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Nonuniformity of Energy Absorption Capabilities of ZnO Varistors

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The nonuniformity of energy absorption capability of ZnO varistor is systematically discussed in this paper. The nonuniformity of electrical characteristics and microstructure leads to decrease the energy absorption capability of ZnO varistor. The energy absorption capabilities were measured under different current waves, the experimental results stated that they have highly scattered phenomena. The influences of varistor surface area and nonuniformity of electrical characteristics to the energy absorption capability and the nonuniformity of commercial ZnO varistors were analyzed There is a high nonuniformity existing in the energy absorption capability of commercial ZnO varistors

Key words : ZnO varistor, Energy absorption capability, Nonuniformity, Impulse current, Current concentration

I. Introduction

Since Matsuoka *et al.*[1,2] reported the non-ohmic characteristics of ZnO ceramics, ZnO varistors have been being studied in wide and different aspects. Martusoka,[3] Eda,[4,5] Gupta,[6] Sumiyoshi,[7] Levison and Philipp,[8] Einzinger,[9] and Greuter *et al.*[10] published a series of very good reviews on the progresses in fabrication technology, application, conduction and degradation mechanisms and electrical characteristics of ZnO varistors. ZnO varistors consist of ZnO polycrystalline sintered bodies with a few mole percent of additives such as Bi_2O_3, CoO, MnO and Sb_2O_3. ZnO varistors have good nonlinearity, low residual voltage and high energy absorption capability. The nonlinearity of ZnO varistor is caused by the grain boundaries in the polycrystalline sintered bodies. The nonlinear current(I)-voltage(V) characteristics of ZnO varistor is similar to two back-to-back Zener diodes, which limits overvoltages in both polarities and can be used in ac, dc and surge fields over a wide range of voltages. ZnO varistors are easy to realize the insulation coordination between them and the protected devices, the safe margin is increased and the overvoltage level endured by protected devices is decreased, so they are widely used to protect power apparatus and electronic devices and systems from dangerous voltage surges.

But differences of barrier voltage, grain size, grain boundary characteristics, and energy absorption capability in the same ZnO varistor and among different ZnO varistors have been observed from experimental results, which are caused by the nonuniformity of ZnO varistors. Due to the nonuniformity, the current handling capability, energy absorption capability and the electrical characteristics of ZnO varistors are lowered. In high voltage system, ZnO varistors with large sizes and heights are needed to decrease the insulation level of power system. However, in enlarging the varistor, the nonuniformity of electrical characteristics caused by density, grain size and barrier voltage distribution and other factors, becomes a serious problem, which leads to decrease the energy absorption capability of ZnO varistor.

The purpose of this paper is to discuss the nonuniformity of energy absorption capability of ZnO varistors. In our knowledge, the systematic discussion on this field can not be found in literature.

II. Experiment Arrangement

The primary function of ZnO varistors is to discharge the transient surges and limit the overvoltage to a level that is not harmful to the protected electrical devices and systems. The energy absorption capability is the secondly most important property of ZnO varistors next to nonlinearity.[6] The absorbed energy E by ZnO varistor can be derived by the following integral:

$$E = \int_0^T vidt , \qquad (1)$$

here, v is the applied voltage on ZnO varistor and i is the current through it, 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/cm^3. In ordinary, the permitted energy is the one which leads varistor failure.

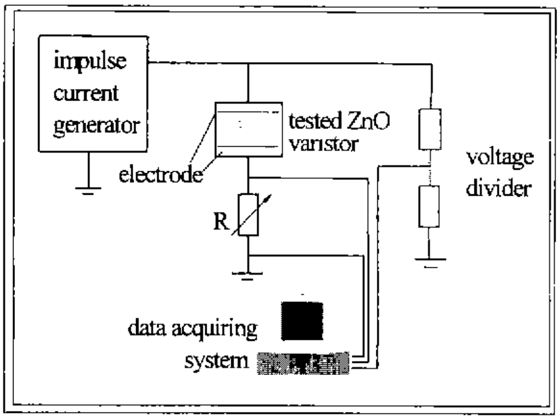

Fig. 1. The test system of the energy absorption capability.

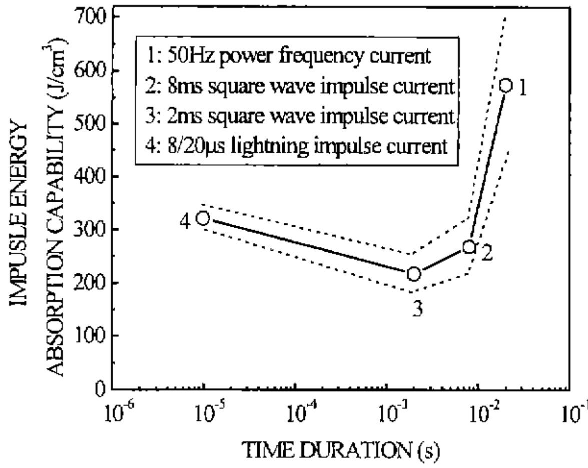

Fig. 2. The relationship between the energy absorption capability and the time duration of applied current.

The test system of the energy absorption capability is illustrated in Fig. 1, 50 Hz AC current and impulse currents with different time durations were applied to commercial ZnO varistors which were manufactured by Xi'an High Voltage Electrical Pocerlain Company. The current was obtained from the measured voltage of the small resistance R and the voltage was obtained from the voltage divider and the energies absorbed by ZnO varistor were calculated. Two types of disk-shape varistors with different sizes were tested, one has a diameter of 52 mm and a height of 10 mm, another has a diameter of 32 mm and a height of 10 mm.

III. Nonuniformity of Energy Absorption Capability of ZnO Varistors

The energy absorption capability is directly relative to the current waves. And we had measured the energy absorption capability of commercial disk-shape ZnO varistors with a diameter of 52 mm and a height of 10 mm under different current waves. When a low current with a long time duration was applied to a ZnO varistor, the energy absorption capability is very high We used 2 A/cm^2 50 Hz power frequency current to test the ZnO varistors with a size of 52×10 mm, the energy absorption capability is in the range between 450 and 700 J/cm^3, the results are largely scattered. When square wave impulse currents with 2 ms and 8 ms time durations were applied to ZnO varistors with the same size, the limited impulse energy absorption capabilities are 216 J/cm^3 and 269 J/cm^3, respectively. The limited impulse energy absorption capability under 8 ms time duration is higher than that under 2 ms time duration, the ratio under 8 ms and 2 ms is 1.2. The impulse energy absorption capability under long time duration is higher than that under short time duration When low current with long time duration is applied to the varistor, the generated heat in one part of varistor could be uniformly conducted to the whole varistor and the surroundings, so the phenomenon of overheat in one part is decreased, then the energy to cause the varistor destruction would be increased. When an 8/10 μs lightning current with a magnitude of 15 kA is applied to ZnO varistor with the same size, the limited impulse energy absorption capability is in the range between 309 J/cm^3 and 335 J/cm^3. So when a high current with a short time duration is applied to varistor, the limited impulse energy absorption capability would increase, too. It is perhaps due to the destruction is difficult to be formed in time, then the limited impulse energy absorption capability would be increased.

The tested results are illustrated in Fig. 2, the black line is the average values. The relation between the energy absorption capability and the current time duration is a U-shape curve, the values in the middle is lower than that in two ends. Between the dot lines, it is the measured range of energy absorption capability, high differences exist among different varistors.

It should be pointed out that the impulse destruction is a complicated process, which is related not only to impulse current time duration, but also to the uniformity of microstructure and electrical characteristic and to the accumulation under multiple-impulses. The experimental results stated that there is a highly scattered phenomenon in the test results of energy absorption capability.

IV. Analysis on Nonuniformity of ZnO Varistors Based on Energy Absorption Capability

The impulse energy absorption capability of ZnO varistors is related to their microstructures.[11,12] ZnO varistor is a kind of polycrystalline sintered ceramic, a large number of ZnO grains and grain boundaries in parallel and in series form the sintered body. That is to say, the ZnO varistors are multijunction devices composed of a number of micro-devices connected in parallel and in series. Generally, we would think that a thicker device should have a higher threshold voltage, and a varistor with a larger electrode area should have greater energy absorption capability. But, actually, the sintered polycrystalline is not uniform in the structure, so that the energy absorption capability does not increase proportionally with the electrode area.

Some experimental results on the energy absorption capability has been reported.[11,12] The test results stated that the deviation of the destruction energy is more pronounced for electrodes with larger areas, the energy absorption capability per unit volume decreases as the electrode area increases. The lower energy handling capability and larger deviation of larger area electrode are thought to be caused by the nonuniformity of the sintered ZnO varistors.[11]

We tested 52×10 mm and 32×10 mm disk-shape ZnO varistors when square wave impulse currents with 2 ms time duration were applied to them, the limited impulse energy absorption capabilities are 216 J/cm^3 and 271 J/cm^3 in average, respectively. The surface area ratio of 52×10 mm and 32×10 mm ZnO varistors is 2.64, but the ratio of the absorbed impulse destruction energy by two different kinds of varistors is 2.10 which is less than the surface area ratio 2.64. The experimental results showed that there was not a linear increase of absorbed impulse destruction energy with the increase of the varistor surface area. The energy absorption capability per unit volume decreases when the surface area increases. The larger the surface area of ZnO varistor is, the lower the energy absorption capability is. This phenomenon is due to the nonuniformity in the microstructure of varistor and the nonuniformity of absorbed energies in different portions in the varistor. The nonuniformity in the microstructure includes of the nonuniformities of electrical and thermophysical properties.

The energy absorption capability is related to the time duration of applied current, different applied currents would lead to different failure phenomena. Three failure modes have been classified to date[6]; electrical puncture, physical cracking and thermal runaway. The thermal runaway is related to current and voltage instability. The electrical puncture is caused by current concentration. We think the electrical puncture and physical cracking are related to the nonuniformity.

When a high current with short time duration is applied to a ZnO varistor, the energy is quickly injected into the ZnO varistor and brings a thermal insulated temperature rise process. The temperature gradients exist among different parts in the varistor due to the electrical characteristics of microstructure and the absorbed energies of the varistor vary from part to part. Then huge thermal stresses are formed among different parts in the varistor and lead the varistor to a cracking destruction. When a small current with long time duration is applied to a ZnO varistor, there is a current concentrated phenomenon to cause the grain boundary melted and form a punctured hole due to the electrical property nonuniformity.[11] The energy absorption capability of ZnO varistor leading to puncturing destruction can be analyzed by thermal mechanics.

When a part in a ZnO varistor absorbs energy P, then the thermally insulated temperature rise ΔT is expressed as:

$$\Delta T = \frac{P}{\Delta V \rho C_p}, \tag{2}$$

where, ΔV is the volume of the part, ρ the specific gravity, and C_p the specific heat constant. The specific heat constant C_p at 20°C is 498 J/kg°C, and the specific gravity ρ is 5600 kg/m^3.[22] If the temperature rises of two close parts are ΔT_1 and ΔT_2 respectively, then a thermal stress f would be formed between them[13]:

$$f = \frac{Ea(\Delta T_1 - \Delta T_2)}{1-\mu}, \tag{3}$$

where, a is linear expansion coefficient, μ is Poisson's ratio, and E Young's modules of elasticity. Because the respective values of these parameters for ZnO varistors can not be found in literature, those values for porcelain are used in the following calculation due to the ZnO varistor belongs to porcelain, the selected parameters are a=4.86×10^{-6}/°C, μ=0.30, and E=6.9×10^7 kPa.[23] The critical thermal stress f_c cause varistor cracked was selected in the range between 17.2 and 48.3 MPa,[13] and 17 2 MPa was selected for the calculation.

Because the contact conditions between the surface of a ZnO varistor and the electrode, and the electrical characteristics among different parts in the ZnO varistor are different, the energies absorbed by different parts in the varistor and the energies absorbed by inner parts through the surface parts vary from part to part when a current is applied to it. The energy absorption uniformity S is defined as the ratio of the minimum and the maximum energies absorbed by inner units, when S=1, then the energy absorption of a varistor is very uniform.

It is found from equation (2) that the temperature rise of a part in the varistor caused by absorbed impulse energy is directly determined by the heat capacity ρC_p. But differences of the heat capacity ρC_p exist among different parts in the varistor. So the heat capacity uniformity B is defined as the ratio between the minimum and the maximum values of the heat capacity ρC_p among all parts, $(\rho C_p)_{min}$ and $(\rho C_p)_{max}$, respectively:

$$B = \frac{(\rho C_p)_{min}}{(\rho C_p)_{max}} \tag{4}$$

We define $(\rho C_p)_{av}$ as the average value of $(\rho C_p)_{min}$ and $(\rho C_p)_{max}$, so we can use B and $(\rho C_p)_{av}$ to present $(\rho C_p)_{min}$ and $(\rho C_p)_{max}$. When B and S exist, now the maximum temperature difference between two parts in the varistor would be:

$$\Delta T_1 - \Delta T_2 = \frac{P/S}{\Delta V(\rho C_p)_{min}} - \frac{P}{\Delta V(\rho C_p)_{max}} = \frac{P(1+B)(1-SB)}{2\Delta VBS(\rho C_p)_{av}} \quad (5)$$

From equations (3) and (5), the impulse energy absorption capability P_B of cracking destruction per unit volume caused by the synthetical effect of the energy absorption uniformity and the heat capacity uniformity could be calculated by the following equation:

$$P_B = \frac{2f_c(\rho C_p)_{av}(1-\mu)SB}{Ea(1+B)(1-SB)} \quad (6)$$

The energy absorption capability P_B of cracking destruction caused by the synthetical effect of energy absorption uniformity S and heat capacity uniformity B are illustrated in Fig.3. The actual energy absorption capabilities of the commercial ZnO varistors were tested, which were in the ranges between 216 and 269 J/cm^3 when switching impulse currents were applied to them. So, when B=100%, the energy absorption uniformity S is in the ranges from 63.0% to 68.9%; when B=90%, then S is in the range of 74.0% and 79.2%. When B=100%, the S of the used varistor is in the range of 68.7% and 72.4%. So there are large nonuniformities existing in the energy absorption capability and the heat capacity. The energy absorption capability is seriously affected by the nonuniformity of ZnO varistors, the energy absorption capability of cracking destruction would increase quickly with the improvement of nonuniformity of ZnO varistors.

The heat capacity nonuniformity includes two aspects: firstly, from experimental results,[14] the thermophysical parameters C_p and k are strongly determined by temperature, k is the thermal conductivity. So different parts in varistors have different thermophysical parameters due to the temperatures vary from unit to unit, and the temperature difference is caused by the nonuniformity of absorbing energies by different units. Secondly there are differences of thermophysical parameters ρ and C_p among different parts in the varistors caused in

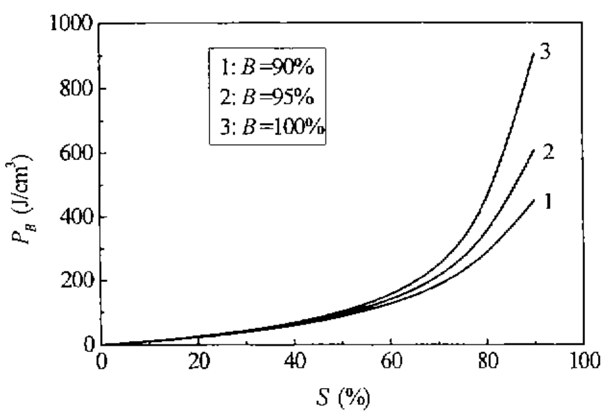

Fig. 3. The energy absorption capability of cracking destruction P_B caused by the synthetical effect of energy absorption uniformity S and heat capacity uniformity B.

the sample preparation and sintering processes.

The nonuniformity of absorbed energies by different parts in a ZnO varistor is caused by the nonuniformity of electrical characteristics of ZnO varistor. Eda[11] measured the distribution of the threshold voltages in ZnO varistors by applying spot electrodes on both lapped surfaces opposite each other. For a typical sample, it has a small region with lower threshold voltage than the other region by 5%, but for a less uniform sample, the region having lower threshold voltage than the other region reaches 11%. Such nonuniformity must lead to current concentration, in the mean time, an energy concentration phenomena will follow the current concentration, and leads to decrease the global energy absorption capability. Energy concentration will cause cracking destruction and small energy absorption capability when a current with short time duration is applied as analyzed above.

In the other hand, the energy concentration because of low threshold voltage will lead to puncturing destruction phenomena when a current with long time duration and high magnitude is applied to ZnO varistor.[11] In this condition, a heat conduction process exists among different portions inside ZnO varistor, and the surface of varistor would transfer heat to the surroundings, the energy concentration causes the temperature of this range having lower threshold voltage than other ranges of the varistor increase quickly, when the temperature exceeds the melting point of grain boundary which is dominated by Bi_2O_3, and the melting point of Bi_2O_3 is around 820°C, then the grain boundary is melted to form a punctured hole through the ZnO varistor. This phenomenon can be simulated by heat conduction process.[11]

Many researchers had measured the barrier voltages of single grain-boundaries in ZnO varistors by different methods,[15-19] a high nonuniformity of barrier voltages exists, e. g. , the measured barrier voltage is in the range between 1.6 V and 6.0 V.[19] Hohenberger *et al.*[20] observed the nonuniformity of 1 mA voltage on different part of the surface of ZnO varistor by a special method. So, it is not difficult to understand there are paths with low breakdown voltages in ZnO varistors.

The area nonuniformity effect F is defined as the ratio of the area with threshold voltage decreasing 5% and the total surface area, if the F is equal to 0, then the deviation of lower threshold voltage in the sample surface would be minimum. The energy absorption capability resulting to puncture destruction by simulating calculation,[24] when 3 kA square wave current is applied to a varistor, is illustrated in Fig. 4 as a function of F. As shown in this figure, the energy absorption capability increases as the area nonuniformity effect F increases. Therefore as the sample area became large, the deviation of lower threshold voltage in the sample increases, so that the deviation of the energy absorption capability resulting to puncture destruction also in-

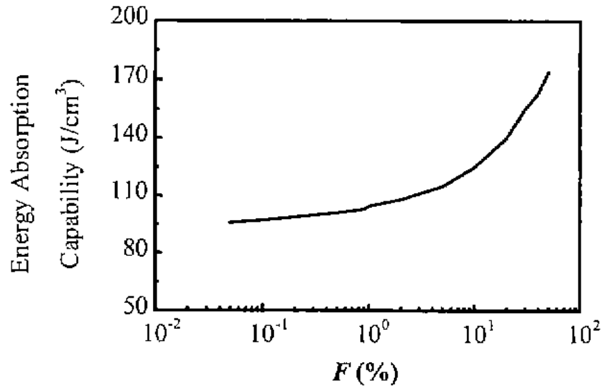

Fig. 4. The effect of area nonunifornity ration F to the energy absorption capability.

creases. These results leads to current and energy concentrations.

In very recent years, Bartkowiak *et al.*[21] simulated the current concentration phenomena by Voronoi network based on the nonuniformity of grain boundaries which is the origin of nonuniform electrical characteristics of ZnO varistors. We use the Voronoi network to analyze the current concentration phenomena, too. An apparent path of current concentration can be observed in the current distribution in Fig. 5, when "good" and "bad" grain boundaries exist in ZnO varistors in arbitrary distribution. In Fig. 5, the gray-level spectrum from white to black represents the relative value of the current passing through a grain, the darker the color in a grain is, the more current passes through the grain. Hohenberger *et al.*[20] observed a nonuniform distribution on the surface of ZnO varistor by galvanic method.

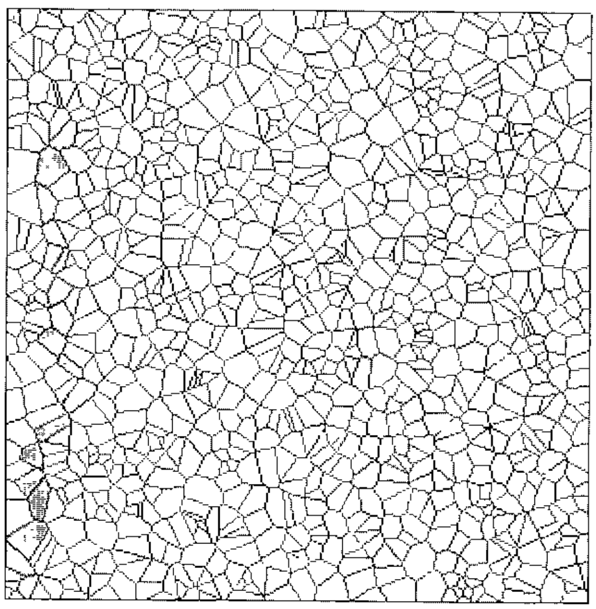

Fig. 5. The current concentration phenomena based on the nonuniform electrical characteristics of ZnO varistor simulated by Voronoi network.

V. Influence of Nonuniformity on Energy Absorption Capability of ZnO Varistors

Mizukoshi *et al.*[12] analyzed the influence of nonuniformity on energy absorption capabilities of zinc oxide elements by monitoring the surface temperature distribution of ZnO varistors with an infrared radiation thermo-camera. Local heating is induced by current concentration in some portion of the varistor. The place where there is a high temperature has a high current through, so where nonuniformity exists. The nonuniformity factor δ is defined as:

$$\delta=\frac{T_{max}-T_i}{T_{min}-T_i} \tag{7}$$

T_{max}, T_{min} are the maximum and minimum temperatures of a ZnO varistor when voltage is applied to it, and T_i is the initial temperature. The highest δ reaches about 1.7. The energy absorption capability reaches about 700 J/cm^3 with the uniform varistors, but when δ=1.7, the energy absorption capability is only 400 J/cm^3. In many cases the punctured area of a varistor agreed with the hot spot in the thermograph, it is felt that the varistor is melt by current concentrations. So when an overvoltage is applied to a ZnO varistor, the portion with the highest nonuniformity first reaches its punctured energy, and the varistor would be broken. There is a difference of 1.5 times between uniform and nonuniform varistors.

We measured the actual energy absorption capability of the commercial ZnO varistors, which were in the range of 218 and 269 J/cm^3 when a switching impulse currents were applied to them, it is only 31.1-38.4% of that of the uniform varistor tested by Mizukoshi *et al.*.[12] So there is a very high nonuniformity existing in our measured commercial ZnO varistors.

Therefore, it is reasonable that the energy absorption capability of a varistor would be largely decreased if it has a high nonuniformity. So, to improve the uniformities of the electrical characteristics and thermophysical parameters of ZnO varistor would largely increase their energy absorption capabilities.

The uniformity of the ZnO varistor could be improved by modification in the forming method, sintering method, cooling method, and materials *et al.*, in the mean time, the surface of ZnO varistor should be very plain, and good contact condition with electrode should be reached.

VI. Conclusions

The nonuniformity of electrical characteristics of ZnO varistors leads to decrease their energy absorption capabilities. The impulse energy absorption capability is directly relative to the impulse current waves. The energy absorption capability of commercial ZnO varistors under different impulse current waves were measured. The relation between energy absorption capability and impulse current time duration is a *U*-shape curve, the values in the middle is lower than that in two ends. The experimental results stated that there is a highly scattered phenomenon in the test results of energy absorption capability. The experimental results showed that there was not a linear increase of absorbed impulse destruction energy with the increase of the varistor surface area. This phenomenon is due to the nonuniformity in the microstructure of varistor and the nonuniformity of absorbed energies in different parts in the varistor. The nonuniformity in the microstructure includes of the nonuniformities of electrical and thermophysical property. As the sample area became large, the deviation of lower threshold voltage in the sample increases, so that the deviation of the energy absorption capability resulting to puncture destruction also increases. These results leads to current and energy concentrations.

The measured actual energy absorption capability of the commercial ZnO varistors is only 31.1-38.4% of that of the uniform varistor. There is a very high nonuniformity existing in the energy absorption capability of our measured ZnO varistors.

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