Diagnostics of High-Voltage Varistors by Acoustic Emission

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Abstract

Varistors, widely used in surge arresters, have to be tested at the final stage of their production. The existing testing methods demand a usage of high voltages and intensive currents that is inconvenient, destructive and needs extensive power consumption. Application of an acoustic emission signal analysis for prediction of varistor quality has been proposed in the paper. The system prepared for this purpose was described and the results of measurements were analyzed and compared with other non-destructive testing methods.

Introduction

Non-ohmic ceramic devices (also known as metal-oxide varistors) are commonly-used cheap electronic devices applied in electrical systems as solid state switches with large energy handling capabilities designed for protection against excessive voltage shocks. Their current-voltage characteristics is strongly non-ohmic and therefore they can be used to shunt a current created by this voltage away from the sensitive elements in a system. Varistors are polycrystalline materials, multi-junction semiconductor devices are usually produced from zinc oxide (ZnO) cylindrically-shaped structures made by sintering ZnO powder with other metal-oxides of small amount. Their quality depends on technological conditions at stages of their shape forming and firing. The sintering process gives rise to a structure which consists of ZnO grains surrounded by very thin insulating intergranular layers. The structure has nonlinear characteristics attributed to the formation of double Schottky barriers at the ZnO grain boundaries.

According to the industry standards they should be tested at the final stage of production by measuring their leakage current at sufficiently high voltage. These tests are expensive and time consuming. A new method of non-destructive varistor testing before contact metallization is strongly needed. We had used for this purpose a few such methods: measurement of nonlinearity by means of Third Harmonic Index (THI) [1], Resonant Ultrasound Spectroscopy (RUS) [2-4], Electro-Ultrasonic Spectroscopy [5] or inherent low-frequency noise measurements [6]; now an Acoustic Emission (AE) phenomenon as a diagnostic tool.

In this exploratory study the utilised system and experimental results that substantiate the proposed method has been described. The experiment was performed on two batches of ZnO structures, named as lower and good quality due to different ways of their preparation. The acquired experimental data were analysed and the results were compared to effects of other methods (especially to RUS) of lower quality items detection.

Varistor structure samples

Varistors are produced from zinc oxide in a matrix of other metal oxides (bismuth, cobalt, manganese) [4]. The material mixture is cylindrically shaped in a press and fired later at high temperature, when ZnO aggregates into grains. The aggregation process depends on how the used materials are mixed and squeezed. Variations of technological parameters during these processes lead to various grain size that determines contacts between the grains and the final current-
voltage characteristic. Then, metal contacts are made on both sides and the product is ready for packaging.

It is known that large grains of ZnO can be characterised by highly non-linear contacts between them. When grains are smaller, the contacts are weakly non-linear or even ohmic only[1].

In the experimental phase some pieces of varistor structures before metallization for 280 V, 440 V and 660 V have been accurately selected from two sets of samples: a good quality and produced with defected structure one. They had each other quite different alternative parameters and characteristics (nonlinearity index, structure parameter tested by resonant ultrasound spectroscopy, granulation observed by Atomic Force Microscope)) deciding on their quality.

Two batches of ZnO structures were prepared with significantly different grain types to assure material for the detailed measurements of two various groups – one with tiny grains was marked as a poor quality group (“A”), and the latter with larger grains was marked as a good one (“O”).

Three types of varistors having different voltage threshold (280 V, 440 V and 680 V) have been measured. All varistors have the same diameter (30 mm with a tolerance 0.5 mm – Fig.1) but higher voltage thresholds were obtained for thicker samples (3 mm, 4 mm and 5 mm, respectively) [7].

Two batches of samples 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 an each batch as a result of changes introduced artificially into the material composition. It had impact on their DC current-voltage characteristics [1]. Therefore, one of the batches could be treated as a group of lower quality varistors – with higher leakage currents.

When ZnO grains were squeezed, various pressures resulted in a different grain size after firing. This operation provided a sufficient number of low quality ZnO structures that are not so abundant during standard production.

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 [2]. 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 µm × 50 µm are shown in Fig. 2.
Marked differences in grain structures between higher (denoted as „O“) and lower quality (denoted as „A“) samples can be seen.

Due to a long-time AE measurement cycle, only a few samples of varistor structure for every voltage before their surface metallization have been accurately selected. They had quite different values of a Third Harmonic Index (THI as $U_3/U_1 \times 10^5$) for 100V [1] and a parameter $Q$ [6] (Table 1). The parameter $Q$ was evaluated by means of RUS on the basis of the values of resonant frequency $f_r$ and actual dimensions of the investigated varistor. Taking into account that the resonant frequency $f_r$ depends directly on varistor dimensions, the following relation to calculate the parameter $Q$ was applied [8]:

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

where: $w$ – a width of a varistor [m],
$d$ – a diameter of a varistor [m].

<table>
<thead>
<tr>
<th>Nominal varistor voltage</th>
<th># sample</th>
<th>$U_3/U_1 \times 10^5; U_1 = 100V$</th>
<th>$Q = f_r \sqrt{(w^2 + d^2)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>280 V</td>
<td>O14</td>
<td>13.2</td>
<td>5235</td>
</tr>
<tr>
<td>280 V</td>
<td>A98</td>
<td>5.9</td>
<td>5098</td>
</tr>
<tr>
<td>440 V</td>
<td>O56</td>
<td>13.6</td>
<td>4594</td>
</tr>
<tr>
<td>440 V</td>
<td>A79</td>
<td>6.95</td>
<td>4492</td>
</tr>
<tr>
<td>660 V</td>
<td>O30</td>
<td>10.2</td>
<td></td>
</tr>
<tr>
<td>660 V</td>
<td>A29</td>
<td>6.65</td>
<td></td>
</tr>
</tbody>
</table>

**AE measurement system**

The samples was measured using a specially prepared system (Fig. 3) with varied linearly in time a mechanical stress enabling to register ultrasonic signals emitted during pressing the ZnO sample and detected by a piezoelectric sensor and saved by a Vallen AMSY-5 recorder. The system registered in parallel the signal from the tensiometer circuit proportional to the value of comprehensive stress.
An AE signal emitted by the tested varistor was sampled on the output of the piezoelectric sensor with the sampling rate $f_s = 8$ MHz by means of the VALLEN AMSY-5 recorder. The signal acquisition during a fixed time period started when an instantaneous value of AE signal exceeded a settled threshold level. The source of a tension in the measurement system (Fig. 4) was a water container filled with an established low rate ensuring a linear dependence of tension in time.
Besides of ultrasonic signals the measurement system recorded tensometric signal proportional to an instantaneous value of a tension submitted to a tested varistor sample. To reduce the clicks appeared between the sample under test and metallic parts of the construction on account of a small contact area a special plexiglas separators matched to the dimensions of tested varistors have been used (Fig. 9).

**AE signals**

The registered waveforms were quite typical for AE signals having a shape of harmonic oscillations with a specific amplitude modulation (Fig. 10a). The short-time power spectral density (PSD) of these signals had typically the local maxima near frequencies about 300 kHz and 500 kHz (Fig. 10b).

![Fig. 10. Typical AE waveform of measured varistor structures (a) and its PSD (b)](image)

**Measurement results**

In Fig. 11 and in Fig.12 the exemplary normalized energy of registered AE signals in time (from the very beginning of a measurement for the zero value of tension) versus linear changes of tensions stressed on tested varistor structures have been shown. Additionally, the values of measured THI (the ratio of third harmonic to the value of stimulated voltage) for the tested samples have been denoted on all below figures.

![Fig. 11. Total energy (normalized) of AE signal in time (dotted lines) for linearly increasing tension (solid lines) for varistor structures on 280 V: a – lower quality (sample #A98), b – good quality (sample #O14)](image)
Fig. 12. Total energy (normalized) of AE signal in time (dotted lines) for linearly increasing tension (solid lines) for varistor structures on 660 V: a – lower quality (sample #A29), b – good quality (sample #O30)

From the results visualized on these charts we can conclude that samples with a good quality (denoted as “O”) emit ultrasound signals having energy more linearly depended on the load than samples with lower quality (“A”) starting with an emission at a higher level of a tension. It results from the inherent varistor structure properties. Samples with poor quality have more grains ensuring an ohmic contact on grain boundaries (see Fig. 2). On the contrary, good quality varistors have many more grains forming on a boundary nonlinear connection. Therefore samples with poorer quality should be more plastic than the good ones having better elasticity.

In Fig. 13 exemplary power spectral densities (PSD) of registered AE signals during a load increasing from 0 kG to 25 kG have been presented.

Fig. 13. Exemplary power spectral densities of AE signals: a – varistors on 280 V, b – varistors on 440V; dotted lines – lower quality samples

The results do not enable to predict explicit conclusions about samples quality. A little higher level of PSD in some frequency intervals has been observed for samples prepared as less homogeneous.

More unambiguous conclusions can be received from estimators of probability density of AE signals (Fig. 14).
Fig. 14. Measured normalized estimators of probability densities $x(t)$ for varistors on 440 V (a) and 660 V (b); $\sigma_x^2$ – variance of registered AE signals, solid lines – lower quality samples

Samples prepared as more imperfect had greater values of $p(x)$ for relatively higher level of AE amplitudes because of having more grains giving ohmic contacts and more elastic properties. These items under the exterior stress emitted ultrasound signals having relatively great instantaneous values only after prior compressing of elastic areas. Good samples having more “linear” grains were more resilient.

Conclusions

The presented results show that an analysis of AE signals can be a source of useful information for a quality estimation of varistor structures. In this work we have tested only samples with lower quality prepared in a one way, having no cracks or other impurities inside. In other cases the results could be probably more spectacular. However taking into account a very long time of measurement and processing of recorded data, they can be helpful only in a laboratory investigation to verify results achieved using other method of quality prediction.

References

7. Surge arresters GXO-LOVOS-5/10 kA. Data sheet LVA/06/02. ABB Poland.