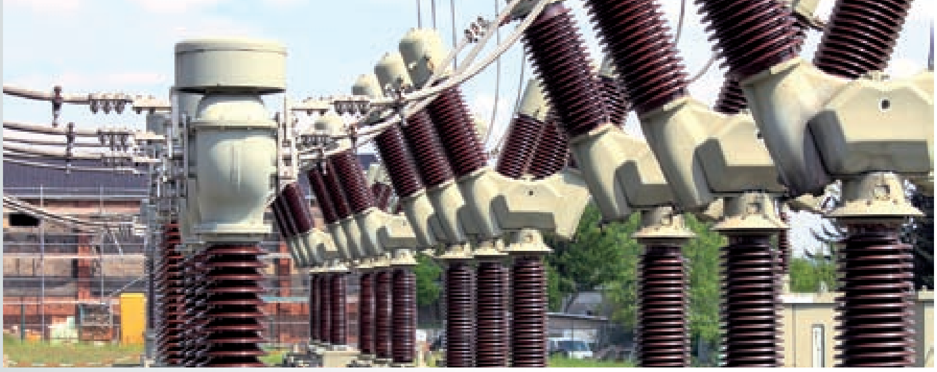
ENERGO-COMPLEX

Comprehensive diagnostics
of transformers technical condition



Introduction

The lifetime of a power transformer is determined by technical condition of its insulating system, in particular the solid insulation based on a cellulose. It is frequently stated that a transformer's lifetime equals lifetime of paper used in its insulation.
The degradation process of cellulose insulation causes the deterioration of its mechanical parameters and elasticity loss, and hence the loss of the initial winding tension crucial for its mechanical strength and resistance to dynamic effects of short-circuit currents.
For the transformer with advanced ageing process of the paper insulation, even relatively low short-circuit current is dangerous, which would not threaten a new unit. It can easily shift or deform discs and decrease oil gaps between them, additionally the solid insulation can crumble and therefore lead to further reduction of dielectric strength of the winding. Another atmospheric or switching surge can result in breakdown of weakened insulation and transformer failure during its operation.
The reduction of short-circuit resistance is not the only threat to aged units. The increase of moisture level in the insulation entails restrictions on the transformer load and increases failure risk due to bubble effect (see frame nr. 1).
Transformers with advanced age have often highly degraded insulating oil, whose decomposition products with particles of aged cellulose insulation form solid particles suspension, that sediments as sludge on windings. This reduces heat transfer and by increasing the temperature significantly accelerates cellulose degradation processes (see frame nr. 6). The active part is not the only cause of serious problems for operated units. Constantly ageing equipment, especially HV bushings, are often the cause of serious failures resulting in the transformer fire.
Therefore it is very important to use comprehensive diagnostics allowing to perform technical condition assessment of solid insulation, determining the moisture level, detecting the sludge presence and also early detecting the winding deformation, complemented by technical condition assessment of additional equipment. Our company performs a series of diagnostic tests which are the base for accurate assessment of technical condition and potential threats for the tested transformer as well as preparation of recommendations for further operation of the unit.
Energo-Complex offers full range of diagnostic services based on noninvasive measuring methods which allow to precisely estimate the risk of further operation and to determine proper restrictions in operation of tested unit.

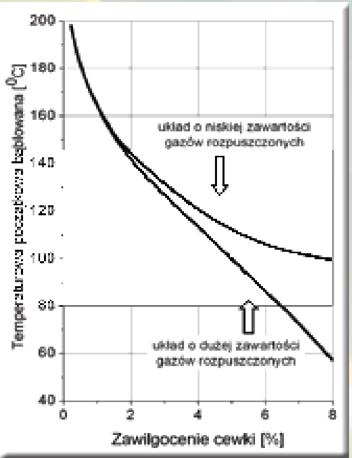
Solid insulation tests

The basic factors determining the degradation process dynamics of the insulation are operation temperature, water accumulation in pressboard and cellulose. The increase of moisture content causes significant acceleration of ageing processes in the insulation (cellulose fibers depolymerization), and thus significant shortening of its lifetime.
The process of moisture absorption from the atmosphere to paper through the oil lasts continuously for many years, so it is necessary to systematically monitor the amount of water stored in cellulose insulation.
Solid elements of the insulation store approx. 98% of water contained in the whole paper-oil insulating system and the moisture level generally determines the water content in oil.
The correct determination of percentage amount of water in paper along with cellulose ageing level assessment has fundamental importance for the elaboration of recommendations of further operation of tested transformer as well as for estimation of its remaining period of operation.
Standard measurements of tgδ at 50 Hz do not provide a reliable assessment of the solid insulation condition. Commonly performed measurements of water contents dissolved in oil may be helpful in the determination of moisture content in paper, however, require special conditions of sample acquiring and the analysis based on this requires much experience and often is subject to considerable error due to lack of a real state of moisture content equilibrium between the solid insulation and the oil.
It is therefore important to use several complementary measuring methods, based among others on the polarization phenomena and chemical analysis of oil samples. The group of used measurements include joint measurement of RVM and PDC, performed at the same time (Return Voltage Measurement and Polarization Depolarization Currents) as well as frequency spectroscopy FDS, in other words measurement of dielectric losses coefficient tgδ in wide frequency range. These measurements provide a precise identification of insulating system moisture level and also help to detect precipitation of sludge on the windings.
Oil tests in addition to the standard range include the determination of furane compounds. The scope of tests is chosen individually depending on the specific technical conditions, such as the history of operation or repairs performed on the analyzed object.

1

BUBBLE EFFECT

A high water content in transformer's insulating system is a risk of bubble effect presence. This term means rapid freeing of moisture in the form of steam, which is contained in solid insulation.
The appearance of gas bubbles inside the transformer is a direct threat for this unit, which can be damaged or destroyed as a result of pressure increase leading to tank leaks and voltage stress increase by lowering dielectric strength of insulating system.
When moisture level excess 3%, the temperature of effect initiation is so low that it is necessary to limit the range of allowed operation temperatures. This way the unit cannot be operated with full load and even short overloading may lead to the failure.

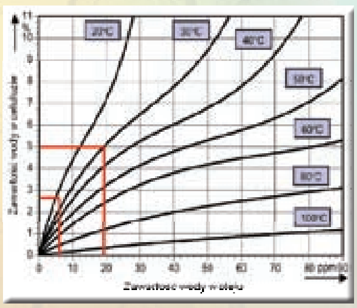


The dependency of bubble effect initiation temperature from moisture level.

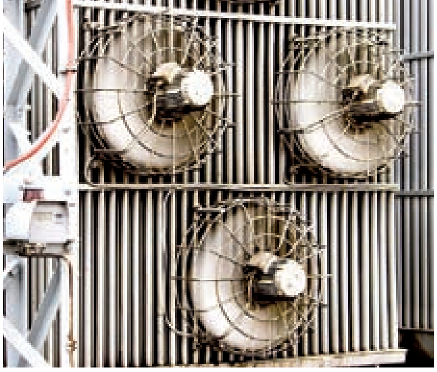
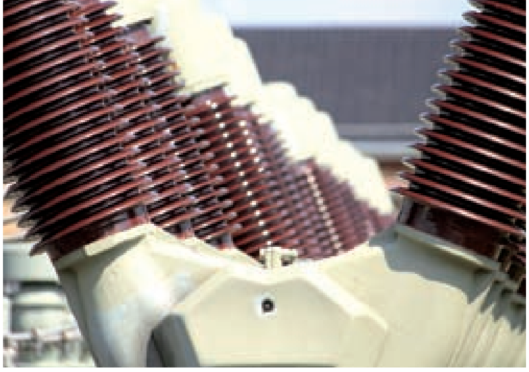
2

THE DEPENDENCY BETWEEN MOISTURE CONTENT IN THE SOLID INSULATION AND WATER AMOUNT DISSOLVED IN OIL

With changes of transformer's operation temperature water migrates between the paper insulation and oil.
The curves show the water amount dissolved in the oil depending on the moisture content in paper and oil temperature.
In practice, the estimation of solid insulation moisture content on the base of water amount dissolved in oil does not give satisfactory results. For typical values of moisture content and operation temperatures due to the steepness of the characteristics in this range even small deviations in the measurement of water content in oil result in a huge scatter in the estimation of the percentage value of cellulose moisture content.



For moisture content from 8 to approx. 20 ppm estimation of moisture content in the solid insulation gives values scatter from 2.5% to 5.5%. Such big uncertainty forces application of other – more exact – methods for the assessment of moisture content in the solid insulation.


3

CELLULOSE FIBERS STRUCTURE

High mechanical strength of insulation during transformer's lifetime is provided by a chain structure of cellulose and formation of macromolecules with linear structure. With maintaining an adequate level of moisture content, the criterion for insulation ageing is not a loss of dielectric strength, but loss of mechanical strength. During transformer lifetime the macromolecular structure is deteriorated, which is determined mainly by the temperature of the process and moisture content:
The increase of operation temperature by 6-8°C leads to shortening the paper insulation lifetime by a half.
The lifetime of cellulose insulation with assumption of constant moisture level equal 0.5% is

- for hotspot temperature of the winding equal 80°C – 500 years,
- for temperature 100°C – 50 years,
- for temperature 120°C – approx. 6 years,
- for temperature 140°C – approx. 1 year.

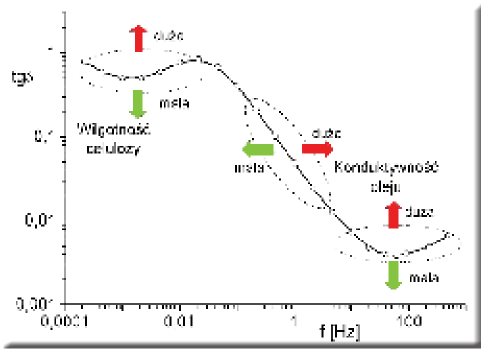
Every doubling of moisture content shortens durability of the paper insulation by a half.
With assuming as reference point moisture level equal 0.5%, the increase of moisture content to 1% shortens the lifetime by a half, while the increase to 2% shortens it to a quarter.
The process of cellulose ageing is connected with breaking of cellulose macromolecules bonds and their shortening, and at the same time freeing their end groups and creating smaller particles compounds: water and carbon oxides, in limited range hydrogen and hydrocarbons C1 and C2, as well as more complex compounds, including furan compounds.
The furan compounds found among other by-products of cellulose ageing, and especially the most numerous furfural aldehyde 2FAL are specific products of cellulose ageing process.
By determining their amount in electroinsulating oil samples it is possible to assess the level of deterioration of cellulose insulation, which is expressed in the loss of its mechanical properties (depolymerization level DP).

4

DIELECTRIC LOSSES COEFFICIENT TGΔ

The AC voltage applied to the capacitor effects in a capacitive current flow Ic which is shifted earlier in phase by 90O. The Ic current grows with the increase of permittivity (ε) and voltage frequency f. In addition through the capacitor flows a low dielectric losses current Ir, which is in the same phase as the voltage. The quotient of these two currents is called dielectric losses coefficient tgδ = Ir/Ic.

The cyclic change of voltage polarization causes rotation of molecules in a dielectric, which leads to appearance of losses. They have the biggest value for a given frequency, depending on the relaxation time of the molecules. Above such frequency, due to molecules inertness their rotation is limited and therefore losses and dielectric constant ε are lower, as well as capacitance of the insulating system. In the case of paper-oil insulation with water content the frequency of maximum losses depends also on amount of water contained in the insulation. On the base of described phenomena determination of function tgδ = f(f) and its analysis gives information on the condition of insulating system.

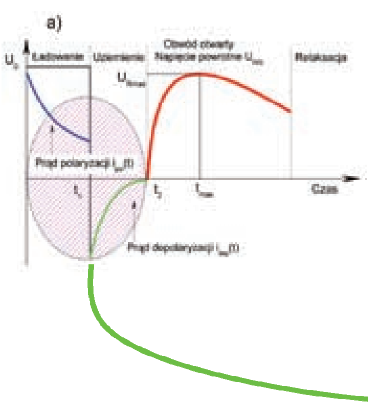


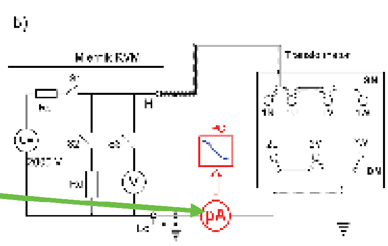
The basics of tgδ = f(f) characteristics analysis

5

MEASUREMENTS OF THE RETURN VOLTAGE RVM AND POLARIZATION AND DEPOLARIZATION CURRENTS

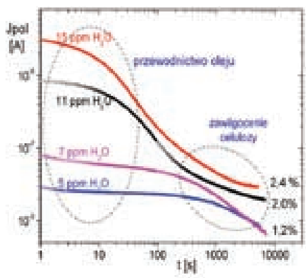
The paper-oil insulation consists of a paper layer and an oil gap, and each of them is characterized by other dielectric constant ε and conductivity σ. The basic voltage distribution on the paper layer and the oil gap after applying DC voltage is determined by the quotient of dielectric losses εr of oil and paper. However the final distribution after lapse of time constant t depends from quotation of conductivities σ of these materials. The charge accumulated in these two dielectrics is given off in the form of unipolar voltage function with given times of rise and decay. This return voltage contains several time constants corresponding with relaxation frequencies of each molecular groups taking part in the relaxation process.





The RVM-PDC device at first charges the capacitance of tested insulation with DC voltage for tc period, and subsequently shortens terminals and discharges this capacitance for period tc/2. After opening shorted terminals appears the return voltage, which increases to the maximum value Um and then decreases. The graph of Um=f(tc) in the wide range of tc values can be interpreted as indicator of water content in oil or level of cellulose ageing. The measuring procedure of joint RVM-PDC measurement is not substantially different from standard measurement of return voltages, but is supplemented by exact measurement of polarization and depolarization currents. They are measured during main measurement cycle (charging and discharging). The analysis of measured characteristics allows to determine cellulose conductivity and with use of patterns also the calculation of moisture content of solid insulation. The application of two measuring methods based on different physical properties of insulating system allows to avoid measurement mistakes, exact assessment of the insulation with minimization of time necessary for conducting tests.

RVM-PDC measurement principle



The analysis of polarization currents characteristics Determination of cellulose conductivity and relaxation parameters. Examples of transformers having moisture content from 1.2 to 2.4%.

RVM-PDC measuring device *Sludge on the transformer windings*

SLUDGE

The pollutants, created in processes of oil oxidation and cellulose decomposition, during many years of transformer operation lead to formation of colloidal suspension in electroinsulating oil. After exceeding some concentration level of pollutants, they are precipitated in the form of sludge on elements of transformer's active part.

As a result on the surface of the windings there is a layer of pollutants, which apart from its chemical and dielectric influence (loss of insulation resistance) make worse cooling properties of the active part. The decrease of oil gaps cross-section inside of coils and insulating layer of pollutants on the surface lead to temperature increase inside windings. The typical example of such situation are symptoms of extensive low temperature overheating in DGA tests, still increasing in spite of constant load and keeping relatively low oil temperature indicated by thermometers. This situation leads to rapid thermal degradation of the cellulose.

The active part of a 16 MVA transformer during internal inspection.

The research showed precipitation of sludge, after one year the transformer was sent to repairs.

The internal revision showed complete degradation of the cellulose insulation.

Detection and assessment of mechanical deformations of windings

Relatively fast detection of winding deformation can prevent major failures, it is also helpful in the rational planning of repairs of units in service, and thus can optimize the cost of their operation.

The leakage reactance measurement at power frequency used for many years does not allow to detect local displacements of windings, due to insufficient sensitivity of the method. Such possibility is given by the method based on winding's transfer function measured in wide frequency range (SFRA).

The transformer winding can be considered as a network of RLC elements, and therefore every coil has characteristic frequency response. It is a unique identification ("fingerprint") of the winding, determined by its geometric structure and arrangement. Any shift or deformation of the windings, which will change the capacitance and leakage inductance will influence to some extent the answer. Practically applied method of transfer function determination is based on measurement of winding's response to applied sine voltage signal in given frequency range. This type of measurements is called SFRA measurement.

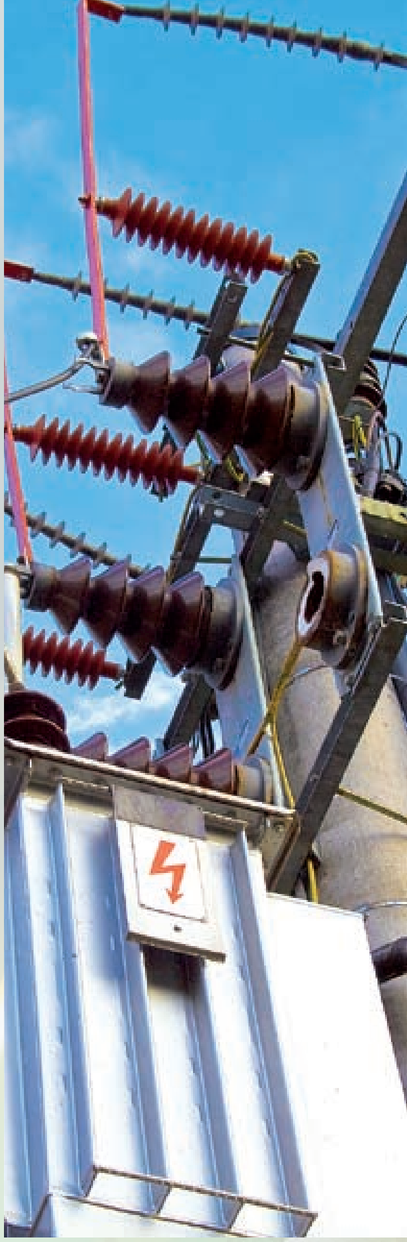
SFRA used as the only method for windings condition assessment allows to detect already existing deformations, however this method does not detect loosening and depressing of windings if the geometry is unchanged. Full information on mechanical condition of transformer's active part can be obtained from correlation of SFRA with vibroacoustic tests.

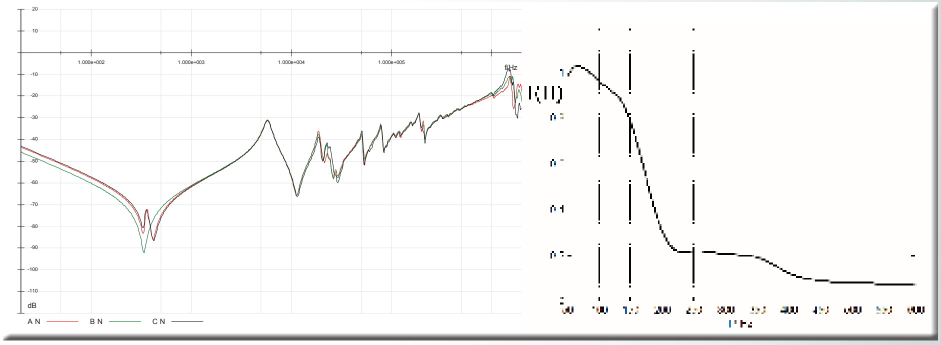
Recent research showed a close correlation between vibroacoustic spectrum recorded by contact accelerometers mounted to the transformer tank and the mechanical condition of the active part, especially proper pressing of windings.

Recorded time dependencies allow to determine descriptors in time domain, which represent "fingerprint" of tested transformer, similarly to SFRA curves.

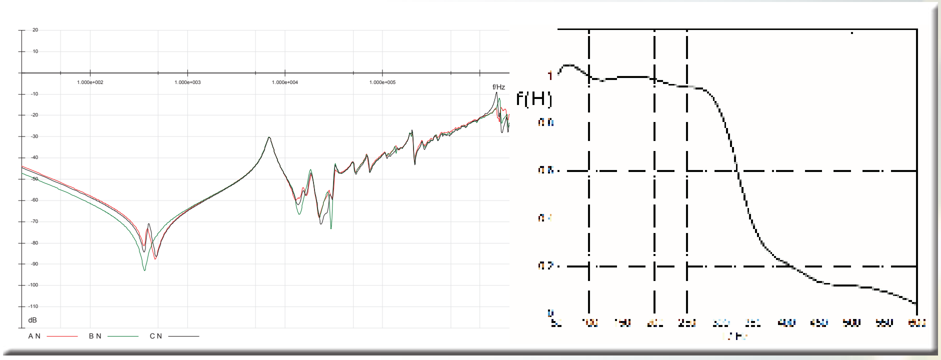
The correlation of vibroacoustic method results with SFRA measurement results allows to perform full assessment of mechanical integrity of active part, including level of winding and core pressing.

SFRA and vibroacoustic tests are used in practice as: acceptance tests of new units, as tests after fault measurements (launch of protection devices), after installation measurement performed to exclude coils shifts during transportation, and also with insulation condition analysis as supporting tool for planning operation and repairs.





The transformer in good mechanical condition of the active part.

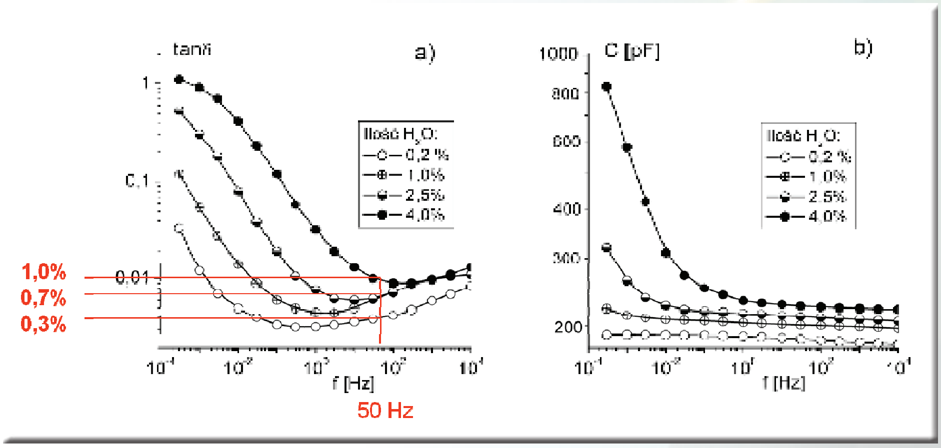


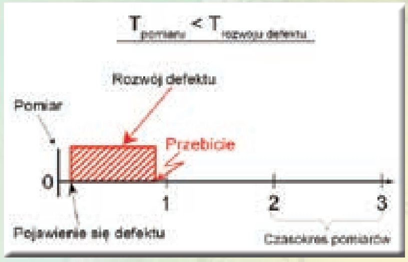
The transformer with deformed and loosened windings.

Bushings diagnostics

In constantly ageing population of transformers degradation processes take place not only in the active part of transformer, but also in the insulation of HV bushings. Their failure could lead to the complete destruction of transformer. Hence, effective diagnostics of insulating bushings is becoming increasingly required by power transformer operators.

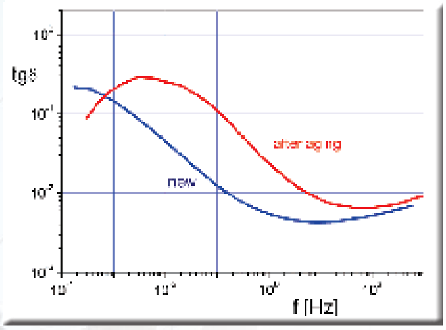
Used in practice as a standard diagnostic method measurement of tgδ at power frequency (50Hz) is inadequate for many reasons. Measurement made at a voltage much lower than the operating voltage and at a temperature of bushing core different from standard operation temperature is not sensitive enough to identify the initial stage of degradation of the insulating bushing.



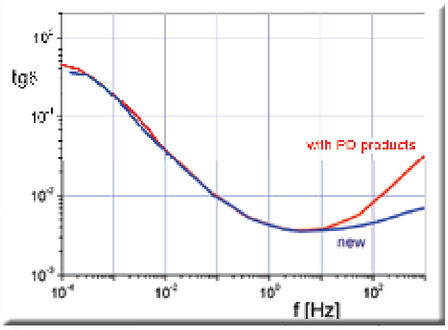


The period of defects development in the insulation is significantly shorter than typical periods between successive diagnostic tests.

The application of polarization methods, such as frequency spectroscopy and PDC in insulating bushing diagnostics gives good results in detection of degradation and moisturization of insulation. These tests are called off-line methods requiring switching off the unit.

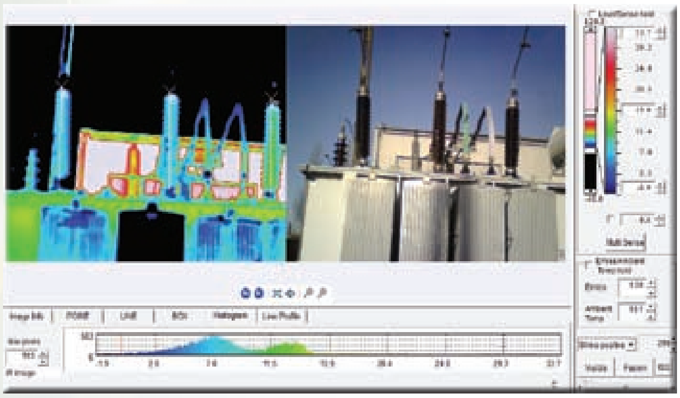


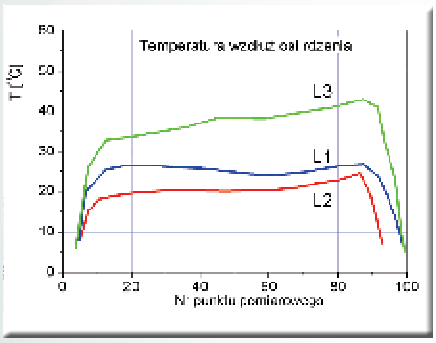
Frequency dependency of tgδ for the new and aged RBP bushing.



Frequency dependency of tgδ for the new OIP bushing and the one with products of PD presence.

A much better approach are measurements of capacitance and dielectric losses coefficient tgδ in wide frequency range. Unfortunately, these methods also require switching off the transformer.
Experiences show that often switching off is not possible, therefore in the first stage of bushing assessment for its further operation we use external methods, based on thermographic analysis and mathematical transformation of measured signal.





Thermograph of bushings and calculated temperature distributions along the core axis.

The aged insulation of RIP bushing

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