The Effects of Electrical Degradation on the Microstructure of Metal Oxide Varistor

K.P. Mardira, T.K. Saha, *Senior Member, IEEE*, and R.A. Sutton

Abstract**--**In this paper, the findings from systematic experiments with the purpose to determine the degradation effect of single and multiple current pulses on the microstructure of the Metal Oxide (MO) varistor are described. Six distribution class varistors from one manufacturer were used in these experiments. The first part of the paper describes the electrical condition after application of single and multiple lightning current pulses. The results (before and after each elevated current impulse test) of 1mA AC reference voltage and residual voltage are presented in this section. We have also investigated a new technique called "Return Voltage Measurement" for monitoring of the degradation in MO varistors. This is described in detail. The second part deals with the microstructure observations of MO varistors. The results of microstructural examination of impulse current on MO varsitors are examined in detail. This section also explains the relationship between the microstructural changes and electrical degradation of MO varistors.

Index Terms**—**metal oxide varistor, return voltage measurement, electrical degradation, microstructure.

I. INTRODUCTION

A metal oxide varistor is an electronic ceramic device with a highly non-linear (V-I) characteristic whose main function is to clamp transient surges. A good MO varistor should return to its original properties (microstructure and electrical) after a surge without being destroyed. The operational reliability of a MO varistor is substantially influenced by its surge withstand capability. However, a MO varistor experiences degradation due to any excessive surges exceeding the varistor's rating while in operation. Many investigations were conducted in the past to determine the electrical degradation phenomena of a MO varistor after various stresses. Different diagnostics and measuring techniques have been implemented to provide a meaningful interpretation of a MO varistor's electrical condition and aging mechanism [1]-[4]. The microstructure of a MO varistor, especially those of grain size, grain boundary and crystalline bonding, have been extensively studied by material scientists [5]-[7]. The degraded microstructure condition of a MO varistor related to its electrical properties however has not been studied in depth.

K.P. Mardira and T.K. Saha are with the School of Computer Science and Electrical Engineering. The University of Queensland, Australia.
R.A. Sutton is with the Department of Mining, Minerals and Materials Engineering. The University of Queensland, Australia.

We have recently conducted systematic experiments on six distribution class 5kV-10kA MO varistors to determine the effects of electrical degradation on the microstructure of MO varistors. The results from this study are presented in this paper.

II. METHODOLOGY

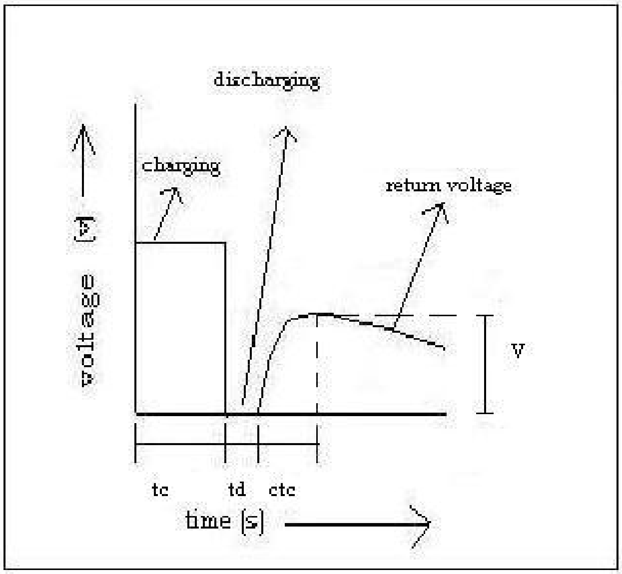
The MO varistors used in this test were artificially degraded by the application of single or multiple 8/20µs lightning impulse currents. Multipulse lightning currents were produced by a lightning impulse generator [11], which can deliver standard single and multipulse 8/20 µs lightning impulse currents (up to six successive pulses with inter-pulse time intervals of 15 to 150 milliseconds).

The electrical degradation was monitored using before and after diagnostic test results. These included measurements of 1mA AC reference voltage and residual voltage at rated current. The changes were identified by after/before ratios of the diagnostic test results. The allowable changes according to Australian Standard AS 1307.2-1996 were ±5% for both cases [12].

We have also investigated a new diagnostic technique called "Return Voltage Measurement" (RVM) for monitoring the degradation of a MO varistor. The basic principle of RVM comprises of three cycles: (i) charge the MO varistor for a pre-selected time with a DC voltage much lower than the MO varistor rated voltage, (ii) discharge the MO varistor for a short period of time (normally ½ of charging time) and (iii) measure the voltage build up across the MO varistors,which is known as the "return voltage" [8]-[10]. Figure 1 shows the steps and general shape of a return voltage.

The MO varistors were examined microstructurally using optical microscopy and X-Ray Diffraction (XRD) and results are compared between the pulsed and unpulsed microstructures. This allowed the examination of any distinct changes to the microstructure as well as the determination of any crystalline phase changes.

The XRD analysis of the MO varistors was performed by scattering in which the X-rays were scattered by Cu atoms without any changes in wavelength. The MO varistors were analysed over a diffraction angular range of 5 to 90 degrees at a scan rate of 1.5 minutes/degree with steps of 4 degrees. Quantitative analysis of diffraction data was obtained using integrated peak areas.



Legend:

V : Maximum Return Voltage
td : Discharging Time
tc : Charging Time
ctc: Central Time Constant

Figure 1. A Typical Return Voltage Waveshape

III. EXPERIMENTAL PROCEDURE

The tested MO varistor blocks were commercial devices produced by one manufacturer. They are identified as B3, B4, B5, B7, B8 and B9. They were new varistors and had identical characteristics in terms of reference voltage, residual voltage and return voltage.

Experimental procedures are summarised as follows:

1. All MO varistors were short circuited to ground for 24 hours. This step was to eliminate any impacts from previous tests.
2. Reference voltages at 1 mA AC current were measured for all test samples.
3. Residual voltages were measured at rated current (10 kA) for all test samples.
4. One cycle of "Return Voltage Measurement" was performed on the MO varistors with 500 V DC, 200 s charging time and 100 s discharging time.
5. All MO varistors were then systematically degraded as follows:
   a. B3, B4 and B5 were subjected to 15 single pulse (8/20µs) at rated current, 1.5 p.u. and 2 p.u. with intervals of 1 minute respectively.
   b. B7, B8 were subjected to 3 groups of multipulse current with time intervals of 2 and 5 minutes respectively. The multipulse current test consisted of the application of quintuple (5) 8/20µs lightning current impulses (rated current).
   c. B9 was subjected to 5 groups of Multipulse current (rated current) with a small time interval required to charge the system.
6. Steps 4, 2 and 3 (in this order) were repeated.
7. Step 5 (2nd Degradation) was repeated.
8. Steps 4, 2 and 3 again were repeated.
9. All MO varistors were prepared for the microstructure examination. The MO varistors were first sectioned perpendicular to the contacts using a diamond saw, and then ground. Finally the MO varistors were polished with 1micron diamond paste. The MO varistors were then preferentially etched using 10 M NaOH solution.
10. The Optical Microscopy of prepared MO varistors was performed.
11. Prepared MO varistors were analysed using XRD.

IV. TEST RESULTS

The electrical effects of the impulse current tests on the MO varistors are first described. The results from 1 mA AC reference voltage and residual voltage measurements on the varistors are presented in Tables I and II respectively. The changes in 1 mA reference voltages were within ±5% after the 1st and 2nd set of degradation except for B4 and B5. B4 and B5 showed changes of more than 16.1% and 37.5% respectively. The changes in residual voltages were within the ±5% limit for all MO varistors. Return voltage results for both unpulsed and pulsed varistors are presented in Tables III and IV. Table III shows that the return voltage maximum value of all the MO varistors decreased after they were subjected to the 1st degradation test. Maximum return voltage also decreased after the 2nd set of degradation with the exception of B3 and B7. This is most probably due to occurrence of a surface flash over during the application of the 2nd set of lightning current impulses, which means the current did not damage the material. Return voltage maximum values of B4 and B5 dropped sharply (decreased more than 20% of the original return voltage value). A typical return voltage result from one such varistor is shown in Figure 2. Figure 3 displays surface flashover tracks on a few pulsed MO varistors. Table IV indicates the degree of degradation of the MO varistors in terms of their central time constant (time to reach the peak return voltage). The central time constant also decreased for all varistors after the 1st set of degradation with an exception of B4. While the central time constant continued to drop after the 2nd set of degradation, B3 and B7 increased. This is difficult to explain. Once again B4 and B5 showed the most significant reduction of their central time constants.

The physical effects of the impulse current tests on the MO blocks are also presented. Using optical microscopy, it was found that the grain size appeared to be smaller in the pulsed specimens. It reduced from 21µm to 12µm in B5. The typical comparison is shown in Figure 4. A comparison of XRD patterns of new and pulsed varistor material was used in an attempt to examine the phase and intensity of this grain. Figure 5 shows this comparison. The relative intensities of the diffraction were almost identical, no significant changes in terms of composition and peak value were observed. However, there is an indication that the peak position had shifted. It suggests that the lattice parameters experienced some changes. It was most probably due to the non-uniform conduction in the blocks, creating hot spots and leading to localised degradation of the material.

Table I. Before and After 1mA Reference Voltage Results

Sample	Reference Voltage (kV) at 1mA				
	Original Voltage +ve & -ve polarity	After 1st degradation +ve & -ve polarity	Change in After/Before Ratio (%)	After 2nd degradation +ve & -ve polarity	Change in After/Before Ratio (%)
B3	6.3 & 6.4	6.4 & 6.2	1.6 & -3.1	6.6 &6.5	4.8 & 1.6
B4	6.2 & 6.3	5.2 & 5.1	-16.1 & -19.1	3.1 & 3.0	-50.0 & -52.4
B5	6.2 & 6.4	4.1 & 4.0	-33.9 & -37.5	2.6 & 2.5	-58.1 & -60.1
B7	6.1 & 6.2	6.3 & 6.2	3.3 & 0	6.4 & 6.3	4.9 & 1.6
B8	6.1 & 6.2	6.1 & 6.0	0 & -3.2	6.1 & 6.1	0 & -1.6
B9	6.2 & 6.4	6.5 & 6.4	-4.8 & 0	6.5 & 6.5	4.4 & 1.6

Table II. Before and After Residual Voltage Results

Sample	Residual Voltage (kV)				
	Original Voltage	After 1st degradation	Ratio (%)	After 2nd degradation	Ratio (%)
B3	15.73	15.63	-0.6	15.97	1.5
B4	15.85	15.35	-3.2	15.23	-3.9
B5	15.69	15.25	-2.8	15.2	-3.1
B7	15.78	15.38	-2.5	15.87	0.6
B8	16.21	15.92	-1.8	16.17	-0.2
B9	15.85	15.79	-0.4	15.92	0.4

Table III. Before and After Maximum Return Voltage Results

Sample	Maximum Return Voltage (V)		
	Original Voltage	After 1st degradation	After 2nd degradation
B3	4.5	4.5	8.1
B4	5.3	5.2	3.8
B5	4.3	3.6	3.2
B7	4.2	3.6	6.3
B8	4.3	4.0	3.7
B9	4.2	4.0	4.0

Table IV. Before and After Central Time Constant Results

Sample	Central Time Constant (s)		
	Original Value	After 1st degradation	After 2nd degradation
B3	39.3	35.9	46.4
B4	31.9	34.9	26.5
B5	36.6	29.9	24.1
B7	35.1	32.1	40.8
B8	36.1	33.4	28.4
B9	37.6	32.7	36.5

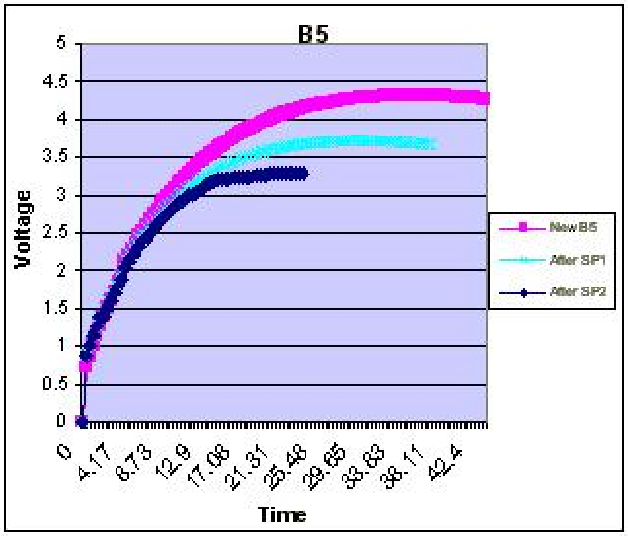


Figure 2. Return Voltage on B5

Figure 3. Surface Flash Over Tracks on Three MO Varistor Blocks

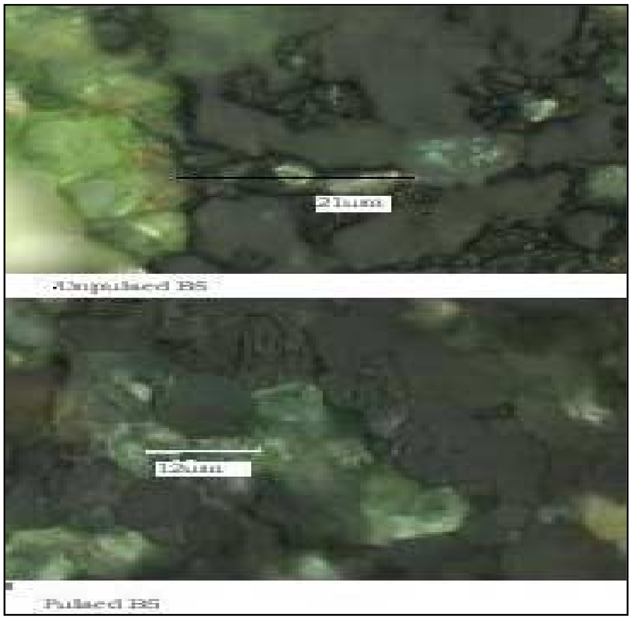


Figure 4. Comparison of Grain Size of MO Varistors (B5)

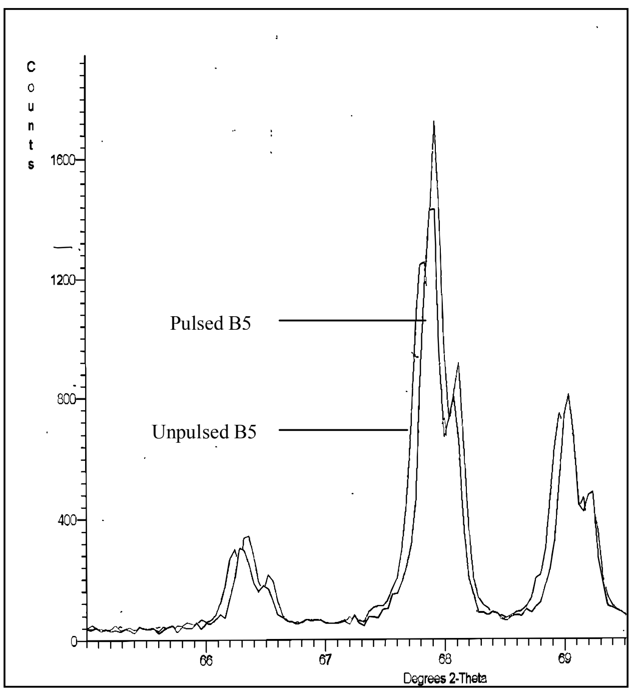


Figure 5. XRD comparison of Pulsed and Unpulsed MO Varistors

V. DISCUSSION

It is well known that MO varistors experience degradation due to single and multiple current impulses. The above results have evidenced some characteristic changes, particularly for varistors that experience 1.5 p.u. and 2 p.u. rated single pulse current. . The results from residual voltage comparison did not show any trace of the degradation of varistors. However, 1 mA reference voltage tests showed significant changes for 2 out of 6 varistors.

The new diagnostic technique "Return Voltage Measurement" has shown some comparable results concerning the evaluation of the MO varistors condition to the 1mA reference voltage. Figure 6a and 6b show a comparison of the results of different diagnostic methods. It displays the same tendency of degradation as other methods, although the return voltage technique shows a greater degree of degradation. It shows clearly that return voltage, central time constant and 1mA reference voltage decreases while the residual voltage changes insignificantly.

Optical microscopy revealed small changes in the average grain size possibly due to the rapid cooling of the localised hot spots. The regions near these hot spots may reach high temperatures sufficient enough to recrystallise the matrix. The material further away from this region would not reach these temperatures. This would cause a non-uniform energy distribution. If the temperature exceeds the varistor quenching capabilities, the material would contain some cracks. This would lead to a significant change in the leakage current.

X-ray diffraction did not show any changes in the intensities and peak values. A small change in the peak position was observed between the pulsed and unpulsed samples. This suggests that the lattice parameters were changed possibly due to solid solution. The non-uniformly conduction in the material, creating hot spots and leading to localised degradation of material was possibly dissolving some other phases. The pulse energy was believed to be concentrated in a very small region.

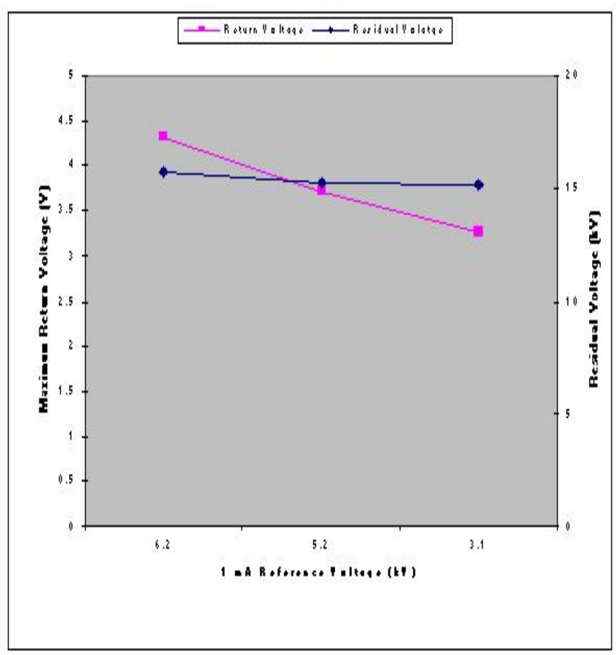


Figure 6a.Comparison of The Return Voltage to Different Diagnostic Methods on B5

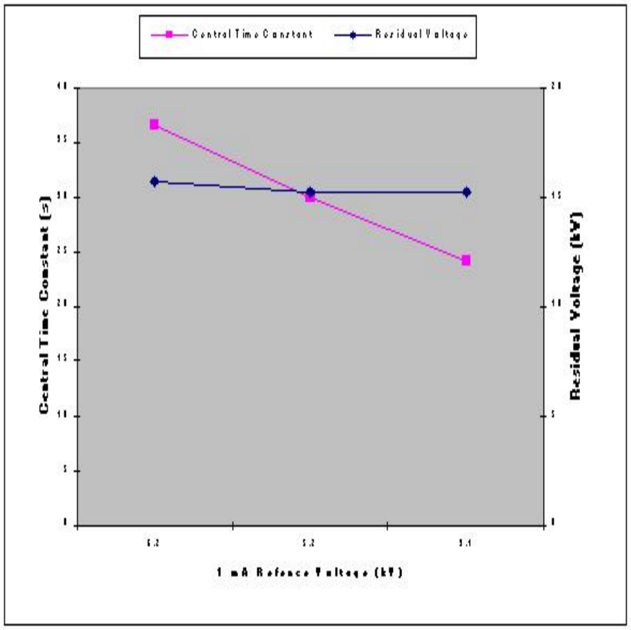


Figure 6b. Comparison of The Central Time Constant to Different Diagnostics Methods on B5

VI. CONCLUSIONS

1. The existing diagnostic techniques such as 1 mA reference voltage and residual voltage are only able to determine the pass/fail condition for MO varistors not the degree of degradation. They often do not provide a meaningful interpretation about the condition of MO varistors.

2. The return voltage measurement has shown the same tendency of degradation as the 1 mA reference voltage. It has also shown a comparable degree of degradation. This suggests that RVM can be used as a suitable method to evaluate the performance of MO varistors.

3. The degraded varistors were found to have smaller average grain size and change in the diffraction peak position compared to a new sample. A possible explanation is the non-uniform temperature distribution in the material due to the development of localised hot spot during the current impulse and the dissolving in some other phases.

4. The reduction in average grain size and change in the lattice parameters could affect the electrical properties by lowering the resistance of bulk material at low voltages. Hence it changes the leakage current.

Further work is needed to clarify the aspect of accuracy of the return voltage measurement and to establish the firm correlation with other measurement techniques. Additional observations concerning the microstructure of pulsed varistors using Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) will be investigated to confirm the phenomena described in this paper.

VII. ACKNOWLEDGEMENT

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IX. BIOGRAPHIES

Karl Primardi Mardira, born in 1976, graduated with a Bachelor of Engineering (Honours) in Electrical Engineering from the University of Queensland in 1998. His research interests are in power system analysis and power system protection. Now He is pursuing his Ph.D. studies at the University of Queensland, Australia.

Tapan Kumar Saha is Senior Lecturer in the School of Computer Science & Electrical Engineering, University of Queensland, Australia. He is a Senior Member of the IEEE and a Chartered Professional Engineer of the Institution of Engineers, Australia. His research interests include power systems & condition monitoring of electrical equipment.

Roberta Sutton graduated with a Bachelor of Engineering (Honours) in Manufacturing and Materials Engineering from the University of Queensland in 1990. She obtained a M.S. and a Ph.D. from Carnegie Mellon University in 1992 and 1996, respectively, and subsequently worked there doing first principles calculations. She is currently working at the University of Queensland, with research interests in computer modelling of materials, and electronic materials.