**Development and Analysis of a Health Index-Based   
Multi-Criteria Assessment Model for Power Transformer Condition Monitoring**

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**Abstract.** Failure that occurs in the course of power transformers does have direct impacts on the system reliability. Early detection of the technical condition of the system of transformer insulation is very important so that such malfunctions could be avoided and minimize losses incurred in eliminating them. This article describes a multi-criteria approach to assessing the overall condition of transformers based on the concept of a technical condition indicator (Health Index). The model considers the physicochemical characteristics of transformer oil that is used as the insulating medium, thermal loads, and deformation of windings, and many other significant factors.

**Keywords:** health index, power transformer, including electrical criteria, thermal criteria, mechanical criteria, optical criteria, diagnostic model

# Introduction

The power transformers are a compulsory element in the distribution and transmission of electricity. Being constructed mostly so that they can work safely within 20-35 years, the adequate maintenance structures enable their service life to be long enough to reach 60 years (and more) [2, 3]. Yet, it is usually not very cost-effective to perform deep tests and thorough technical examinations of operating transformers that have been in service over long years. Therefore, developing monitoring and diagnostic strategies that allow for real-time observation of these transformers' technical condition and contribute to extending their service life is becoming a pressing issue [1]. The quality state of insulation system is important when evaluating the technical state of transformers. The process of aging of this system is what has a direct effect on the reliability with which the whole transformer operates [7, 8, 9, 10]. In this respect, the monitoring and diagnostic technologies that involve the electrical, thermal, mechanical, and optical standards, among others, are being adopted in great number. These methods serve to determine the degree of degradation of transformer insulation, plan maintenance, and prevent unexpected malfunctions [5, 6, 7].

In recent years, the concept of the Technical Condition Index (Health Index) has been introduced for comprehensive assessment of power transformers' technical condition [2, 5, 7]. This index represents the transformer's overall technical condition, aging stage, and reliability level as a single numerical indicator. In calculating the index, both the traditional measurements and modern non-invasive measurements are put into consideration. Namely, high-frequency parameters of loss at 1 MHz, conductivity factor and polarization index are found during dielectric measurements to enable a better evaluation of the technical state.

# Materials and Methods

The first thing needed is that the overall state of insulation system should be reliable to work with the transformer. This aging process of this system can be defined by electrical, thermal, mechanical and chemical factors. The situation is assessed with such main parameters:

Dielectric properties

• The age of oil and physicochemical condition

• Deformation of windings Mechanical

• Thermal conditions and temperature at the surface

• Contact zone status as well as vibrations

In recent years, the technical condition indicator (Health Index - HI), which represents all these indicators in a single numerical value, has been widely used.

Technical condition indicator is calculated with the help of the following formula:

(1)

where: index for the i-th diagnostic parameter (in the range of 0-4); weight coefficient of this parameter.

Depreciation of transformer oil is characterized by the following reactions:

(2)

where: concentration of acidic, ionic, polar and contaminated products; transformer internal temperature.

Each reaction is defined by Arrhenius's law:

(3)

Frequency-dependent dielectric function of oil:

(4)

If we express dielectric losses in terms of the tangent loss coefficient, we obtain the following:

(5)

increases due to ions, polymers, and polyelectrolytes.

This value is exponentially related to moisture, acids, residual ions:

(6)

molar conductivity of each ion; their concentration (ppm).

The probability of dielectric failure is given by the Weibull distribution:

(7)

Considering the presence of particles and water in the oil, we get:

(8)

The decrease in surface tension is determined by the following formula:

(9)

surface-active components (acidic products, aromatics, water); surface reaction sensitivity.

Transformers can be deformed due to disruption of heat exchange:

(10)

where: convective heat transfer coefficient;

If cooling does not work, heat accumulates, deformation and aging accelerate. If the transformer winding undergoes deformation, then its electrical resistance changes. This is determined by the following physical model:

(11)

As resistance increases, local heating occurs, oxidation intensifies, and DI decreases.

Transformers amplify oscillations at resonant frequencies.

(12)

hardness; mass.

If new harmonics or resonance occur, there is a possibility of mechanical failure. The deviation in winding resistance is used to detect mechanical deformation of transformer windings, cold welding and contact malfunctions, thermal loads, winding displacement or breakage. This parameter is said to be a sensitive tool of detecting variations in internal condition by checking the three-phase symmetry.

As for the effect of temperature, the conductivity of a metal (e.g., copper or aluminum) depends on temperature:

(13)

T₀ – base temperature (usually taken as 20°C or 75°C).

Thus, when the temperature of a copper wire increases, the internal crystal lattice expands under the influence of heat, which hinders the movement of free electrons, and as a result, electrical resistance increases.

(14)

Comparing interphase resistances, the temperature-adjusted resistances of the three phases are:

RA, RB, RC

Average resistance:

(15)

Each phase deviation:

(16)

Through these differential deviations, the violation of phase symmetry is determined.

For each physical parameter , a diagnostic normalization function was established:

(17)

In a limited range, the value is converted to 0-4.

(18)

Discrete diagnostic index:

(19)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **TABLE 1.** Diagnostic index values by deviation   |  |  | | --- | --- | | **ΔR (%) Condition DI** | | | ≤ 1.0  1.0 – 2.0  2.0 -3.5  3.5. – 5.0  > 5.0 | Excelent 4  Good 3  Avarage 2  Poor 1  Very poor 0 | |

# Results and Discussion

The viability of oil power transformers was determined through experimental works. Table 2 gives the outcomes of physicochemical analysis of the transformer oil.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **TABLE 2.** Weight factors on the basis of the results of the physicochemical analysis of transformer oil | | | | | |
| **Parameter** | **Measured value** |  | **Normalization formula** |  | **Score ()** |
| Acid number 0.26 mg KOH/g 4  Humidity (%) 36 ppm 4  BDV (kV) 34 kV 0 | | | | | |

Based on the normalized parameters measured above, the total indicator of transformer oil () was calculated (weights were taken as ):

The calculated value according to the value of the discrete diagnostic index was (average).

Winding resistances were measured for each phase of the transformers (Table 3).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **TABLE 3.** Temperature-adjusted three-phase resistance values | | | | | |
| **Phase** |  |  | **(Ohm, 75°C)** |  |  |
| A 0.108  B 0.112  C 0.105 | | | | | |

Based on the values in Table 3, the average resistance was calculated:

Based on the value of the average resistance, relative deviations by phases were determined:

Considering that the value of the largest deviation is , and the discrete index is (average).

Thermal imaging analyses of the transformers were carried out. During the thermographic observation, it was established that the maximum temperature in the contact zone is , .

Convective heat flow:

(20)

(21)

This has to do with heat storage and area heating in the contact regions. The presence of such areas is indicators of possible occurrence of oxidation, mechanical loosening, or poor load distribution. This temperature is an indication to harmonic heating and higher resistance.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **TABLE 4.** DI and its weighting factor for each parameter | | | | | |
| **Parameter** |  |  | **DI** |  | weight **()** |
| Oil quality 2 0.4  Winding resistance 2 0.4  Thermal Condition (Contact Zone) 1 0.3 | | | | | |

Based on the parameters given in Table 4, the final value of the technical condition indicator (HI) of oil power transformers was assessed:

This calculated value is classified in the HI category as follows:

# Conclusion

Due to the calculations, the indicator of technical condition of the transformer as a whole was evaluated as HI = 1.7. This shows that the transformer is under very bad condition. The parameters of the oil quality have surpassed the permissible level, a resistive deviation is manifested, as well as a winding deformation is observed, the accumulation of heat at points of contact is identified.

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