Insulation Resistance of Power Transformers – Method for Optimized Analysis

André P. Marques, Cláudio H. B. Azevedo, José A. L. dos Santos, Felipe R. de C. Sousa
CELG Distribuição S.A. and Federal Institute of Education, Science and Technology of Goiás, Goiânia, Brazil
andre.pm@celg.com.br

Federal University of Goiás, and Goiano Federal Institute, Goiás, Goiânia, Brazil
cacildaribeiro@gmail.com

Abstract – This paper proposes a method for evaluating and classifying transformers, using equations to obtain scores and ratings for insulation resistance tests as a function of the age of these devices, resulting in recommendations to support decision-making. Analyses were made of test results of power transformers of 1 MVA to 50 MVA, wrapped in insulation Kraft paper and immersed in insulating mineral oil, with nominal voltages of 13.8 kV to 230 kV, ranging from 1 to 51 years old, whose ratings varied from “A” (excellent) to “E” (very poor). The methodology was developed using computational methods of equation optimization involving the hill-climbing algorithm associated with the 1/5th success rule. It was concluded that the combined use of maintenance engineering criteria and computational optimization techniques resulted in an efficient diagnostic method for these devices.

Keywords: electrical test, insulation resistance; optimization; power transformers

I. INTRODUCTION

Insulation resistance testing of power transformers stands out, among other applications [1], in non-invasive predictive techniques of the field of preventive maintenance, which enables real-time detection of defects and failures through quantitative and qualitative analysis as well as efficient diagnoses.

In this context, this article proposes a method for the analysis and classification of power transformers in terms of insulation resistance testing, including dielectric discharge magnitudes and polarization and absorption indexes according to the age of the transformer, which differentiates this work.

The criteria for maintenance engineering defined here are based on the following sources: the experience of specialists, bibliographical research, and statistical surveys of a database of electrical tests carried out over a 34-year period (from 1982 to 2016) at CELG Distribuição, an electric utility company that supplies electricity to 2.8 million consumer units.

Insulation resistance, which is directly associated with the dielectric robustness of the insulation, can be analyzed quantitatively by means of its test. The polarization and absorption indexes, as well as the dielectric discharge factor, are directly related to the state of conservation of the insulation system. These indices allow one to evaluate the insulator qualitatively and to infer if it is in a good state of conservation or degraded. Considered together, one thus has a quantitative and qualitative evaluation of the insulation system.

The existing literature, for example [2-7], provides some information about insulation resistance testing, but there are gaps in the explanation of the results of analysis (ranges of values), which makes it difficult to classify power transformers; moreover, their ages are not taken into account.

Therefore, this paper aims to address these gaps and contribute to existing studies by proposing an optimized and efficient method of analysis to aid in power transformer diagnostics.

II. INSULATION RESISTANCE TEMPERATURE CORRECTION FACTOR FOR THE REFERENCE TEMPERATURE (20ºC)

The value of insulation resistance changes according to temperature, the presence of moisture and dirt, and also as a function of the degradation of the insulation material.

Thus, it is possible to deduce the state of power transformer insulation systems and to detect tendencies and insulation decay rates by monitoring and comparing the results of insulation resistance tests. However, before comparing such results, these tests must be referenced to the same temperature.

Complementing earlier studies, this article presents two options of efficient mathematical equations to determine the correction factors of resistance values measured at the same reference temperature of 20ºC, and also discusses two approximate conversion methods, as follows:

- The temperature conversion method by the 2/decade factor [8] establishes that, at each increase of 10ºC, the value of insulation resistance decreases by approximately one half [2]. This rule has a direct practical application, but may compromise the accuracy of results, especially in non-multiple temperature intervals of 10;
- The table of conversion factors recommended by the American National Standards Institute - ANSI / NETA [3] is directly applicable but may compromise the accuracy of the results, especially with measurements outside multiple ranges of 5; and
- The mathematical equations presented below are easy to implement and provide accurate results.

A. Equation developed in this work: correction factor

An insulation resistance (IR) value at 20ºC can be referred to, according to eq. (1),

\[ R_{20ºC} = IR_{at~T} \cdot K_T \]  

where:
- \( R_{20ºC} \): IRat MΩ, corrected at 20ºC;
- IRat: IR at temperature T.


\[ R_T = \text{IRat MΩ, at the test temperature T in°C; and} \]

\[ K_T = \text{IR correction factor for the temperature of 20°C.} \]

Using exponential interpolation tools and taking as reference the values listed by manufacturers of measuring instruments, equation (2) was developed in this work for the correction factor \( K_T \),

\[ K_T = 0.23991 \cdot e^{0.0697T} + 0.0222 \tag{2} \]

where:

\( K_T \): IR correction factor for the temperature of 20°C; and
\( T \): Temperature of the insulation system measured during the test, in °C.

B. Equation of the ANSI/NETA MTS table: correction factor

From the data of the ANSI/NETA MTS table \([2]\), and using the mathematical tool, we obtained the correction factor given by (3) for application in equation (1),

\[ K_T = 0.2525 \cdot e^{0.0697T} \tag{3} \]

where:

\( K_T \): IR correction factor for the temperature of 20°C; and
\( T \): Temperature of the insulation system measured during the test, in °C.

The mathematical equations presented here both have the above described advantages, and it is up to the analyst to choose the one that best suits him.

III. CLASSIFICATION CRITERIA

Based on the experience of specialists, bibliographical research, and statistical surveys in a database of 529 electrical tests performed on 237 devices – including power and distribution transformers and mobile substations – with nominal voltages of 13.8 kV to 230 kV, power rating of 1 MVA to 50 MVA, ranging from 1 to 51 years old, carried out over a 34-year period (from 1982 to 2016), criteria were developed in this work for the evaluation and classification of \( R_H \), \( R_{HL} \), and \( R_L \) insulation resistances, according to the age of the device. The values of these resistances were corrected to 20°C by means of equations (1) and (2), as indicated below:

\( R_H \): IR from HV (high voltage) winding to ground;

\( R_{HL} \): IR between HV and LV (low voltage) windings;

\( R_L \): IR from LV winding to ground.

It should be noted that statistical studies of the insulation resistance were also carried out as a function of the nominal voltage of the equipment. However, the differences observed in the statistical distribution were not enough to justify a refinement of the criteria. Tables I and II describe the criteria defined according to age.

The polarization index (\( PI \)) \([2]\) and the absorption index (\( AI \)) were calculated based on the results of the insulation resistance tests, according to equations (4) and (5), respectively, and their classification criteria are presented in Tables III and IV, as a function of the age of the equipment.

\[ PI = \frac{R_{10 min}}{R_{1 min}} \tag{4} \]

\[ AI = \frac{R_{1 min}}{R_{30 s}} \tag{5} \]

where:

\( R_{10 min} \): IR (MΩ) measured after 10 min of testing;

\( R_{1 min} \): IR (MΩ) measured after 1 min of testing;

\( R_{30 s} \): IR (MΩ) measured after 30 seconds of testing.

The Dielectric Discharge (\( DD \)) index was also calculated based on the test results, according to equation (6).

\[ DD = \frac{I_{1 min}}{V \cdot C} \tag{6} \]

where:

\( I_{1 min} \): current measured after 1 minute (mA);

\( V \): test voltage (V); and

\( C \): capacitance (µF).
C. Measured capacitance (F).

However, it was only included recently in the database of the tests carried out by the company, after the acquisition of new instruments that enabled this complementation of the diagnosis, and it was not possible to draw up statistics based on age. Table V lists the classification criteria for DD.

**TABLE V. CLASSIFICATION CRITERIA FOR THE DIELECTRIC DISCHARGE (DD)**

<table>
<thead>
<tr>
<th>Rating</th>
<th>Dielectric Discharge (DD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (Excellent)</td>
<td>$DD \leq 1$ ms</td>
</tr>
<tr>
<td>B (Good)</td>
<td>$1 \text{ ms} &lt; DD \leq 2$ ms</td>
</tr>
<tr>
<td>C (Marginal)</td>
<td>$2 \text{ ms} &lt; DD \leq 4$ ms</td>
</tr>
<tr>
<td>D (Poor)</td>
<td>$4 \text{ ms} &lt; DD \leq 7$ ms</td>
</tr>
<tr>
<td>E (Very Poor)</td>
<td>$DD &gt; 7$ ms</td>
</tr>
</tbody>
</table>

The ranges of values developed here offer advantages over those reported in the literature, e.g. [7], because they consider age as a parameter, associating variations in IR to the aging of equipment. Furthermore, the values listed in Tables I to V are more rigorous, and therefore, more conservative than those in the literature.

IV. OPTIMIZED ANALYSIS OF INSULATION RESISTANCE

This work was developed using the hill-climbing optimization algorithm [9,10], which is associated with the mechanism of parameter adaptation by the “1/5th rule,” which resulted in the optimized analysis of insulation resistance values, in accordance with maintenance engineering criteria.

The objective function used here served to minimize the sum of the error modules of the comparisons between the classification provided by the method and that provided by the specialists. The error was calculated from the integer distance between the expected rating and the obtained rating, presenting a maximum error equal to 1.

The data used are diverse and come from 150 significant tests – 70% of the cases used for training the method, and the remaining 30% corresponding to different transformers to validate the results, for which the diagnostic criteria were verified, extracted from the abovementioned main database, and were classified by a team of experts, using final ratings that varied from “A” (excellent) to “E” (very poor). Accuracy rates of 86.7% and 88.9% of the cases were obtained in training and validation sets, respectively.

Within the scope of this work, which focused on insulation resistance tests of two-winding power transformers, one has the following optimizable parameters:

- $w_{R,RH}$: Weight of Resistance of insulation $R_{RH}$;
- $w_{PI,RH}$: Weight of the PI of insulation $R_{RH}$;
- $w_{R,RHL}$: Weight of Resistance of insulation $R_{RHL}$;
- $w_{PI,RHL}$: Weight of the PI of $R_{RHL}$;
- $w_{R,RL}$: Weight of Resistance of insulation $R_{RL}$;
- $w_{PI,RL}$: Weight of the PI of $R_{RL}$.

Table VI presents the weights obtained through computational optimization and compares them with the expected values, based on the expertise of the team of engineers and on maintenance engineering criteria.

**TABLE VI. EXPECTED AND OPTIMIZED VALUES OF THE WEIGHTS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expected Values</th>
<th>Optimized Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w_{R,RH}$</td>
<td>0.2800</td>
<td>0.2790</td>
</tr>
<tr>
<td>$w_{PI,RH}$</td>
<td>0.0533</td>
<td>0.0417</td>
</tr>
<tr>
<td>$w_{R,RHL}$</td>
<td>0.2800</td>
<td>0.2790</td>
</tr>
<tr>
<td>$w_{PI,RHL}$</td>
<td>0.0533</td>
<td>0.0641</td>
</tr>
<tr>
<td>$w_{R,RL}$</td>
<td>0.2800</td>
<td>0.2721</td>
</tr>
<tr>
<td>$w_{PI,RL}$</td>
<td>0.0533</td>
<td>0.0641</td>
</tr>
<tr>
<td>Total:</td>
<td>1.000</td>
<td>1.000</td>
</tr>
</tbody>
</table>

As can be seen, the optimization results are close to the expected values, meeting the previously specified maintenance engineering criteria.

The values were double weighted, first according to the importance of the variable (Weight of the Variable, $w_v$) in the evaluation of the equipment, and then as a function of the individual score attributed to it (Weight of the Score, $w_s(s)$), according to equation (7).

$$w_s(s) = 7.0876 \cdot e^{-1.8332 \cdot s}$$ (7)

Figures 1 to 3 show graphs of the individual scores – with respective ratings (“A” to “E”) – as a function of the variable, for each of the parameters of interest. Note that, in all the cases, the criterion varies according to the age (in years) of the equipment.
Thus, the best individual scores related to variables in good condition are associated with considerably lower weights than scores attributed to variables in poor condition. Therefore, poor condition are associated with considerably lower weights than variable on the evaluation of that equipment.

Table VII. CRITERIA FOR OBTAINING FINAL RATING AND RECOMMENDED ACTIONS

<table>
<thead>
<tr>
<th>Final Rating</th>
<th>Final Score</th>
<th>Recommended Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (Excellent)</td>
<td>$S_F &gt; 0.8536$</td>
<td>Continue operating the equipment normally</td>
</tr>
<tr>
<td>B (Good)</td>
<td>$0.6618 &lt; S_F \leq 0.8536$</td>
<td>Continue operating the equipment while monitoring the evolution of the results in the subsequent records</td>
</tr>
<tr>
<td>C (Marginal)</td>
<td>$0.5659 &lt; S_F \leq 0.6618$</td>
<td>Investigate and perform other tests in the short term to confirm results and tendencies</td>
</tr>
<tr>
<td>D (Poor)</td>
<td>$0.3070 &lt; S_F \leq 0.5659$</td>
<td>Schedule the removal of the equipment from operation for internal inspection, location and correction of defects</td>
</tr>
<tr>
<td>E (Very Poor)</td>
<td>$S_F \leq 0.3070$</td>
<td>Remove the equipment from operation immediately for internal inspection, location and correction of defects</td>
</tr>
</tbody>
</table>

V. CONCLUSIONS

The diagnostic criteria presented here refer to two-winding power transformers. However, for the diagnosis of three-winding transformers (HV, LV, TV), the equipment can be analyzed in subsets of two-winding transformers, i.e., by making a diagnosis for HV/LV, another for HV/TV and another for LV/TV, and in the end, considering the worst case. In addition, it should be noted that this work was based on statistical data from transformers ranging from 13.8 kV to 230 kV, wrapped in insulation Kraft paper and immersed in insulating mineral oil. However, this method is also expected to present satisfactory results for power transformers with higher voltages.

This article highlights the importance of evaluations to obtain scores and ratings, generating an expression characterized as a double-weighted and normalized sum, which, applied to the evaluation and classification of insulation resistance tests, presents good results (accuracy rate of 88.9% of cases) and only minor variations from the values expected by maintenance engineering criteria.

Thus, it can be concluded that the criteria presented here contribute significantly to the analysis. The combined use of maintenance engineering criteria and computational optimization techniques resulted in a practical and efficient method that is widely applicable to the power sector for the analysis of insulation resistance tests and the diagnosis of power transformers.

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REFERENCES