Scattered Phenomenon of Energy Absorption Capabilities of ZnO Varistors

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Abstract: A comprehensive review for the scattered phenomenon of energy absorption capabilities of ZnO varistors was presented in this paper. The pronounced and complex scattered phenomena were revealed according to experiments under varied test conditions. Those experiment phenomena were well explained by numerical simulations with microscopic circuit and heat transfer models of ZnO varistor based on Voronoi network. Furthermore, the methods to weaken the current localization and improve the energy absorption capability of ZnO varistor were also analyzed.

Key words: ZnO varistor, energy absorption capability, nonuniformity, impulse current, current concentration

INSTRUCTION

Due to their good nonlinearities[1], low residual voltages and high energy absorption capabilities, ZnO varistors are wildly used as surge absorbers in kinds of electrical and electronic systems.

In high voltage power systems, ZnO arresters, made up of ZnO varistors, are generally accepted as key components for protecting against overvoltages and decreasing system insulation levels. In China, the UHV power system is being researched at present and to be constructed in the near future. Regarding the UHV system, the overvoltage level, which is decided by the residual voltages of ZnO varistors, plays an extra important role in its economical construction and reliable running. On the other hand, the UHV transient surge voltages and currents are definitely remarkable, which result in huge energy to be withdrawn by ZnO varistors during lightning and switching overvoltages.

The absorbed energy by ZnO varistor can be derived by

\[ E = \int_{0}^{T} vi dt \]

where, \( v \) is the applied voltage on ZnO varistor, \( i \) is the current through it; and \( T \) is the time duration of current.

The energy absorption capability usually is referred to the permitted energy absorbed by unit volume of varistor, measured in J/cm³. In order to discharge more energy, ZnO varistors with larger sizes are necessary for the UHV system. However, in enlarging the ZnO varistors for higher overvoltage level, the scattered phenomenon of energy absorption becomes a more serious problem [2-5]. In this paper, we would give out a more comprehensive review of scattered phenomenon of energy absorption capabilities of ZnO varistors, focusing on detailed analysis with experimental results and numerical simulations.

THE SCATTERED PHENOMENA OBSERVED FROM EXPERIMENTS

Commercial ZnO varistors manufactured by one high voltage electrical porcelain company from China were used for experiments.

Firstly, the energy absorption capabilities of those ZnO varistors with diameter of 52 mm and height of 10 mm were measured under different applied current waveforms, including 8/20 μs lightning current, 2 ms and 8 ms impulse square current, and 50 Hz AC. Regarding the experimental results shown in Fig. 1, the scattered phenomenon could be found under each current waveform, and such phenomenon became more pronounced while the time duration related to the current waveform increased. The average energy absorption capabilities were also diverse under different current waveforms, behaving a U-shape curve according to the time duration of current waveform.

In addition, the energy absorption capabilities of those ZnO varistors with different sizes were measured under 2 ms impulse current. The sizes of one group of tested varistors were 52 mm in diameter and 10 mm in height.
while those of another group were 32 mm and 10 mm respectively. As shown in Fig. 2, the increment of the varistor surface area resulted in the reduction of the energy absorption capability, along with the more pronounced scattered phenomenon.

![Graph showing energy absorption capability of ZnO varistors](image)

**Fig. 2.** The energy absorption capability of ZnO varistors with different sizes.

![Diagram illustrating impulse destruction of ZnO varistors](image)

**Fig. 3.** The impulse destruction of ZnO varistors.

According to the definition of the energy absorption capability, ZnO varistor would be damaged once the energy absorbed by varistor exceeds its permitted capability. Four different destruction phenomena under impulse current were observed during experiments, illustrated as Fig. 3. In following, phenomenon (a) and (b) were classified as puncture destruction, while phenomenon (c) and (d) as cracking destruction.

**Table 1.** The test conditions for the impulse destruction phenomena of ZnO varistors.

<table>
<thead>
<tr>
<th>Test Sample</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impulse Square Current</td>
<td>Duration (ms) 2</td>
<td>8</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Intensity (A/cm²)</td>
<td>30.3</td>
<td>12.3</td>
<td>29.3</td>
</tr>
<tr>
<td>ZnO Varistor</td>
<td>Diameter (mm) 32</td>
<td>32</td>
<td>52</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td>Height (mm)</td>
<td>8</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Tested Number</td>
<td>30</td>
<td>32</td>
<td>24</td>
</tr>
</tbody>
</table>

When the varistors were tested under the conditions of Table 1, their destruction phenomena were also scattered as the results in Fig. 4. The puncture destruction was dominant under low impulse currents with long time duration, and the cracking destruction preponderated under high impulse currents with short time duration.

All above experimental results had revealed that there were pronounced and complex scattered phenomena of energy absorption capabilities of large-size ZnO varistor samples under varied test conditions. Such phenomena were quite different from the test results of small-size ZnO varistors, which had showed no scattered property [2].

**Fig. 4.** The destruction ratios of ZnO varistors.

**NUMERICAL SIMULATION ANALYSIS**

It is already well-known that the current localization phenomenon of ZnO varistors was the crucial important fact for their energy absorption capabilities. Such current localization phenomenon is mainly due to the nonuniformity of microstructures and electrical characteristics of ZnO varistors, such as grain sizes and barrier voltages. The Voronoi network was used to simulate the microstructures of ZnO varistors and study the current localization phenomenon [5].

![Diagram illustrating Voronoi cell structure](image)

**Fig. 5.** The Voronoi cell structure with different values of disorder parameter $d$.

![Diagram illustrating microscopic circuit and heat transfer models](image)

**Fig. 6.** The microscopic circuit and heat transfer models of ZnO varistor based on Voronoi network.

However, the existent study conclusions have not revealed and can not exactly explain the scattered phenomenon of absorption capabilities of large-size...
ZnO varistors observed from our experiments. Similarly, Voronoi cell structure was used to simulate the microstructure of ZnO varistor as Fig. 5. Based on such simulated microstructure, the microscopic circuit and heat transfer models of ZnO varistor were given as Fig. 6. Then, the further simulations for characteristics of ZnO varistors with different parameters under varied experiment conditions was carried out.

![Simulated current localization phenomena](image1)

**Fig. 7.** The simulated current localization phenomena.

![Current localization ratios](image2)

**Fig. 8.** The current localization ratios of ZnO varistors with different disorder parameters.

![Current localization ratios with distributed barrier voltage variances](image3)

**Fig. 9.** The current localization ratios of ZnO varistors with distributed barrier voltage variances.

The current localization phenomena of ZnO varistors could be easily found according to the simulated results as Fig. 7, while the extent of current localization was quite diverse under varied test voltage grads. The current localization ratio $J_{\text{max}}/J_{\text{av}}$ was defined to represent the diversity of the current localization phenomena. Here, $J_{\text{max}}$ was the maximum value of the current density $J$ inside ZnO varistor and $J_{\text{av}}$ was the average value of $J$. Figs. 8 and 9 described the current localization ratios of ZnO varistors with different disorder parameters and distributed barrier voltage variances respectively under varied test voltage grads.

In both conditions, the current localization ratios decreased against the test voltage grads rising above 3 kV/cm. The higher the test voltage grads are, the lower the current localization is, which brought on a lower extent of the scattered phenomenon of energy absorption capability of ZnO varistor. It quite fitted what illustrated in Fig. 1, where shorter time duration of the applied current waveform with higher voltage resulted in less scattered phenomenon of energy absorption capability. As a further conclusion, the current localization could be weakened by enhancing the uniformity of ZnO grain sizes and its barrier voltages, while the first method was more viable and effective comparatively.

![Maximum temperature rise of ZnO varistors](image4)

**Fig. 10.** The maximum temperature rise of ZnO varistors with different disorder parameters.

![Maximum thermal stress of ZnO varistors](image5)

**Fig. 11.** The maximum thermal stress of ZnO varistors with different disorder parameters.

![Maximum temperature rise of ZnO varistors with different grain sizes](image6)

**Fig. 12.** The maximum temperature rise of ZnO varistors with different grain sizes.
However, the current localization ratios could not directly explain the scattered destruction phenomena of ZnO varistors in Fig. 4 and their U-shape energy absorption capabilities in Fig. 1. Thus, the temperature rise and thermal stress of ZnO varistors under varied conditions were simulated based on aforementioned microscopic models. From Fig. 10 to 13, the maximum temperature rise and thermal stress of ZnO varistors with different disorder parameters and grain sizes under impulse square current were illustrated respectively.

During the first instant time duration, the maximum thermal stress increased more rapidly to exceed the permitted capability, rather than the maximum temperature. Thus, the cracking destruction generated by excessive thermal stress is dominant under high impulse currents with short time duration as shown in Fig. 4. Under such conditions, the current localization ratio would play a dominant role to the energy absorption capability. Therefore, that the capability increases when the impulse current becomes higher and its duration time becomes shorter as left half of U-shape curve in Fig. 1, is due to a lower current localization ratio.

When the time duration became longer, the maximum thermal stress approached its saturation, while the maximum temperature rise increased continually. Hence, the puncture destruction by excessive temperature rise became main factor under low currents with long time duration as shown in Fig. 4. Under such conditions, the current time duration had an important effect on heat transfer inside ZnO varistor, so the energy absorption capability increased when the impulse current became lower and its duration time became longer as right half of U-shape curve in Fig. 1.

Furthermore, the energy absorption capability of ZnO varistor could be improved by enhancing uniformity of ZnO grain sizes or reducing their sizes, while the second method was more viable and effective.

CONCLUSIONS

The pronounced and complex scattered phenomena were revealed according to experiments about energy absorption capabilities of large-size ZnO varistor samples under varied test conditions. The scattered phenomenon became more serious while the time duration of the applied current waveform or the size of ZnO varistor increased. But the average energy absorption capabilities behaved a U-shape curve related to the time duration of current waveform. The scattered destruction phenomena of ZnO varistors were also found, while the puncture destruction was dominant under low impulse currents with long time duration, and the cracking destruction prepondered under high impulse currents with short time duration.

Those experiment phenomena were well explained by the numerical simulations with microscopic circuit and heat transfer models of ZnO varistor based on Voronoi network. Under high test voltage grads, the current localization ratios decreased against the voltage grads rising. During instant time duration, the maximum thermal stress increased more rapidly to exceed the permitted capability than the maximum temperature, while the maximum temperature rise played an important role during longer time duration.

What’s more, the current localization could be weakened by enhancing the uniformity of ZnO grain sizes and its barrier voltages, while the energy absorption capability of ZnO varistor could be improved by enhancing uniformity of ZnO grain sizes or reducing their sizes.

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