Considerations on Using the Discharge Current Charge to the Evaluation of a Switching Surge Performance of a Metal Oxide Surge Arresters

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Abstract: **This paper presents a new approach to verify the discharge current capacity of metal oxide surge arrester resistors. The proposed approach deals with the maximum charge versus discharge current peak curve. The discharge current withstanding limit of the tested metal oxide resistors, the prospective energy absorption capacity limit and the charge capacity are determined, by means of laboratory testing and, when necessary computed by means of traditional numeric techniques. Comments on the obtained results are presented.**

Keywords: Surge Arresters, Metal Oxide Resistors Withstanding Limits, Energy Absorption Capacity.

I. INTRODUCTION

This paper discusses a non-standard approach to demonstrate the withstanding capacity of metal oxide arrester resistors. The developed approach is based in the duty factor method [1]. In spite of being considered a very crude conservative mathematical model, once improved, by means of an statistical data analyse, the duty factor can be successfully applied to check the withstanding capacity of metal oxide resistors.

The duty factor approach deals with the discharge current - the stress - discretization and with the relation between the current peak and the discharge time - the withstanding capacity - of the metal oxide resistors, as stated by (1) and (2), respectively .

$$S = \sum_{i=1}^{n} \frac{\Delta T_i}{T_{R_i}} \qquad (1)$$

where: S - Discharge current duty factor, ΔT_i - i^{th} Rectangular impulse discharge time and T_{R_i} - i^{th} Maximum rectangular impulse discharge time (2).

$$T_R = \beta_R \, I^{-\gamma} \qquad (2)$$

where: β_R and γ - are generic constants and I - Current pulse peak.

The duty factor approach takes into account the possibility of current concentration on small conducting channels, i.e. *Hot Spots*. This results in a local differential heating and, as consequence, in a series of mechanical stresses that can destroy the resistor. Therefore, once reached a local critical temperature gradient, associated to a defined destroyer energy, that depends, basically, on the position, relative area and threshold voltage reduction of the hot spot, the resistor collapsed, normally, by cracking, as observed during all carried out tests. These hypoteses and therefore the associated failure process can be modelled by means of thermal stresses analyses or even by means of huge laboratory works.

According to these rules, the relation between time and current (2), can be developed by using a simplified thermal model that considers, for instance, the particular condition associated to the existance of a concentric hot spot [2] and, the tangential thermal stress, usually the highest, can be computed by (3).

$$\sigma_T = \kappa \frac{E \, \alpha_l \, q}{\rho \, c \, (1 - \nu)} \qquad (3)$$

where: σ_T – Tangential thermal stress, E – Modulus of elasticity, ρ – Density of the resistor, c – Heat capacity, α_l – Coefficient of thermal expansion, κ – Numeric coefficient that, in a general case, computes the effect of the position, of the size and of the threshold voltage reduction of the Hot spot, q – Specific energy absorved by the metal oxide resistor *[kJ/kV]* and ν – Poisson's ratio.

A further development of (3) that, specifically, shows that the energy absorption capacity is constant, at least when of failures by cracking, permits to obtain (2). This was proofed by extensive laboratory work and, as follow, results in some interesting considerations.

II. BASIC DATA DETERMINATION

The discharge current and energy absorption capacity of metal oxide resistors are usually obtained by the transmission line discharge test. This test was designed to provide withstanding-failure data on silicon carbide arresters. However, as verified by field practice, it can be successfully applied to metal oxide arresters.

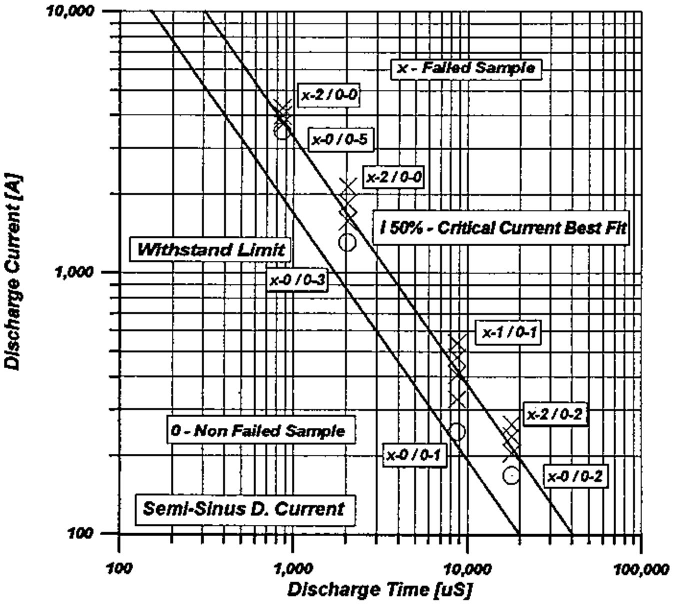

Figure 1 - Samples Discharge Current and Time Data Summary

The simplified duty factor laboratory work deals with a test set up able to produce a damped half sinus current shape. This set up must generate current impulses covering three current peak and three discharge time decades. The *up and down testing method*, one sample per level, in order to obtain $I_{50\%}$, is presently adopted. As proposed the laboratory work requests sample batches, containing *20-25* metal oxide resistors per current discharge time. It is used a visual inspection to verify the sample withstanding or failure. For each discharge current time, data point characteristics, i.e., mean current value, standard deviations and confidence limits are computed by the likelihood method. To consider the statistical current and discharge time relation it is proposed the use of the Symmetric Weibull Distribution.

The results presented in figure 1, part of a wide study on *350* samples, are related to *82* metal oxide resistors, divided in *4* sets, submitted to damped half sinus current applications. The following rule was applied, high current-short duration and low current-long duration impulses, that is in agreement with (2). The obtained data ranged from *850* µs to *18,000* µs. This figure shows a result summary and the computed critical current - $I_{50\%}$ and withstanding limit current - $I_{0\%}$ discharge time relations. For each discharge time, for the superior and for the inferior current level, the number of non-failed and the number of failed samples are presented[3].

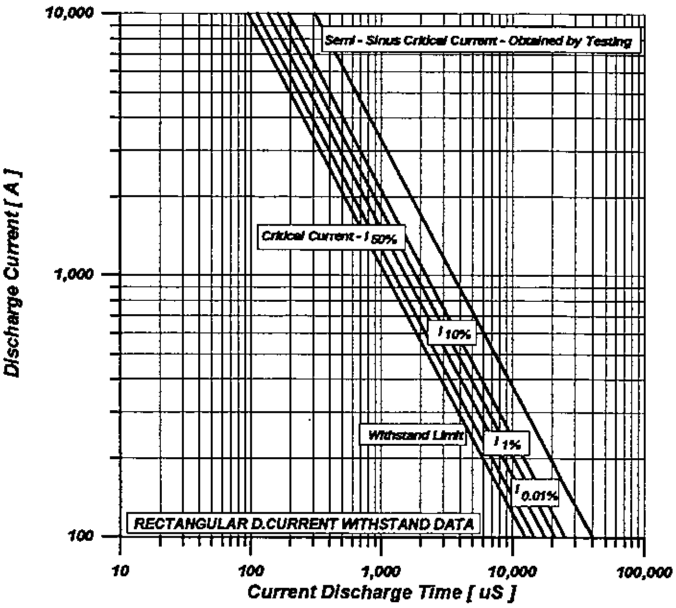

Figure 2 - Rectangular Current Withstanding Data Based on Damped Sinus Shape Discharge Current Testing

Equation 4, obtained from (1) and (2), with bases on the damped half sinus testing results computes the rectangular current versus time relation. In this case it is considered, for both shapes, the same current stress. It also interesting to remember that (4) can be obtained, directly, by the development of the thermal stress model.

$$T_R = \frac{\pi \beta_S}{\int \sin^{\gamma} x \, dx} I^{-\gamma} \qquad (4)$$

where: T_R - Maximum rectangular current discharge time, and β_S - Proportional coefficient of the time versus current curve, for a damped half sinus current shape, obtained by testing.

From figure 1 and (4) it is possible to obtain the data issued on figure 2 where, it is plotted, for the damped half sinus shape, the critical discharge current $I_{50\%}$ versus time characteristic and the computed rectangular shape series, basis for the duty factor approach.

III. COMMENTS ON THE RESULTS

Regarding the duty factor approach and presented testing method it is necessary to state two key points. The first is: *As proposed, the obtained data intend to represent the differential heating transient process of metal oxide resistors submitted to a single discharge current impulse. This model does not cover any surge ageing process*. The second is: *The global surge arrester risk of failure is associated to the surge arrester design. Therefore, it is interesting to observe that to get the same risk of failure, a metal oxide distribution surge arrester can deal with a higher metal oxide resistor probability of failure.*

After computing the complete discharge current failure-withstanding behaviour, as issued in figure 2, it is necessary to define the working limit for the probability of failure of the metal oxide resistors. This depends on the final arrester design and system application. The withstanding limit characteristic, i.e., the *0%* - probability of failure characteristic is the logical choice, However, it is sometimes necessary to work with a *"non-zero"* probability of failure. Therefore, for practical purposes the *0.01%* - probability of failure characteristic at which a *"duty factor - S=1"* is assigned seems to be a reasonable work limit for the probability of failure of the metal oxide resistors. For a *144 kV* surge arrester, this results in a withstanding probability of *99.5%*.

After defining the resistor probability of failure, according to (1), it is computed, for any non-standard current shape, the current peak versus current discharge time relation, as issued in figures 1 and 2. Once obtained the basic current parameters, peak and duration, the metal oxide resistor prospective energy absorption capacity is computed by a simple time integration of the voltage and current product. Figure 3, shows the current peak versus specific energy *kJ/kV* data for the tested samples. The current peak and the metal oxide arrester prospective energy absorption capacity are common results of a power system transients study.

During a power system transient study it is usual to consider that the energy absorption capacity does not depend on the current peak and shape. As can be seen on figure 3 this is not correct. The energy absorption capacity depends on (1) or (3) γ parameter. According to (5), a current peak increase results in an increase on the energy absorption capacity limit. Finally it is possible to state that for the tested samples when $\gamma \approx 1$, according to (5), the energy absorption capacity slightly depends on the current shape. As a remark, to the development of (5) it was considered the metal oxide resistors residual voltage model stated by (6).

$$\frac{E_R}{E_S}=\frac{\int_0^{\pi} \sin^{\gamma} x \, dx}{(2-\frac{\pi}{2})\frac{k_2-Ln(I)-1}{k_2-Ln(I)}+\frac{\pi}{2}} \qquad (5)$$

where: E_R - Energy absorption capacity of a resistor submitted to a rectangular current, E_s - Energy absorption capacity of a resistor submitted to a damped half sinus current and I - Current peak.

$$U=\frac{k_1}{k_2-Ln(I)}+k_3 I \qquad (6)$$

where: U - Metal oxide resistors residual voltage and $k_1-k_2-k_3$ - Residual voltage model generic constants.

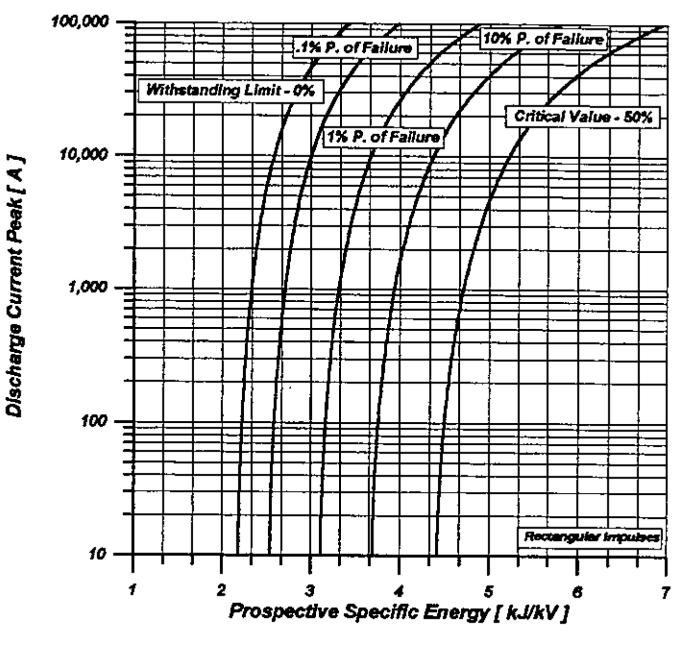

Figure 3 - Discharge Current versus Prospective Specific Energy and Probability of Failure

In this case, considering the tested resistors, according to (5), for a current peak lower than *1,000 A*, the energy absorbed by the resistors does not depend on the current shape, what fits to the thermal stress modeling. Now for a γvalue of *1.60*[1] and considering a current peak lower than *1,000 A*, the ratio of the energy absorbed by the resistors submitted to a rectangular current by the energy absorbed by the resistors submitted to a damped half sinus current is close to *0.80*. For this ratio the manufacturer states a value of *0.57* [1]. According to the development of (3) these results are almost impossible to be obtained, because it is, firstly, necessary to consider (7).

$$T_R = \kappa \frac{k_2 - Ln(I)}{k_1} I^{-1} \qquad (7)$$

where: κ – Mechanical data proportional coefficient.

Equation 8 was obtained considering typical values for the generic constants $k_1 - k_2 - k_3$.

$$T_R \approx \beta I^{-(1+\varepsilon)} \qquad (8)$$

where: ε – Exponent coefficient mismatch and, therefore, comparing with (2) results that $\gamma \approx 1 + \varepsilon$.

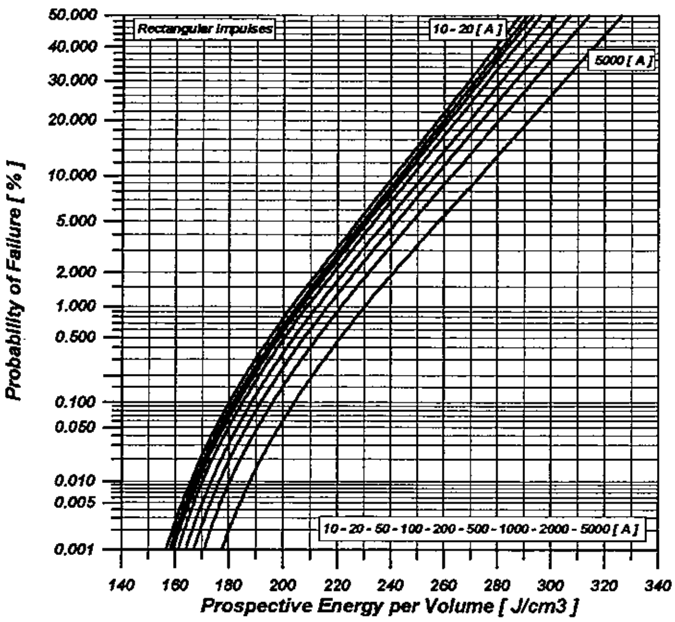

Figure 4 - Prospective Energy and Probability of Failure

Recently published results, for the ratio between discharge current peak and discharge time are in a good agreement with the presented testing results, i.e., the γvalue is close to *1.00* [4].

Similar results for the ratio between the energy capacity and the current peak, as shown in figure 3, were also recently obtained [4]. According to the figure 4, for the presented tested samples, the energy absorption capacity depends only on the current peak. The lowest value of the energy by unit of volume must be considered as the metal oxide resistor design limit. In the present case, depending on the probability of failure, this amounts to a value between $145J/cm^3$ and $160J/cm^3$.

The problem is that similar results of different testings result in a twofold interpretation. If the relation between the discharge current and discharge time can be modelled by (2) and the metal oxide resistors fail by cracking, the energy withstand capacity must be constant. However as shown in figure 3, computed values, and by [4], measured values, the energy withstand capacity of a metal oxide resistor depends, at least, on the peak of the discharge current what is in a complete disagreement with the proposed model.

The residual voltage measurement system used to obtain the values applied to compute the energy withstand capacity, issued on figure 3, does not take care with the inductive loop formed by the testing sample and by the voltage divider. Therefore, this measuring error, that increases with the current peak and rate of rise, can be responsible for the observed deviations of the testing and computed results regarding the proposed thermal stress model.

As shown by (9), that was developed from (3), the γ coefficient value can be computed from the residual voltage nonhomic exponent - α.

$$\gamma = \frac{\alpha + 1}{\alpha} \qquad (9)$$

where: α – Residual voltage nonohmic coefficient.

From figure 1 or from figure 2 it is possible to obtain, for the tested samples, the value of the γ coefficient, that, in the present case, is equal to *1.059*.

Considering a carefull residual voltage measuring, avoiding the effect of any inductive loop, using, for instance, a transmission line discharge current, using (9), it is obtained, for a current range from *100A* up to *4,000A*, a value of *1.05* for the γ coefficient. This means, strictly speaking, that in this current range, the energy absorption capacity is constant. This is not in a close agreement with the data issued in figure 3, that were computed using standard residual voltage measurements. However fits pretty well the proposed model.

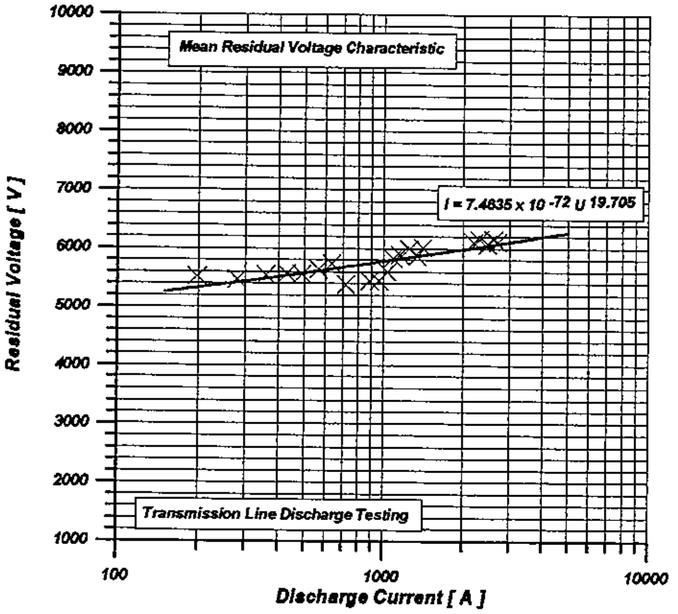

Figure 5 - Transmisson Line Residual Voltage Characteristic

V. THE CURRENT CHARGE ANALYSE

According to the previous discussion, the energy absorption capacity of a metal oxide arrester can be modelled by the duty factor approach.

Considering the proposed model and that the discharge current - discharge time characteristic and the residual voltage data were obtained with the help of two independent testing methods, it is possible, according to (5), to observe that, if the coefficient γ is close to *1.00*, that the metal oxide arrester energy absorption capacity does not depend on the current shape, at least for a not so narrow current margin.

However, in this case, as shown in figure 3 or even in figure 4, the metal oxide arrester energy absorption capacity still depends on the discharge current peak. As commented, both figures were obtained using the standard residual voltage data, as issued by the manufacturer.

Therefore, considering (9) and figure 2 and 5 data, it is possible to conclued that the main problem in computing the energy capacity of a metal oxide resistor appears to be assigned to confidence of the residual voltage characteristic, specifically, with the voltage measurement accuracy.

Trying to solve this, avoiding the technical measuring problem, it is possible to work with the discharge current charge (10),

$$Q = \int I(t)\, dt \qquad (10)$$

where: Q – Current associated charge.

and, assuming a rectangular current shape it is possible to transform (10) in (11),

$$Q = I\, T_R \qquad (11)$$

from (2), the original duty factor approach equation, it is obtained (12).

$$Q = \beta I^{(1-\gamma)} \qquad (12)$$

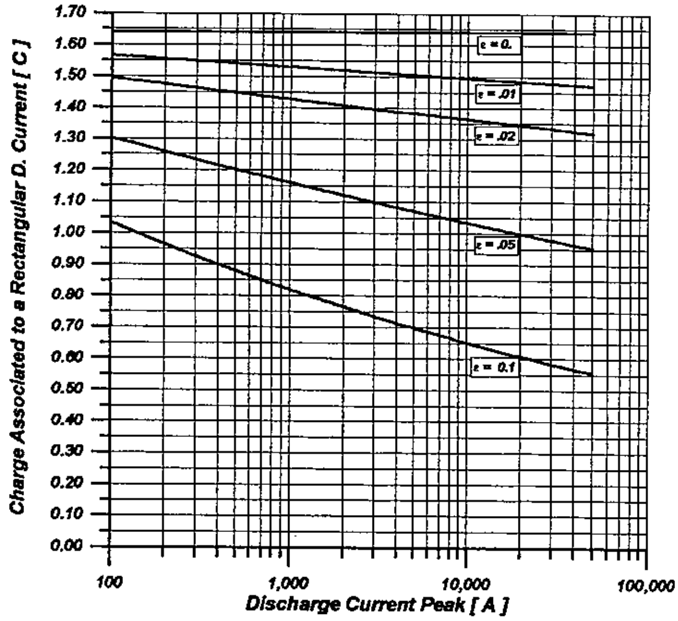

Figure 6 - Charge and Discharge Current Curve for the Tested Metal Oxide Resistors

Equation (12) can be also obtained, for instance, for a damped half sinus current shape. In considering, ideally, $\gamma \approx 1$ (12) the limit, before failure, for the charge that flows through a metal oxide resistor does not depend on the current peak or even on its shape. For the tested resistors this value is *1.64 Coulombs*.

To assume $\gamma \approx 1$ is, in fact, a severe simplification, therefore, sometimes it is necessary to deal with (13).

$$Q = \beta I^{\varepsilon} \quad (13)$$

where:

$$\varepsilon = \frac{1}{\alpha} \quad (14)$$

In a general way, according to (13) and figure 6, the charge that flows through a metal oxide resistor, before failure, depends on the current peak.The amount of charge depends on (13) $\varepsilon-$exponent coefficient mismatch that, according to (14), is related to the residual voltage nonohmic coefficient.

FINAL COMMENTS

The developed thermal stress model claims that the energy absorption capacity of a metal oxide resistor does not depend on the discharge current peak and shape.

Recent data, as in figure 2 and 3, has shown that for a γ value of *1.00* that the energy absorption capacity, computed or even measured [4], increases with the current peak. Previous data, for a γ value of *1.60* and similar conditions, [1] had led to the conclusion that the energy absorption capacity decreases with the current peak and also depends on the discharge current shape.

The charge capacity analyses, basically, depends only on the discharge current peak and when simplifying the problem, i.e., assuming that $\gamma \approx 1$ results that the charge capacity does not depend on the current shape and peak.

Considering the above discussion, it is also necessary to observe the following question, i.e., What is the best approach, the energy or the charge one ? The answer to this question is not very easy. Before starting, it is first necessary to determine the $\varepsilon-$exponent coefficient mismatch. If this value is close zero the charge approach is the best one because it does not depend on any specific testing set up to obtain the residual voltage data. Otherwise, the traditional energy approach appears to be the best choice because according to the present knowledge, at least for switching currents and for cracking failures, it is possible to assume that the energy absorption capacity of a metal oxide resistor is constant.

This sounds reasonable because even when considering any residual voltage measuring error, as shown in figure 3, for this current range, the relation between the discharge current and the propective energy is practically flat. The problem appears when computing or measuring the energy absorption capacity for higher discharge currents, in the lghtning impulse region.

The increase in the energy absorption capacity observed in figure 3 and [4] can be assigned to a residual voltage increase. This means that the energy absorption capacity analyses, claim for a careful residual voltage measurement. In this case, depending on the accuracy of the measurements it is necessary to consider that the energy absorption capacity depends at least on the current peak, as in figure 3, what is in a complete desagreement with the proposed model.

Finally, considering how the metal oxide resistors fail during testing it is possible to observe that for TOV - low amplitude long duration currents - the failure is associated to punctures, for switching and low peak lightning impulse currents, according to the presented testing, the failure is related to crackings and for high peak impulse currents the failure is assigned to an external dieletric breakdown or to crackings close to the electrodes edges, phenomena associated to a high electric field concentration. This behaviour induces to the conclusion that the present observed energy absorption capacity increase does not fit well with the whole failure mechanism. The solution to this impasse claims for more testing.

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