EVALUATION OF THE EXTENT OF AGEING OF PAPER IN OIL-IMMERSED POWER TRANSFORMERS

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SUMMARY

The paper is devoted to the analysis of problems connected with the evaluation of ageing of the insulating paper used in oil-immersed power transformers, with the numerical value of the degree of polymerization of the paper being used as a viewing angle. Results of our own experimental investigation on samples of successively ageing Kraft paper are presented. The methods of mathematical statistics, mainly regression and correlation analysis were widely used in this investigation. The presented results extend and complete the hitherto obtained conclusions which have been published in this field. The application of these results enables the owner of the oil-immersed power transformer to formulate opinion on a further operation of the installed transformer. This is especially important in case of transformers-veterans.

KEY WORDS

Power transformer - Ageing of paper - Degree of polymerization - Extent of paper ageing - Paper ageing scale

1. INTRODUCTION

Frequent operational experience reveals that the life time of power transformers depends especially on the mechanical strength of paper insulation because the electric strength of the paper is maintained practically unchanged for many years, provided the transformer has been operated in a normal way. Consequently, this means that there are nearly always some mechanically weak spots which limit the life time of oil-immersed power transformers.

It is evident that, from purely mechanical point of view, it is impossible to characterize the extent of ageing of oil-impregnated paper insulation by means of dielectrical indicators, but this is enabled by mechanical indicators or by properly chosen indicators of chemical and/or physical-chemical nature.
Indicators of mechanical nature: These indicators, complying with the above considerations, have the character of direct ones and all other indicators should thus be compared with them. However, mechanical indicators have a disadvantage consisting in the fact that they exhibit – even in case of unaged paper – a wide dispersion of measured values. In case of aged paper this considerable dispersion increases even more. Another disadvantage of mechanical indicators is that their application requires samples with relatively great geometrical dimensions.

Indicators of chemical nature: These indicators, complying with the above considerations, have the character of indirect ones. However, they exhibit a small dispersion of measured values and enable to carry out the measurement on relatively small samples.

Within a series of chemical indicators coming into account in this sense, there exists a very convenient indicator which consists in assessing the numerical value of the degree of polymerization of the paper and enables
- to observe the extent of ageing in the whole range, i.e. on new and slightly aged papers as well as on very or even extremely aged ones;
- to perform a direct numerical evaluation which can be carried out with a relatively high accuracy.

When comparing the direct and indirect indicators, it is thus necessary to deal in more detail with the correlation between the degree of polymerization of the paper and its mechanical strength.

2. CORRELATION BETWEEN MECHANICAL STRENGTH OF THE PAPER AND ITS DEGREE OF POLYMERIZATION

It follows from the analysis of mechanical stress of the transformer winding that the mechanical forces acting on the winding can be divided into radial and axial forces. However, each of them stresses individual windings in a different way. A radial force produces compressive stress of the internal winding and tensile stress of the external winding. The total axial force produces compressive stress of the interturn washer and, maybe, of the supporting structure of the winding.

It is therefore important to deal more closely with the correlation between the degree of polymerization and the mechanical tensile strength of the paper.

A wide series of experiments in this field was performed by EGÚ Brno, plc. in the last years. The investigation was carried out on samples of the successively ageing Kraft paper. The samples of paper made by various manufactures and having different thickness were examined.

In order to assess the mechanical tensile strength of paper samples we used the test procedure frequently utilized for testing papers and paperboards in paper industry. This test procedure is standardized. Having in mind the required reproducibility, the obtained values of the rupture weight were converted by calculation to the corresponding values of the rupture length by applying the formula of Hoyer.

A test procedure described in IEC Publication 450 was used for assessing the value of the degree of polymerization.
The experimental investigation revealed the following:

- The dependence between the degree of polymerization of the paper and its rupture length is non-linear, falling down and of a concave character: At first, a uniform decrease of the degree of polymerization results in a slow, later in a strong and still later in a very strong decrease of the rupture length of the paper.
- With regard to the application of mathematical statistics, mainly of regression and correlation analysis, the correlation between the rupture length of the paper and its degree of polymerization can be described by the equation which is valid for the hyperbola of the second degree – see Appendix 1.
- The zero rupture length \( (L_r = 0) \) of papers with different thickness and made by various manufacturers was assessed at the degree of polymerization moving in the range \( DP = 100 \ldots 150 \).
- Representation by means of the resulting mathematical-statistical model: It is evident from the shape of the dependence between the degree of polymerization of the paper and its rupture length that the rupture length of the papers changes (decreases) slightly up to a certain value of degree of polymerization (\( DP = 1000 \)) and that it remains practically unchanged. In the interval \( DP = 999 \ldots 601 \) the rupture length of the paper decreases only slowly. In the interval \( DP = 600 \ldots 251 \) it decreases quickly and in the interval \( DP = 250 \ldots 151 \) it decreases very quickly. At \( DP = 150 \) the rupture length of the paper is practically equal to zero.
- When the degree of polymerization decreases to \( DP = 400 \ldots 300 \), the rupture length of the paper (with different thickness and made by various manufactures) decreases to about 50% of its initial value.
- Note: In case of paper with the degree of polymerization in the range \( DP = 200 \ldots 151 \) the rupture weight is non-zero but it is not measurable.

3. EVALUATION OF THE EXTENT OF AGEING OF PAPER IN OIL-IMMERSED POWER TRANSFORMERS. PAPER AGEING SCALE

It follows from the preceding chapter that the extent of the decrease of the degree of polymerization of the paper enables us to judge about the extent of paper ageing.

For practical applications, the author of the paper proposes the following scale for evaluation (“EA/P scale”):

- \( DP \geq 1000 \) Paper practically unaged
- \( DP = 999 \ldots 601 \) Paper slightly aged
- \( DP = 600 \ldots 401 \) Paper medium aged
- \( DP = 400 \ldots 251 \) Paper strongly aged
- \( DP = 250 \ldots 151 \) Paper very strongly aged
- \( DP \leq 150 \) Paper extremely aged
4. PRACTICAL APPLICATIONS. EXAMPLES

Example 1
Power transformer in which one or more segments of the paper of winding insulation have the degree of polymerization in the range DP = 400 … 251 (other segments of the paper have a higher degree of polymerization):
The owner/operator of the transformer must then consider whether the transformer will be kept in operation. It is recommended to carry out an appropriate strategic, technical and economical analysis in this connection.
In case of network and power plant transformers the following recommendation may be given: If the respective degree of polymerization of the insulating paper falls down into interval DP = 400 … 300, the operation of the transformer must be ended definitively.
Note 1: Shutting down of power transformers in the transmission network and of block transformers in power plants – when the respective degree of polymerization decreases to DP = 400 (proposal).
Note 2: Shutting down of power transformers in the distribution network and of self-consumption transformers in power plants – when the respective degree of polymerization decreases to DP = 300 (proposal).
Note 3: Shutting down of other power transformers (transformers installed in industry, etc.) – when the respective degree of polymerization falls down into the interval DP = 299 … 251 (proposal).

Example 2
Power transformer in which one or more segments of the paper of winding insulation have the degree of polymerization in the range DP = 250 … 151 (other segments of the paper have a higher degree of polymerization):
The transformer may be operated only exceptionally in this case – only in quite extraordinary cases!
The further operation of the transformer must then be regulated by a special instruction.
However, it should be pointed out that such an operation of the transformer is already very risky due to a considerable decrease of the mechanical strength of the paper. This risk increases with the decreasing degree of polymerization of the paper.
The risk is extraordinarily high at the degree of polymerization of the paper in the range DP = 200 … 151

Example 3
Power transformer in which one or more segments of the paper of winding insulation have the degree of polymerization DP ≤ 150 (other segments of the paper have a higher degree of polymerization):
In this case the transformer should not be operated – no exception in this sense can be admitted!
5. CONCLUSIONS

- The measure of the ageing of paper in oil-immersed power transformers is the decrease of its mechanical strength.
- The value of the degree of polymerization of the paper can indicate its mechanical strength accurately enough.
- We can judge about the extent of paper ageing from the extent of the decrease of the degree of polymerization of the paper.
- The author has proposed a special scale for evaluation (“EA/P scale”) which enables to evaluate the extent of ageing of the paper used in oil-immersed power transformers. This scale was described numerically and verbally.
- From the extent of the decrease of the degree of polymerization of the paper on the most exposed spot (from the point of view of the actioning of relevant degradation factors) we can judge about the extent of ageing of the winding insulation of power transformers. It is therefore possible to formulate opinion on a further operation of the transformer in question, i.e. on the possibility of its loading, its possible transportation, repairs or shutting down. This is especially important in case of transformers-veterans.

6. REFERENCES

Appendix 1

The result of regression and correlation analysis of experimental data:

The correlation between the rupture length of the paper and its degree of polymerization can be described by the regression equation which is valid for the hyperbola of the second degree, i. e. by means of the following formula:

$$ Y = a_0 + a_1 \cdot x^{-1} + a_2 \cdot x^{-2} $$  \hspace{1cm} (1)

when $a_0 > 0$

$a_1 < 0$

$a_2 > 0$

i. e. when formally rewritten by equation

$$ L_r = a_0 - a_1 \cdot D^{-1} + a_2 \cdot D^{-2} $$  \hspace{1cm} (2)

where $L_r$................. rupture length of the paper

$D$...............degree of polymerization of the paper

$a_0, a_1, a_2$.....regression parameters.