DYNAMIC IMPULSE CONDUCTION IN ZnO ARRESTERS

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ABSTRACT

In this paper, new fast-impulse test data obtained on ZnO surge arresters with a special coaxial test cell are presented. The time-to-peak of the discharge current was observed to become shorter as the magnitude was increased. An explanation for this phenomenon is suggested based on changing current paths within the material. To account for this dynamic behaviour, we propose an equivalent circuit which uses parallel paths with associated inductances and resistances to model the conduction process in the intergranular layer.

1 INTRODUCTION

Since the introduction of zinc-oxide material in 1968, much research has been directed towards the characterisation of the electrical behaviour of the material under various stress conditions. There is now an extensive published literature on the response of the material to impulse current stresses of different shape and amplitude. An aim of some of these investigations is to achieve an equivalent circuit representation which would adequately simulate the observed test results[1-7].

A feature of many of the published equivalent circuits[1] is the representation of the zinc-oxide material by two series sections; i) to account for the resistance of the zinc oxide grains and ii) to simulate the properties of the intergranular layers. The zinc-oxide grains are represented by a low resistance R_{grain} whose effect is of importance at very high impulse discharge currents only. The intergranular layers are represented by a parallel resistance (R_{Ig}) - capacitance (C_{Ig}) network, the resistance branch having a strong non-linear voltage-current characteristic. For impulse currents in the kilo-ampere range, the resistive current dominates and the capacitance component can be neglected. The impulse response in the low conduction regime of the material, however, shows a significant capacitive component of the current. For impulse currents in the low-conduction regime, the material may be simulated by the capacitance branch. Evidence has been published that indicates that this capacitance is also non-linear. In addition to this basic representation, other components may be included such as an inductive component to represent the equivalent inductance of the metal oxide material/arrester body or to account for the material's response to steep currents.

Much recent research on zinc-oxide surge arresters has concentrated on the very fast transient response characterisation [2-5]. Due to the difficulty in obtaining reliable test data for fast-rate-of-rise impulse currents, the IEEE working group 3.4.11 (Application of Protective Devices Subcommittee, Surge Protective Devices Committee)[4] has limited its efforts to the modelling of metal oxide surge arresters to current impulses with rise times of 0.5μs or greater. Extensive reviews have been published [1,4,6] on the ZnO impulse response, voltage measurement and equivalent circuits.

The present work is concerned with the transition from low to high conduction under fast-impulse conditions. Firstly, new improved impulse test data are presented. These test data were obtained using a fast transient coaxial test module and improved voltage measurement methods[2,7]. The new test data obtained show that there is no evidence of an overshoot on the residual voltage trace. In addition, they show, for the first time, that the discharge current exhibits a longer time-to-peak at low amplitudes than at high amplitudes. Finally, an equivalent circuit is proposed to account for these new observations. The circuit response is also computed and compared with the test data.

2. FAST-IMPULSE TEST DATA

2.1. Test Procedure

In order to carry out fast transient tests with minimum circuit inductance a new coaxial test module has been designed and constructed[7]. The module is a low-inductance, test facility incorporating integral voltage and current transducers. It allows tests to be carried out on 15kV arresters with measurements to 50kV at 1kV/ns and 5kA at 10A/ns. For the very fast fronts, the source capacitors were arranged in a coaxial configuration to minimise source inductance.

The inductive effects on the measured values could be further minimised by measuring the value of the residual voltage at the instant of peak current when the rate of change of current is zero. In this way, a more realistic representation of the resistive behaviour of the arrester can be achieved independently of the test circuit by eliminating the effects of di/dt on the measuring system, thus allowing comparison between different results.

2.2. Effect of Current Shape

Tests were carried out applying impulses of similar amplitude but of different waveshape in order to determine the effects on the voltage-current characteristics of the arrester. Two capacitor banks with a similar capacitance value but of different internal inductances were used in order to produce the desired current impulse shapes. It was observed that after the voltage front (~40ns) the shapes of the resulting residual voltage waveforms are quite dissimilar, the difference becoming more notable at higher discharge currents. Because the residual voltage has not yet reached its peak value according to the voltage-current curve, it is continuing to increase at a slower rate than the initial jump due to the high non-linearity of the material. The

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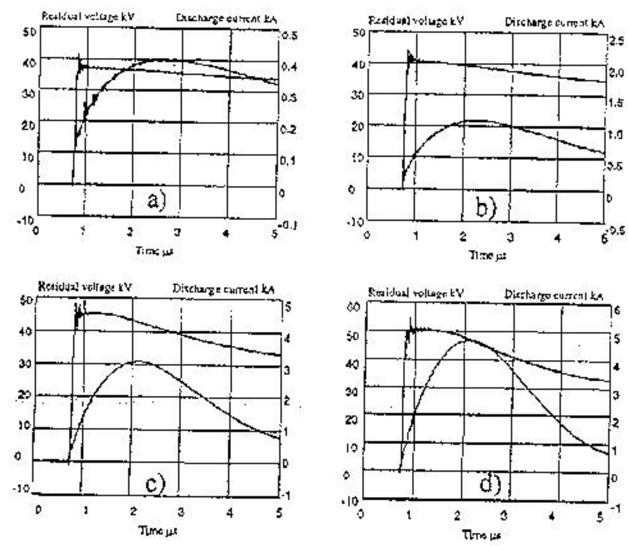


Figure 1: Measured voltage and current oscillograms for a 15kV-rated arrester at various discharge current levels.

arrester branch inductance produces a voltage fall which is proportional to the rate of change of current which becomes smaller towards the current peak value.

The residual voltage at peak current was found to vary little for the two sources for similar discharge current amplitudes, suggesting a unique resistance-voltage curve for the zinc-oxide material for this range of fast fronts.

2.3. Effect of Current Amplitude

Tests at increasing charging voltage of the capacitance bank were conducted in order to check the voltage-current characteristics of various distribution zinc-oxide surge arresters. Figures 1.a to 1.d show voltage and current records measured on a 15kV rated surge arrester. These tests revealed, for the first time, that the time-to-peak of the current decreases as the amplitude of the current increases. Furthermore, it can be seen that the voltage traces do not show the initial voltage overshoot previously associated with zinc-oxide tests even for these voltage risetimes of not more than 40ns. In the case of the low–inductance source, it was found that the time-to-current peak decreases from about 2.5µs at a peak current of 100A to approximately 1.5µs at 5kA.

Figure 2 shows the relationship between time-to-current peak and the amplitude of the current peak for three arresters of different manufacture (arresters A, B and C). It can be seen that the time to current peak reaches a constant value (~1.5µs) when the arresters are operating in the high-conduction regime (above ~1kA). In this region, most of the intergranular layers have broken down forming many current paths through the material. It is in this region that the resistance of the zinc-oxide grains becomes the main limiting factor for conduction. In contrast, the low-conduction regime shows time-to-current peaks ranging from about 1.6µs for current amplitudes of approximately 500A to time-to-peaks in the order of 5µs for currents less than 100A.

3. Static voltage-current characteristic of zinc-oxide surge arresters

The V-I characteristic may be divided into three regions; the pre-breakdown region, the breakdown region and the upturn region. The pre-breakdown region of the characteristic is determined from direct or power-frequency voltages. The amplitude of the applied voltage is such that the resulting current is usually less than 10mA. Continued application of current amplitudes greater than this value can result in excessive heat dissipation which may lead to premature ageing and thermal runaway of the arrester. Consequently, for characterisation where currents are in the hundreds of amperes and into the kilo-ampere range, impulse currents are applied. For current up to about 500A, switching impulses may be used. For characterisation in the kilo-ampere range, lightning or fast impulses are used because of their lower energy content.

In order to determine the equivalent circuit components, low voltage tests[1] or computations[6] are used to estimate C_{Ig} while high current impulse data is used to calculate the series grain resistance R_{grain} and the non-linear intergranular-layer resistance R_{Ig}.

The voltage V_{Ig} appearing across the intergranular layer resistance is a non-linear function of the current I. It can be written as

$$V = I\left[R_{grain} + R_{Ig}\right] = I\left[R_{grain} + k \ I^{\beta - 1}\right] \qquad (1)$$

Based on experimental data and for, the following expression is obtained for arrester B:

$$V = I[1.1 + 24000 I^{0.935}] \qquad (2)$$

Circuit simulations of the laboratory set-up where the arrester was represented by this non-linear resistive function were carried out using the SPICE transient analysis program. The simulation was used to check the accuracy of the expression and also to confirm that the parallel capacitance C_{Ig} had no effect on the characteristic for the studied range of current magnitudes.

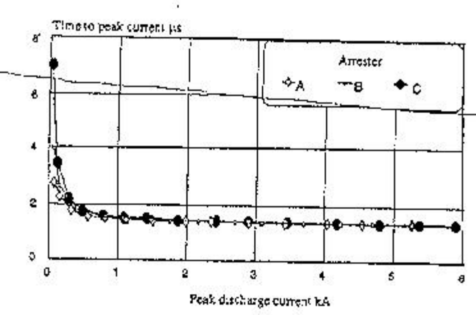


Figure 2: Variation in time-to-current peak as a function of current peak for three 15kV-rated ZnO surge arresters.

4. Multiple-current-paths concept

The experimental results (Figs. 1 and 2) show that zinc-oxide arresters have a dynamic voltage-current characteristic. The salient features of this dynamic behaviour are; i) a dependence of current time-to-peak on current amplitude and ii) a residual voltage reaching its peak value before the discharge current reaches its peak.

The time-to-current peak is seen to decrease to a minimum as the current amplitude increases. The simple standard representation of zinc-oxide surge arresters cannot account for the decrease seen in the time-to-peak of the discharge current. A constant inductive element would produce a shorter time-to-peak at a lower current than at a higher current, which is the opposite of the measured effect. A non-linear inductance could be used to simulate this effect, but it is difficult to determine its parameters from measurements. An alternative simpler approach is to consider the development of discrete current paths through the zinc-oxide material, with the number of paths increasing as the impulse voltage amplitude increases. The low current (when the level of impulse voltage is low) will flow through the zinc oxide taking a path where intergranular layers are the easiest to break down. This path may not be the most direct path through the material, but as the level of the impulse voltage increases the intergranular layers which could not previously be broken down by the lower voltage amplitude are now bridged. This results in the current paths increasing in number and becoming more direct. To simulate this physical relationship would ideally require a circuit containing a large number of paths. The paths would have differing characteristics to simulate this current growth as the level of the applied impulse increased. However, for simulation purposes a model containing two parallel paths is proposed. It was found that the model gave good correlation with the laboratory test data.

5. Proposed equivalent circuit

The proposed equivalent circuit is shown in Figure 3. It comprises two series sections; one to represent the resistance of the zinc-oxide grains (R_{grain}) and the self-inductance (L_{body}) due to the physical size of the arrester body and a parallel network to represent the properties of the intergranular layers. One branch of the network carries the high amplitude discharge current, so that the branch has a highly non-linear resistance R_{Ig} and a low value inductance L_{c1}. The second branch has a linear resistance R_c and a higher value inductance L_{c2} to account for the delay in low-current fronts and the multiple –current path concept. A capacitive element C_{Ig} to represent the arrester shunt capacitance was also included in the equivalent network.

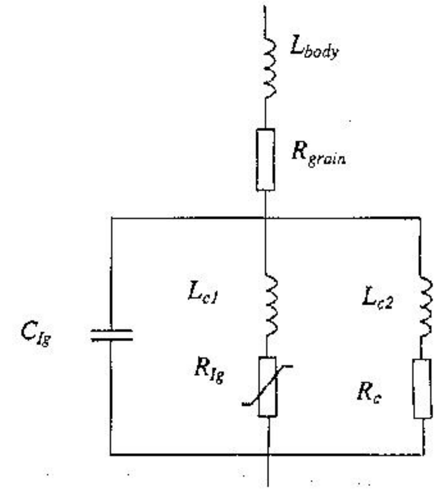


Figure 3: Proposed ZnO equivalent circuit for multiple-current-path representation.

6. Circuit simulation

The laboratory test circuit incorporating the equivalent circuit representation of the arrester described in the previous section is represented in Figure 4. The circuit parameters were determined from laboratory measurements or where applicable obtained from manufacture's data. The stray components were estimated on the basis of the test circuit physical arrangement.

Figure 5 shows voltage and current oscillograms from the circuit simulations representing the residual voltage of the arrester at the point of measurement (R_{cct}-L_{cct}) and the discharge current through the arrester. Examination of the records show that the current shapes give good

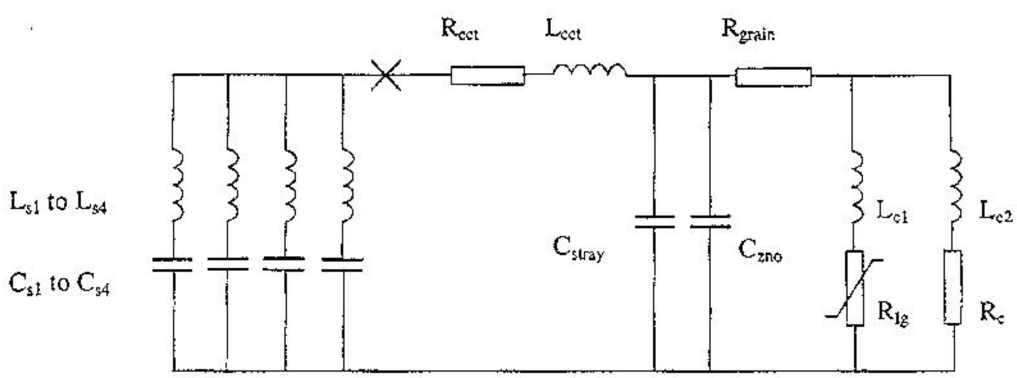


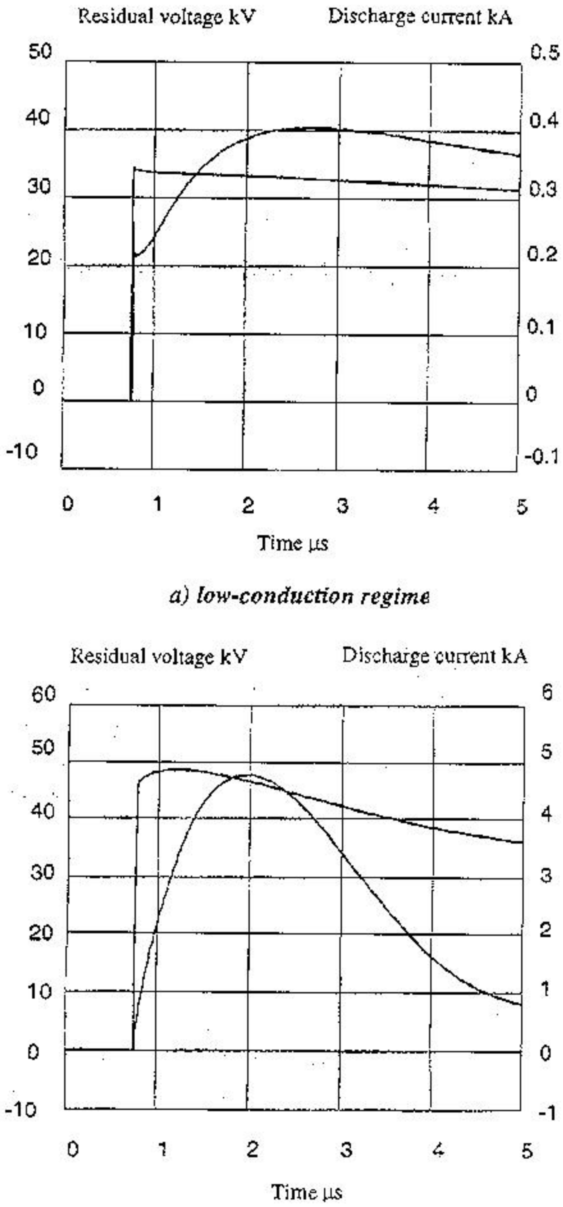
Figure 4: Simulated laboratory test circuit.

$C_{s1}=C_{s2}=C_{s3}=C_{s4}=0.15\mu F$, $L_{s1}=L_{s2}=L_{s3}=L_{s4}=0.04\mu H$, $R_{cct}=0.5\Omega$, $L_{cct}=L_{stray}+L_b=1\mu H$, $C_{stray}=20pF$, $C_{zno}=60pF$, $R_{grain}=1.1\Omega$, $L_{c1}=0.01\mu H$, $R_{1g}=f(I,V)$, $L_{c2}=75\mu H$, $R_c=100\Omega$

agreement with those obtained in the laboratory (Figure 1). Both the laboratory test results and the simulations show similar time-to-current peaks for a similar current amplitude. Furthermore, for current amplitudes in excess of 1kA the residual voltage at current peak shows good agreement between laboratory test results and simulations.

7. Conclusions

The laboratory tests showed that the time-to-peak of the arrester discharge current is dependent upon the amplitude of the current. For low amplitude currents, the arrester exhibits longer time-to-peaks than at higher amplitudes.



a) low-conduction regime

b) high-conduction regime

Figure 5: Simulated voltage and current signals at two discharge current levels.

Since a single non-linear resistance function cannot reproduce the dependence of current time-to-peak on current amplitude, an equivalent circuit for zinc oxide has been proposed to simulate the observations made in the laboratory, namely the effect of a decreasing time-to-current peak as the amplitude of the current increases. The equivalent circuit is based upon the assumption that multiple current paths are formed through the zinc oxide and that the number of paths increases and the path lengths decrease as the current amplitude increases. The results from the simulations show agreement with those obtained in the laboratory.

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