

Third harmonic index as a diagnostic tool 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. This method requires also metallization of the ZnO structures that increases a cost of testing. Another method of varistor quality and endurance evaluation by the third harmonic index measurement at relatively low voltage range has been proposed. In this experimental study, we present results of the third harmonic index measurements in the selected varistors types. The applied measurement system and results of the THI (Third Harmonic Index) measurements for the selected high-voltage varistor types have been presented. It was proved that the proposed procedure can be applied for preliminary selection of the tested 280 V structures at their fabrication stage.

INTRODUCTION

Metal-oxide varistors (non-ohmic ceramic devices) are widely used as surge arresters in electrical and electronic applications. Their application limits overvoltage disorders caused by lightning or other electrical shocks. High quality varistors are characterised by strongly nonlinear resistance that depends on technology and materials used within preparation process. These elements are produced mainly as a mixture of ZnO grains and some additives that significantly influence their properties. The DC current-voltage characteristic of a high-voltage varistor has three distinguishable regions: pre-breakdown, breakdown and saturation (Fig.1).

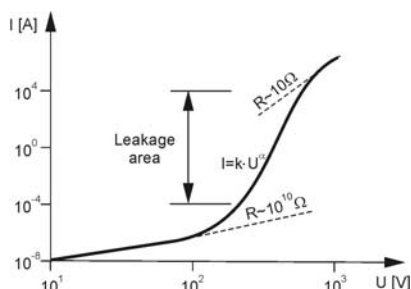


Fig. 1: Varistor current-voltage characteristics

At a breakdown region the DC current I is nonlinearly proportional to the applied DC voltage U :

$$I = k \cdot U^\alpha \tag{1}$$

where: k – constant depending on varistor type. The nonlinearity exponent α (a measure of characteristic curve nonlinearity) depends on a type of boundary junctions that exist between grains.

In practice, varistors should exhibit as much as possible nonlinear characteristics, it means high value

of a parameter α . There are good, low nonlinear and linear junctions between the ZnO grains (Fig.2).

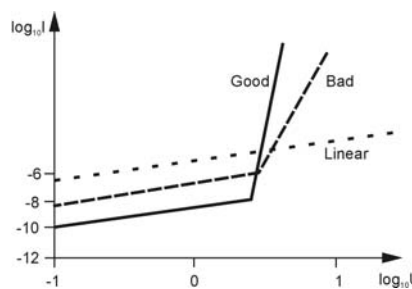


Fig. 2: The current-voltage characteristics of the distinguished types of boundary junctions between ZnO grains

The exponent $\alpha > 30$ indicates the most required grain contacts. The low nonlinear contacts exhibit $\alpha \approx 10$. These various types of contacts can be discriminated by the voltage-current characteristics of a varistor.

An outcome characteristics of a real varistor as a mixture of various grains depends on amount of grain types that exist in its structure. The presence of linear or weakly nonlinear grain contacts decreases α and diminishes desirable nonlinear varistor characteristic at its relatively low voltage region. Industrial standards predict leakage current measurements at DC voltage about 400V. The leakage DC current doesn't exceed hundreds of μA in the properly prepared samples. Too high value means rejection of the tested specimen. Another method applies high voltage impulses that cause intensive current flows. A current flows mainly through narrow paths comprised of grains with linear (ohmic) junctions. High current density and intensive heating there causes irreversible destruction of the tested varistor. Both methods are used when a grained structure of ZnO has metalized contacts. It means that elimination of the defective specimen need a production of the expensive contacts when

compared to a relatively small cost of ZnO material. Therefore, it is valuable to propose another method of ZnO structure selection before printing metallized contacts.

We suggested measuring a third harmonic index at small currents that flow through the varistor excited by a harmonic signal at voltage amplitude up to 100 V. Such tests are non-destructive but demand a measurement system that can precisely measure a third harmonic component being five orders lower than the excitation signal. The poor quality specimens can be pre-selected and excluded from further processing. Thus, varistors quality can be assessed by linearity of their DC characteristics in this voltage range. In such way dangerous and energy consuming testing at high voltage range can be replaced by the more convenient non-destructive testing method.

HIGH-VOLTAGE VARISTOR SPECIMENS

Metal-oxide high-voltage varistors are strongly non-linear resistors with certain semiconductor properties. The nonlinear resistance of a varistor depends on technology and materials used within preparation process. They are usually produced from a mixture of ZnO grains and some additive dopants that significantly influences their properties.

Three types of varistors (Fig. 3) for a different voltage threshold - 280V, 440V and 680V - were investigated. All varistors have the same diameter (30 – 0.5 mm) but the higher voltage threshold was obtained for thicker samples (3 mm, 4 mm and 5 mm, respectively).



Fig. 3: Varistor structures: a - after being fired (top row) and with a metallized 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 voltage thresholds were prepared 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 [1,2].

The structure of grains was investigated by means of an atomic force microscope (AFM) with a scanning probe enabling to obtain of 3D images of scanned surfaces with a resolution of single atoms. 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 the Fig. 4 and Fig. 5. Marked differences in the grain structures between higher and lower quality samples can be seen.

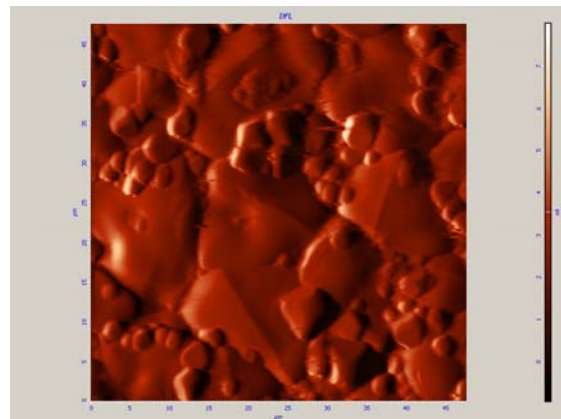


Fig. 4: Surface of higher quality varistor 280 V structure

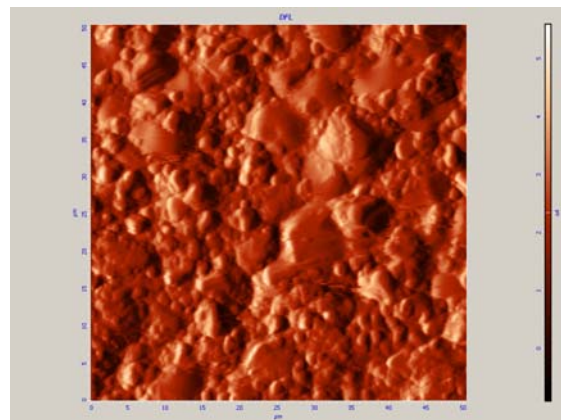


Fig. 5: Surface of poor quality varistor 280 V structure

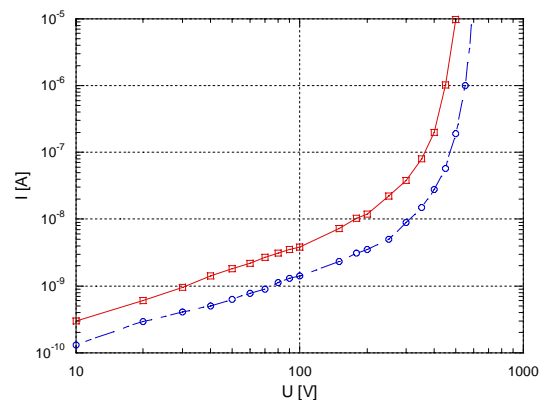


Fig. 6: Exemplary characteristics of two varistors 280 V (log-log scale): higher (red squares) and poor (blue circles) quality

It had impact on their DC current-voltage characteristics (Fig. 6 and Fig.7).

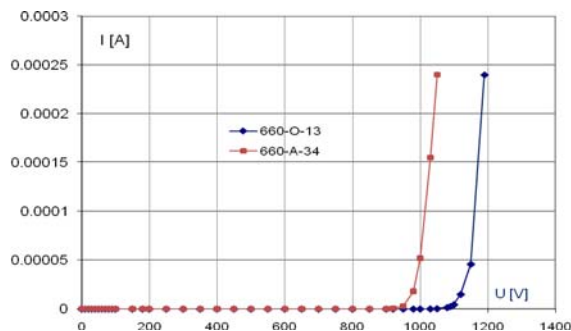


Fig. 7: Exemplary characteristics of two varistors 660 V (lin-lin scale): higher (red squares) and poor (blue squares) quality

Therefore, one of the batches could be considered as a group of lower quality varistors – with higher leakage currents.

MEASUREMENT SYSTEM

The amplitude of the third harmonic U_3 was measured in a specially prepared setup (Fig. 3) 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 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.

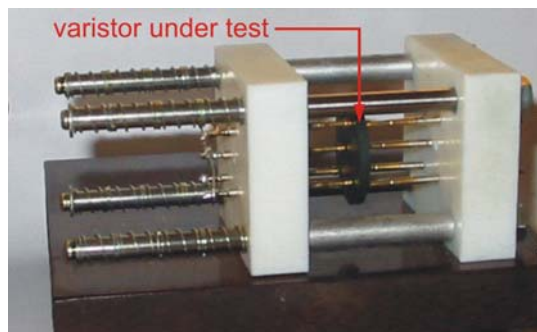


Fig. 8: Head for non-metallized varistor measurement with multiple contact electrodes that grip the tested ZnO specimen

The head with multiple contact electrodes enabled to differentiate varistors for which the current density was not homogeneous in the varistor volume. However, the varistor specimens were prepared by the producer in such a way that the structures were homogeneous and differentiated only by having different grain type. Therefore multiple contact electrodes ensured almost uniform and regular current distribution into varistor structure.

To measure the third harmonic voltage U_3 the excitation harmonic signal U_1 at frequency 10 kHz was applied [3]. The non-linearity of the tested varistor impedance Z_v is determined by measurement

of the third harmonic component at 30 kHz. The meter consists of a generator, together with low-pass and high-pass filters that separate an excitation signal and a third harmonic component. The 10 kHz low-pass filter effectively blocks the 30 kHz signal (about 140 dB). The necessary computation to obtain U_3 value was performed with by the meter.

The excitation harmonic signal at frequency 10 kHz was applied. The non-linearity of the tested varistor impedance is determined by measurement of a third harmonic component at 30 kHz by the *Device Linearity Tester typ LTC-1020* [4]. The meter was controlled by the computer through the GPIB interface. A virtual instrument, prepared in LabVIEW software, automated serial measurements within the established DC voltage range, up to hundred volts. Measurements were repeated several times to obtained averaged values that were saved in a computer memory. The meter automatically changed its range when necessary.

The measurement system enabled to establish the value of U_3 even within a range of tens μV only. The results of measurements were strictly repeatable. When a position of the tested varistor was changed by its rotation the maximal difference between the results of U_3 measurements didn't exceed 3%. This means that we can apply the prepared head with five electrodes for the measurement of devices without metallized contacts on their surfaces. This method is simpler, cheaper and quicker in comparison with destructive leakage current measurements.

EXPERIMENTAL RESULTS

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.

At the first stage, a third harmonic index of some specimens was measured within a voltage range 10÷100 V of the harmonic excitation signal amplitude U_1 (Fig. 9).

The exponential dependence between U_1 and the measured third harmonic component U_3 was observed. Varistors from the high quality batch exhibited on average slightly lower exponent around 2 when compared with the results observed in the low quality batch. Additionally, high quality varistors had on average larger value of the THI than measured in the latter group. This outcome is in a good agreement with the observed differences in DC current-voltage characteristics for both batches. A more linear DC characteristic at low voltage range for low quality batch means lower third harmonic component that begins to rise faster (higher exponent) when compared with behaviour observed for high quality specimens. Thus, we decided to set for a numerous

survey measurements of third harmonic index an amplitude $U_1=100$ V of the applied sinusoid.

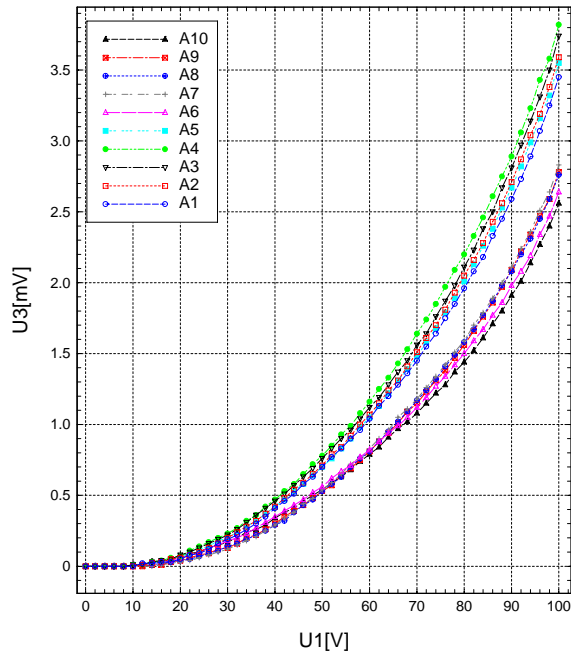


Fig. 9: U_3 vs U_1 for 440 V samples; A1 ÷ A5 higher quality, A6 ÷ A10 poor quality

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 680V. The statistical data for the series 280V without metallization has been shown in Fig. 10.

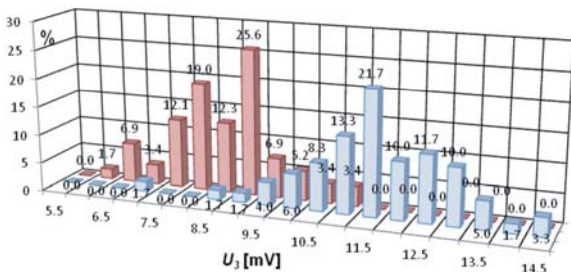


Fig. 10: Distribution of third harmonic component U_3 observed at excitation signal of amplitude $U_1=100$ V within low and high quality varistor batches without metallization for series 280V

The high quality batch exhibits on average significantly higher third harmonic component value. A difference between these averaged values is up to 30%.

The somewhat less evident difference was observed for series 440V. Even smaller difference was identified for the series 680V. This result arises from the alterations in their DC current-voltage characteristics. Series that are prepared for higher voltages start to bend their DC characteristic at relatively higher voltages. It means that an arbitrary chosen value of $U_1=100$ V seems to be right only for a series that was prepared for the lowest threshold voltage 280V. It is worth to mention that even higher voltage U_1 does not increase significantly power

consumption during tests. The results for the same volume batches of samples 440V but with metallization are shown in the Fig. 11.

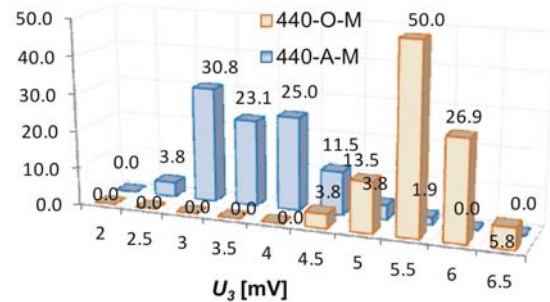


Fig. 11: Distribution of U_3 observed at $U_1=100$ V for series 440V with metallization

Another problem of the proposed method of varistors diagnostic that should be considered is a time interval that is necessary for acquiring repeatable measurement results. When varistors didn't have metallized contacts on their surfaces time of measurement extends up to a few seconds. Time decreases significantly below this period when printed metal contacts were produced before measurement.

CONCLUSION

A proposed new method of varistor quality and endurance testing 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 higher excitation signal to achieve sufficiently high variety of this parameter. This method could be applied for quality detection of other grainy materials that are subject of thorough research if they exhibit sufficient nonlinearity.

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