



Current Distribution in MOV Element Stressed by 4/10 μ s Impulse Current

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Abstract— This study focuses on current distribution in a metal oxide varistor (MOV) element stressed by 4/10 μ s impulse current studied using the finite-difference time-domain (FDTD) method. After 100 kA shots, V_{1mA}/mm values, which indicate deterioration of nonlinear characteristics of MOV, in edge parts of MOV elements decreased more than those in center parts. FDTD analysis was conducted in two ways, namely 1-D and 3-D models. The varistor is represented with many nonlinear cubic cells of 3 mm \times 3 mm \times 3 mm. It turns out from the 3-D FDTD analyses that the skin effect is insignificant for a lightning current having a rise time of 4 μ s. However, if there is small difference in the nonlinear characteristic of a ZnO element between its periphery and other parts, the distributions of current density are considerably affected, which may result in enhanced degradation of a varistor element in its periphery.

Keywords—component; MOV, ZnO, varistor, surge withstand capability, SPD

I. INTRODUCTION

Lightning protection using surge arresters and surge protective devices (SPD) plays an important role for improving reliability in power delivery. Metal oxide varistors (MOVs) are their important components.

In order to satisfy diverse needs for SPDs, various tests using impulse currents to confirm their performance are defined by standards. The performance is evaluated by the peak current value, the charge value and the number of repetitive shots. It has been reported that the failure modes and degree of degradation depend on the test current waveform⁽¹⁾.

The authors reported on the behavior of varistor voltage, V_{1mA}/mm , stressed by a single shot of impulse current with various waveforms, and discussed its degradation mechanism⁽²⁾⁽³⁾. Different current waveforms with the same charge transfer of an impulse bring about different behavior of varistor voltage drop, an indicator of degradation of MOV. For example, at 10/350 μ s waveform, varistor voltage drop

occurred in the region above 0.2 C/cm² in charge transfer and showed -10 % change above 0.35 C/cm². On the other hand, at steep waveforms like 4/10 μ s or 8/20 μ s, the degradation move forward rapidly. Varistor voltage drop occurred at 0.03 C/cm² and reached -10 % at above 0.1 C/cm² of charge transfer.

In the present study, impulse current of 4/10 μ s is mainly used because it is for preconditioning of operating duty test of surge arresters according to IEC standards.⁽⁴⁾ By the investigation using spot electrodes for MOV elements and analysis of impulse current distribution by two ways of FDTD analysis, the authors try to clarify the mechanisms of degradation of MOV by impulse currents.

II. INVESTIGATION ON TESTED MOVs

4/10 μ s, impulses were used in this study and the test procedure was based on IEC standards.⁽⁴⁾ Two MOV samples having the same chemical composition and size (diameter 41 mm and height 36 mm) were prepared. Then, 2 shots of 100 kA were applied to one sample. The 100 kA current impulse is typical value in the operating duty test for distribution-class surge arresters.

In order to investigate distribution of degree of degradation in a MOV element after application of impulse currents, the spot electrode method was employed. MOV elements were horizontally sliced into 3 disks to check the deviation in the height direction. Then, numerous silver electrodes having a 2-mm square area were attached on the upper and lower surfaces by silver paste printing on sliced pieces of MOV elements. After drying, the voltages at DC 1mA are measured for each spots and V_{1mA}/mm values were obtained for each part.

Table 1 shows the result of V_{1mA}/mm measurements for spot electrodes at sliced MOV elements both with and without application of 4/10 μ s impulse currents.

Table 1 Result of V_{1mA}/mm measurements for spot electrodes at 36-mm thick MOV elements both with and without application of $4/10 \mu s$ impulse currents.

Slice	V_{1mA}/mm in center parts		V_{1mA}/mm in edge parts	
	Average (V/mm)	Standard deviation (V/mm)	Average (V/mm)	Standard deviation (V/mm)
Without impulse current application				
Upper	265.3	0.3	268.3	0.4
Middle	267.4	0.2	269.1	0.8
Bottom	263.7	0.3	268.4	0.5
After application of $4/10 \mu s$ impulse current twice				
Upper	276.1	0.6	272.4	0.8
Middle	276.0	0.6	275.9	1.0
Bottom	278.3	0.6	275.6	3.9

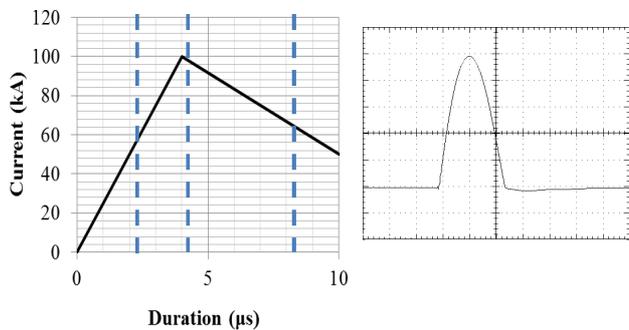
In the MOV element without impulse current application, V_{1mA}/mm in the center parts is higher than that in edge parts regardless of sliced position. On the other hand, after 100 kA shots, V_{1mA}/mm in edge parts of upper and bottom side decrease than that in center parts. From these results, by 100 kA application, the edge parts are clearly degraded. Therefore, it was inferred that such distribution of degradation was caused by non-uniform current distribution.

III. FDTD ANALYSIS AND MODELING

A. Modeling

FDTD⁽⁵⁾ method is widely used in lightning surge analysis, however, analysis of the current distribution inside of a MOV element, which has non-ohmic electrical performance ($V-I$ characteristics), is a challenging subject. In this study, the calculation by two method (VSTL⁽⁶⁾ by broken line approximation and modification method using functional approximation) were carried out and their validities were confirmed.

The impulse current source output the triangle waveform having $4 \mu s$ rise time, $10 \mu s$ time to tail and 100 kA peak value as shown in Fig. 1 a) in order to simulate real waveform as shown in Fig. 1 b)



a) Impulse current input b) Oscilloscope of $4/10 \mu s$ impulse ($5 \mu s/div.$)

Fig.1. Waveform generated by the lumped current source.

For the calculation, non ohmic electrical conductivity and physical property and relative permittivity were used. The model consists of the MOVs connected in both series and parallel, impulse current source and conductors. The size of a cell is $3 \text{ mm} \times 3 \text{ mm} \times 3 \text{ mm}$ and They are connected as shown in Fig.2 b) in order to simulate cross section area of 42 mm diameter of a real MOV like Fig. 2 a). Because the purpose of this study is the impulse current distribution, the current value at both edge (red part) and center (blue part) was calculated.

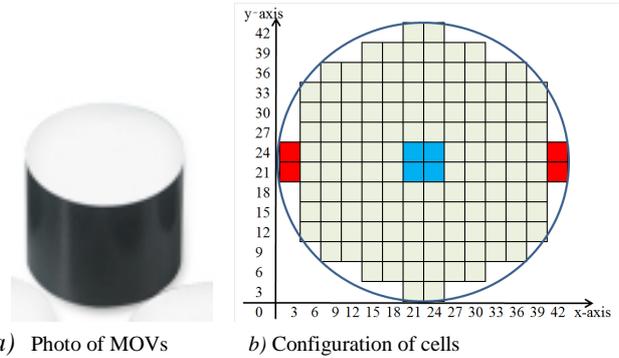


Fig.2. FDTD representations of a nonlinear cubic cell, and the cross-section of the 42-mm-diameter ZnO element.

In homogeneity model as shown in Cl. III B and C, the cell having same $V-I$ characteristics located in all position. In inhomogeneity model as shown in Cl. III E, the characteristics of the edge parts are different from that of other parts intentionally.

B. Calculation by VSTL method

VSTL method which Central Research Institute of Electric Power Industry developed was used. ⁽⁶⁾ The cells stacked 3 steps in only z directions in order to simply the calculation. The resistivity of a cell was $3 \times 10^4 \Omega \cdot m$ below 1100 V and $5.5 \Omega \cdot m$ over 1100 V based on the data of MOVs,

Fig. 3 shows the behavior of impulse current with time for each position and Fig. 4 shows the relationship between current value at peak value (at $4 \mu s$) and the position of cell.

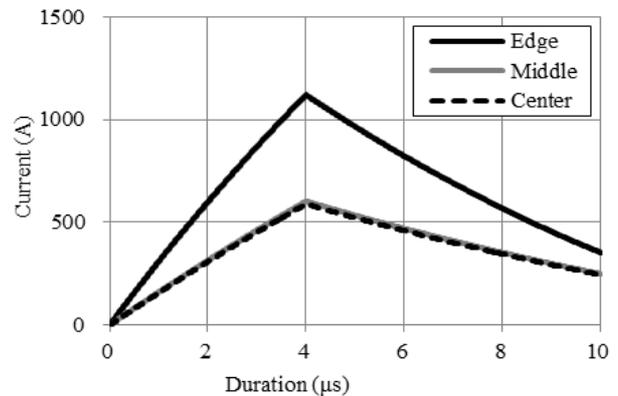


Fig.3. Current waveforms at center, intermediate and edge parts of model MOV element stressed by $4/10 \mu s$ impulse current calculated by VSTL

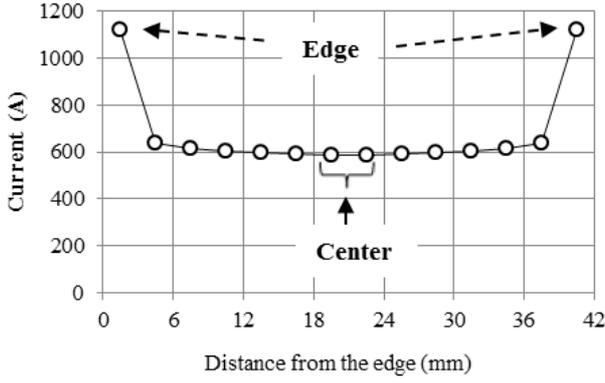


Fig.4. Calculated impulse current peaks at nonlinear elements along the diameter

Because it was found that the current density of edge parts was about 2 times higher than that of center parts as calculation result by VSTL, the possibility of skin effect could be presumed at that moment.

Secondary, for 3D calculation using VSTL, the arrester models which a lot of small cells having $V-I$ characteristics in all directions (x , y and z) three dimensionally stacked are tried to calculate. However, the calculation resulted in numerical divergence. Therefore, the modification of the analysis was also considered.

C. Modification of FDTD method

The relationship between resistivity and electrical field was converted from the measured $V-I$ characteristics of MOVs. Then, the relationship approximated as function in shown in the following equations. ⁽⁷⁾ If $V-I$ characteristics changes, the coefficient and constant in equation also have to change. But, it is relatively easy to approximate

$$\begin{aligned} \rho(E) = & 4.8087 \times (3.0 \times 10^{-6} E)^{-28.16} \\ & + 6. \times 10^3 \times (3.6 \times 10^{-5} \times E)^{-4.255} \\ & + (10.8 \times 10^{-8} / 24.5) \times E \end{aligned} \quad (1)$$

In this modification, by applying the resistivity in equation (1) to normal renewable equation of electrical field as shown in (2) as the example of x direction, non ohmic property can be expressed and the convergence calculation is not necessary.

$$E_x^{n+1} = \frac{\varepsilon_r \varepsilon_0 - \frac{\Delta t}{2\rho(E_x^n)}}{\varepsilon_r \varepsilon_0 + \frac{\Delta t}{2\rho(E_x^n)}} E_x^n + \frac{\Delta t}{\varepsilon_r \varepsilon_0 + \frac{\Delta t}{2\rho(E_x^n)}} \left(\nabla \times \mathbf{H}^{n+\frac{1}{2}} \right)_x \quad (2)$$

The arrester model included a lot of small cells having $V-I$ characteristics in all directions (x , y and z) stacked three

dimensionally. In addition, 12 cells are stacked in vertical direction in order to get 36 mm height.

D. Comparison between VSTL and this modification for homogeneity models

Fig. 5 and table 2 show the current values of each part in z direction at $t = 2 \mu s$, $4 \mu s$ and $8 \mu s$ after impulse application for each calculation.

Table 2 Current values of each part at $t = 2 \mu s$, $4 \mu s$ and $8 \mu s$

	VSTL (1D)			Modification (3D)		
	Edge	Center	Ratio	Edge	Center	Ratio
2 μs	599 A	308 A	1.945	305 A	300 A	1.017
4 μs	1119 A	588 A	1.902	607 A	602 A	1.007
8 μs	568 A	345 A	1.645	403 A	405 A	0.996

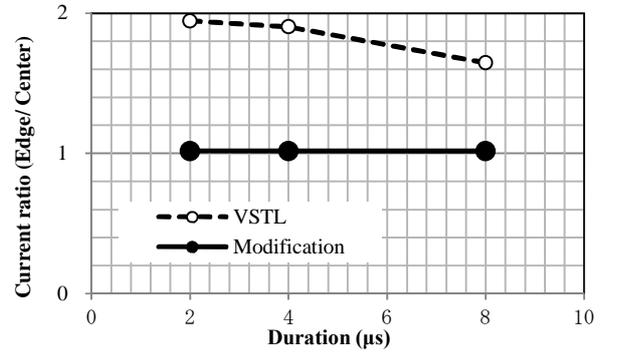


Fig.5 Current ratio (edge/ center part) at $t = 2 \mu s$, $4 \mu s$ and $8 \mu s$

In VSTL, It was found that the current flows inuniformly because current value of edge part was over 60 % higher than that of center parts. On the other hand, in the modification model, the current of edge parts are 1.7 % at $t = 2 \mu s$ and 0.7 % at $t = 4 \mu s$ higher than that of center parts and the current of edge parts are 0.4 % lower than that of center parts in case of $t = 8 \mu s$. It was found that the current flows uniformly and the current increases by skin effect in the front of waveform was quite small.

From the difference of calculation result, the latter method might be appropriate and reasonable for non ohmic elements because both the correct electrical value by functional approximation and the (x , y and z) three dimensionally configuration and were important.

E. Comparison between homogeneity and inhomogeneity models for modification method

In modification model, it was found that the impulse current distribution was almost uniform. However, the V_{1mA} distribution by spot electrodes showed the degradation at the edge parts according to table 1. In order to clarify this contradiction, we consider the possibility of inhomogeneity of $V-I$ characteristics in only high current region as shown in Fig. 6. It was assumed that the difference of residual voltage

between edge parts and other parts was 4 %. (Edge part was lower)

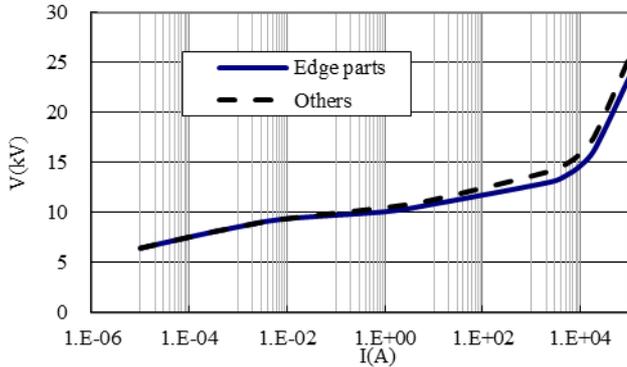


Fig.6. Two V-I characteristics of a ZnO element for representing its periphery and the other part

Table 3 Comparison of the current values by the difference of V-I characteristics at t= 4 μs

	Modification (3D)		Ratio
	Edge cell	Center cell	
Homogeneity	607 A	602 A	1.008
Inhomogeneity	710 A	590 A	1.203

As a result, table 3 shows the current value in the position as same as that in Fig. 2. It was found that the current of the edge parts was about 20 % higher than that of other parts. Therefore, it was found that slight inhomogeneity brought larger current distribution and was one of the causes of V_{1mA} degradation illustrated by spot electrodes.

IV. DISCUSSION

It is difficult to demonstrate the inhomogeneity in high current region. However, if the ZnO grain size of edge parts is smaller than that of other parts, the V-I characteristics (residual voltage / V_{1mA}) of edge parts become smaller than that of other parts and the residual voltage becomes lower even if they have same V_{1mA} . This hypothesis seems to be reasonable to explain the result in the inhomogeneity model.

As a cause of the smaller size of ZnO grain in the edge, the difference of the green density by friction at the molding tool during press process or the difference of ZnO grain growth by the thermal transfer and cooling condition during sintering process are potential.

V. CONCLUSION

- In MOV without impulse current application, V_{1mA}/mm in center parts is higher than that in edge parts regardless of sliced position. On the other hand, after 100 kA shots, V_{1mA}/mm in edge parts of upper and bottom side decrease than that in center parts.
- It is effective for FDTD analysis that V-I characteristics transfers to the relationship between resistivity and

electrical field and the equation was made by function approximation of the relationship. This equation can apply three directional cells without any problems.

- In homogeneity model, modified FDTD calculation shows the impulse current of 4/10 flows uniformly and the skin effect is quite small.
- It was demonstrate that the fractional voltage difference in high current region causes larger distribution of impulse currents. This inhomogeneity may originate in difference of ZnO grain size and it depends on the conditions in MOV manufacturing process.

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