

Power transformer maintenance. Field Testing.



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Introduction

The politic change in some companies had a great influence in maintenance and operation works in their electric machines. Those, have seen many times a decrease in maintenance works allowing a cost decrease in a short term but generating a greater risk of use of them in a mean and long term. The operating conditions also have changed in the sense of taking the maximum advantage of each machine making it work at the maximum possible ratings and some times above nominal values. This situation trends to premature age the machine fleet and if those are not part of a minimum maintenance program detecting risk situations or load limitation, the resultant situation will lead in a mean time to an irregular manoeuvre field (breakdowns, forced outages, supply interruptions...) that today are so usual and negative to the end customer.



FIG 1. Breakdown of the dielectric system in a power transformer column. Courtesy from Electric Works Molina, Córdoba.

Power transformer is an electric machine with a useful life cycle of some 30 years. This doesn't mean to say that cannot be used above this time, in fact, a great part of the electric and industrial fleet is being operated with reliable machines above this time. The really important fact is to know the status and evolution of the transformer to be in conditions to operate it with the maximum security and know if it is appropriate to continue it's use, know overload capacity, limit load, refurbish it or either take it out from active service.

There is a group of maintenance techniques that from an electric point of view and through some field tests are going to allow us to trace the transformer status as indicated and in the case of breakdown diligently detect the real problem and perform the required actions.



FIG 2. Field testing of a power transformer before putting into service (50MVA).

POWER TRANSFORMERS FIELD TESTING.

As a result of the owner company, the importance of the machine and the outage possibilities, it is necessary to perform on each transformer a fitted maintenance program with a test protocol previously accorded. Next will be indicated a series of test that can set up this program and that are something like a continuation of validation tests performed when manufacturing the transformer but adapted to field testing.

We have to take under account that in the field, in transformer installations, is not usually possible to have bulky equipments, what states certain limitations to field test with respect to manufacturing ones.

Described tests are chosen from the commercially available ones, standardized and usual into test programs.

MAGNETIC / ELECTRIC CIRCUIT TESTS.

Those will be performed with portable instrumentation (easily transported in vehicle/test van) of a series of measurements that allow obtaining base parameters from the transformer. It will be studied the punctual status to perform a diagnose and parameter trending values to perform scheduled works. All this tests are off-line.

Electric/Magnetic field testing:

- No-load test. Turns Ratio (TTR). Polarity, connection group y excitation current.
- Load test (short circuit test, impedance measurement).
- Winding resistance.
- Frequency response analysis (FRA).

- No-load test. Turns Ration. Polarity, connection group and excitation current.

This test usually known as "no load" test and involves inserting an alternating voltage in the high voltage winding of the transformer in each of it's phases with low voltage side open. With the result values can be obtained basic parameters from the transformer:

Transformer Turns Ratio (TTR): quotient between high voltage / low voltage. Must match with protocol /nameplate values.



FIG 3. Monophase transformer turns ratio unit, from Megger Company, model TTR100.

In the power transformer with tap changer you will take advantage to make the register of each position from it giving extra information on its status and that of the On Line Tap Changer (OLTC). This measurement will directly inform of the existence of shorts between turns.

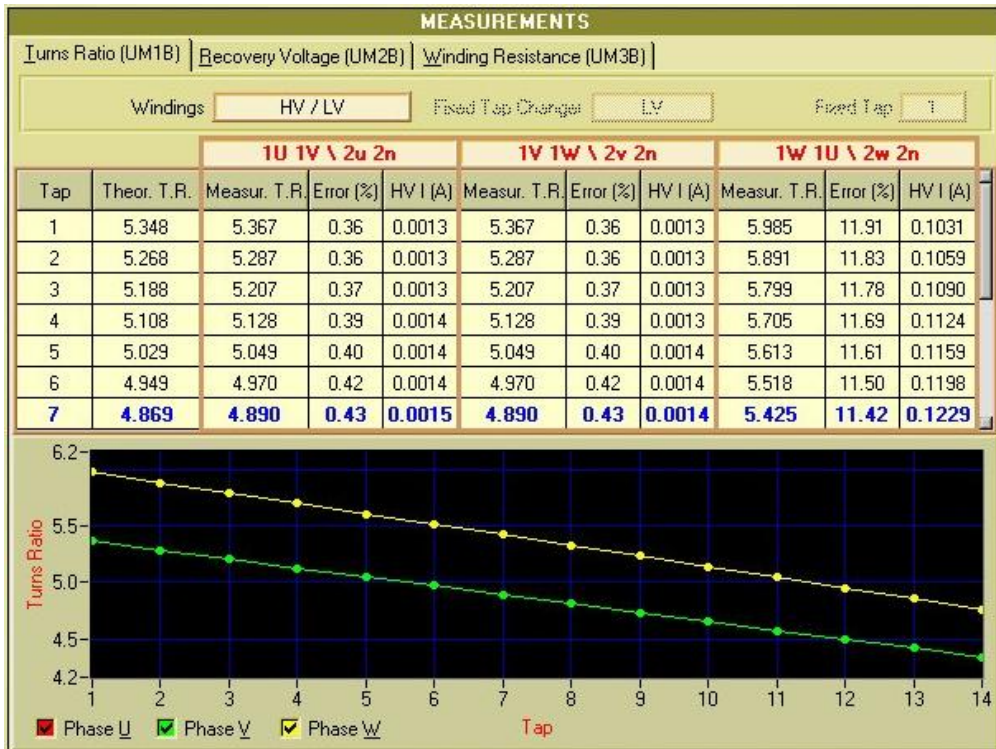


FIG 4. Results of a turns ratio test determining a short circuit between turns at low voltage side. Diagnose software from ETP system (TRR unit UM1B from UNITRONICS). Red and green phases over imposed, yellow separated.

Polarity / connection group. Connection group can also be checked with the previous results and aided with voltage diphasé between high / low voltage.



FIG 5. 3-phase Transformer Turns Ratio Meter Unit from UNITRONICS Company, model UM1B.

Excitation current. It's the current flowing into the high voltage winding with the low voltage side open. This current should be proportional to the No-load acceptance test but with the difference resultant from the use of test voltages different from nominal values.



FIG 6. Transformer Turns Ratio Meter Unit from Megger Company, model TTR.

It shouldn't exist excessive deflection from values measured between phases and its normal a slight difference (geometric) between extreme and central windings. It will exist great changes when appear heat points, degradation in the magnetic package, loose core or detached magnetic shunt.

- Load test (short circuit test, Impedance measurement).

This test usually known as "short circuit test" is based in the insertion of a voltage in one winding (high voltage one) with the other winding short-circuited. This test simulated the factory one but its not at all comparable in results because of not flowing nominal values. It is usual to register nominal and extreme positions if the transformer had an OLTC.



FIG 7. 3phase short circuit impedance unit from UNITRONICS company, model UM5B.

Short circuit voltage. This parameter usually expressed in % and identified in the nameplate of the transformer is the extrapolated result from the test voltage to

nominal voltage and should be near the protocol /nameplate value from the transformer. It's change will indicate irregularities in the magnetic core, winding displacement, short-circuits, mechanical deformations...

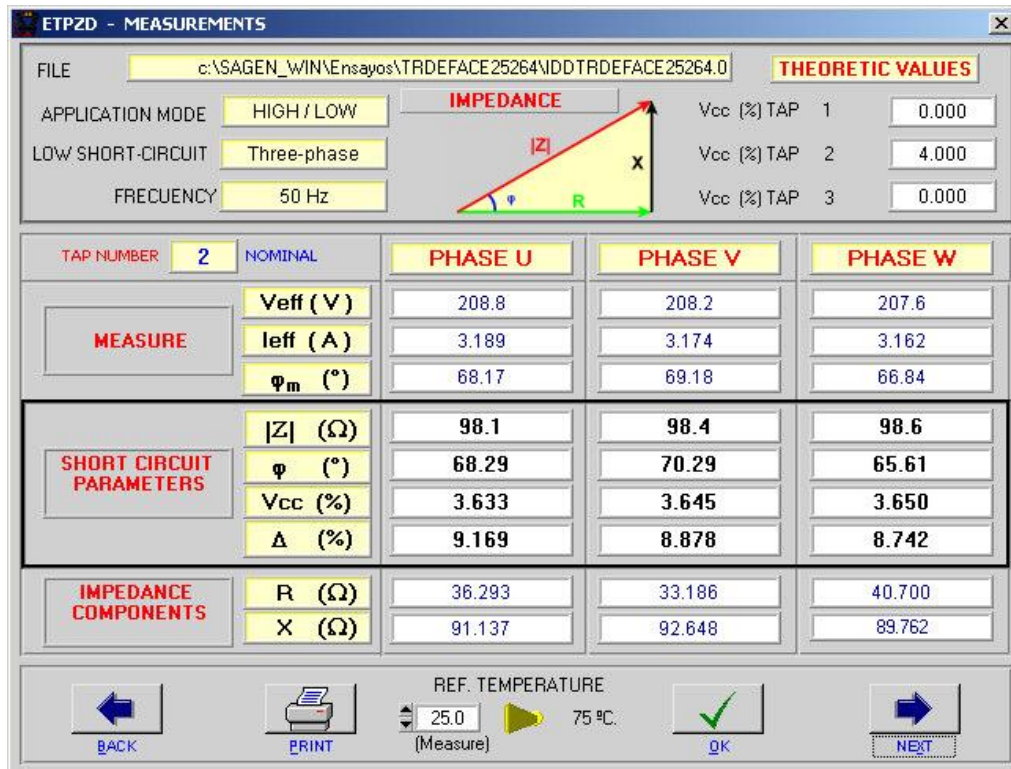


FIG 8. Results screen from a short circuit test (unit UM5B, UNITRONICS company) indicating changes in the geometric circuit.

- Winding Resistance.

With this test we search determinate the pure **ohmic resistance** from each phase windings both in high and low voltage and it exist a tap changer in each position. What in a first approach can be easy to measure, its not so, because it is necessary to make flow relatively high currents to register the usual low resistance values $\mu\Omega/m\Omega/\Omega$ with the required precision. This currents must also flow through the equivalent inductances of the transformer.

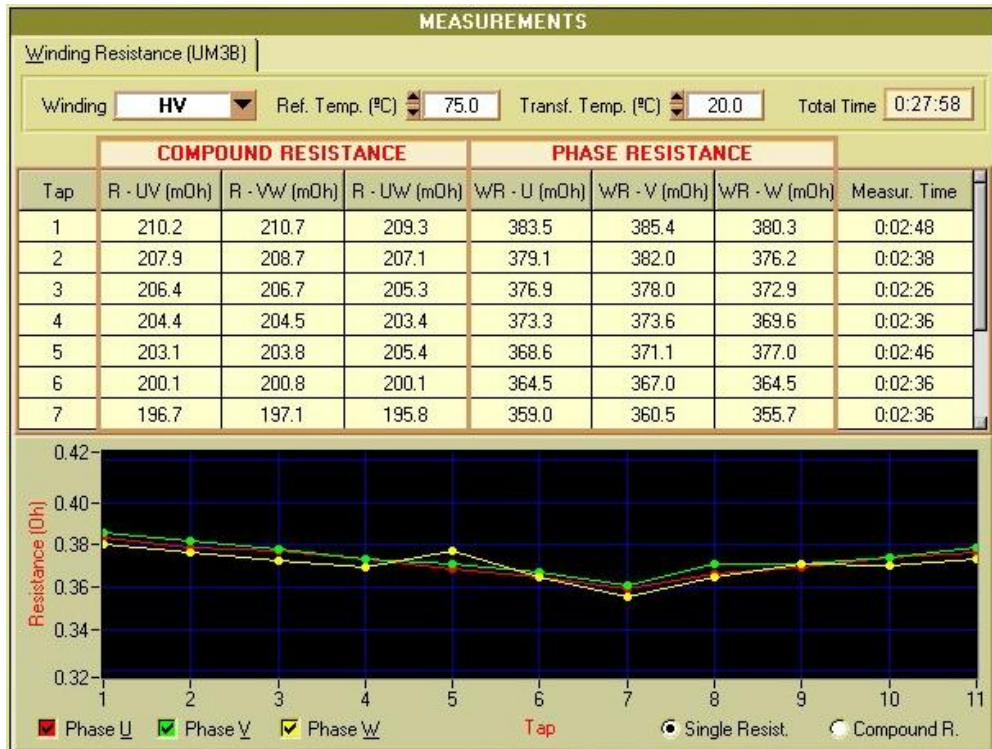


FIG 9. Results from a Winding resistance test showing a problem in the high voltage winding (system UM3B, UNITRONICS Company).

The high inductive character of power transformers (Equivalent L and magnetic core) implicates magnetization time and measurement stabilization should be taken under account while determination the measurement end and give the results.



FIG 10. 3-phase winding resistance meter from UNITRONICS Company, model UM3B.

This has more relevance in high power transformers or from special designs or configurations.

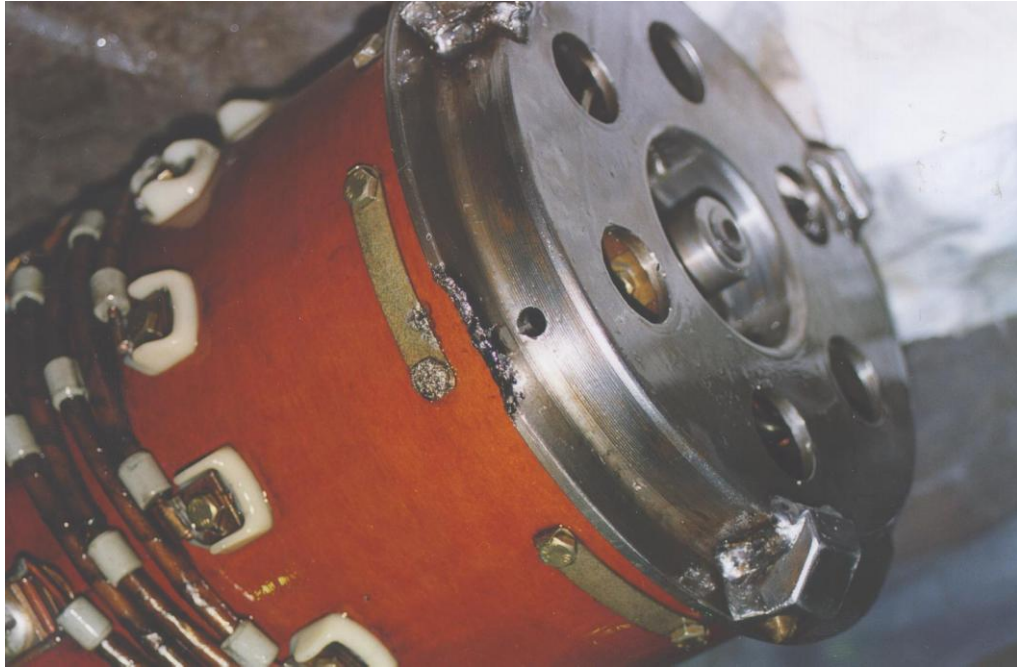


FIG 11. Detected fault in an OLTC from the previous test results.

Final results must be temperature normalized to get results comparable in time and compose parameters must be converted into simple ones (this is, when measuring a Wye and the measure was performed between phases without; should extract each phase winding values separately). This test result must be comparable with factory protocol and will give clear information on the winding status, the tap changer and connections (slacking or heating).

- Frequency Response Analysis testing.

The main purpose of this test is to determinate the frequency response graph of the equivalent electric / dielectric / magnetic / mechanic altogether evaluated. There are two approaches to this test:

Frequency sweep technique. A low voltage sweep generator is used synchronized with a level meter that for each phase register a frequency response plot. The result is a graph that correlates frequencies in horizontal axis and attenuations per phase in vertical axis.

Pulse technique. A fast pulse of $\sim 500V$ is given to the transformer and taken both at the input and output in each phase.

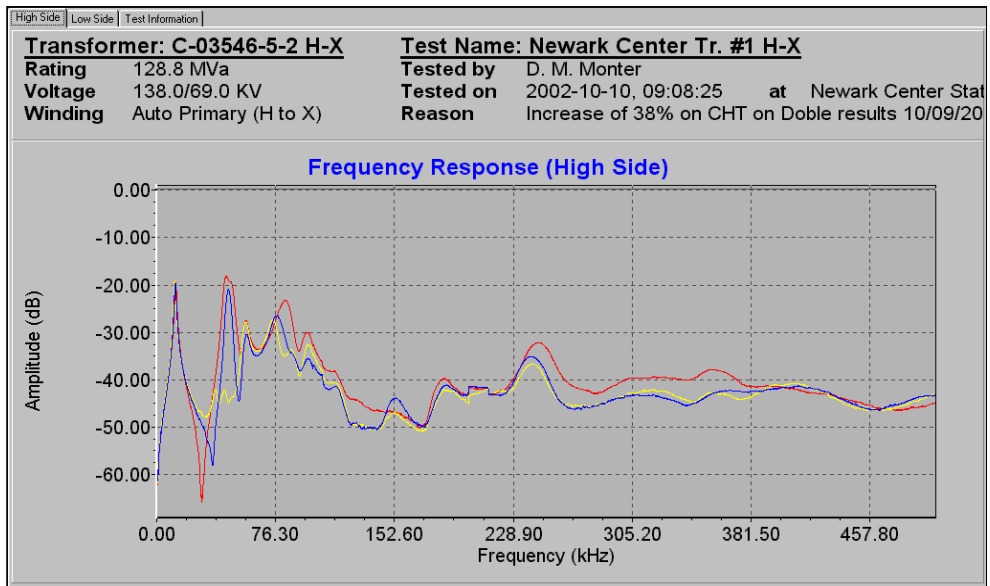


FIG 12. FRA "signature" of a test with a problem in transformer windings detected with FRAMIT system.



FIG 13. Collapsed winding photograph and loose connections in the previous test transformer.

Next and in the computer, are used digital signal processing techniques with mathematic algorithms that change from time domain to frequency domain giving the same results than from sweep technique..

Both techniques give as a result the "signature" of the transformer with the inside information of the complete electric / dielectric / magnetic / mechanic status. This test is very useful as a complement of the usual tests and can also check that no

alterations were derived from transportation, loose windings or displaced, problems in the magnetic core, etc.



FIG 14. FRA unit from Starlogic Company , model FRAMIT, represented in Europe by UNITRONICS.

Diagnosis and trending

Each previous test results are changed into the different registered parameters from the transformed that were previously programmed in the test protocol.

This parameters will be submitted to a criteria evaluation to the [diagnosis](#) emission.

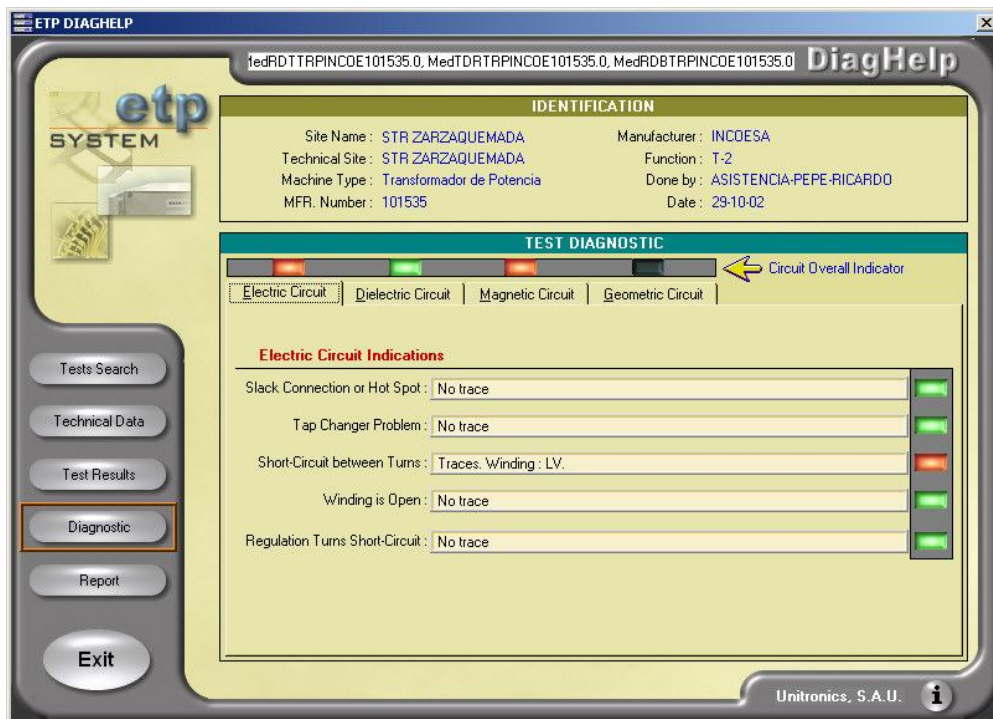


FIG 15. Lookup of the Expert Diagnosis Software for Power Transformer Evaluation ETPDiagHelp from UNITRONICS Company.

Diagnose criteria can change depending on the transformer, depending of the companies, but it exist a minimum values, another normalized and other ones than from an empiric approach conform Expert Diagnose Software that could be a failure

criteria interpretation. This software applications give an orientation of the machine status, but must be the maintenance expert who with all the machine data indicates end diagnosis and performs necessary actions: repair, continue operation, program new test, recommend service limitation...

Another scope will come from the [historic/trending](#) of the transformer. The parameter's evolution could help detecting machine's degradation speed and the new maintenance exigencies.

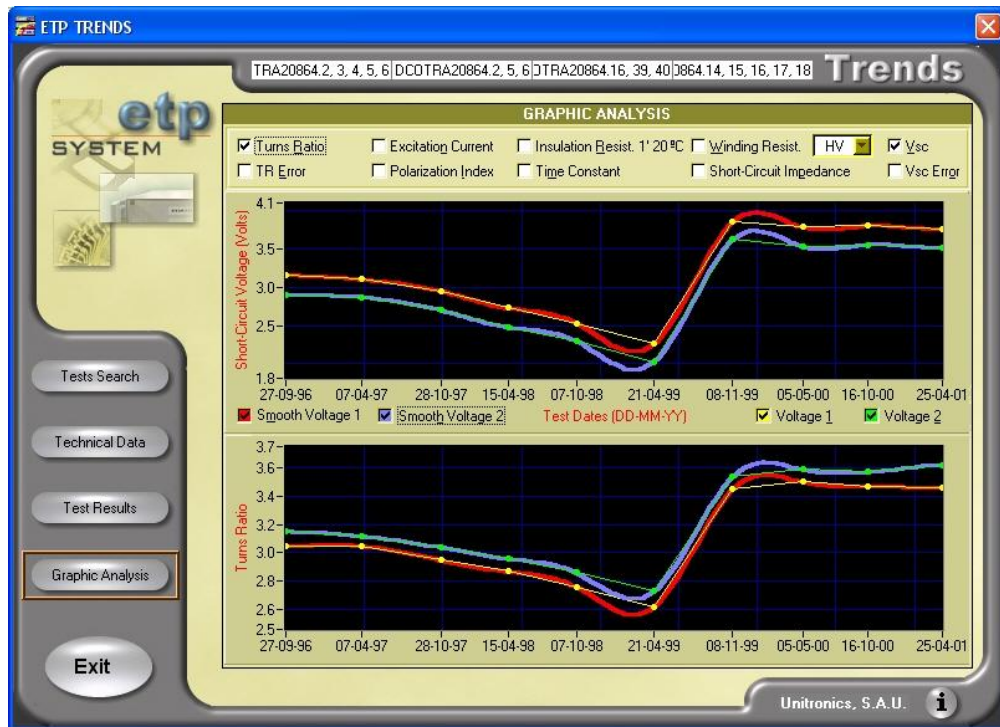


FIG 16. Lookup of Trends Software ETP Trends, showing a fault in the regulator and a later repair (From UNITRONICS Company).

DIELECTRIC SYSTEM TESTS.

One of the operating key elements in the power transformer and the one determining its remaining useful life is the dielectric. Dielectric could be split in: [liquid dielectric](#) (usually mineral oil) in which we'll have certain manipulation degree trough possible treatments and [solid dielectric](#) (paper) in which our work is limited only to the external indirect check of it's status. As a function of the maintenance policy of the owner company, the importance of the machine and the tolerable failure risk, its suitable to perform on it tests with a previously accorded program and protocol. Maintenance programs will give as a result a bigger knowledge of the status and availability of transformers. In a long term, this will translate in a very important concept: ["Extension of the life of Power Transformers"](#).

In this section we will insist in the electric detection methods although we will also comment that there are another focused to laboratory and related to oil sampling. The object of this article is to state the knowledge of this tests both if performed in the utilities as if contracted to extern facilities. Next are resumed the usual field test performed on the power transformer dielectric system.

ELECTRIC TESTS TO THE DIELECTRIC CIRCUIT.

It is a group of test that with measuring electronic instrumentation that can give a punctual status evaluation of the dielectric in the power transformer. We will describe the most usual test. Again, all they will be off-line (transformer out of service) apart from the indicated exceptions.

Dielectric circuit tests.

- Insulation Resistance and Polarization Index (IR, PI).
- Recovery voltage Measurement (RVM) and time constant.
- Capacitance, Dissipation (power) factor ($\tan \delta$) and insulation losses in dielectric / bushing.
- Partial Discharge (PD).

Oil sampling.

- Dielectric Strength.
- Moisture content.
- Dissolved Gases.
- Furnan Analysis.

- **Insulation Resistance.**

This test has been the most usual historically, being called to "*megger*" the transformer (the term comes from the firm of the first Megger systems).



FIG 17. Insulation Resistance and Polarization Index system, Firm Megger, model BM25.

This test is performed on a measuring tester able to generate high continuous voltages usually of 5000V that applied between both dielectric terminals of the power transformer (one terminal to all the bushings joined in high voltage, the other to low voltage and ground) allow evaluating the punctual dielectric status inside. The tester has a high voltage tester operating from batteries or from the main. Measuring

principle is based in measuring current / voltage in a continuous way that evolves as an answer to a voltage step.

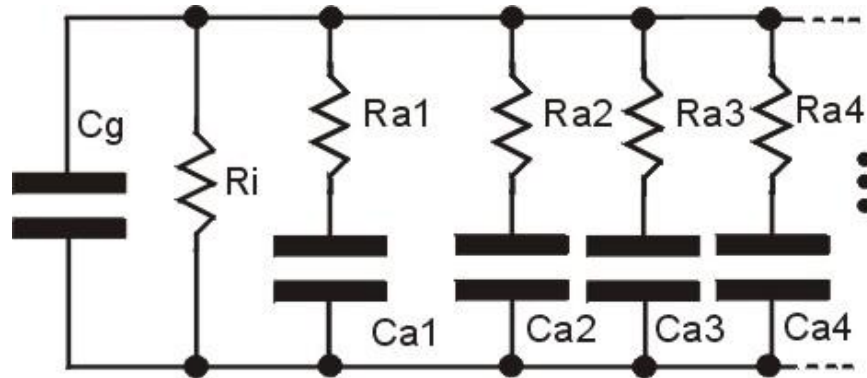


FIG 18. Equivalent diagram of the dielectric circuit of a transformer. R_i is the insulation resistance, C_g the geometric capacitance and the different R_a/C_a emulate the equivalent dielectric absorption circuit.

Insulation Resistance will be the quotient between voltage and current at the end of minute 1 of the test ($\sim R_i$ in figure 18). This parameter should be above a minimum normalized value. It contains direct information from the dielectric system status in the transformer, but is very influenced by temperature (and should be temperature normalized / corrected). So, its usual another parameter named **Polarization Index (PI)**. To measure it, the test is extended from minute 1 to minute 10, being PI, the quotient of currents in both time instants. This value is now independent from temperature and should be comparable in consecutive tests.

Recovery Voltage Measurement (RVM).

Other approach to get a generic knowledge of the dielectric status inside the transformer (**paper-oil**) is with recovery voltage testing. With this test is obtained the polarization spectrum of the dielectric mixing information both of dissolved humidity and components degeneration.

Any dielectric can be simulated with an equivalent diagram as from figure 18. Recovery voltage testing pursues determining "temporal spectrum" of the different circuits R_a/C_a who include information of moisture/degradation in the dielectric.

Test is performed with the circuit from figure 19. It has several charge / discharge steps of the dielectric from a continuous voltage source V whose result composes a plot spectrum named polarization spectrum. Each point comes from a charge process while a time T (S_1 closed and S_2 open) of the sample and discharges in a time $T/2$ (S_1 open and S_2 closed). Finally an electrometer ($E =$ very high impedance voltmeter) registers the point as the maximum of the recovery voltage curve given by the R_a/C_a .

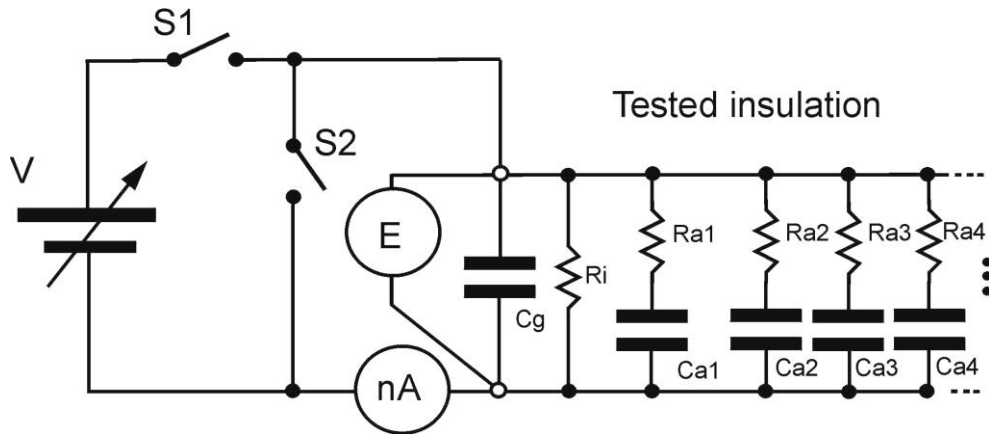


FIG 19. Operation diagram of the recovery voltage meter (RVM).

The final plot (figure 20) follows the equivalent spectra of all the Ra/Ca related to the circuit in figure 18. The appearance of the plot and the position of the maximum are indicative of the final quality of the dielectric paper / oil. Greater moisture = bigger deflection of the maximum to the left in the time axis.

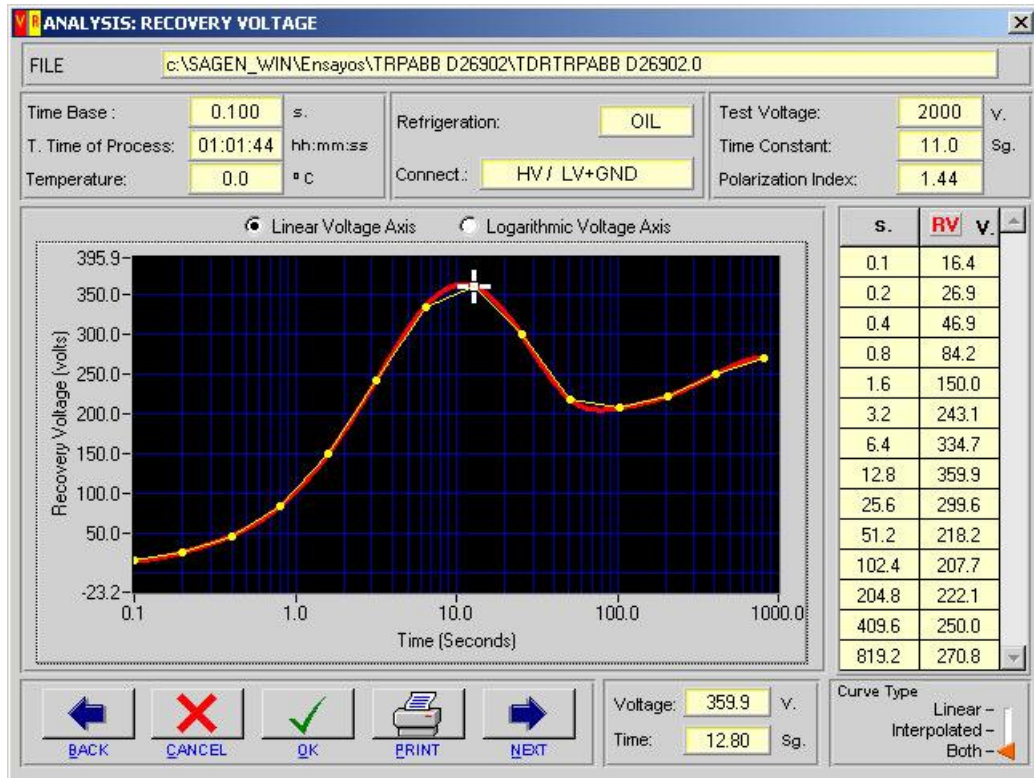


FIG 20. Test screen from Unitronics RVM UM2B.

Test voltage has standardized in 2kV to be comparable and applicable to all power / power / distribution oil submerged transformers. In figure 20 screen you can see in horizontal axis cycle and in vertical axis maximum per cycle of recovery voltage. In figure 21 system, apart from RVM test, includes in a time cycle greater than 10 minutes insulation resistance, polarization index and resistance evolution plot.



FIG 21. Unitronics Recovery Voltage Meter / RVM, model UM2B.

Capacitance / Tan delta (Dissipation Factor) & dielectric losses /bushings).

Another usual approach when performing dielectric evaluation is tan delta. This test uses AC and pursues to know loss angle of the tested element. This test system is usually more bulky because in order to generate current enough in AC voltage its necessary a greater power source. This measurement technique is again off-line although there are systems that allow an on-line approach. This measurement includes information of the moisture and contamination degree and emulates (greater voltage) the behaviour and voltage aggressions similar to service ones. It is important to take note of transformer temperature and environmental moisture (surface leakage).

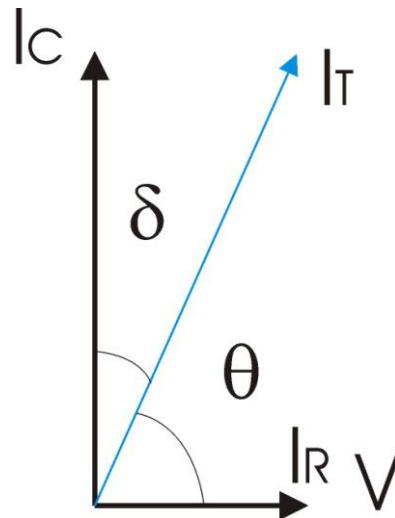


FIG 22. Diagram of currents flowing through dielectric, I_R resistive is in phase to voltage and capacitive I_C out of phase 90° . Total I_T , defines δ angle and tangent.



FIG 23. Tan delta meter from Megger, model Delta 2000.

- **Partial Discharge test.**

It is possible to make partial discharge testing on power transformers, most of all on the most powerful or critical units. Partial discharge are small discharges that appear inside of the dielectric as a sign of its degeneration. They appear as a result of the increase of the electric field in small gaseous voids inside the oil and also inside the paper, epoxy or as a result of the presence of metallic contamination, etc. This discharge accelerate the thermal degradation effects and though for the oil are auto-regenerable, lead sometimes exponentially to the power transformer destruction. There are two usual detection systems, acoustic and electric. **Acoustic** system seeks sound mechanic manifestation (in ultrasonic range) of discharges even enabling eco-location. **Electric** systems should allow determinate discharges and correlate them with another parameters. This test can be made online or offline if a source apart is used to energize the machine (difficult chance in field). In this test is important again to take note of the temperature of the machine and environment conditions.

PHYSICAL – CHEMICAL TESTS.

Another important test group are those in which in the field you only extract properly (see normative) an oil sample on/off line from which certain operating characteristics of the transformer can be deduced.

- **Breakdown voltage.**

Oil degradation can be easily appreciated with this parameter tested. The test is based in the insertion of electrodes immersed in oil of an increasing voltage up to when discharge happens. Test is repeated six times to get a repeatable measurement. The only disadvantage is that it is necessary to extract from the transformer a significant sample (test cell will have 350...600ml). The report will include sample temperature.

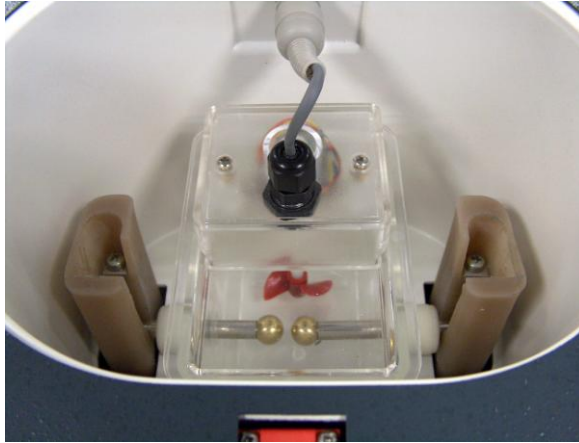


FIG 24. Inside of the test vessel for breakdown voltage in oil of a Megger, model OTS60SX system. It can be seen discharge terminals and agitation propeller.

- **Moisture (Water content).**

Until recently, dissolved moisture in oil was a relatively complex laboratory process. Today, Megger company has got out to the market a [portable](#) unit that close to easy to locate reagents and minimal test care, can perform the test in field / plant / repair shop in an easy and handy way. Implemented system is Karl-Fischer, the usual and laboratory regulated but in a portable manner. It has good repeatability and accuracy. It does only need a small oil sample (1ml) and the system executes the complete control of the chemical process eliminating dissolved moisture and indicating quantity in ppm, %...



FIG 25. System for moisture determination in oil, from Megger, Model KF875.

[Another oil parameters.](#)

Other usual laboratory test reporting complementary information of the oil / transformer status are:

Power factor in liquids, interfacial tension, acid number, Oxidation Inhibitor, colour, appearance, fire point, viscosity, PCB...

- **Dissolved Gas Analysis & Ratios.**

Oil dissolved gases testing started around 1956 in investigation from Buchholz relay trigger in transformers. Some investigation of the gases generated there have created

specific normative that allow the interpretation of the possible problems inside the transformer. Base parameters are both quantities of some generated gases as relative proportions between gases and apparition / variation speed in taken samples. It can be taken so indirect evidence of Partial Discharge, hot points, arcing, combustion, aging and overheating, detecting incipient failures that could end the transformer life.

- Furan Analysis.

This laboratory test seeks determine the amount of some component (furaldehyds) in an insulating oil sample. Theory says that this kind of furanic derivates is never present in oil in a natural way and will only exist as a sub product of paper degeneration inside the transformer.

As a complement, we will indicate that exist treatments to decrease moisture and purify the oil eliminating degradation products and taking away metallic particles, etc. Anyway paper access is limited to the interface with oil, so **transformer life is paper life.**

Conclusions

From the short downtime available nowadays it is necessary to use test systems that allow a maximum automation of tests to perform and conform a database with all the test performed to can optimize diagnosis and trending.

It is also necessary to perform zero test either in installations or on new machines: first to be certain the machine is in proper condition of use and fulfill contractual requirements and second to have data available with which perform a later predictive monitoring of faults.

Again we need the maintenance people to have a deep knowledge of this tests and the way to perform them in order to get from them the maximum reliability either if made by the own utility as from subcontracted to avoid weak. This tests though easy and automatic, take with them some measurement details to take in account in order the measurements to be reliable all this apart from the security details of the user.



FIG 26. Theoretical – practical formation in field testing on electric machines in UNITRONICS.

We have described most of the usual "standardized" test in measurement protocols. With a short number of measuring elements we can have a clear idea of the complete transformer status. Anyway, it is of a great importance to go more deeply in the knowledge of this tests to insure their tracking both in the performance on our own or subcontracted.

This test will be performed taking into account a series of precautions related both in their normatives and in the experience logic. In all dielectric system tests, is important to take note of transformer temperature and around conditions.

Its crucial that workers who make the test have an optimal formation in this kind of testing, both making the tests as in diagnosis and trending.

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