

# NONDESTRUCTIVE TESTING IN DIAGNOSTICS OF HIGH-VOLTAGE VARISTORS

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**Abstract** – High voltage varistors that consist of grained ZnO have to be tested before assembling. The recommended method for standard industrial testing of varistors demands application of high voltages and intensive currents that is inconvenient and needs extensive power consumption. Nondestructive methods for varistor quality and endurance evaluation have been proposed. They rely on the application of resonant ultrasound spectroscopy and nonlinearity testing. The parameters of assessment have been proposed and the results of measurements performed for several hundreds of varistor samples are quoted.

**Keywords:** varistor, diagnostics, non-destructive testing

## 1. INTRODUCTION

Varistors used in high-voltage electrical systems for over-voltage protection have to be tested during manufacturing using high-voltage (above 400V) and intensive current shocks. A high current density and an intensive heating can cause irreversible destruction of the tested varistors [1-3]. Moreover, these testing methods require metallization of the varistor structures and therefore can be carried out at the end stage of production process. It means that elimination of a defective specimen needs an earlier preparation of expensive contacts when compared to a relatively small cost of the pure ZnO material. We propose non-destructive methods using a Resonant Ultrasound Spectroscopy (RUS) or a nonlinearity measurement, effectuated at significantly lower power consumption in the earlier production stage before metallization. Such test demands measurement systems that can precisely measure a resonant spectrum of tested objects in the appropriate frequency range or measure a Third Harmonic Index (THI) after a stimulation of tested sample by an appropriate harmonic signal. The defective specimens can be then excluded from the further processing. Another nondestructive method rely on the noise spectroscopy [4].

The current-voltage characteristic of varistors depend on amount of grain types existing in its structure. The widespread presence of different kind grain contacts diminishes desirable nonlinear varistor characteristics and influences on its inhomogeneity manifesting itself in the mechanical properties which can be detected by RUS.

## 2. VARISTOR SAMPLES

The DC current-voltage characteristic of a high-voltage varistor has three distinguishable regions: prebreakdown, breakdown and saturation (Fig. 1a). A varistor behaves as a highly resistive resistor ( $\sim 10^9 \Omega$ ) at low voltage region. At breakdown region the DC current  $I$  is exponentially proportional to the applied DC voltage  $U$ :

$$I = k \cdot U^\alpha \quad (1)$$

The exponent  $\alpha$  depends on a type of boundary junctions that exist between the grains. Varistors saturate at higher voltages and their resistance does not exceed tens of ohms. They should exhibit as much as possible nonlinear characteristics (high value of a parameter  $\alpha$ ). There are good, low nonlinear and linear junctions between the ZnO grains. The exponent  $\alpha > 30$  indicates the most required grain contacts. The low nonlinear contacts exhibit  $\alpha \approx 10$ . These various contacts can be discriminated by the shape of their voltage-current characteristics (Fig. 1b).

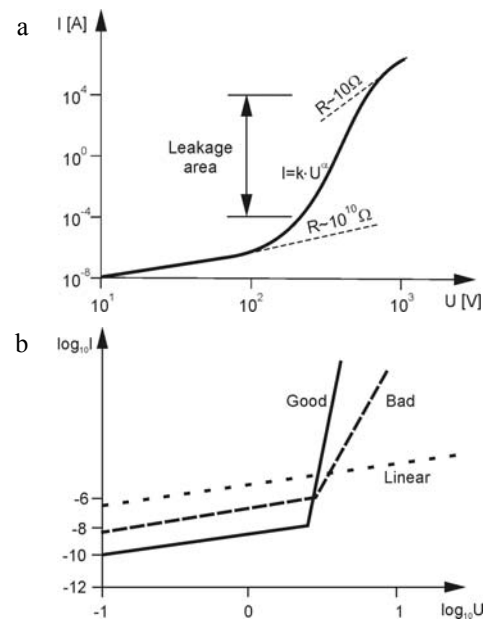


Fig. 1. Varistor current-voltage characteristics: (a) - general, (b) - distinguished types of boundary junctions between ZnO grains

A real varistor is a mixture of various grains and its outcome characteristic depends on amount of grain types that exist in its structure. The widespread presence of linear or weakly nonlinear grain contacts decreases  $\alpha$  and diminishes desirable nonlinear varistor characteristic at its relatively low voltage region, for example up to a hundred volts. Thus, varistors quality as a nonlinear element can be evaluated by a degree of linearity of their DC characteristics in the mentioned voltage range.

Three types of varistors having different voltage threshold (280 V, 440 V and 660 V) have been measured. All varistors have the same diameter (30 mm with a tolerance 0.5 mm – Fig. 2) but the higher voltage threshold was obtained for the thicker samples (3 mm, 4 mm and 5 mm, respectively).



Fig. 2. Varistor specimens: a – ZnO structures after being fired (top row) and with a metalized contacts (bottom row); left – 280 V, middle – 440 V, right – 660 V; b - surge arrester with ZnO varistor

Two batches of samples (every containing 100 specimens) for all the mentioned above voltage thresholds were produced for testing. There was a difference between proportions of linear and nonlinear grain junctions presented in each batch as a result of changes introduced artificially into the material composition. It had impact on their DC current-voltage characteristics. Therefore, one of the batches could be treated as a group of lower quality varistors – with higher leakage currents.

Variations in grain size of ZnO structures suggest differences also in their mechanical properties (for example stiffness, sound velocity) that can be identified by convenient measurements during their fabrication. The paper proposes a new method of quality assessment of ZnO structures based on resonant ultrasound spectroscopy (RUS) that can be implemented in an industrial application for the low cost and short measurement time.

The structure of grains in tested specimens was preliminary observed by means of an Atomic Force Microscope (AFM) with a scanning probe enabling to obtain of 3D images of scanned surfaces. The AFM measured an interaction between the probe and the surface of a varistor

during its scanning by means of a laser beam. The images of scanned surfaces having dimensions  $50 \mu\text{m} \times 50 \mu\text{m}$  are shown in Fig. 3. Marked differences in the grain structures between higher and lower quality samples can be seen.

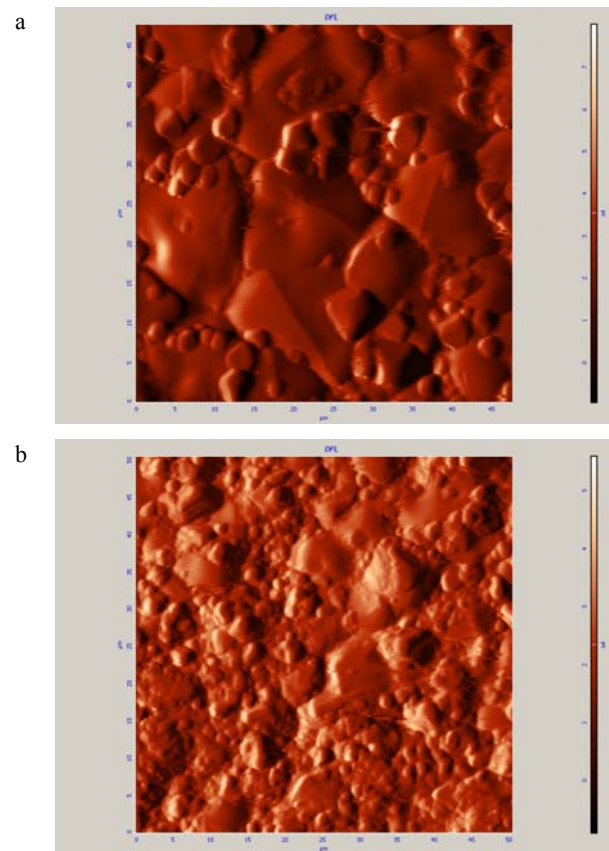


Fig. 3. Surfaces of varistor structures on 280 V structure: a- higher quality, b – poor quality

Marked differences in the grain structures between higher and lower quality samples can be seen.

### 3. RESONANT ULTRASOUND SPECTROSCOPY

RUS is known as an acoustic, nondestructive technique used to study the elastic properties of various materials [5]. It enables to measure natural frequencies of free elastic vibrations of a simply shaped specimens. A typical measurement relies on scanning a selected frequency range including the appropriate resonances of the measured specimens. Using this method it is possible to measure resonant frequencies and frequency responses even for the small samples (mm sized).

To analytically determine the natural resonance frequencies of the varistor discs specimens and to prevent from detecting spurious resonances that can appear due to mechanical and electrical coupling in the measurement system the Finite Elements Method (FEM) modelling of the tested object was used. The measured varistor discs were modelled using elastic constants corresponding to zinc oxide. Shapes of the two lowest resonance modes for a varistor on nominal voltage 280 V are shown in Fig. 4 [7].

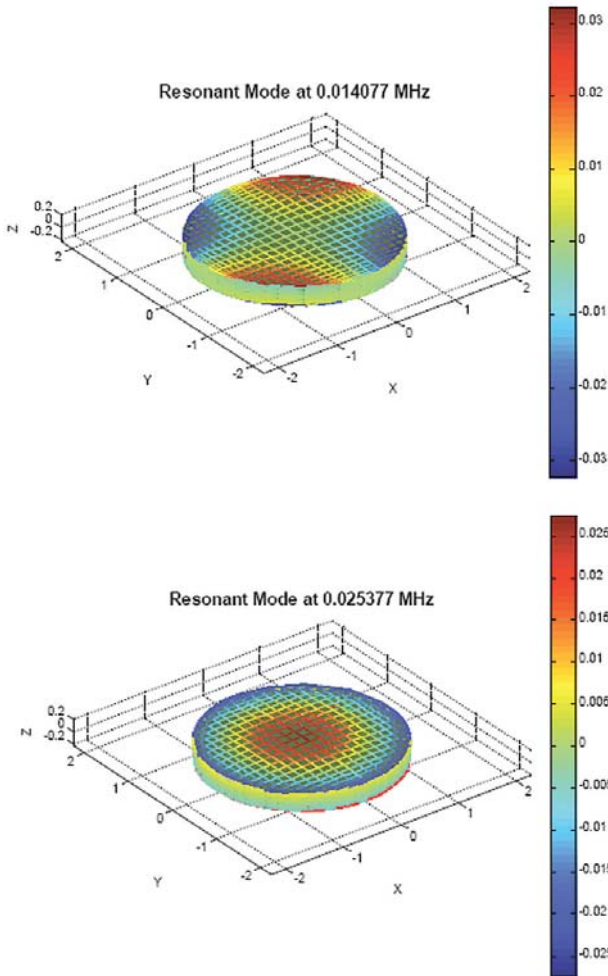


Fig. 4. First two resonance modes calculated for the 280 V varistor

It should be noted that proper identification of the lowest modes is particularly important for the RUS procedure proposed by Migliori[5].

### 3.1. System for RUS

Samples have been mounted between two transducers at opposite corners with a minimal pressure. One transducer excited the sample and the other one measured its response. A harmonic signal with sweeping frequency was put into the input of the sensor exciting vibrations in the tested varistor (Fig. 5 and Fig. 6).

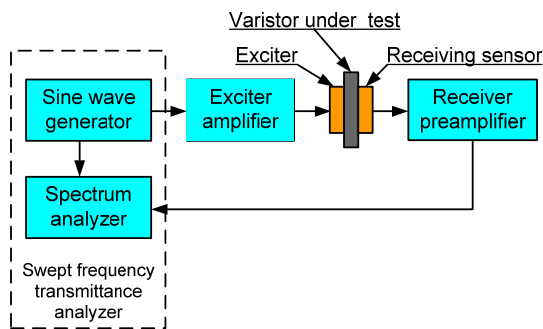


Fig. 5 Simplified block diagram of system for RUS of varistors

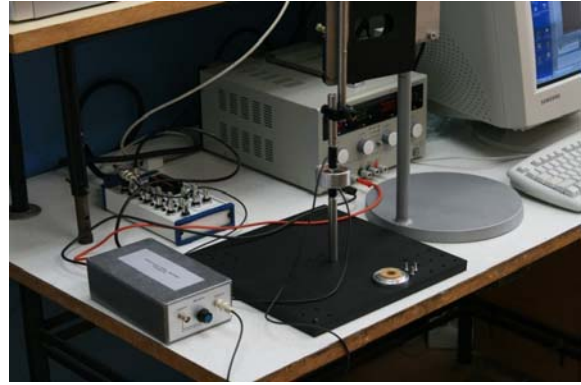


Fig. 6. Overall view of system

The varistor was closed into the specially shielded round metal box padded with a cork as an anti-vibration isolation material (Fig. 7).

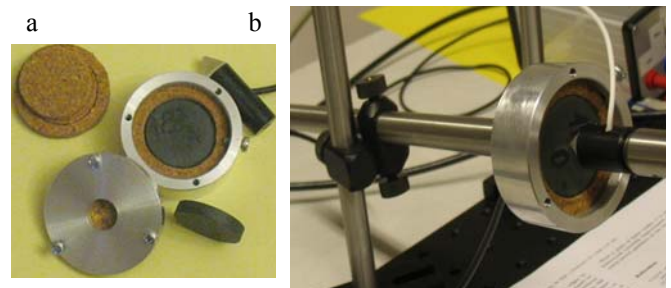


Fig. 7. Mechanical parts of RUS system: a – metallic shielded box with cork surrounding measured varistor, b – handle of the box

Signals of both sensors were amplified by two independent amplifiers; the receiving preamplifier was working as a charge amplifier (its inherent noise should be negligible). As a stimuli the generator (NI PCI 5406) was used, and the output signal from the receiving preamplifier was put into the NI PCI 6132 DAQ enabling the signal processing up to 3 MHz/s/channel. The system can measure varistor vibrations within the frequency range 100÷350 kHz by sweeping the frequency with a resolution below one Hz. The whole system was working under the LabVIEW control (Fig. 8) [6].

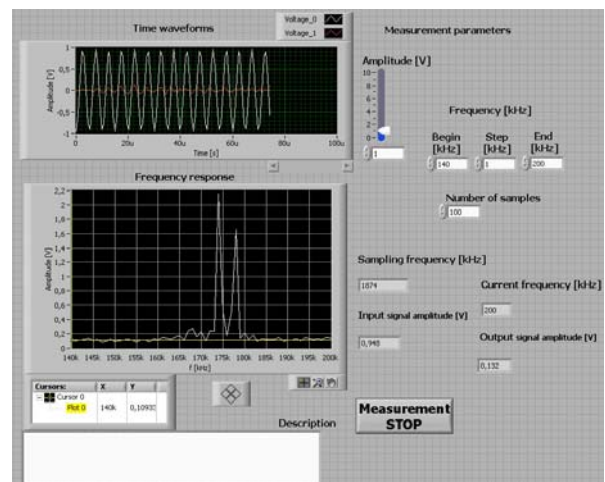


Fig. 8. Front panel of virtual instrument prepared to measurement system control



The procedure enables to set the amplitude of the stimuli signal, the frequency range and the step of frequency sweeping what gives appropriate spectrum resolution.

### 3.2. Results of measurements

Taking into account the average velocity of ultrasonic signal in the varistor material (about 8300 m/s) and frequencies of different elastic modes, the appropriate resonance frequencies was chosen to select during testing good and defected samples. It was 175 kHz, 153 kHz and 130 kHz for specimens 280 V, 440 V and 660 V, respectively. Exemplary resonance spectra for sample 280 V no. 57 is shown in Fig. 9.

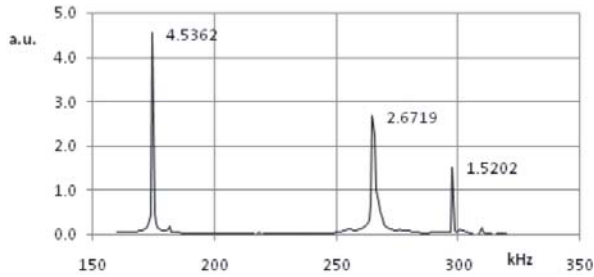


Fig. 9. Spectrum of resonances for sample 280-A57

Generally, varistor resonance frequencies have been shifted to the lower frequency range for samples with a poor quality (Fig. 10).

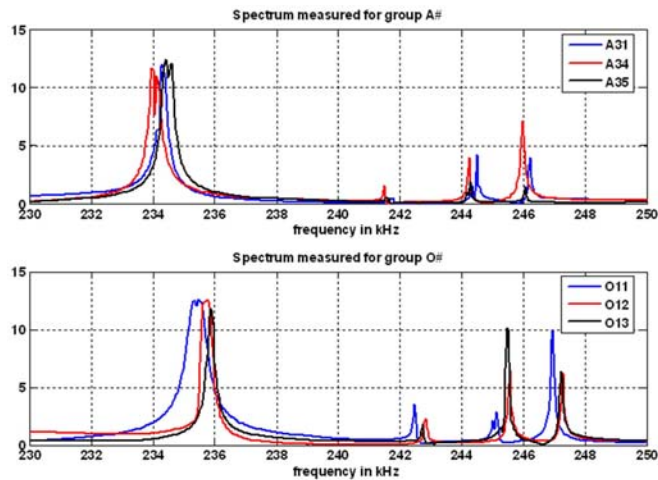


Fig. 10. Difference (only for three samples due to clarity) between resonance frequencies for group A (poor quality, at the top) and group B (good quality, at the bottom) for the same type of varistor structures

We propose to use a homogeneity parameter  $Q$  as a criterion of sample selection during industry production. The parameter  $Q$  was evaluated on the basis of the values of resonant frequency  $f_r$  and actual dimensions of a tested disc-shaped varistor structures:

$$Q = f_r \sqrt{(w^2 + d^2)} \quad [\text{Hz}\cdot\text{m}] \quad (2)$$

where:  $w$  – thickness of varistor,  $d$  – diameter of varistor.

Thus, the parameter  $Q$  can be interpreted as proportional to an average sound velocity within a varistor structure and the velocity is dependent on a quality (homogeneity) of a varistor.

The exemplary collective statistical results of the  $Q$  value for the 100 samples 440V are shown in Fig. 11 [5].

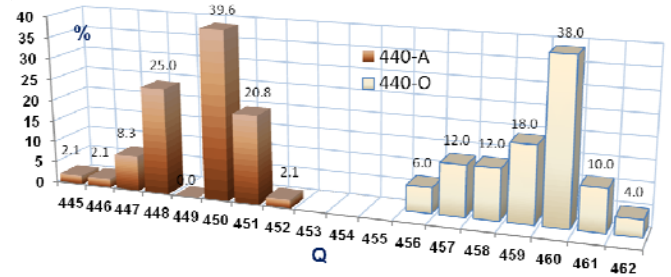


Fig. 11. Statistical shift of parameter  $Q$  to the lower values for 440 V samples with poor quality (440-A – poor quality samples, 440-O – good quality samples)

A shift of the  $Q$  values into the left for the defective samples can be easily seen. It is due to the lower velocity of the signal in the poor quality, heterogenous samples. A full separation between good and defected samples has been achieved. Therefore the proposed parameter  $Q$  seems to be a good criterion for the selection of varistors on good and poor quality components.

## 4. TESTING OF NONLINEARITY

Differences in grain structures between high and lower quality samples have impact on their DC current-voltage characteristics (Fig. 12).

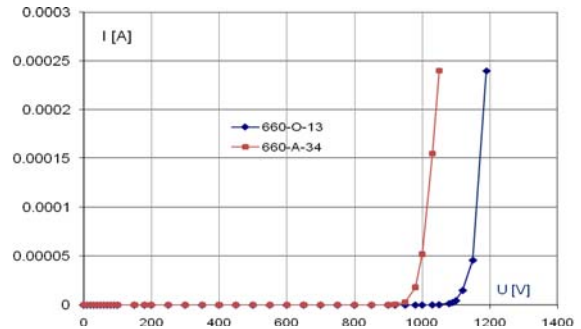


Fig. 12. Exemplary characteristics of two varistors 660 V (lin-lin scale): higher (red squares) and poor (blue squares)

We decided to measure the THI at small currents that flow through the varistor excited by a harmonic signal at voltage amplitude up to 100 V. Such tests are nondestructive but demand a measurement system that can precisely measure a third harmonic component being at least five orders lower than the excitation signal. Thus, varistors quality can be assessed by linearity of their DC characteristics [8] in this voltage range

The amplitude of the third harmonic  $U_3$  was measured in a specially prepared setup (Fig. 13) that consisted of a head with five contact electrodes for each side of a varistor, a THI

meter and a computer controlling the data collection process. The head with multiple contact electrodes enabled to differentiate components for which the current density was not homogeneous in the varistor volume. The springing contact electrodes gripped firmly the varistor. Additionally two trusses at the bottom of the head centred position of the varistor to make measurement results more repeatable.

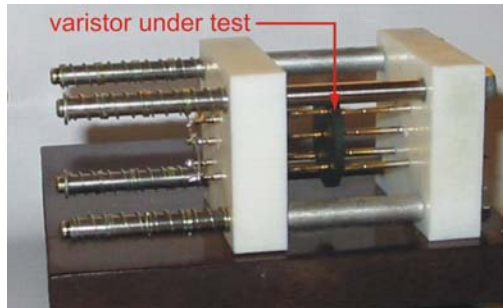


Fig. 13. Head for non-metallized varistor measurement with multiple contact electrodes that grip the tested varistor

We measured within all groups of the prepared varistors whether it is possible to identify their quality by measurement of the third harmonic index at relatively low voltage only. Thus, the third harmonic index was measured at 100 V within a set of the prepared samples to settle this issue.

The exponential dependence between the excitation signal  $U_1$  and the measured third harmonic component  $U_3$  was observed. Varistors from the high quality batches exhibited on average slightly lower exponent around 2 when compared with the results observed in the lower quality batches. This outcome is in a good agreement with the observed differences in DC current-voltage characteristics for both types of batches. A more linear DC characteristic at low voltage range for the lower quality batch means lower THI component that begins to rise faster (higher exponent) when compared with behaviour observed for high quality specimens. At the next step, the measurements were made within a set of about hundred specimens for each batch, separately for all three voltage series: 280V, 440V and 660V. The exemplary statistical data for the series 280V without metallization has been shown in Fig. 14.

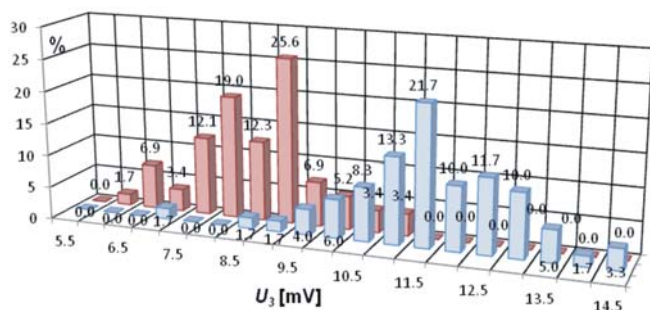


Fig. 14. Distribution of third harmonic component  $U_3$  observed at excitation signal of amplitude  $U_1=100V$  within low and high quality varistor batches without metallization for series 280V

The high quality elements exhibit on average significantly higher third harmonic component value – a difference is up to 30%.

## 5. CONCLUSIONS

A proposed non-destructive methods of varistor quality and endurance testing (RUS and THI measurement) could be successively applied for varistor specimens at the production stage before the metallization of contacts. An amplitude  $U_1=100 V$  of a harmonic excitation signal is sufficient to distinguish between higher and poor quality varistors prepared for the threshold voltage 280 V. The differences in third harmonic index values between both groups of varistors were up to 30%. Varistors series on higher voltages need an excitation signal with higher amplitude to achieve sufficiently high variety of this parameter however such an instrument was not available during our studies. A full separation between good and defected samples has been achieved for RUS.

These methods could be applied for quality detection of other grainy materials. Unfortunately, noise spectroscopy [4] is a very time consuming method and because of interferences in an industry environment could be applied only in the laboratory researches.

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