THE MODELLING AND HARMONIC CONTENT OF THE RESISTIVE COMPONENT OF CURRENT IN ZnO VARISTORS

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Abstract

Recent work on old and failed arresters have shown that there is only a weak correlation between changes in the parameters of an ac model - based on microstructural theories of conduction in ZnO varistors - and high values of the odd harmonics of the resistive component of the varistor leakage current. Here the extrapolation of microstructural theories of conduction for bulk samples is validated. The harmonic components of the leakage current as modelled by the ac power frequency model is found and compared to the experimental data.

1. Introduction

Studies of varistor blocks from old and failed arresters removed from service has shown that there is only a weak correlation between the changes in the ac model parameters and the harmonic content of the resistive component of leakage current [van der Linde & Swift, 1998]. Eight varistor blocks from new arresters and 27 blocks from old and failed arresters were studied. The data was used to validate a model of conduction in bulk ZnO based on micrsotructural theories of conduction. Changes in the parameters of the blocks from old and failed arresters were then quantified in terms of changes relative to the average values found for new blocks. The harmonic content of the resistive component of current was also measured and quantified in terms of changes from the maximum harmonic values measured for the new blocks. A comparison showed that large values of the harmonic magnitudes did not necessarily coincide with abnormal parameter values of the ac model. Furthermore, large values of the fifth harmonic were measured which is contrary to the findings of other researchers [Dengler, Feser, Köhler, Richter & Oehlschläger, 1996; Dengler, Feser, Köhler, Schmidt & Richter, 1997].

Some explanations for these discrepancies such as errors in the measurement of the parameters [van der Linde & Swift, 1996] and the difficulty in measuring the relatively small components of current that are present in the harmonics [van der Linde et al, 1998] have already been explored. However, the statistical nature of the measurement of both the parameters and the harmonics made in these studies, should lead to reasonably accurate results, particularly in the low-field region.

In this report further work to determine the cause of these discrepancies is considered. The validity of the extrapolation of the microstructural theories from small to bulk samples is investigated. The theoretical harmonic content of current for the ac model is determined and then compared with the existing experimental data.

2. Model

The model under study here is a power frequency model that consists of a voltage dependent capacitance in parallel with two non-linear resistive elements [van der Linde et al, 1998]. Only the resistive elements will be considered here.The resistive elements are modelled using microstructural theories of the conduction in ZnO material. The final temperature independent elements used have the following forms:

$$\ln(I) = b_2 + c_2 V_a^{1/2} \qquad (1)$$

$$\ln\left(\frac{I}{V_a^2}\right) = s_2 + \frac{\gamma}{V_a} \qquad (2)$$

I is the resistive component of the leakage current through the varistor in the low- (Equation 1) and high-field (Equation 2) regions respectively, V_a is the voltage applied to the varistor block and b_2, c_2 and s_2 are constants dependent on the characteristics of the material. The equations are represented in the form they were used to measure the constants.

These two equations are simplifications of the electric-field-current density relationships for Schottky [Dissado & Fothergill, 1992, 222; Eda, 1978; Levinson& Philipp, 1975] and Fowler-Nordheim tunneling [Eda, 1978; Levinson et al, 1975] conduction-mechanisms - valid in the low- and high-field case respectively. The original equations used are:

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$$J = A^* T^2 \exp\frac{-E_B}{kT}\exp\frac{\sqrt{\frac{e^3 F_i}{4\pi\varepsilon_0\,\varepsilon_r}}}{kT} \qquad (3)$$

$$J = A F_i^2 \exp\left(\frac{\gamma}{F_i}\right) \qquad (4)$$

where

$$\gamma = \frac{4\sqrt{2m}}{3\hbar e} \qquad (5)$$

where J is the current density, F_i is the applied electric-field, A* is Richardson=s constant, E_B is the activation energy, e is electron charge, ε_0 and ε_r are the permittivity of free space and the relative permittivity respectively, k is Boltzmann=s constant, T is temperature, m is the electron mass and ≤ is the modified Planck constant. The high-field part of the model, as represented by equation 1, was found to be accurate in the region of the kneepoint or for voltages higher than that depending on how the parameters were measured. This aspect may be due to a lack of complexity in the behaviour of the model and a more suitable model may be based on conduction such as that described by Mahan, Levinson & Philipp [1979].

3. Extrapolation to multiple boundaries

Equations 3 - 5 describe the behaviour of single insulating boundaries that needs t be extrapolated to multiple boundaries as they are found in large samples of the material.

ZnO material does not consist of semiconducting ZnO grains with a continuous Bi-rich layer between them. Instead, it has a sophisticated structure involving various phases. As well as thin Bi-rich intergranular layers between the ZnO grains, some of the ZnO grains are in direct contact with each other - with the interface areas doped with Bi atoms [Olsson & Dunlop, 1989]. This structure can be simplified on the following assumptions:

! Only those boundaries containing thin Bi-rich layers or with doped ZnO interfaces are active.
! Whichever type of boundary is active, it is continuous through the material.

Based on these assumptions, the structure can be reduced to that illustrated in figure 3-14(a). If it is further assumed that the volt drop only occurs in the intergranular layer that is perpendicular to the electric field, then this structure can be reduced to that shown in figure 3-14(b) [Shirley & Paulson, 1979]. The structure represented in figure 3-14(b) can be further refined by randomly varying the thickness of the intergranular layer and hence the size of the ZnO grains [Shirley et al, 1979]. Herein it is also assumed that the sample is large enough to permit the use of the average dimensions throughout the simplified structure.

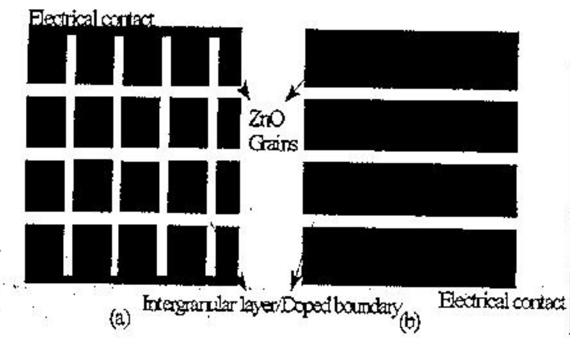

Figure 1 ZnO material (a) idealised structure and (b) structure with only intergranular layer/doped boundaries perpendicular to electric field

Using this simplified structure, the complete volt drop over a sample can, therefore, be said to be the total volt drop over the ZnO grains plus the volt drop at each intergranular layer/doped boundary (for Schottky and Poole/Frenkel conduction respectively). The volt drop over the ZnO grains can be neglected in the region of operation that is of interest herein. Consequently, the volt drop will be the sum of the forward- and reverse-bias boundary volt drops or the sum of the volt drops over the doped boundaries. The barrier voltages have statistically distributed values, but the mean ones are usually used [Olsson et al, 1989; van Kemenade & Eijnthoven, 1979].

If Schottky or Poole/Frenkel conduction is rigidly applied to the structure of Figure 3-14(b), the complete device would not turn-on until the sum of all the barrier voltages has been exceeded by the applied voltage. That is, if there are n boundaries, each with a barrier field of E_n and the total applied field E_T is uniform - conduction in phase with an applied ac voltage will only occur once:

$$E_T > E_1 + E_2 + E_3 + \ldots + E_n \quad (6)$$

In reality, the process is probably much more complex - with the current initially flowing along some parallel paths that have very low total barrier fields. As the applied field increases, more of the boundaries will become active, thereby increasing the number of parallel paths available for conduction. This process will effectively create a system of parallel paths of current each with its own turn-on field. For p parallel paths, each with its own total barrier field E_p, reflected in the constant b_{Ep}, equation 1 gives:

$$I_T = I_1 + I_2 + I_3 + \ldots + I_p \quad (7)$$

Hence,

$$I_T = A * T^2 \exp(\frac{c\sqrt{E}}{kT})[\exp(\frac{-b_{E1}}{kT}) + \ldots + \exp(\frac{-b_{Ep}}{kT})] \quad (8)$$

This expression for Scottky conduction neglects the effect of the reverse-biased boundaries. It is similar in form to equation 1 and the extrapolation is, therefore, valid in the low-field region.

Similarly, the current flowing when the fields are higher - and the conduction is dominated by tunneling - can be calculated in large samples. Using equation 2, the total current under high-fields is:

$$I_T = s_{\phi 1} V_a^2 \exp(\frac{\gamma_{\phi 1}}{V_a}) + \ldots + s_{\phi p} V_a^2 \exp(\frac{\gamma_{\phi p}}{V_a}) \quad (9)$$

Where $s_{\varphi 1}, s_{\varphi 2}, s_{\varphi 3}, \ldots, s_{\varphi p}$ and $\gamma_{\varphi 1}, \gamma_{\varphi 2}, \gamma_{\varphi 3}, \ldots, \gamma_{\varphi p}$ are the simplified Fowler-Nordheim parameters for paths 1, 2, 3, ..., p respectively. Accordingly, s is an inverse function of the barrier height φ_{Bs} and γ is a function of $\varphi_{Bs}^{3/2}$. If it is assumed that both these values are unique for the individual parallel paths, two constants can be defined such that:

$$k_{\varphi 1} = s_{\varphi 1} \exp(\gamma_{\varphi 1}) + .. + s_{\varphi p} \exp(\gamma_{\varphi p}) \quad (10)$$

and

$$k_{\phi 2} = s_{\phi 1} + s_{\phi 2} + s_{\phi 3} + \ldots + s_{\phi p} \quad (11)$$

then equation 3-12 can be written as:

$$I_T = V_a^2 (k_{\phi 1} - k_{\phi 2} \exp(V_a)) \quad (12)$$

This equation is not of the same form as equation A1-52 but does give a highly non-linear characteristic. However, if it is assumed that $eE >> \varphi_{Bs}$ under high-fields, then the different barrier values $\varphi_{\varphi 1}, \varphi_{\varphi 2}, \varphi_{\varphi 3}, \ldots, \varphi_{\varphi p}$ can be assumed equal to φ_s and hence the values $s_{\varphi 1}, s_{\varphi 2}, s_{\varphi 3}, \ldots, s_{\varphi p}$ and $\gamma_{\varphi 1}, \gamma_{\varphi 2}, \gamma_{\varphi 3}, \ldots, \gamma_{\varphi p}$ can be assumed to be equal to s_s and γ_s respectively. For this case,

$$I_T = p s_s V_a^2 \exp(\frac{\gamma_s}{V_a}) \quad (13)$$

This expression is of the same form as equation 4 and for these conditions the extrapolation to a large scale model element is valid.

4. Harmonic content of resistive component of current for specific parameter values

The study reported in ICLP >98 [ICLP98] found parameters of the resistive elements described by the voltage-current relationships for eight blocks from new arresters and 27 blocks from old and failed arresters. The mean values of the arrester parameters and harmonic content of current for the new blocks are listed in Table 1 and 2. The parameters were found model the voltage-current characteristic well in the low-field region and reasonably well in the high-field region - depending on whether the model is optimised for the kneepoint region or voltages above that. The experimental parameters values will be used to calculate the theoretical harmonic content of the resistive component of the current which can then be compared with the experimental values. An interesting aspect of these results is the large magnitude of fifth harmonic present in the current.

Table 1 Average parameter values for eight new blocks

b_2 (ln A)	c_2 ((ln A)/%V)	s_2 (ln(A/V^2))	γ (ln(A/V))
-12	0.0442	11.8	-165760

Table 2 Average harmonic contents of the resistive component of current for eight new blocks as percentages of the fundamental

3rd Harmonic	5th Harmonic	7th Harmonic
11 %	37 %	17 %

The theoretical harmonic content of the resistive component of current was calculated using the Fourier

$$f(t)=\sum_{n=1}^{\infty}\left(A_n\cos\left(\frac{2\pi nt}{T_p}\right)+B_n\sin\left(\frac{2\pi nt}{T_p}\right)\right)$$

series expressions for a function f(t):
where n is the order of the harmonic, t is time and T_p upper limit of the period of integration. The factors A_n

$$A_n=\frac{2}{T}\int_0^T f(t)\cos\left(\frac{2\pi nt}{T}\right)dt$$

$$B_n=\frac{2}{T}\int_0^T f(t)\sin\left(\frac{2\pi nt}{T}\right)dt$$

and B_n are determined by evaluating the expressions:
The analytical solutions of these integrals for equations 1 and 2 are sometimes too cumbersome to be interpreted and it was decided to evaluate them numerically using Matlab7.

The third, fifth and seventh harmonic as a function of voltage is illustrated in Figure 2.

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References

Dengler, K, Feser, K, Köhler, W, Richter, B & Oelschläger, P, (1996), Aac-characteristics of MO-arresters under pulse stress≅, *International Symposium on Electromagnetic Compatibility (EMC=96 ROMA)*, September 17-20, 1996, Rome, Italy, Volume 1, Paper H-1, pp. 306-310

Dengler, K, Feser, K, Köhler, W, Schmidt, W & Richter, B, (1997), AOn-line diagnosis of MO-varistors≅, *10th International Symposium on High Voltage Engineering (ISH)*, August 25-29, 1997, Montréal, Québec, Canada

Dissado, LA & Fothergill, JC, (1992), AElectrical degradation and breakdown in polymers≅, Peter Peregrinus Ltd on behalf of the Institution of Electrical Engineers, London, 1992

Eda, K, (1978), "Conduction mechanism of non-Ohmic zinc oxide ceramics", *Journal of Applied Physics*, Vol. 49, No. 5, May 1978, pp. 2964-2972

Levinson, LM & Philipp, HR, (1975), "The physics of metal oxide varistors", *Journal of Applied Physics*, Vol. 46, No. 3, March 1975, pp. 1332-1341

Mahan, GD, Levinson, LM & Philipp, HR, (1979), "Theory of conduction in ZnO varistors", *Journal of Applied Physics*, Vol. 50, No. 4, April 1979, pp. 2799-2812

Olsson, E & Dunlop, GL, (1989), "Characterization of individual interfacial barriers in ZnO varistor material", *Journal of Applied Physics*, Vol. 66, No.8, 15 October 1989, pp. 3666-3675

Shirley, CG & Paulson, WM, (1979), AThe pulse-degradation characteristic of ZnO varistors≅, *Journal of Applied Physics*, Vol. 50, No. 9, September 1979, pp. 5782-5789

van der Linde, FJ & Swift, DA, (1996), ASurge protection in power engineering: assessing the deterioration of nonlinear resistors≅, *23rd International Conference on Lightning Protection*, Florence, Italy, 23-27 September, 1996, Volume 2, pp. 646-652

van der Linde, FJ & Swift, DA, (1998), AA harmonic and parametric assessment of the role of lightning impulses on in-service failures of distribution surge arresters≅, *24th International Conference on Lightning Protection*, Birmingham, UK, 14-18 September, 1998, Volume 2, pp. 594-598

van Kemenade, JTC & Eijnthoven, RK, (1979), "Direct determination of barrier voltage in ZnO varistors", *Journal of Applied Physics*, Vol. 50, No. 2, February 1979, pp. 938-941