

An Assessment of Ageing of Oxide Varistors Exposed to Pulse Hazards Using Dielectric Spectroscopy

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Abstract: The common use of zinc oxide varistors has brought about qualitative changes in the overvoltage protection of electronic and electric power equipment. This is due to the special properties of ZnO varistors, mainly the high current-voltage characteristic nonlinearity and the capacity to withstand strong current surges. In service conditions varistors are exposed to the sustained action of constant or variable voltage or momentary overvoltage pulses. As a result varistors may undergo degradation reflected in changes in their current-voltage characteristics. The changes are manifested in an increase in leakage current and are limited to a highly thermally activated low-current region where the performance of the varistor is determined by the parameters of the potential barriers. Thus one can conclude that the degradation is a result of processes leading to the movement of ions and the deformation of the potential barriers. Therefore dielectric spectroscopy (testing of the dielectric response in a wide frequency band) could be useful for the investigation of degradation changes, and so this method is proposed in this paper.

INTRODUCTION

Varistors are ceramic elements whose current-voltage (I-U) characteristic is highly nonlinear. Varistors are usually manufactured in the ceramic process in which pressed zinc oxide with admixtures of other metallic oxides (Bi_2O_3 , CoO, MnO, CaO, SrO or BaO) is sintered.

The microstructure of such materials consists of semiconducting ZnO grains surrounded by a non-conducting intergranular phase (Fig. 1) formed by admixtures (usually bismuth oxide) showing a distinct tendency towards segregation on the boundaries of ZnO grains. It has been found that the potential barriers along the boundaries of ZnO grains, whose presence is associated with the energetic and spatial distribution of trap states on the interface, are the prime factors contributing to nonlinear electric conduction in ceramic varistors [1-4].

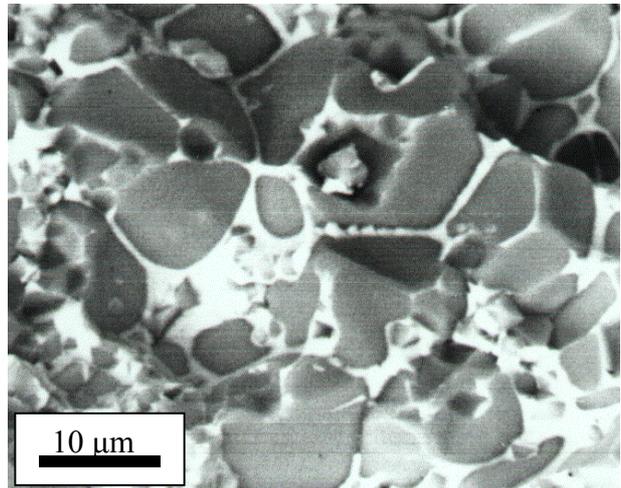


Fig. 1. Microstructure of varistor ZnO ceramic - surface microphotograph

Both the shape of the current-voltage characteristic (Fig. 2) – with a clear division into a nearly ohm-like part and a highly nonlinear part for respectively low and high current densities – and its very strong dependence on temperature for low current densities indicate the existence of at least two different dominant mechanisms of electric conduction.

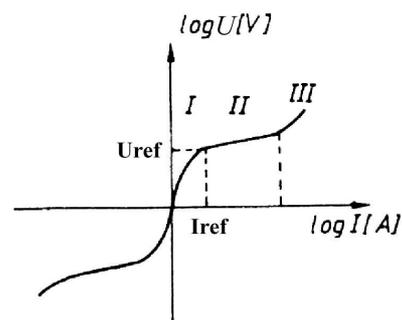


Fig. 2. Typical current-voltage characteristic of ZnO varistor

Most researchers agree that in the low voltage range (the leakage current region) thermionic emission through the Schottky barrier is the mechanism responsible for the ceramic varistor's conduction. For voltages above the characteristic voltage the proposed model usually assumes the tunnelling of electrons by

the potential barrier [2-4]. In the literature on the subject one can come across different approaches to: the potential barrier shape, the effect of the intergranular phase and surface states, the occurrence of factors which lower the height of the barriers or the energetic structure of the grain boundary. The existing conduction models do not explain all the phenomena that occur in ZnO ceramics. In service the varistor is exposed to the sustained action of constant or variable voltage or overvoltage pulses. As a result the varistor may undergo degradation reflected in changes in its current-voltage I-V characteristic. The changes, consisting in an increase in leakage current, cause an increase in the generated power and may lead to the failure of the varistor caused by loss of thermal equilibrium.

The degradation of the I-V characteristics occurs only in the leakage current region and decreases as current density increases. The amount of degradation increases with the applied (sustained and pulse) load and with voltage impact time. The increase in the varistor's working temperature activates degradation and dramatically increases its rate. The rate of degradation decreases with time and stabilizes after a certain time and then again increases, resulting in the thermal failure of the varistor.

The character of the observed degradation, mainly its long course and strong thermal activation, point to the movement of ions in ZnO ceramics as the cause of the degradation. This has been corroborated by the results of structural examinations [5] which show that as degradation proceeds, the profile of Bi and Co concentration on the ZnO grain boundary perpendicular to the direction of the electric field and devoid of grain phase changes. No such changes are observed on the boundary parallel to the direction of the electric field.

For the same reasons as in the case of the formulated models of the conduction mechanism, the mechanism of degradation is still far from being fully understood.

RESEARCH METHODS

Varistor degradation studies were carried out on commercial varistors used in the production of HV overvoltage arresters. The varistors had the shape of disks with a diameter of 70 mm and a height of 20 mm. The varistors were subjected to sustained current surge resistance tests in conformance with standard PN-IEC 99: 4. The degree of varistor degradation caused by the applied exposures was studied at different temperatures using dielectric spectroscopy. In the technique, an AC electrical signal is applied to the sample and the real and imaginary components of the complex response are observed as a function of the AC frequency. The response may be presented among other things in terms of the electrical admittance $Y(\omega)$ or capacitance $C(\omega)$:

$$Y(\omega) = G + jB = j\omega C = j\omega(C' - jC'') \quad (1)$$

where ω is the angular frequency.

The measuring system for the analysis of spectral dielectric response included a digital Schlumberger Solartron Frequency Response Analyser (model 1172) with a measuring frequency range of 10^{-4} – 10^4 Hz. A schematic diagram of the measuring system is shown in Fig. 3.

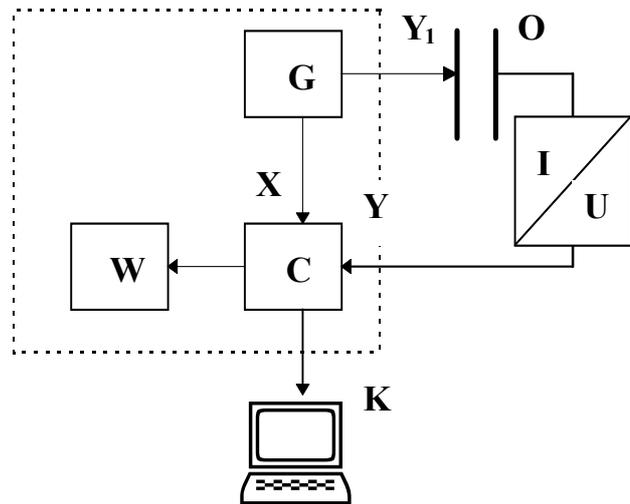


Fig. 3. Schematic diagram of system for investigating frequency spectrum of dielectric response: G – voltage wave generator, C – correlator, W – display, O – investigated specimen, I/U – current-voltage converter, A – frequency analyser, K – computer, X – input voltage signal, Y1 – specimen's current, Y – output voltage current.

RESEARCH RESULTS

Frequency relations for dielectric loss factor $\text{tg } \delta$ and capacitance C' , obtained for the specimens of unaged varistor ZnO ceramics (initial specimens) for two different temperatures (25°C and 50°C), are shown in Fig. 4. The system's dielectric response in the test frequency range is characterized by the presence of considerable dispersion and absorption, ascribed here to ionic conduction.

As the temperature of the specimen increases so does the loss factor in the whole test frequency range (up to a frequency at which the first minimum of the dielectric loss factor occurs). The thermal activation of the investigated process indicates that thermionic emission through the Schottky barrier is the mechanism responsible for the conductivity of ZnO ceramics in the low-voltage range (in the leakage current region).

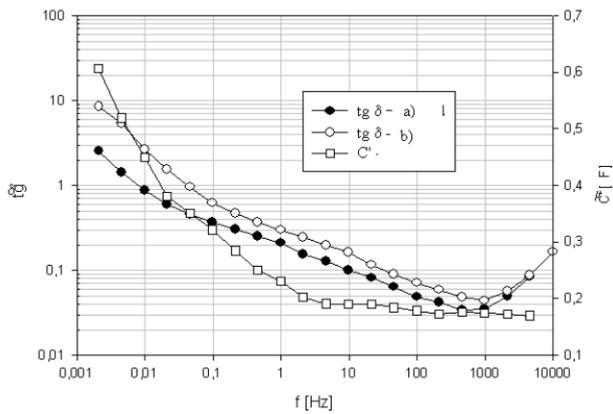


Fig. 4. Frequency characteristic of dielectric loss factor $\text{tg } \delta$ and capacitance C' for unaged specimen of ZnO ceramics for temperatures: a) -25°C and b) -50°C .

The frequency dielectric loss factor characteristic for a varistor ceramic specimen after the sustained current surge resistance test against the characteristic for the undegraded specimen is shown in Fig. 5.

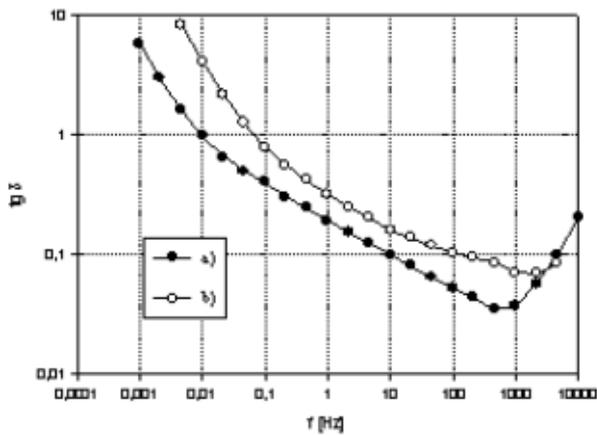


Fig. 5. Frequency characteristic of dielectric loss factor $\text{tg } \delta$ for varistor ceramic specimen: a) unaged and b) after sustained current surge test.

According to the figure, the process of degradation is accompanied by an increase in the dielectric loss factor in the whole test frequency range. Similarly as in the case of temperatures, the increase can be ascribed to changes in the ceramic's structure, leading to increased conductance of the aged specimens. These are mainly changes in the insulating intergranular phase separated from the semiconducting grains by interfacial surfaces whose properties determine the conduction mechanisms.

Figure 6 shows the dielectric behaviour of the real (C') and imaginary (C'') components of complex capacitance C for respectively the unaged specimen and the specimen after the sustained current surge test. From Fig. 6 it can be seen that both components (C' and C'') show an increasing tendency toward lower frequencies. This behaviour is typical for low-frequency dispersion

(LFD) [6-8]. Ageing of samples only results in frequency shift of the curves.

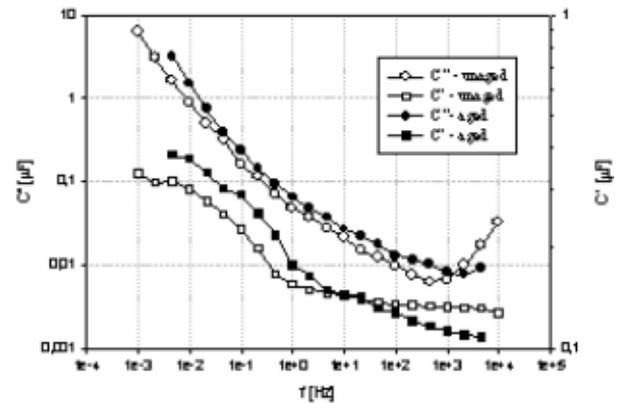


Fig. 6. Frequency characteristics of real (C') and imaginary (C'') components of complex capacitance C for varistor ceramic specimens: a) unaged, b) after sustained current surge test.

CONCLUSIONS

Because of its high sensitivity to changes in the macro- and microstructure of the material, dielectric spectroscopy was chosen as the method for ageing testing of zinc oxide varistor ceramics. The method's sensitivity is due to the close relationship between the material's structure and the polarization and conductance phenomena that proceed in the material. It is assumed that in the course of degradation of ZnO ceramics the processes participating in the low-frequency dielectric response undergo fundamental changes. This applies mainly to the movement of the electric charge in the material's structure formed by semiconducting grains and the nonconducting intergranular phase, separated by interfacial surfaces whose properties determine the conduction mechanism. The research has shown that in the low-frequency range the system's dielectric response is characterized by the presence of substantial dispersion and absorption, ascribed to ionic conductance. The fact that degradation is thermally activated points to thermionic emission through the Schottky barrier as the mechanism responsible for the conductance of ZnO ceramics in the low-voltage range.

The process of degradation is accompanied by an increase in the dielectric loss factor in the whole test frequency range, related to the increase in the conductivity of the tested specimen.

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