DEGRADATION DUE TO ENERGY PULSE IN HIGH-ENERGY ZnO VARISTORS

Zhang Shugao Huang Baiyun Fang Xunhua

(Powder Metallurgy Research Institute, Central South University of Technology, Changsha 410083, China)

Ji Youzhang

(Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China)

Abstract The degradation phenomena due to the energy pulse in the high-energy ZnO varistors used for de-exitation and overvoltage protection of hydroelectric generator are investigated. The energy pulse, obtained by releasing the energy stored in an inductor, can be equivalent to the combination of the DC field components and the energy component. The variations of the characterized voltages, nonlinear coefficients and pre-breakdown $V-A$ characteristics, increase with the number of the applied energy pulse. The asymmetrical variations of the electric properties of the high-energy ZnO varistors after the energy pulse arise from the deformation of the double Schottky barriers due to the ion migration occurring in the depletion layer and in the grain boundary.

Key words high-energy ZnO varistors; energy pulse; degradation; $V-A$ characteristics; grain boundary barrier; ion migration

ZnO varistors have been extensively applied to electronic and electric systems as energy surge absorber since they were invented in 1968[1~4]. It has been a commercially successful technology to use high-energy ZnO varistors for de-exitation and overvoltage protection of hydroelectric generator. When applied in this way, the varistors have to be subject to a continuous electric stress and to a discontinuous energy pulse, which cause a static degradation and a dynamic degradation in the high-energy ZnO varistors, respectively[5~7]. The static degradation due to the DC stress[5], AC stress[5,10] and SCRV stress[5] has been investigated by many researchers, and several mechanisms have been proposed to explain the observed degradation phenomena, e.g. electron trapping[11], oxygen desorption[12], ion migration[13,14] and linear chain[5,15]. Additionally, the studies on dynamic degradation under pulse stress have also been reported[16,17]. For example, the degradation due to the current pulse with the waveform of 8/20$\mu$s was presented in Ref. [16]. The work in this paper is presented about the degradation in the high-energy ZnO varistors due to the energy pulse obtained by releasing the energy stored in an inductor.

1 EXPERIMENTAL METHODS

1.1 Preparation of Samples

The high-energy ZnO varistors are different from the common ones mainly in that they have the different grain size, i.e. the former have larger grain size than the latter, which could be realized by adding the grain-promoting agent such as TiO$_2$ and the semiconducting agent such as Al$_2$O$_3$ to the composition of the common ZnO varistors. The disc shape samples with the diameter of 90 mm and the height of 10 mm are prepared with the conventional technique for electronic ceramics. The details of the technique can be seen in Ref. [5].

1.2 Generation of Energy Pulse

The energy pulse is obtained by releasing the energy stored within a hollow inductor with the inductance of 0.89H, as demonstrated in Fig. 1.
this figure, when the switch connected, the inductor is charged by the rectifier and stored with the energy of $0.5LI$ (where $L$ is the inductance and $I$ is the charging current), and when the switch disconnected, the inductor begins to release the stored energy to the high-energy ZnO varistors, resulting in an energy pulse. The resultant surge current flowing through the varistor and the corresponding voltage across the varistor are measured by means of the resistors, $R_x$ and $R_z$, respectively, the time-dependance of current $i$ and voltage $u$ are expressed as:

$$i = I_0(1 - t/\tau)^{\beta/\nu}$$
$$u = U_0(1 - t/\tau)^{\beta/\nu}$$

where $I_0$ and $U_0$ are constants, $\tau$ is the energy-releasing time, and $\nu$ is the reciprocal of the nonlinear coefficient of the varistor. The energy $W$ absorbed by the varistor is calculated by the formula

$$W = \int_0^t u i dt$$

In this study, the current waveform with the surge current of about 200A, corresponding to the energy of about 17 kJ absorbed by the varistor, and the voltage waveform with the voltage of about 460 V and the surge duration of about 400 ms, are schematically shown in Fig. 2. The total number of the applied energy pulse is 40 times. Between two times enough time is allowed to cool down the varistor to the room temperature (30 °C), and the characterized voltages as well as the V-A characteristics are measured.

1.3 Measurement of $U_{1mA}$, $U_{10mA}$ and Pre-breakdown V-A Characteristics

The characterized voltages, $U_{1mA}$ and $U_{10mA}$, are defined to be the voltage crossing the varistor at the current of 1mA and 10 mA (corresponding to the current density of 0.016 mA/cm² and 0.16 mA/cm² with respect to the samples employed in this study) flowing through the varistor, respectively, and are measured with the DC field. The nonlinear coefficient $\alpha$ is calculated by the equation

$$\alpha = \left[\frac{\log U_{1mA}/U_{1mA}}{\log U_{10mA}/U_{10mA}}\right]^{-1}.$$  

The pre-breakdown V-A characteristics are obtained by measuring many groups of current and voltage with the DC field. The measurement in the forward direction is made by the DC field with the same polarity of the surge current, meanwhile, that in the reverse direction is made by the DC field with the opposite polarity.

2 RESULTS

2.1 $U_{1mA}$, $U_{10mA}$ and $\alpha$

The values of $U_{1mA}$, $U_{10mA}$ and $\alpha$ as well as their variations in the forward direction corresponding to the pulse number of 0, 10 and 40 times, respectively, are shown in Table 1. This table indicates that the $U_{1mA}$, $U_{10mA}$ and $\alpha$ change to smaller values after the energy pulse, and that the variations increase, but the change rates decrease, with the pulse number.

<table>
<thead>
<tr>
<th>pulse number</th>
<th>$U_{1mA}$ (V)</th>
<th>$\Delta U_{1mA}$</th>
<th>$U_{10mA}$ (V)</th>
<th>$\Delta U_{10mA}$</th>
<th>$\alpha$</th>
<th>$\Delta \alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>306</td>
<td>334</td>
<td>-6.2%</td>
<td>328</td>
<td>-1.8%</td>
<td>17.2</td>
</tr>
<tr>
<td>10</td>
<td>287</td>
<td>-8.5%</td>
<td>325</td>
<td>-2.7%</td>
<td>15.4</td>
<td>-41.4%</td>
</tr>
<tr>
<td>40</td>
<td>280</td>
<td>-6.2%</td>
<td>328</td>
<td>-1.8%</td>
<td>17.2</td>
<td>-34.6%</td>
</tr>
</tbody>
</table>

2.2 Pre-breakdown V-A Characteristics

The variations of the pre-breakdown V-A characteristics with the pulse number are shown in Fig. 3. This figure indicates that, (1) The V-A characteristics in the forward direction move to the lower position, i.e. the variation is negative, after the energy pulse is applied. (2) The variations increase, but the change rates decrease, with the pulse number. (3) The variations of the V-A characteristics at smaller current region both in the forward direction and in the reverse direction are larger than that at larger current region, and the variation of the V-A characteristics in the reverse direction even begins to be positive at a certain larger current (about 9mA in this study). (4) The variations of the pre-breakdown V-A characteristics at smaller current region in the reverse direction are