the particular insulation system. The increased moisture content of the insulation results in a changed dielectric model and, consequently, a changed dielectric response. By measuring the dielectric response of the equipment in a wide frequency range, the moisture content can be assessed and the insulation condition diagnosed. For the dielectric response test, the test performed is a traditional ungrounded specimen test made from the high voltage winding to the low voltage winding (CHL) in a two winding transformer. We are most concerned with the CHL test, as this is the measurement which contains the most cellulose insulation material. The test connections and modes are the same as used in a traditional transformer insulation power-factor test with the difference being the test is performed at a low voltage, up to 200 Vp-p, and the test is performed at frequencies from 1 kHz to 1μHz. The only other critical data needed to complete the test is the temperature of the oil

Figure 2 is the response curve for oil-impregnated paper. This curve shows a frequency vs. dissipation factor relationship. The higher frequencies display the moisture and aging of the cellulose. Moving from left to right the frequency is reduced and the oil conductivity properties are displayed. In the millihertz range, the insulation geometry comes into play. As the moisture properties of the cellulose change so does the shape of the curve.

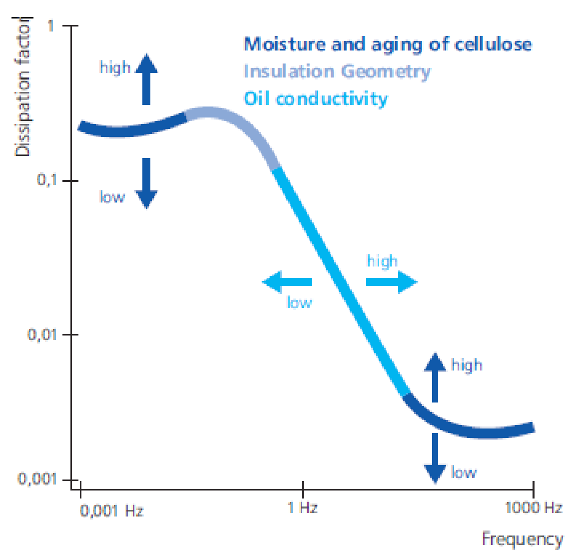

Figure 2 — Dissipation factor vrs. frequency

The most common techniques used to measure this response are frequency domain spectroscopy (FDS) and polarization and depolarization current (PDC) methods. Using the frequency domain spectroscopy, the dissipation factor of the insulation system under test is measured by frequency sweep. The FDS allows fast measurements at high frequencies but requires long measurement times at frequencies down to 0.1 millihertz.

The current measurement in the time domain, also called the polarization and depolarization current method, where a dc voltage is applied to the insulation system under test for a specific time and the polarization current is measured. After this, the insulation system is shorted and the depolarization current is measured. From the polarization and depolarization currents the dielectric response is evaluated, and the dissipation factor frequency characteristic is calculated. The PDC method is much faster than the FDS at very low frequencies, but the upper frequency is limited due to the finite rise time of the dc pulses. Measurements in the very low frequencies are important because that is where moisture content is most clearly indicated.

Both of these can be compared by transforming the results from the time domain into the frequency domain or vice versa. With improvement in technologies, we can now use two well-established dielectric response measurement techniques together and reduce the time of measurement down to less than three hours whereas with the separate measuring techniques it could take up to eight hours to perform the test.

After the test is completed the results must be compared to a standard to determine the actual moisture content. IEC 60422 and IEEE 62-1995 have defined moisture classifications. Some test sets allow the evaluation of the data with consideration of the conductivity of the oil which will increase with age. The quality of dielectric response analyzers is not primarily given by the accuracy of the measurement device but rather by the built-in knowledge of the analysis software.

One is often faced with the question of "What do these results mean?" Whether the moisture in oil tests (with equilibrium charts) or advanced dielectric response methods are performed, each test technique should lead to some conclusion about the condition of the transformer. Much study and work has been performed in evaluating what to do with moisture results. In some cases, a wet transformer may be vacuum processed, reducing the moisture content to an acceptable level. In cases where the transformer is very old and there is concern that exposing the insulation system to vacuum processing may do more harm than good (further reducing the mechanical strength of the insulation), this information can be used to assist in an assessment as well. In general, dielectric frequency response methods are more accurate than traditional oil sample analysis. Because of this increased accuracy, better decisions can be made and useful life extension solutions can be provided to the end user.

So the next time you test transformer oil and still have questions, ask yourself if a more advanced test is needed to completely diagnose the condition of the transformer.

Will Knapek is an Application Engineer for OMICRON electronics Corp, USA. He holds a BS from East Carolina University and an AS from Western Kentucky University both in Industrial Technology. He retired from the US Army as a Chief Warrant Officer after 20 years of service which 15 were in the power field. He has been active in the testing field since 1995 and is certified as a Senior NICET Technician and a former NETA Level IV technician.

Jeff Foley is an Application Engineer for OMICRON electronics Corp, USA. He holds a BSEET from Milwaukee School of Engineering. Jeff has 15 years experience working in the field of power systems testing, maintenance, design and commissioning.