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Issue: „Trend Analysis of Power Transformers with FDS-Measurements“

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Trend Analysis of Power Transformers with FDS-Measurements

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***Abstract*:** In the recent years, the diagnostics to determine the state of a power transformer has become more and more important due to technical and economical reasons. The main issue for the power transformers for electrical energy supply is the diagnostics of the insulation system, which determines essentially the product life time.

To analyze the system state of a power transformer, knowledge about the operating conditions, the measurands and their effects on the insulation system is necessary. The data can be measured online or offline.

The FDS (frequency domain spectroscopy) method is an offline diagnostic method in low frequency ranges. If the geometrical data and the behaviour of the measuring data due to changes in the insulation system are known, conclusions about the insulation system of the power transformer are possible.

However, all this data and information are not always available. In that case, a transformer can be monitored using the FDS method, comparing a reference measurement (fingerprint) in the beginning with later FDS measurings.

The comparison is based on the division of the complex capacitance $\underline{C}_x(\omega)$ at time $t=x$ by the complex capacitance $\underline{C}_0(\omega)$ at time $t=0$ or by a modelled reference capacitance. The resulting function separates and shows the change of the individual dielectric system properties i.e. conductivity, polarisation and the dielectric permittivity at 1 kHz. The individual system properties are mainly influenced by the material, the temperature, the moisture content and the ageing products.

The FDS measurement on the power transformer is performed at a given temperature of the transformer. To achieve more exact diagnostics, the effect of the measuring temperature on the reference measurement or on the reference model must be considered. The effect of the temperature between the reference measurement and the measurement at time $t=x$ can be compensated by experimental measurings of the oil/paper insulation systems to reach a more exact analysis.

The paper describes the method of the analysis, how and which system properties can be recognized so far, which problems can be expected and which effect the temperature has on the analysis.

1 INTRODUCTION

The aim of this work is to enhance the diagnostics of power transformers to optimise the cost effectiveness and to improve the operating reliability.

The trend analysis with FDS measurements is an offline method enabling the monitoring of power transformers. Starting from a reference measurement, the changes of the insulation system are monitored and evaluated. Here, the knowledge about the insulation geometry is necessary only if the temperature of the FDS measurement on the power transformer differs strongly from the reference measurement temperature.

The main part of this paper consists of the *B*-Function, that separates the conductivity, the relaxations and the instantaneous polarisation. With this function the changes in the insulation system of a power transformer or in the material samples can be visualised.

To demonstrate the method, material samples like transformer board TIV were mostly used. This approach has the advantage that different parameters like temperature, ageing and moisture content can be tested with small effort and that it is related to the insulation system of a power transformer.

In addition to that, since the B-Function is used, it is possible to automatically approximate the modelling parameters for the Cole-Cole function using the Least-Squares-Method (LS-Method).

2 THEORY

2.1 Cole-Cole-Function

It was possible to emulate the FDS measurements performed so far accurately enough using the Cole-Cole function with conductivity.

The dielectric behaviour of individual insulation materials, like that of oil, paper and transformer board can be described with this function [2]. Due to that, the Cole-Cole function, consisting mainly of three elements - conductivity σ, instantaneous polarisation ε_∞ and relaxations - is seen as a basic function. The relaxations describe here the polarization mechanisms in the measured frequency domain. A distribution of time constants $G(\tau)$ is assumed for every relaxation. The function is [1], [3], [5]:

$$\underline{\varepsilon}(\omega,T) = \underbrace{-j\left(\frac{\sigma_{(T)}}{\varepsilon_0\omega}\right)}_{\text{Conductivity}} + \varepsilon_\infty + \underbrace{\frac{\Delta\varepsilon_{\alpha\,(T)}}{1+(j\omega\tau_{\alpha\,(T)})^{n_\alpha}}}_{\alpha\text{-Relaxation } G(\tau)} + \ldots \qquad (1)$$

parameter:

σ:	$0 \le \sigma$;	specific conductivity [S/m]
ε_∞	$0 \le \varepsilon_\infty$;	instantaneous polarisation
ω	$=2\cdot\pi f$;	angular frequency [1/s]
T		temperature [K]

α-relaxation:

n_α	$0 < n_\alpha \le 1$;	
$\Delta\varepsilon_\alpha$	$0 \le \Delta\varepsilon_\alpha$;	α-dielectricity change
τ_α	$0 < \tau_\alpha$;	α-relaxation time [s]

Multiplying the complex dielectric function $\underline{\varepsilon}(\omega,T)$ with the capacitance of an empty condenser $\underline{C}_0$ results in complex capacitance $\underline{C}$. The complex capacitance of a medium can be measured with an FDS (frequency domain spectroscopy) measurement.

2.2 *B*-Function

The complex B-function, see equation (2), enables the representation of material alteration, e.g. due to moisture content or ageing, or of changes in the insulation system of the transformer. However, attributing these changes unambiguously to a cause is possible only in a limited way.

The principle of the complex B-function $\underline{B}(\omega)$ is a division per element of the individual complex capacitances $\underline{C}(\omega)$ of the respective measurement frequencies by a reference capacitance or a model function:

$$\underline{B}(\omega)=\frac{\underline{C}_{Medium}(\omega)}{\underline{C}_{Modell\,/\,Referenz}(\omega)}=1+j0+\underline{S} \tag{2}$$

The advantage of the B-function lies in the separation of individual elements of the equation (1). This behaviour will be demonstrated through idealised examples.

If a measurement $\underline{C}_{Medium}$ is divided by a model function $\underline{C}_{Model}$ emulating the material behaviour accurately, the B-function shows the following curve run:

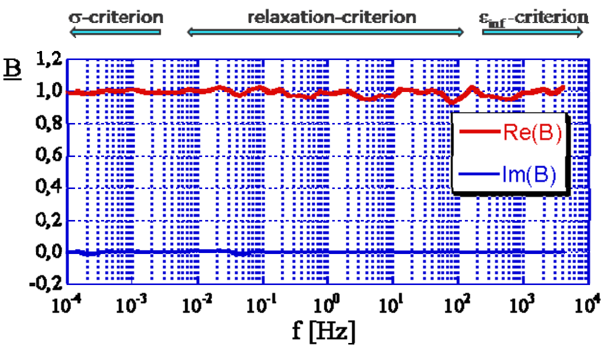

Figure 1 – Curve run of the complex B-function for an idealised model with measurement error $\underline{S}$.

As a principle, the imaginary and the real part of the B-function are mathematically related to the Kramer-Kronig correlation. If, for example, the imaginary part of the B-function is zero ($B''=0$), then the real part of the B-function must always be one ($B'=1$). If the Kramer-Kronig correlation does not apply, an erroneous measurement can be assumed. This relation can primarily be used to check the FDS measurement. For that, the parameters of the model equation (1) must be approximated. If the parameters can be identified accurately enough, correctness of the measured data can be assumed.

Let us examine the B-function in case of a constant difference factor between the measurement and the model for conductivity and the instantaneous polarisation.

The following data (3) was chosen as an example:

$$\underline{B}(\omega)=\frac{-j\dfrac{2.5E-12}{\varepsilon_0\omega}+\dfrac{10}{1+(j\omega 20)^{0,94}}+5+\underline{S}}{-j\dfrac{5E-13}{\varepsilon_0\omega}+\dfrac{10}{1+(j\omega 20)^{0,94}}+2.5} \tag{3}$$

The figure 2 shows that the conductivity coefficient can be extracted in low frequencies and the one for the instantaneous polarisation in high frequencies. It depends on the conductivity, in which frequency the conductivity coefficient can be extracted.

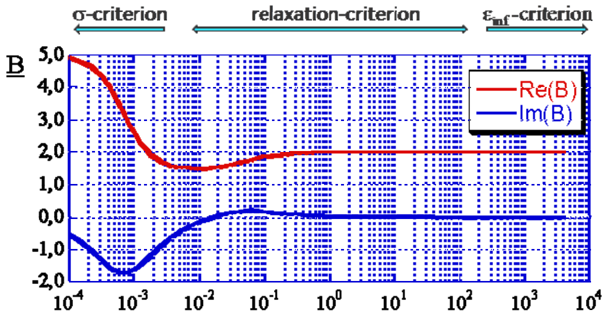

Figure 2 – Curve run of the complex B-function for variable conductivity and instantaneous polarisation.

Alteration of the relaxation time only results in the following curve run:

$$\underline{B}(\omega)=\frac{-j\dfrac{5E-13}{\varepsilon_0\omega}+\dfrac{10}{1+(j\omega 3)^{0,94}}+5}{-j\dfrac{5E-13}{\varepsilon_0\omega}+\dfrac{10}{1+(j\omega 2)^{0,94}}+5} \tag{4}$$

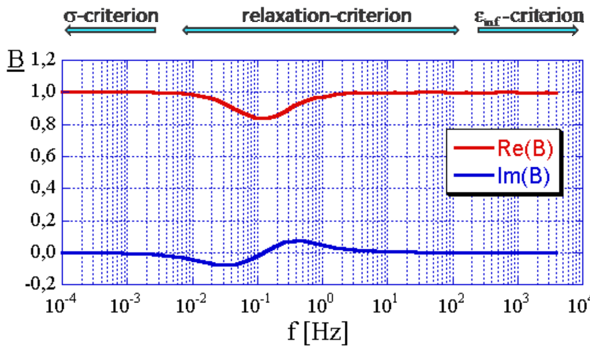

Figure 3 – Curve run of the complex B-function with different relaxation times τ_α.

Examining the real part of the B-function shows that the conductivity coefficient can be recognized in the low frequencies, the instantaneous polarisation coefficient in high frequencies and the changes due to relaxations in middle frequencies (Fig. 2-3). If the frequency domain is too small, the conductivity factor, for example, can not be accurately extracted. In such case the domain can be artificially enlarged after modelling first the measurements with the Cole-Cole function (1).

3 TREND ANALYSIS

With the complex B-function $\underline{B}(\omega)$ it is possible to identify alterations in insulation systems due e.g. to moisture content or ageing. If, for example, a measurement is performed at time $t=0$ (reference measurement) and repeated later at time $t=x$ (x>0), the changes in the insulation system can be observed using the complex *B*-function $\underline{B}(\omega)$. The following equation applies:

$$\underline{B}(\omega) = \frac{\underline{C}_{Messung\,(t=x)}(\omega)}{\underline{C}_{Messung\,(t=0)}(\omega)} = B' + jB'' + \underline{S} \tag{5}$$

If the insulation system has not changed in the time range between $t = 0$ and $t = x$, the B-function should ideally yield $\underline{B}(\omega) = 1+j0+\underline{S}(\omega)$. Due to environmental influences and imperfection of the measuring system, a measurement deviation $\underline{S}$ can be expected.
In case of an alteration of the insulation system, the factor $B'(\omega)$ describes the strength of the alteration for the respective frequency domain (see Fig.2-3).

3.1 Influence of the Measuring Temperature

The measuring temperature plays an important role in the trend analysis of power transformers. Ideal would be the same temperature during the reference measurement and the measurement at time $t=x$, as the insulation material is temperature-dependent. How strongly the temperature influences the measurements, shall be demonstrated with transformer board TIV (1 mm) in two different temperatures. The material sample was dried and impregnated prior to the measurement. The moisture content was below 0.4%. The reference measurement was done at the temperature of 25°C. Figure 4 shows the curve run of the B-function of the measurements at temperatures 10°C and 40°C. As can be seen, the conductivity changes slightly.

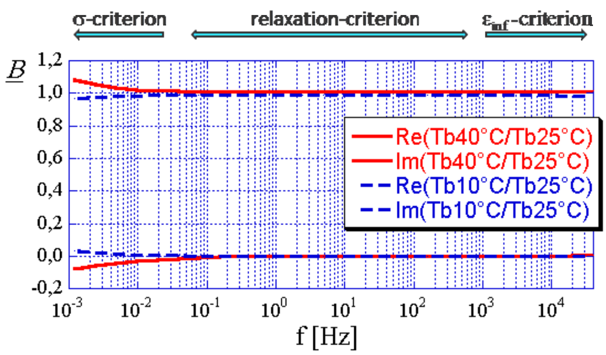

Figure 4 – Curve run of the B-function of impregnated transformer board at measuring temperatures 10°C, 40°C and during the reference measurement at 25°C.

The behaviour (fig. 4) of aged material samples in different temperatures should also be investigated. Here, the impregnated transformer board was artificially aged at 120°C for approximately 600h. The moisture content of the sample was here also below 0.4%. The figure 5 shows the curve run of the B-function at 10°C and at 40°C and the reference measurement at 25°C. The real part of the B-function shows a strong thermal dependency caused by changes in the conductivity and the relaxation.
It can be assumed that the measuring temperature influences the power transformers in a similar way. To compensate the thermal influence a temperature-dependent model could be used for the reference measurement.

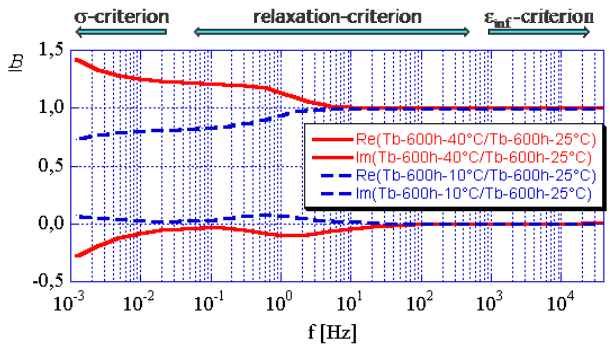

Figure 5 – Curve run of the B-function of artificially aged transformer board at measuring temperatures 10°C, 40°C and during the reference measurement at 25°C.

3.2 Diagnostic

The state of machines is evaluated with diagnostic methods. For a power transformer, above all, the state of insulation is of importance [4]. With the trend analysis, changes can be detected and monitored using the B-Function (Eq. 6) and a reference measurement. A quantitative statement can be made about how strongly the insulation system of the power transformer has changed over a time period. Material measurements can partly help to estimate the state of the insulation system.
The figure 6 shows three curve runs of material measurements (transformer board TIV) in different states. For the reference capacitance a new, dried and impregnated transformer board TIV was measured.

- The sample Tb1 was like the reference sample of another series of measurement.
- The sample Tb2 was like the reference sample with a moisture content of 1 %.
- The sample Tb3 was also an impregnated transformer board TIV with an artificial ageing of 600 hours at 120°C.

The measuring temperature was 25°C for all samples.

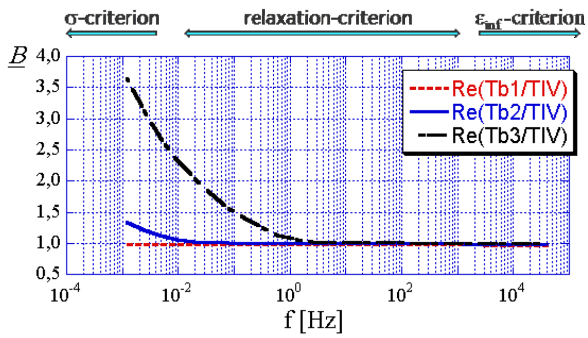

Figure 6 – The run of the complex B-function for impregated transformer boards with different states of material.

The artificially aged material sample Tb3 shows the strongest change. Both the conductivity and the relaxations change.
The sample Tb2 changes mostly in the conductivity and slightly through relaxations. The sample Tb1 does not show any change of behaviour, having like properties with the reference sample.

This principle can also be used for power transformers. The reference model should nevertheless take the thermal effects into account to optimise the diagnostics.

4 Determining the Cole-Cole-Parameters

So far, a fundamental property of the *B*-Function was not mentioned. Mathematically seen, the real part of the *B*-Function contains the complete information of the complex dielectrical function (Eq. 1). This is true also for the imaginary part of the *B*-Function. This makes it possible to approximate the complex dielectrical function (Eq. 1) – also called the Cole-Cole function – with real methods, e.g. the method of least squares (LS).
Here the measurement data is divided by the Cole-Cole function and the imaginary part of this *B*-Function ist set to zero:

$$1+j0=\frac{\underline{C}_{Messung}(\omega)}{C_0\left(-j\left(\frac{\sigma}{\varepsilon_0\omega}\right)+\varepsilon_\infty+\frac{\Delta\varepsilon_\alpha}{1+(j\omega\tau_\alpha)^{n_\alpha}}+\dots\right)} \tag{6}$$

For the automatic determination of the parameters the following procedure has proved itself: The instantaneous polarisation can be determined with the equation (7) in high frequencies 1kHz>ω>500Hz.

$$\varepsilon_\infty=\frac{\mathrm{Re}\left[\underline{C}_{Messung}(\omega)\right]}{C_0} \tag{7}$$

After that, a value range for the conductivity is approximated and the remaining parameters are determined through recursive usage of the LS-method and the equation (6). The optimal conductivity can be detected at the minimum of the sum of the least square deviations between the model and the measurement. The procedure is as follows:

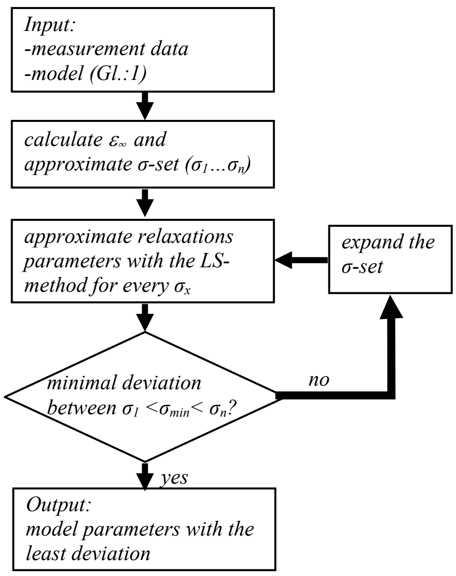

Figure 6 – Procedure to determine the Cole-Cole parameters.

Theoretically, also the real part of the equation (7) can be used. However, it has been shown that the imaginary part has a more stable behaviour for approximation. The reason is that the strongest changes of the imaginary part are in the middle of the frequency domain and not in the sides.

5 CONCLUSION

The paper describes a method to represent and separate the changes of the power transformer or material samples over time. Here, the changes respective to the conductivity, instantaneous polarisation and relaxations are represented through the real part of the *B*-Function. Material examinations can attribute these changes at the moment only partly to the reasons behind them. The temperature influences most of all the measurements with aged materials, whereas new materials show only a slight change of conductivity.
For the diagnostics of the state of a power transformer, a reference measurement or an adequate model able to replace the reference measurement must be available. Both references should take the thermal behaviour into account for a better exactness. So far, it could be determined if the state of the power transformer changes or not. The actual state of the power transformer can only be estimated.
In addition to that, it has been shown that the *B*-Function can be well applied to approximate the Cole-Cole parameters using the LS method and the real part of the *B*-Function can describe the exactness of the approximation. Particularly, the determination of the model parameters can be used to control the FDS measurement.
How well this trend analysis can be applied for the diagnostics has yet to be examined more carefully, and above all, with many real measurements at the power transformer.

6 REFERENCES

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