Dielectric Response Analysis and PD Testing for Condition Assessment of HV Bushings

Michael Krueger[1], Maik Koch[1], Gunther Kopp [2], Michael Muhr[3]
[1] Omicron Electronics, Oberes Ried 1, 6833 Klaus, Austria
[2] ABB Micafil, Switzerland
[3] TU Graz, Austria
E-mail: michael.krueger@omicron.at

***Abstract* – Dielectric breakdown of the HV bushings is one of the most frequent failure causes for power transformers. This paper discusses new diagnostic methods to assess the dielectric condition, including the analysis of the dielectric response and partial discharge measurements, and reports several case studies. Dielectric response measurements in frequency domain (FDS) or time domain (PDC) measure capacitance and dissipation factor over a very wide frequency range and determine the ageing condition as e.g. the water content. These methods can be applied for bushings as well. Measurement results of Oil Impregnated Paper (OIP), Resin Impregnated Paper (RIP) and Resin Bonded Paper (RBP) bushings are presented for new and aged bushings and limits for the assessment are discussed. Partial discharge (PD) measurements proved the analysis of the dielectric response test. Practical examples illustrate the importance and the efficiency of capacitance, dissipation factor and particularly dielectric response measurements on HV bushings.**

***Keywords* – bushings, OIP, RIP, RBP, dielectric response, FDS, PDC, moisture, partial discharges, 3CFRD**

I. INTRODUCTION

High voltage bushings are essential parts of power transformers, circuit breakers and of other power apparatus. More than 10 % of all transformer failures are caused by defective bushings. A bushing failure can damage a transformer completely. Therefore regular diagnostic measurements are essential for a safe operation of HV equipment. The measurement of capacitance and dissipation or power factor is common since decades. It was performed at line frequency normally. Table 1 shows the 50/60 Hz limits for dissipation factor / power factor and partial discharges according to IEC 60137 and IEEE C57.19.01.

Table 1: Limits for dissipation and power factor and partial discharges

Type	**RIP**	**OIP**	**RBP**
Main insulation	Resin impregnated paper	Oil impregnated paper	Resin bonded paper
DF / tan delta (20°C, IEC60137)	< 0.7 %	< 0.7 %	< 1.5 %
PF cos phi (20°C, IEEE C57.19.01)	< 0.85 %	< 0.5 %	< 2 %
Typical new values	0.3-0.4 %	0.2-0.4 %	0.5-0.6 %
PD (IEC60137) at U_m $1.5\ U_m$ $1.05\ U_m$	 < 10 pC < 5 pC < 5 pC	 < 10 pC < 5 pC < 5 pC	 < 300 pC

Changes of the capacitance of condenser type bushings are typically caused by a partial breakdown between capacitive layers. These lead to a higher field stress for the remaining layers and, over long time, to total electrical breakdown, often combined with dangerous explosions.

An increase in dissipation factor (or power factor, DF/PF) is often an indicator of insulation ageing due to conductive ageing by-products.

Partial discharges (PD) are early indicators of a breakdown.

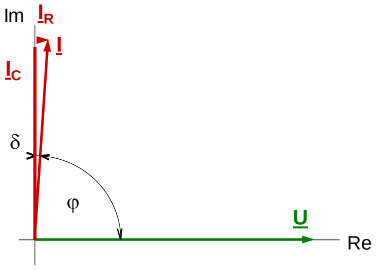

Fig. 1. Vector diagram for lossy dielectrics with angles δ (for dissipation factor tan δ) and φ (for power factor cos φ)

II. MEASUREMENT OF DIELECTRIC LOSSES

For measuring capacitance and losses, manually balanced bridges like the Schering bridge or transformer bridges were used in the first beginning. Later the balance of the bridge was automated by a microprocessor. These solutions are appropriate for measuring at various frequencies. Modern electronics enable the measurement of the dielectric response of the insulation that means the measurement of losses over a wide frequency range. This delivers much more information about ageing, moisture and also faulty contacting of measuring taps and capacitive layers. The principle of a typical measurement circuit is shown in Fig. 2.

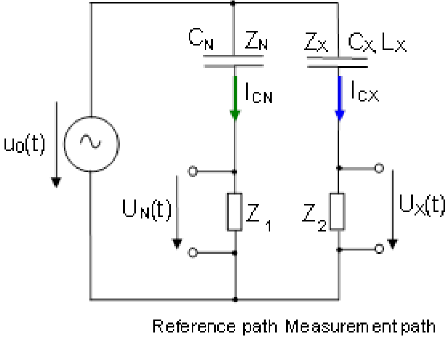

Fig. 2: Measurement circuit for automated dielectric response measurement

The measurement of losses can be done in the frequency domain FDS (Frequency Domain Spectroscopy) with a setup similar to Fig. 2 or in the time domain PDC (Polarization Depolarization Current) using an electrometer. The data can be transformed from the time domain into the frequency domain and vice versa. The FDS measurement covers the whole frequency range from high frequencies down to very low frequencies, but measurements at low frequency need a long measuring time, whereas the PDC is much faster but can only measure up to about 1 Hz. A new approach uses the advantage of both methods and measures the frequencies from 5 kHz down to 0.1 Hz with the FDS and 0.1 Hz down to 50 µHz with the PDC. The PDC data are transformed into the frequency domain and showed as tangent delta values [1]. Fig. 3 shows the principle of the combined FDS-PDC measurement. Combining the two techniques reduces the measurement time by 50-75 % compared to traditional FDS measurements.

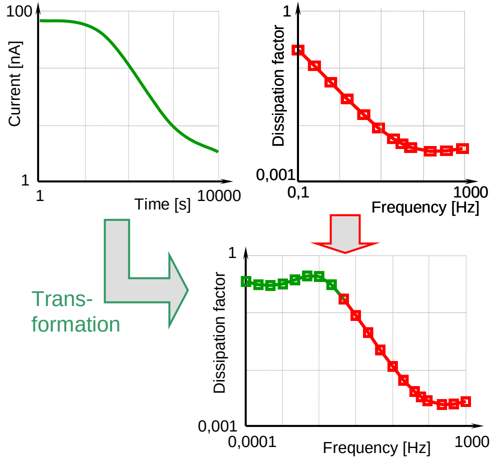

Fig. 3. Combination of time and frequency domain measurements

III. CASE STUDIES OF DIAGNOSTIC MEASUREMENTS ON RIP, RBP AND OIP BUSHINGS

A. *Measurements for New RIP, RBP and OIP Bushings*

The described measurement principle using frequencies between 15 and 400 Hz was applied for diagnostic measurements on RIP, RBP and OIP bushings. In Fig. 4 the dissipation factor curves of new RIP, RBP and OIP high voltage bushings are shown. The frequency range is 15 to 400Hz, the test voltage 2 kV. The curves are rather flat, the minimum of the curves is below the lowest test frequency of 15 Hz. The values at 50 Hz are fulfilling the limits given in Table 1.

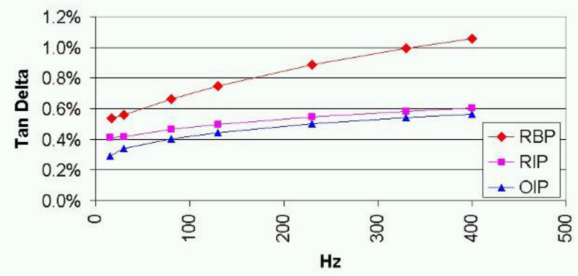

Fig. 4: Dielectric Response of new RIP, RBP and OIP bushings

B. *Influence of Moisture on a RIP Bushing*

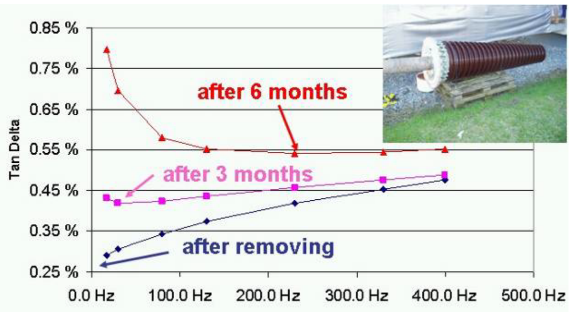

Fig. 5: Dielectric Response of a RIP bushing exposed to wet air

In Fig. 5 a RIP bushing can be seen, which was stored outside without any protection of the oil side. The non protected oil side has been adsorbing moisture from the atmosphere during the months and the change of the dissipation factor can be seen clearly. The moisture increases the dissipation factor particularly at low frequencies, the minima of the dissipation factor curves are shifted to higher frequencies with increasing moisture content.

C. *Diagnostics on a RBP Bushing*

A resin bonded paper 123 kV bushing showed a suspicious dielectric response (Fig. 6, red curve of phase C, blue curve for bushing of phase A).

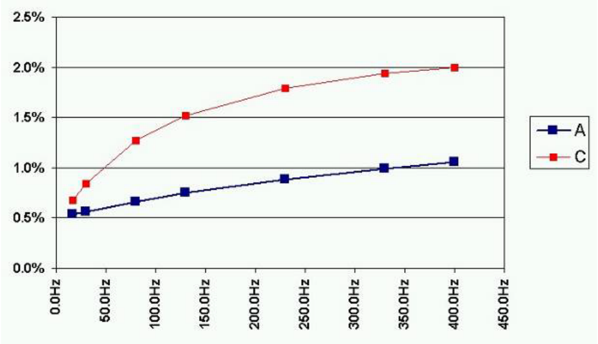

Fig. 6: Dielectric Response of two RBP bushings, one of them showing unusual behavior

The strong increase of the dissipation factor for high frequencies is obvious. The bushings were tested afterwards at line frequency and voltages between 2 and 12 kV (Fig. 7). In this diagram the tan δ curve starts with rather high losses and goes down for higher test voltages. This behavior is known for bad contacts either on the measuring tap or on the contacting of capacitive layers. The bushing was removed from the transformer and dissembled; the inner capacitive layer had no contact to the conductor tube.

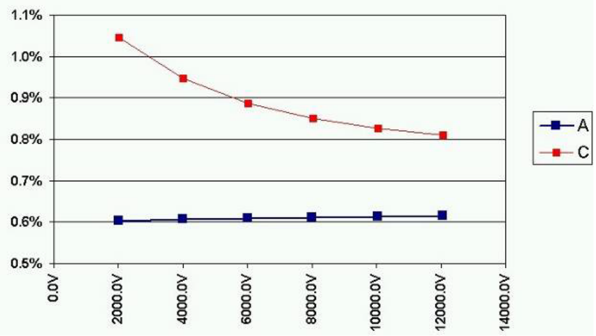

Fig. 7: Dissipation factor depending on test voltage for a healthy (A) and a defective bushing (C)

D. *Influence of Moisture on OIP Bushings*

33 kV OIP bushings were exchanged because of high dissipation factor at elevated temperatures. It was assumed that the inner insulation of the bushings was wet. Fig. 8 shows the dissipation factor of OIP bushings at 50 Hz for different water contents.

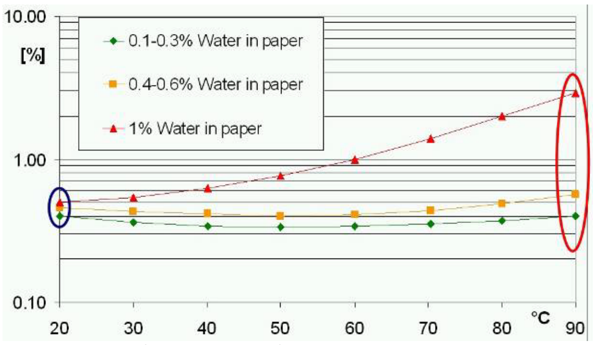

Fig. 8: Dissipation factor at power frequency depending on temperature for different moisture contents

The new and the old bushings were tested at 30°C from 15 to 400 Hz. High differences could be measured particularly at low frequencies (Fig. 9). This example shows very clearly that the dissipation factor measurement at low frequencies can detect water with high sensitivity.

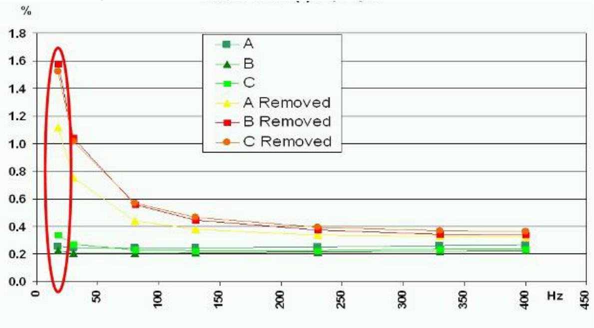

Fig. 9: Influence of moisture on dissipation factor particularly at low frequencies

E. *FDS and PDC Measurements on Bushings*

Fig. 10 depicts the typical dielectric responses for RBP, RIP and OIP bushings as measured with FDS and PDC, [3]. The very wide frequency range of 1 kHz down to 1 mHz obviously delivers more information about the condition of the dielectric.

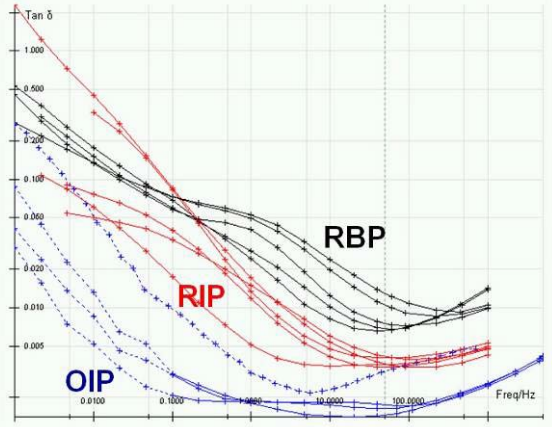

Fig. 10: Typical dielectric responses over a very wide frequency range for RBP, RIP and OIP bushings

Temperature strongly influences the results. With increasing temperature the losses at very low frequencies are increased, whereas the losses at higher frequencies are getting lower and the minimum of the loss curve is shifted to the higher frequencies, Fig. 11. This has to be taken into account for measurements at different temperatures.

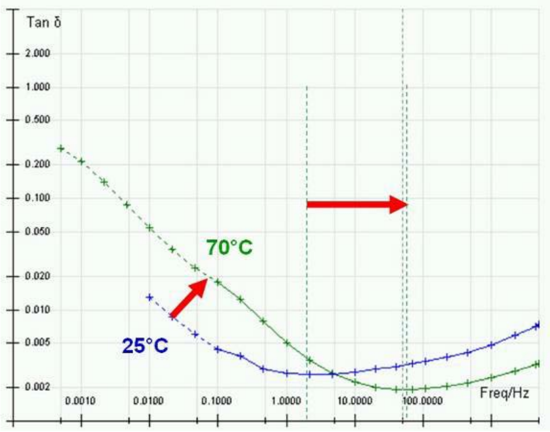

Fig. 11: Temperature influence on the dielectric response of a RIP bushing

F. *Experiments with a 170 kV RIP Bushing*

A RIP bushing was exposed to different moisture and temperature in a climate chamber, [3]. The experiment was started at 20° and 38 % Relative Humidity (RH). The second day the bushing was heated up to 70°C with a RH of 10 % (Fig. 12). The next days the bushing was exposed to high humidity of up to 80 % at 70°C. After the 9th day the dielectric response was measured at 70°C. On the 10th day the relative humidity was reduced to 10 % again. The red curve was measured during the 12th day with 10 % RH at 70°C. Obviously the resin surface is still wet.

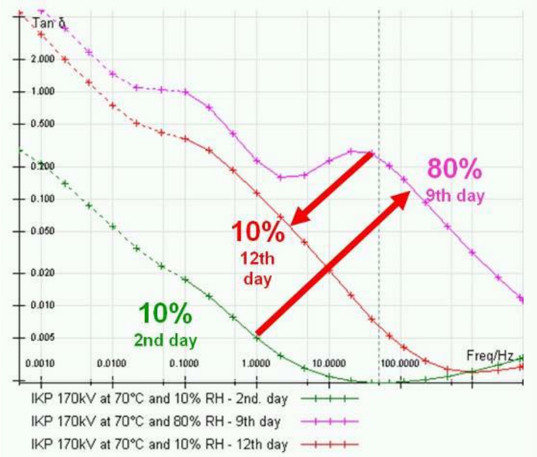

Fig. 12: RIP bushing at different ambient relative humidity

G. *Improved Manufacturing Process for 45 kV RBP Bushings*

45 kV RBP bushings were stored in wooden boxes under the influence of the ambient humidity. Figure 20 shows the FDS-PDC measurement results on three non dried bushings and one that was dried in an oven for one week. By drying the one bushing a clear improvement can be seen. The 50 Hz dissipation factor went down from more than 2 % to 0.66 % which is acceptable. Based on these findings, the manufacturer optimized the production process.

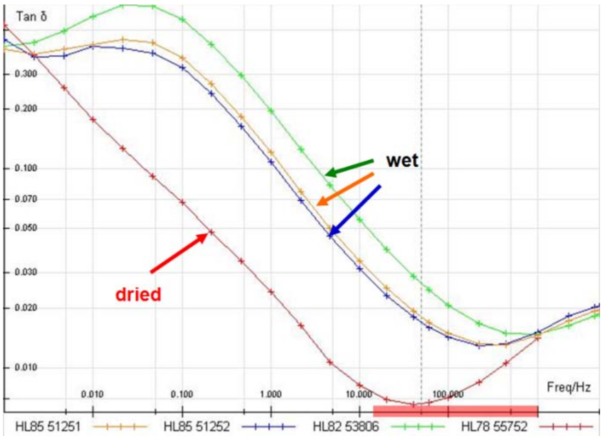

Fig. 13: 45 kV RBP bushings before and after drying

IV. COMBINATION WITH PARTIAL DISCHARGE MEASUREMENTS

A 145kV oil-air bushing was dried in an oven for 12 weeks at 60°C. Fig. 14 shows the results before and after drying.

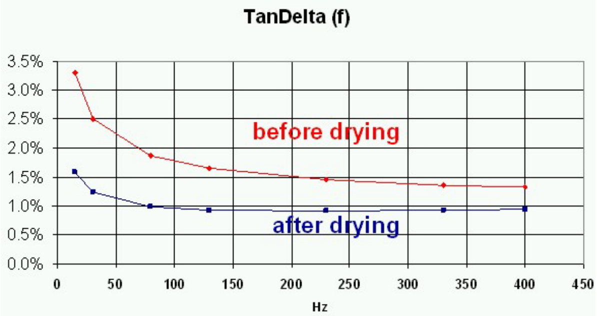

Fig. 14: Dielectric Response before and after drying

The dissipation factor at 50 Hz was reduced from 2.2 % before to 1.1 % after drying. This value is still rather high. A Partial Discharge measurement was performed to check the presence of cracks in the resin due to the drying procedure (Fig. 15).

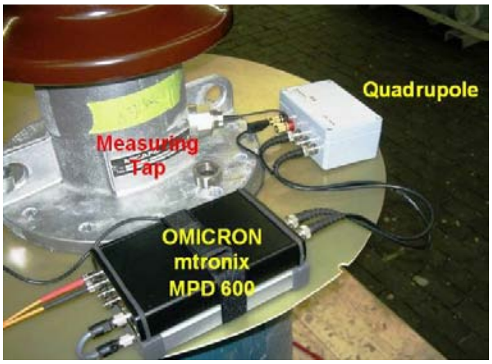

Fig. 15: PD instrument and quadrupole connected to the measuring tap of the bushing

First a PD measurement with conventional phase resolved representation was made. The sum of all PD signals can be seen in the phase resolved PD pattern of Fig. 16. This way pattern recognition is impossible

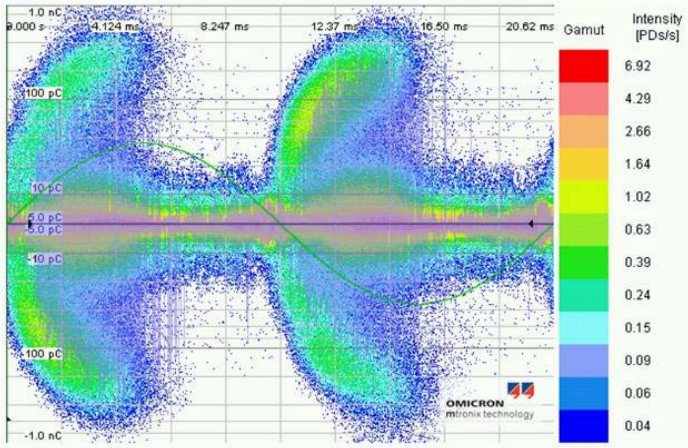

Fig. 16: Phase resolved PD pattern without 3CFRD

Thereafter the PD sources were separated by a 3 Center Frequency Relation Diagram (3CFRD). The 3CFRD discriminates between PD impulses originating from various sources based on their different frequency spectra, Fig. 17. The spectra are calculated simultaneously at 3 different center frequencies, here 500 kHz, 2.8 MHz and 8 MHz, Fig. 18. The amplitudes of each single filter frequency are added, resulting in separated PD clusters for each PD source. The separate clusters can then be displayed in the conventional phase-resolved representation for further pattern analysis. Using this methodology also the intensity as apparent charge of the single PD sources can be measured. For this bushing, a PD intensity of more than 1 nC was detected. Due to the high dissipation factor and the high PD activity it was decided to replace the asset.

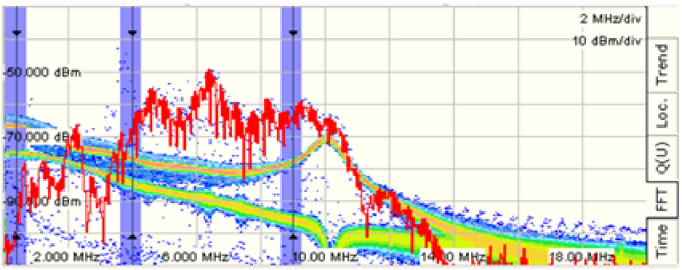

Fig. 17: Spectra of different PD sources with locations of three digital filters

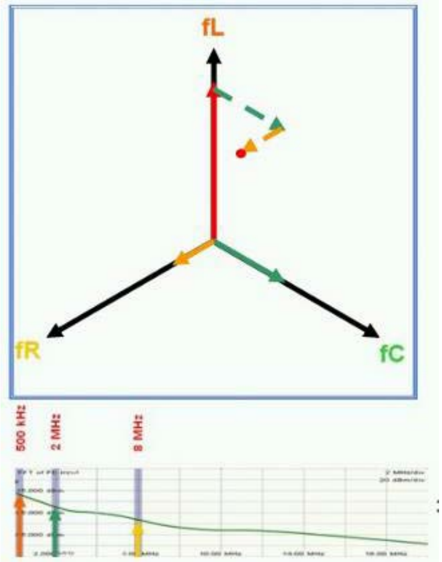

Fig. 18: Principle of the 3 Center Frequency Relation Diagram

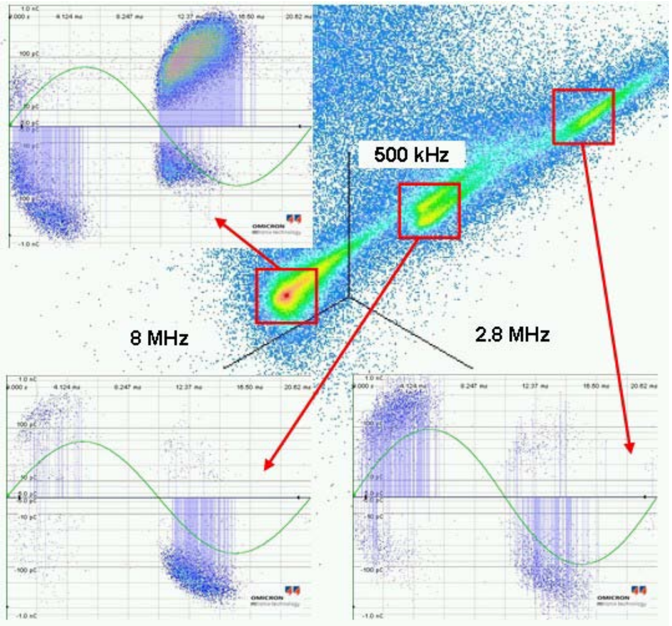

Fig. 19: Separation of PD sources with 3CFRD

V. SUMMARY

Modern technologies enable for very sensitive diagnostics of high voltage bushings. Dielectric response analysis is a very promising method for detecting ageing and moisture in insulations with high sensitivity. Using the 3CFRD, single PD sources can be separated and much better analysis of PD faults becomes possible.

VI. REFERENCES

[1] M. Koch, M. Krüger: “A Fast and Reliable Dielectric Diagnostic Method to Determine Moisture in Power Transformers”, *CMD 2008 International Conference on Condition Monitoring and Diagnosis*, Beijing, China, 2008

[2] ABB, "Dissipation factor over the main insulation on high voltage bushings", *Product Information*, ABB 2002

[3] Muhr, M., Summereder, C., Weingärtner, M.: "Diagnose von Durchführungen mit Hilfe von frequenzabhängigen Verlustfaktormessungen", *DMPT OMICRON Transformer Workshop*, Bregenz, Austria, 2007

OMICRON is an international company serving the electrical power industry with innovative testing and diagnostic solutions. The application of OMICRON products allows users to assess the condition of the primary and secondary equipment on their systems with complete confidence. Services offered in the area of consulting, commissioning, testing, diagnosis, and training make the product range complete.

Customers in more than 140 countries rely on the company's ability to supply leading edge technology of excellent quality. Broad application knowledge and extraordinary customer support provided by offices in North America, Europe, South and East Asia, Australia, and the Middle East, together with a worldwide network of distributors and representatives, make the company a market leader in its sector.

Americas
OMICRON electronics Corp. USA
12 Greenway Plaza, Suite 1510
Houston, TX 77046, USA
Phone: +1 713 830-4660
+1 800-OMICRON
Fax: +1 713 830-4661
info@omicronusa.com

Asia-Pacific
OMICRON electronics Asia Limited
Suite 2006, 20/F, Tower 2
The Gateway, Harbour City
Kowloon, Hong Kong S.A.R.
Phone: +852 3767 5500
Fax: +852 3767 5400
info@asia.omicron.at

Europe, Middle East, Africa
OMICRON electronics GmbH
Oberes Ried 1
6833 Klaus, Austria
Phone: +43 5523 507-0
Fax: +43 5523 507-999
info@omicron.at