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POWER TRANSFORMERS DIAGNOSIS: STATUS EVALUATION

ABSTRACT

The reliability of the electrical grid depends on the availability and performance of crucial components such as power transformers. A failure in these expensive devices threatens supply energy warranty and system overhaul reliability. As transformers approach their end of life, the failure rate tends to increase and, therefore, both equipment diagnostics and working condition assessment are important to detect oncoming faults.

In this work, we develop a state assessment methodology, able to evaluate power transformers health condition. The study is about the transformer operation analysis and the associated status index calculation. This index value classifies the transformer general operation, according to the information of five partial indexes, reflecting the work conditions of most critical equipment: insulating oil and paper, winding and bushings. This contribution also presents an extensive transformer state analysis, backed up by in-service equipment.

Keywords: *power transformer diagnostics; oil dissolved gas analysis; assessment methodology; status index; partial indexes*

1. INTRODUCTION

Power transformers are one of the fundamental building blocks of the electric system, the central hub in the field of energy distribution and transmission. Therefore, their work state condition is a key factor for reliable operation, once any localized fault can bring serious consequences such as a total failure, or even extended damage on goods or property.

Currently, 70% of large power transformers and transmission lines are twenty-five years or older and 60% of circuit breakers are thirty years or older [1]. A catastrophic failure on transmission system threatens the network operation, and current aging transformers may increase the likelihood of this happening.

The preventive replacement after a certain number of operating years is not considered an eco-nomically viable alternative, since the associated costs of replacing these machines can be enormous. Also, the aging depends on the conditions in which the transformer has been operated. Therefore, work condition monitoring, time-based equipment diagnostic and in-service state evaluation have established themselves as the better options.

The long-term reliability of a transformer depends on its initial high-quality operation. An efficient transformer lifecycle management safeguards a good quality of service throughout the trans-former´s entire life [2]. Thus, monitoring the daily work conditions is crucial for the lifecycle management, to ensure the components higher-performance under safety conditions, as well as, to minimize operational costs. The ongoing monitoring with a continuously evaluation of stress points situations is important for the detection of coming faults at an early stage [3]. Not less important is an effective information system based on test reports and guided by maintenance records and incoming inspections.

In this work was developed an accurate state operation assessment methodology and its applicability in many power transformers on the Portuguese national grid. It was used diagnostic techniques in the most critical equipment, such as oil dissolved gas analysis, paper furanic compounds, proporcionais [6], de acordo com a equação (1): bushings and winding degradation status. With these parameters information and their associated state indexes calculation, we can evaluate the global equipment status index.

The broadness of those diagnostic techniques and assessment methodology allow us to view into transformer internal conditions and is a support decision tool to hierarchize maintenance strategies.

2. Transformer equipment diagnosis

2.1. Major components

Although power transformers come in a wide variety of sizes and configurations, they include two main active parts: the core and windings.

The core is made of high-permeability, grain-oriented, silicon electrical steel, layered in pieces. Electrical steel is a critical component because of it great impact on the transformer performance once, if it provides low core loss and high permeability, we have efficient and economical power transformers [4]. The windings, made of copper conductors wound around the core, provide electrical input and output.

Power transformers are produced in two basic configurations of core and windings, frequently called as the core-type and the shell-type, both presented in Figure 1, for a single phase. In the core-type cylindrical windings cover the core legs, whereas the common shell-type transformer, the primary and secondary are both on one leg and are surrounded by the core [5].

The core and windings are contained in a mechanical frame, the transformer tank, used for housing the active part of the transformer, immersed in insulating oil. Tanks are constructions made of welded thin steel sheets and support other parts as bushings, which connect power transformers to transmission lines, tap changers, power cable connectors, gas-operated relays, thermometers, relief devices, dehydrating breathers, oil conservator and other control indicators. In Figure 2 we can see a standard core-type power transformer and some of it major components [6].

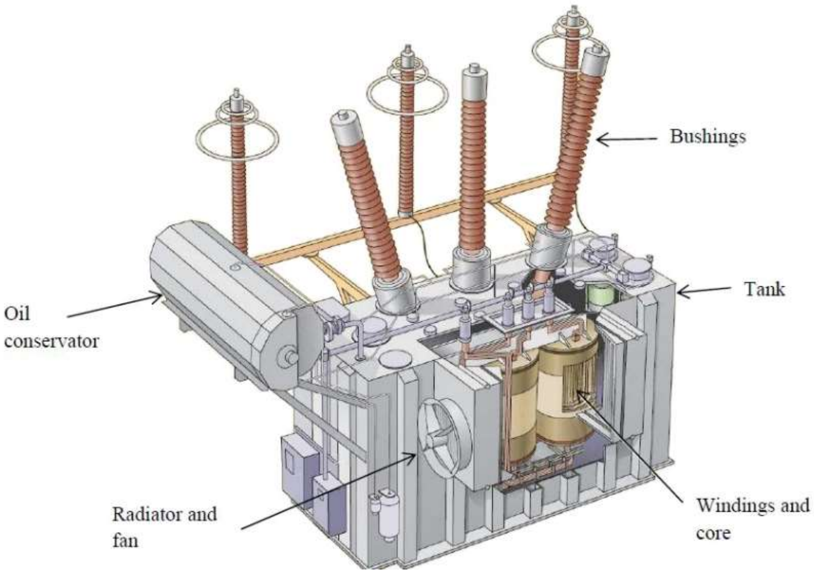


Figure 2 – Transformer major components [6]

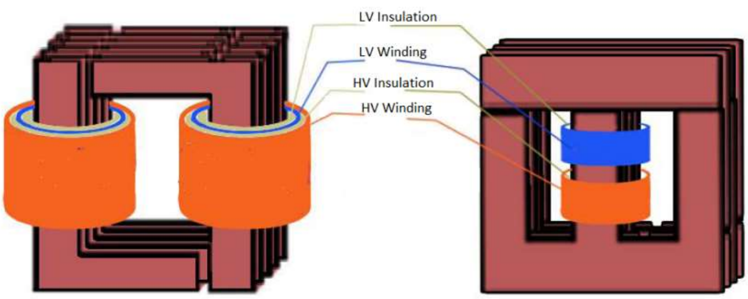


Figure 1 - a) Core type b) Shell type

Along the transformer operation life, chemical contaminants can occur leading to progressive equipment aging, usually caused by the oxidation processes inside the transformer.

Physical contamination of the oil can also occur, like moisture, particles and fibers or by the occurrence of electric arcs, discharges and overheating [7].

The insulation oil degradation, the irreversible deterioration of the paper and active part are some of the most worrisome phenomena, since they cause the decrease of dielectric capacity, mechanical strength and thermal performance of the equipment.

If the transformer lengthen is wanted, lifespan and safeguard its proper functioning it´s essential to carry out diagnostic tools to ensure the accuracy of voltage ratios, verify power ratings, and determine electrical impedances [8], these are the primary security measures to avoid failures.

2.2. Insulating oil

The insulating oil is an important part for a transformer state evaluation because its quality gives important information about internal health and physical condition, without the need to apply for intrusive analysis methods.

During its operating life, transformer oil can deteriorate due to heat or to external and internal contamination. The heat results from inherent transformer operation. External contamination is due to the ingress of water and particles, and internal contamination resulted by products of oil, paper and other material aging [9].

In normal conditions, the dielectric oil existing in a transformer tank will not decompose at a fast rate. However, thermal and electrical faults can accelerate the decomposition of the dielectric fluid, as well as the solid insulation [8].

The relevant information about oil contamination and it consequent internal transformer faults can be analyzed by a diagnostic tool for oil-filled apparatus, the dissolved gas analysis (DGA) test. The existing DGA standard is based on some procedures well controlled under laboratory conditions [10]. For transformers with higher operating temperatures or those designed for extended service life, there may exist further limits for the oil oxidation stability test, according to standard analysis methods [11].

With a frequent taken oil samples, it is possible to control fault gas development, by evaluating ratios of different gases and long-term gas generating rates [12]. The fault gas profiles analysis gives information about the evaluation of kind and severity of the foreseen fault and thus guaranteeing an optimal energy transmission [13].

Gases escaping through the conservator tank may lead to misleading concentration levels and underrated gas generation rates especially for free breathing transformers [14]. In addition, one other way is possible: gases from the ambient air, mainly nitrogen and oxygen, are slowly dissolving in the conservator tank oil and are afterwards mixed with the main tank oil [15].

Other factors may affect the insulation oil feature like the aging, high oil conductivity and an in-crease in the water content, all can be symptoms of the degradation process in the insulation. These symptoms also result in an increase of losses, which can be quantified by measuring the power fac-tor or dissipation factor, both related to the dielectric losses in an insulating fluid when used in an alternating electric field.

When an insulating fluid is subjected to an AC current, there are dielectric losses, which cause two effects. The resulting current is deflected slightly out of phase with the AC field that has been applied, and the energy of the losses is dissipated as heat. The power factor of insulating oil equals the cosine of the phase angle between an AC voltage applied to oil and the resulting current [16].

The power factor test is widely used as a preventive maintenance test for insulating oil. A high-power factor indicates deterioration and/or contamination from byproducts such as water, carbon, or other conducting particles, including metal soaps caused by acids attacking transformer metals, and products of oxidation [17]. A new, clean and dry transformer oil has a very low value of power fac-tor. The contamination by moisture or by other contaminants will increase the oil power factor, as well as the aging and oxidation of the oil.

2.3. Cellulosic insulating paper

For correct function, each transformer winding needs to be insulated turn from turn with different solid insulating materials used for this purpose. In power transformers, cellulosic insulating pa-per, also known as Kraft paper, is by far the most widely used material, although nowadays other synthetic materials can be used as alternative. Kraft paper is a mat of cellulose fibers extracted from wood and other vegetable sources [18]. In Figure 3 we can see the isolated active part of a core-type transformer.

Cellulosic insulating papers must have good electrical properties to withstand electrical stresses as well as good mechanical properties to avoid it became broken whilst in service. However, different mechanical properties may have quite different behaviors during ageing.

Like oil degradation, cellulose degradation is a complex process which can be accelerated by the combined effect of heat, water, acids and oxygen, all of them available to the cellulose environment of the transformer [19], [20].

The DGA approaches can evaluate the ageing process and the deteriorating of cellulose material in the transformer oil, as well as the degree of polymerization measurements. Determining the degree of polymerization (DP) value of cellulose is a standard method of quantifying cellulose paper degradation, DP value indicates the average polymer length of the cellulose molecules [21].

In cellulosic insulating paper, aging caused by thermal stress generates furanic compounds (FUR) as a degradation product. These compounds are a family of chemical substances that differ in stability and production rates. Once these compounds are dissolve in oil, they can be detected and studied by standard analytical methods, how is the case of the Furan analysis test.

Figure 3 - Transformer active part isolated with Kraft paper

2.4. Bushings and windings inspection

As seen, the condition of the oil and cellulosic paper insulation is essential for secure and reliable operation of the transformer. In addition to them, another import cause for transformer outages is the replacement of bushings due to a deterioration or failure of the insulation, they are one of the major components causing forced outages of power transformers.

Measuring capacitance and power factor/dissipation factor are performed to investigate the condition of the insulation in bushings or between windings. Changes in capacitance indicate mechanical displacements of windings or partial breakdown in bushings. By measuring the capacitance and loss-es, problems in the insulation can be detected in an early state, i.e., before a failure occurs.

Aging and degradation of the insulation, coupled with the ingress of water, increase the amount of energy that is converted to heat in the insulation. The rate of these losses is measured by the dissipation factor, called tan (δ).

The dissipation factor is calculated via the tangent of the angle δ between the measured current and the ideal current which would occur if no losses would exist. The power factor is the cosine of the angle ϕ, between the output voltage and the measured current [22]. As seen in Figure 4, the dielectric losses cause a phase shift.

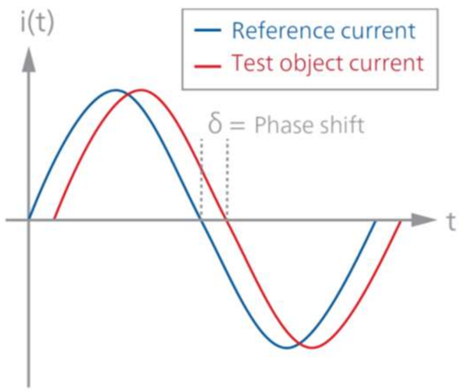
Winding resistance measurements are performed for assessing possible damage in windings or contact problems, such as from the bushings to the windings and the windings to the tap changer. They are also used to check the on-load tap changer (OLTC) as they can indicate when to clean or replace OLTC contacts, or when to replace or refurbish the OLTC itself [22]. With this diagnostic tool, failures can be detected without opening the tap changer compartment.

Static winding resistance measurements are the most common and easiest way to check for issues regarding the winding and OLTC. It investigates the resistance of each subsequent tap position and compares it with the reference measurement data of the manufacturer.

The requirements and tests for different categories of windings carried out on each transformer should follow IEC60076 standard [23].

Those dielectric tests performed on the transformer bushings and windings evaluate the state of insulation through the resistance insulation level and dissipation factor, identifying possible leakage currents in the insulation structure and can quantify its level of degradation.

The combination of these parameters with the oil analysis and the insulation paper provide a very good diagnostic methodology for the global assessment of the power transformer. Therefore, optimizing the combination of various diagnostic techniques is an important issue for the calculation of the transformer status index.



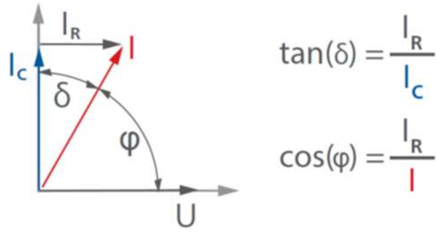


Figure 4 - a) Phase shift b) Dissipation factor / Power factor

3. STATE ASSESSMENT METHODOLOGY

In this work we develop a transformer state assessment methodology, based on the calculation of a numerical indicator, the status index - iET, which gives us a global evaluation of the equipment and its current degree of degradation. This indicator is calculated from five partial indexes, three of them based on the analysis tests carried out on the insulating oil and the other two, based on the analysis of the dielectric tests on windings and bushings.

3.1. DGA index, iDGA – Oil Dissolved Gas Analysis

As seen previously, the dissolved gas analysis can provide a reliable assessment about internal transformer faults. Thermal and electrical failures generate typical fault gases which are dissolved in the oil. The DGA index considers the relative concentration and daily rate of change of the fault gases, accordingly to their standards values.

3.2. FUR index, iFUR – Oil Furanic Compounds

Furaldehyde in oil is generated by the degradation of cellulosic materials used in the solid insula-tion systems of transformers. These compounds are oil soluble and leads to migration into the insulating fluid so, high concentrations or unusual increases concentrations in oil, may indicate cellulose degradation from aging or another fault situation.

Direct measurement of these properties is not practical for in-service transformers, however, the amount of furanic compounds (2-FAL) is directly related to the degree of polymerization (DP) of the paper inside the transformer. The FUR index analyzes the level characterization of the insulation paper degradation, directly related to the equipment life expectancy.

3.3. AOL index, iAOL – Oil Physico-Chemical Properties

The insulating oil deteriorates gradually with use, loosing slowly its dielectric and thermal proper-ties, by a series of physical and chemical reactions.

The causes are the absorption of the moisture from air and outer particles that get into the oil and cause oxidation, decomposition and polymerization of insulation materials, producing non-soluble particles collected in the coil and windings. These sediments do not affect directly the dielectric breakdown, but deposits formed on the winding, hinder its normal refrigeration and accelerate the oil oxidation. The AOL index analyses the concentration of various oil parameters, indicative of natural oil degradation, such as water and sediment content, color, acidity level and disruptive voltage.

3.4. ATV index, iATV – Bushings Degradation

The aim of this index is to establish a classification of the degradation level of the transformer capacitive bushings, by directly measuring its dielectric dissipation factor values, tg(δ), from both primary and secondary bushings, for a test voltage of 10 kV.

3.5. AER index, iAER – Winding Degradation

Similarly, with this index we establish a classification of degradation level of transformer windings, based on the values from dielectric dissipation factor, tg(δ), applied with a test voltage of 10 kV and the values from insulation resistance at a test voltage of 5 kV during 10 minutes.

3.6. Transformer Status Index – iET

The transformer status index iET is obtained by weighing the values of the five indexes, iDGA, iFUR, iAOL iATV and iAER, getting the global indicator of the transformer state. The indexes value weights vary according to the result of each one, affording marked relevance to the priority cases, in a way they are not masked by the calculation of mean values.

The equation (1) gives us the global state index:

$$i_{ET} = i_{DGA} \,.\, K_{DGA} + i_{FUR} \,.\, K_{FUR} + i_{AOL} \,.\, K_{AOL} + i_{ATV} \,.\, K_{ATV} + I_{AER} \,.\, K_{AER} \quad (1)$$

Each of the Kx weighting values is obtained according to equation (2):

$$K_x = \frac{P_x}{P_{DGA} + P_{FUR} + P_{AOL} + P_{ATV} + P_{AER}} \quad (2)$$

where x represents any of the 5 previous parameters. For instance, for the calculation of KDGA, equation (2) is replaced by (3):

$$K_{DGA} = \frac{P_{DGA}}{P_{DGA} + P_{FUR} + P_{AOL} + P_{ATV} + P_{AER}} \quad (3)$$

The weights Px take on values according to their specific index, as seen in equation (4):

$$P_x = 1 + n.\, i_x.\frac{1}{\sum_{j=1}^{T} j} \quad (4)$$

being T the maximum value of the index. In this study we consider T=7, which are seven discrete ranks of classification, ranging from 1 to 7, being 1 the best and 7 the worst. The variable n is used as a decision variable for fine tuning the calculation, allowing to linearly hold off all the weights values, giving more relevance to higher weights in the final equation of i_{ET}.

4. RESULTS AND ANALYSIS

The assessment methodology was applied to 241 in-service power transformers from the Portuguese national grid. In Figure 5, the results are sorted down by the transformer state index. The number of transformers is higher in state index level 2 and 3 (yellow zone), than those in level 1 (green zone). This is expected since they are the first levels at which evident degradation symptoms begin to appear, so this serve as an indication of a warning.

We got more information from this sample, about 77% of the analyzed equipment is in a positive state, the remaining 23% in a non-favorable state, with 2 transformers in a very critical level, red zone in Figure 5.

The worst classified equipment is a three-phase 150/63 kV power transformer with more than 35 years, actually indicated for possible deactivation, due to an advanced degradation of the insulation paper.

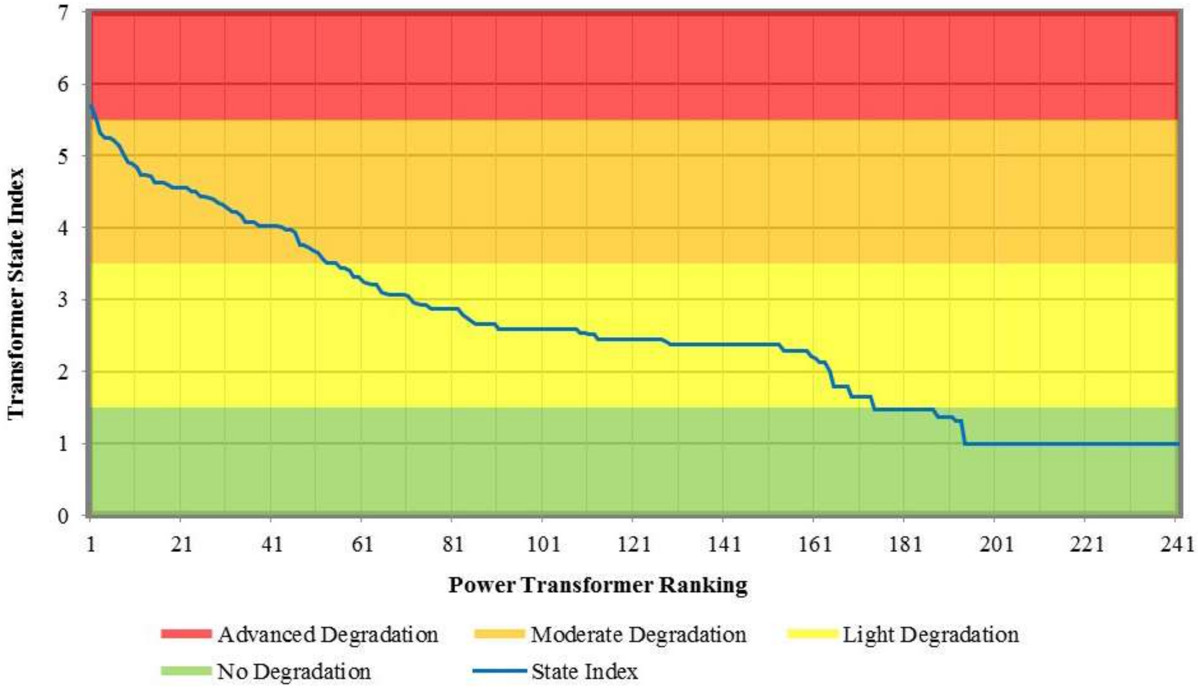


Figure 5 - Power Transformer ranking by state index

The second most critical equipment is a 400/63 kV three-phase transformer, operating for more than 25 years, already indicated for reconditioning, due to an advanced level degradation in oil and in the active part.

Another advantage of this methodology is the state evaluation from the dynamic representation of the partial state indexes and their standard limits, as seen in Figure 6.

The five partial indexes are represented by the central black line, as well as their numerical classification. The lines parallel to the center of the pentagon indicates the partial indicators and the background colors indicate the limits of degradation degrees. The final indicator is on the vertical axis of the polygon and it position depends on their value.

5. CONCLUSION

In this work it was made a diagnostics of transformer equipment, as well as the state indexes analysis. The study proposes a methodology to evaluate the global state of the power transformers in the electrical grid, based on five partial indexes values, three of them from tests carried out on the insulating oil and other two, from dielectric tests on windings and bushings.

The state assessment methodology provides important information about the transformer compo-nents condition in-service and constitute an important decision support to stablish the hierarchy of maintenance activities. Thus, it is possible to identify the degradation degree of some specific equipment, allowing preventive measures to be taken accordingly.

The methodology was applied in real case equipment, with an exhaustive analysis of 241 trans-formers on service in Portuguese national electric grid. With this study it becomes possible, not only a statistical analysis of historical data, but also it can anticipate trends and establish cause-effect relationships upon the different parameters and their operation work conditions.

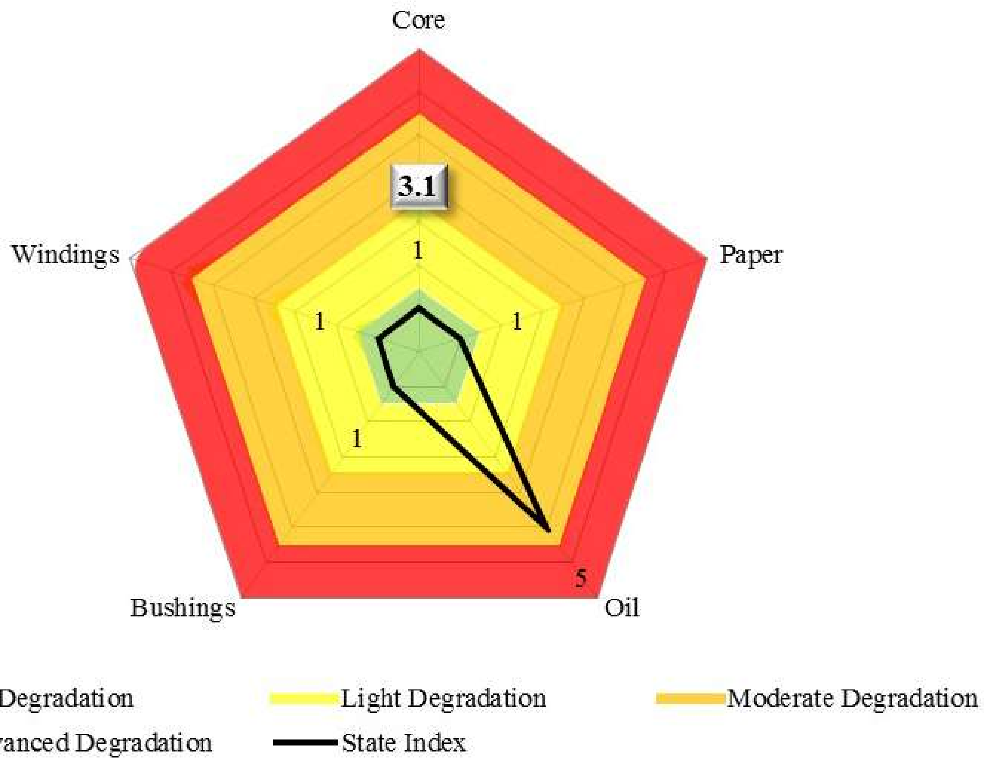


Figure 6 - Power Transformer state index assessment tool

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