Influence of Non-uniform Distribution of Grains on Noise Absorption Characteristics of ZnO Varistors

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Keywords : varistor, microstructure, equivalent circuit, simulation, noise absorption

The noise absorbing characteristics of Zinc Oxide (ZnO) varistors were calculated on the basis of non-uniformity of grains. ZnO varistors are well known as surge-protecting arrestors to protect electrical appliances from electrical surge. In recent years, the use of portable electric appliances is increasing in a good number. At the same time the varistors are needed to become smaller and they are getting smaller day by day. Varistors are widely being used in dc motors to protect them from electrical surge; therefore, we discussed the noise absorbing characteristics of a varistor with an impulse voltage caused by switching phenomenon of a dc motor. The purpose of this study is to simulate noise absorption characteristics of a varistor considering the non-uniformity of grains. As the distributions of the grains are not uniform in the varistors, we regarded a part of the internal electrode. A uniform model with 4×4 grains between the internal electrode was made. At the same time, we considered another model with having the non-uniform distributions of the grains. Figure 1 provides the diagram of the models. The points P and Q of Fig.1 showed the connections of model varistors with the dc motor. The noise absorbing properties were calculated by PSpice circuit simulator for these model varistors. We reviewed noises produced by a counter electromotive force generated in inductance of a dc micro motor when the switching phenomenon occurred in the commutator. We also reviewed about the effect of non-uniformity of grains in absorbing noise.

We made an equivalent circuit for each model. The grain was replaced by a low valued resistance (R_2); whereas, the grain boundary was described by a parallel connection of a voltage dependant resistance (R_1) and a capacitance (C). The parameters

Fig. 1. Model structure for both uniform and non-uniform sizes of grains

Fig. 2. Result of the simulation of absorbing noise for the relevant models

of this circuit were determined as to satisfy the electrical characteristics of samples made for experimental purpose. Here, the values of R_2 and C were 0.1Ω and 7.6pF respectively. The values of R_1 were calculated by PSpice simulator as to satisfy with I-V relationship of the sample. I-V relationship of these models were calculated by the PSpice circuit simulator. The varistor voltage (V_b) was 9.37 V for the uniform model; whereas, it was 9.24 V for the non-uniform model.

A noise absorption analysis was performed with PSpice Circuit Simulator for each model described in Fig.1. When the switching phenomenon had occurred in modeled dc motor, we calculated the transient voltage between P and Q (V_{PQ}) of the models shown in Fig.1. The simulation results were shown in Fig.2. When the switch turns off, the produced counter-electromotive force can be seen in the figure. Each varistors absorbed this noise in different manners.

While absorbing the noise, resonance occurred in the non-uniform model comparing to the uniform model shown in Fig.2. Thus the absorption of noise of non-uniform model was deteriorated. To investigate the reason for the deterioration of absorbing noise, we calculated the transient current of each grains for each models. From the simulation results, localized current was found in the non-uniform model while resonance occurred in them.

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Noise absorbing process of Zinc Oxide (ZnO) varistors was analyzed by using equivalent circuit of the sample varistors. Equivalent circuit for the ZnO varistor was proposed by considering the microstructure of a special type of varistor made for the experimental purpose. We considered every grain between the internal electrodes and made an equivalent circuit. The circuit's parameters were determined by PSpice circuit simulator. We regarded a portion of the internal electrode and made a uniform model with a non-uniform model. A dc motor was connected with these models in parallel to investigate the effects of the non-uniformity of the ZnO grains in noise absorbing characteristics of a varistor. Comparing to the uniform model, resonance occurred in the non-uniform model while absorbing noise, and thus the absorption of noise of the model was deteriorated. Transient current was calculated for each grains of these models to investigate the effect the deterioration of noise absorbing characteristics. Localized current was found in the non-uniform model when resonance occurred to absorb transient voltage from our calculations.

Keywords : varistor, microstructure, equivalent circuit, simulation, noise absorption

1. Introduction

ZnO varistors are well known as surge-protecting arrestors to protect electrical appliances from electrical surge. Several papers are reported since M. Matsuoka had discovered it in order to clarify the non-ohmic electrical behaviour of ZnO varistors⁽¹⁾⁽²⁾. However, the electrical behaviour of a varistor is still not understood properly. So, the studies on varistor are being carried out in many countries with several methods⁽³⁾⁻⁽⁶⁾. One of the objective of these studies is to determine the electrical characteristics of a single grain. We discussed a simple method to describe ZnO varistors by an equivalent circuit considering a single grain in other papers⁽⁷⁾⁽⁸⁾. The results are useful to simulate the noise absorbing characteristics of a varistor.

In recent years, the use of portable electric appliances is increasing in a good number. At the same time the varistors are needed to become smaller and they are getting smaller day by day. As a result, the distance between the internal electrodes of a varistor has become smaller and it reflects on the decreasing of the grains. Conventional varistors work as a whole, but it is assumed that the smaller one is different. So, it is important to consider the single grain characteristics to the account.

From the microstructure of a varistor, it is well known that the distribution of grains are not uniform in a varistor. Many researchers worked on the influence of non-uniform grains' distribution on varistor behaviour⁽⁹⁾⁻⁽¹¹⁾. But the previous works were mainly carried out on energy absorption and *I-V* characteristics of a varistor using an impulse current or voltage. As varistors are widely being used in dc motors to protect them from electrical surge; therefore, it is necessary to discuss the noise absorbing characteristics of a varistor with an impulse voltage

caused by switching phenomenon of a dc motor.

The purpose of this study is to simulate noise absorption characteristics of a varistor considering the non-uniformity of grains. As the distribution of the grains are not uniform in the varistors, we regarded a part of the internal electrodes. A uniform model with 4×4 grains between the internal electrode was considered. At the same time, we regarded another model with having the non-uniform distribution of the grains. In addition, the noise absorbing properties were calculated by PSpice circuit simulator for these model varistors. We reviewed noises produced by a counter electromotive force generated in inductance of a dc micro motor when the switching phenomenon occurred in the commutator. A suitable ZnO varistor connected in parallel to the dc motor can absorb this noise and thus can save the machine. Noise absorbing characteristics of our models were calculated. We also reviewed about the effect of non-uniformity of grains in absorbing noise⁽¹²⁾. The calculated results showed that the noise absorption characteristics were deteriorated by the influence of non-uniformity of grains in a varistor.

2. Equivalent Circuit for a Micromotor

A dc motor is mainly expressed by an inductance L with a resistance R of a coil connecting in series. Generally, the following equation stands for a motor⁽¹³⁾.

$$\begin{aligned}
 e &= Ri + \frac{d}{dt}(Li) \\
 &= Ri + L \frac{di}{dt} + i \frac{dL}{dx} \frac{dx}{dt} \dots\dots\dots (1)
 \end{aligned}$$

If inductance L does not change with locations and the rotating speed of the motor is constant, then $(dL/dx) \cdot (dx/dt)$ can be considered as a constant number. If we substitute it with R' , then the Eq. (1) becomes to Eq. (2).

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Fig. 1. Circuit model for the simulation of absorption of noise

$$e = (R + R')i + L \frac{di}{dt} \quad (2)$$

The resistance $(R + R')$ can be replaced by the total resistance R . Figure 1 describes the model circuit of a dc motor connected with varistor models in parallel. Here, the coil L and the resistance R indicate a dc motor. The value of L and R are 1mH and 40Ω, respectively in the present study. The switch of this circuit represents the switching phenomenon that occurs in the commutator of a dc motor. The switching phenomenon occurs in the commutator and a counter-electromotive force is produced by the coil of the motor, which acts as a noise for the dc motor. The model varistors will absorb this noise by flowing the transient current in the grains. The switching time related to turn the switch off from on is very important for the noise of this simulation. From the previous experiments it is obvious that no effect on noise can be observed if this time is shorter than 10μs⁽¹³⁾. Here, in this simulation this switching time was kept at 0.01μs.

3. Equivalent Circuit

A special type of ZnO varistor with one paired of internal electrodes was used for this experiment. Figures 2 (a) and (b) showed the diagram of an ordinary chip varistor and the sample respectively. On the basis of microstructure of sample varistors and their electrical characteristics, we prepared an equivalent circuit. The details of the sample and their characteristics can be found in other papers⁽⁷⁾⁽⁸⁾. Figure 3 showed the equivalent circuit. Here, grain was replaced by a low valued resistance (R_2); whereas, the grain boundary was described by a parallel connection of a voltage dependant resistance (R_1) and a capacitance (C)⁽¹⁴⁾⁻⁽¹⁶⁾. It is indeed that the distribution of grains is not uniform in a varistor but for the simplicity it was assumed that they are uniform between the internal electrodes. The parameters of this circuit were determined as to satisfy the electrical characteristics of samples⁽⁷⁾⁽⁸⁾. Here, $R_2 = 0.1\Omega$ and $C = 7.6\text{pF}$. The values of R_1 were calculated by PSpice simulator as to satisfy with I - V relationship of the sample. In addition, more than 200 grains were taken into account to make this equivalent circuit. The simulation results with this equivalent circuit showed a good agreement with the previous experiments⁽⁷⁾. When the distribution of grains along Y axis are considered uniform then this circuit represents a phase in XZ directions of a multilayer ordinary chip varistor showed in Fig.2(a). With this circuit the calculations were carried out for this simulation.

(a) Ordinary chip varistor

(b) Sample varistor with only one paired electrodes

Fig. 2. Schematic diagrams of ordinary varistor and sample used in the experiment

Fig. 3. Equivalent circuit for the sample

4. Effect of Non-uniformity of Grains in Noise Absorption

The conditions of grains while absorbing the noise were reviewed. To investigate the absorbing noise properties of a varistor, immense numbers of data are required. Rather, it is convenient to observe a part of internal electrodes and investigate the noise absorbing properties. Moreover, the grain numbers are decreasing as the miniaturizing chip varistors are becoming smaller day by day. So, we regarded a part of the internal

Fig. 4. Model structure for both uniform and non-uniform sizes of grains

Fig. 5. I - V relationship of the proposed models

electrodes of an ordinary chip varistor. In this present study, the calculations were performed for a single phase with less numbers of grains of XZ plane of Fig.2 (a). Thus, a uniform model of 4×4 grains was proposed. This model was shown in Fig. 4(a). The non-uniformity of grains were found in various patterns in many varistor samples⁽⁴⁾⁽¹¹⁾. We considered the non-uniformity in grains near the internal electrodes and for simplicity of the calculations, the non-uniform model was considered in a simple manner. Figure 4(b) provides the diagram of this model. The points P and Q of Fig.4 showed the connections of model varistors with the dc motor as shown in Fig.1. The characteristics of a grain boundary are mainly controlled by the materials of a varistor. So, it can be understood that the characteristics of a grain boundary remain unchanged in a sample model. Again, the value of R_2 is very small compared with R_1 and the change of it is negligible. As a result, only the numbers of the grains changed to make these models.

Equivalent circuits were made for each model with the determined parameters. The process of making the circuits was same as described in other papers⁽⁷⁾⁽⁸⁾. I - V relationship of these models were calculated by the PSpice circuit simulator. The results were shown in Fig.5. The varistor voltage (V_b) was 9.37V for the uniform model; whereas, it was 9.24V for the non-uniform model.

5. Results and Discussion

A noise absorption analysis was performed with PSpice Circuit Simulator for each model described in Fig.4. As the V_b of the above models were less than 10V, we took the rated voltage of the dc motor at 9V. When the switching phenomenon had occurred in modeled dc motor, we calculated the transient voltage between P and Q (V_{PQ}) of the noise circuit model shown in Fig.1. The

(a) For uniform model

(b) For non-uniform model

(c) Experimental result with the sample

Fig. 6. Results of the simulation and experimental of absorbing noise for the relevant models and the sample

measured waveform and simulation results were shown in Fig.6. When the switch turns off, the produced counter-electromotive force can be seen in the figure. Here, the time for keeping the switch on/off position was chosen 0.4ms for this simulation which is similar to the half cycle of the voltage waveform (V_{PQ}) of Fig.6. This period was chosen in a way so that the produced noise does not effect the next cycle of noise. It can be verified from Fig. 6 that the resonance was completely calm down before the switch changes its steady position. The measured waveform of V_{PQ} for the sample described in Fig.2(b) can be seen in Fig.6(c). Both the model varistors and the sample varistor absorbed this noise but their patterns of absorbing noise were not in a similar manner. While absorbing the noise, resonance occurred in the non-uniform model comparing to the uniform model shown in Fig.6. Thus the absorption of noise of non-uniform model was deteriorated. We calculated the transient current of each grains for each models.

We reviewed the transient currents flowing in the grains while

(a) The value of V_{PQ} for uniform model

(a) The value of V_{PQ} for non-uniform model

(b) A ($V_{PQ}=9V$), dot lines show the grains

(b) A ($V_{PQ}=9V$), dot lines show the grains

(c) At B ($V_{PQ}=-11.9V$)

(d) At C ($V_{PQ}=2.8V$)

(c) At B ($V_{PQ}=-11.8V$)

(d) At C ($V_{PQ}=5.3V$)

(e) D ($V_{PQ}=-0.1V$)

(f) Color bar (μA)

Fig. 7. The distribution of transient current flowing in the grains of uniform model

(e) At D ($V_{PQ}=1.5V$)

(f) At E ($V_{PQ}=4.8V$)

Fig. 8. The distribution of transient current flowing in the grains of non-uniform model

absorbing the noise. After turning off of the switch, we calculated the current distribution in the grains elaborately. Figure 7 showed the distribution of the currents in the grains for uniform model. Figure 7(a) showed the V_{PQ} values of uniform model where switching phenomenon occurred. The points of V_{PQ} showed in the graph were discussed elaborately. Figure 7(b) showed the current distributions of grains where the $V_{PQ} = 9V$ (i.e. point A of Fig. 7(a)). The dotted lines expressed the shape of grains in this figure. A color bar representing the current amount of grains can also be seen in Fig. 7(f). The unit of current is μA . The distribution of current for other points (i.e. B, C and D) were showed in Fig. 7(c), (d) and (e). The direction of current was overlooked to map the current distributions for these figures. Remarkable current was found in the grains in vertically between the internal electrodes, as the amount of current in the grains depend on the input voltage. But the current in the area of the grains which are horizontally to the internal electrode were found less than $1nA$.

According to the simulation results of the non-uniform model, the current distributions of grains were found totally different from those of uniform model. Figure 8 showed the distribution of the current in the grains for non-uniform model. Figure 8(a) showed the V_{PQ} values of non-uniform model where switching phenomenon occurred. Figure 8(b) showed the current distributions of grains where the $V_{PQ} = 9V$ (i.e. point A of Fig. 8(a)). The dotted lines showed the grains in this figure. The distribution of current for other points (i.e. B, C, D and E) can be seen in the Fig. 8(c), (d), (e) and (f). Again, only numerical values were taken for current and the direction was overlooked for these figures. The amount of current can be seen by using the color bar of Fig. 7. Here, from the simulation results, remarkable current was also found in the grains in vertically between the internal electrodes. Before the switching phenomenon, the current distributions in the area of the grains which is horizontal to the internal electrodes were found less than $1nA$ at the point of A, B of Fig. 8 (a). But when the resonance started after the switching phenomenon, notable amount of current was found in the same region. The amount of current switched to greater than $1\mu A$. From our calculation results, this amount of current changed with time but always found in the described area when resonance occurred in the absorption of transient voltage caused by a dc motor in the non-uniform model varistor. The current of grain boundary regions for both uniform and non-uniform models were not showed in Fig. 7 and 8. We emphasized on the current flowing in the grains in this study and moreover, it will be difficult to recognize the effects of non-uniformity of grains in absorbing noise if the current of grain boundaries are shown in the graphs. Thus, the current of grains was only showed in Fig. 7 and 8 whereas the current of grain boundaries were not counted here. Again, the calculation results of current in a grain was added in Fig. 9. Figure 9 (a) showed the values of current in a grain in uniform model, whereas the graph for non-uniform model can be seen in Fig. 9 (b). The position of the grains can be seen in Figs. 7(b) and 8(b) with closed white box. The deep and dark lines showed the current which was flowing in the vertical direction to the internal electrodes and the thin lines represented the current of horizontal direction to the internal electrodes. It can be seen that the pattern of current in the vertical direction of both models are quite same but in the horizontal directions, obviously the current of uniform model and non-uniform model are different in shape and size. As described above in the visual expressions of current

Fig. 9. The calculated value of current in a grain of uniform and non-uniform model

patterns in the grains, it is reconfirmed that the current in the uniform model in horizontal direction was less than $1nA$ from our calculation results. However, for the non-uniform model, the amount of current was about 10^4 times greater than that of uniform model. The reasons for resonance in a non-uniform model while absorbing the noise, are not clear from this simulation works. As shown in Fig. 8 and 9, the current in the horizontal directions to the internal electrodes may be a reason for it. Again, the equivalent circuit for a varistor possesses capacitance which repeat the cumulation and discharge of instantaneous electrons. This may be another reason for the resonance. More study is required to understand the characteristics of the resonance. From the simulation results it can be seen that in a very short period localized current were found in this region from the simulation results which may lead to the degradation of varistors⁽⁹⁾.

6. Conclusion

In order to investigate the effect of non-uniformity of grains in noise absorption characteristics for the varistors, we proposed an equivalent circuit model considering the internal structure of the sample varistor. We regarded a portion of the internal electrode and made two models including a uniform model and a non-uniform model. A dc motor was connected with these models in parallel to investigate the noise absorbing characteristics of a varistor. The calculations for the noise absorption characteristics were carried out by the PSpice circuit simulator. The results showed that the non-uniformity of the grains had deteriorated the noise absorbing capability of the varistor. The calculated transient current distributions of the grains were found to concentrate in the portion of some grains of the non-uniform model. This concentration of current is likely responsible for the degradation of varistors.

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