The Energy Absorption Capacity of Metal Oxide Surge Arresters
An Approach for Switching Surges

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Abstract - **The evaluation of the energy withstanding capacity of metal oxide resistors is the key point to compute the withstanding of the complete surge arrester.**

The energy withstanding capacity of a resistor follows a statistical path. Physical and mathematical modeling for the discharge tunneling phenomena, responsible for the instantaneous failure of the resistor is presented.

A testing method able to determine the reliability of the energy withstand capacity of metal oxide resistors is developed. Comments on physical, mathematical and empirical models are presented. Based on this it is possible to conclude that, at least for switching surge impulses, the energy withstand capacity of a metal oxide resistor is constant and independent on the impulse amplitude and shape.

Finally, a model to compute the energy withstanding of a complete metal oxide surge arrester is developed and presented.

Keywords: Surge Arresters Modeling, Energy Absorption Capacity, Insulation Coordination

I. INTRODUCTION

The energy absorption capacity of metal oxide resistors is determined by a group of electrical, thermal and mechanical conditions. Any phenomenon, that results in a concentration of electric field, i.e., in a concentration of discharge current, means a reduction of this capacity.

These phenomena can be associated to the position of the electrodes of the resistors, i.e., to presence of high peripheral electric field, when of currents of high intensity and rate of rise. However, in most cases, this is addressed to the concentration of a discharge current associated to switching surges or to power frequency overvoltages, in areas of relatively reduced resistivity, known as *Hot Spots*.

Associated to the electrical phenomenon, it exists a thermal-mechanical transitory that, depending on its intensity and on the constants of time of the resistor, electrical and thermal, can result in failure. This can be by fragmentation of the disk margin, when of high intensity lightning surges, by fragmentation of the disk when of switching surges or by puncturing when of power frequency stresses.

The theoretical limit for the energy absorption capacity of an uniform metal oxide resistor, i.e., without any punctual defect and not considering the concentration of electric field associated to the electrodes is determined by its mechanical characteristics *(1)*.

$$q_R = \frac{\sigma_R(1-\nu)\rho c}{E\alpha_L} \qquad (1)$$

where:

q_R = *Resistor Specific Energy [J/m^3]*
σ_R = *Minimum Bending Failure Stress [N/m^2]*
ν =*Poisson's Ratio*
ρ= *Density [kg / m^3]*
c = *Specific Heat [J / kg (C]*
ε = *Modulus of Elasticity [N/m^2]*
α = *Coefficient of Thermal Expansion [(C^{-1}]*

When considering the basic values of these parameters it is possible to obtain limits for the energy absorption capacity as shown in *Fig. 1*.

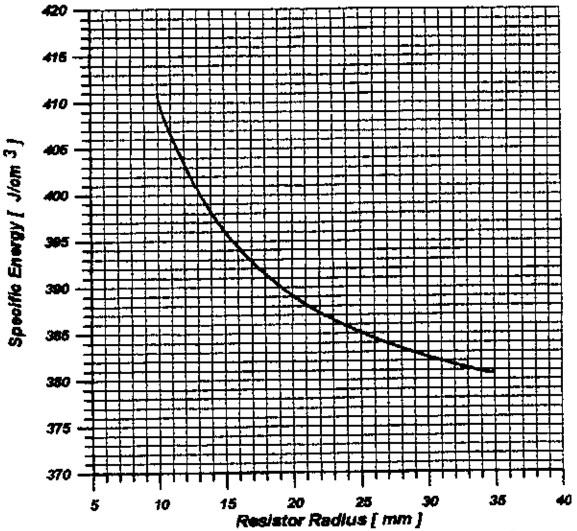

Fig. 1 - Maximum Theoretical Energy Absorption Capacity of a Metal Oxide Resistor

On the limit, the value of the specific energy is of the order of *370 J/cm^3*. However, problems related to the insulating rim material of the resistor, to the possibility of existence of high electric fields in the disk margin, close to the edge of the electrodes, and to the presence of regions of current concentration, *Hot Spots*, can further reduce this value.

When considering the basic values of these parameters it is possible to obtain boundary limits for the energy absorption capacity as in *Fig. 2*. The use of organic insulating rims tends to limit the energy absorption capacity to a value of *270 J/cm^3* because, normally, it is not possible to the organic materials applied to the resistors to operate in temperatures higher than *150 °C*.

The concentration of electric field in the edge of the electrodes tends to channel the discharge current, in reduced areas and, consequently, volume, resulting in a thermal processes acting to destroy the resistors, initially, by small size punctures and finally by fragmentation. The net result of this process is the reduction of the energy absorption capacity.

The model developed in this paper assumes an adiabatic process of absorption of heat and does not take into account the possibility of occurrence of mechanisms of heat diffusion. In spite of the associated electrical transients, considering the thermal mechanical origin of the limits of the energy absorption capacity, and the possibility of occurrence of thermal shocks, it is necessary to state that the boundaries defined by this model must be considered as maxims. Therefore, higher values for the energy absorption capacity when of impulses of high intensity should be faced with a certain reservation.

Once testing metal oxide resistors using high current levels is extremely difficult do not exist many laboratory or field results on these areas of discharge current. This can be addressed to the need of using properly designed isolating systems, able to withstand the stresses associated to discharge currents with a high rate of rise, as well as, to the necessity of adopting, when of the direct analysis of the absorbed energy, electromagnetic coupling free measuring systems. The current limits for the existence of the phenomenon of field concentration in the edge of the electrodes seem to start around of *20 A/mm^2*, i.e., *40 kA* for a resistor of standard commercial diameter.

The current concentration in *Hot Spots* a common and peculiar phenomenon to all metal oxide resistors when discharging switching impulses or lightning impulses of low amplitude, that determines an adiabatic characteristic for the energy absorption, means a reduction in the theoretical limit for energy absorption capacity. A series of works exists in this area and the theoretical models are reasonably well defined for the range of discharge current between *5 A/mm^2* and *50 mA/m^2*.

When the process of energy absorption is not adiabatic, i.e., when it starts to exist a phenomenon of diffusion of heat through the internal structure of the resistors, a possibility attached to low amplitude power frequency overvoltages, the presented model loses its validity. In these cases, it can be observed, when resistors with *Hot Spots*, since they do not present a strong influence in the process of current conduction, an elevation in the energy absorption capacity. In these conditions the resistors enter in failure, mainly, by puncturing.

Figure 2 shows the boundaries for the theoretical energy absorption capacity, as well as, the limits related to the use of organic insulating rim and due to a central *Hot Spot*. Finally, it is important to state that in resistors with a high degree of uniformity, the inadequate choice of the material used in the manufacture of the insulating rim is the main limiting factor in defining a high energy absorption capacity. This enhances the effective importance of a design that privileges the complete manufacture process.

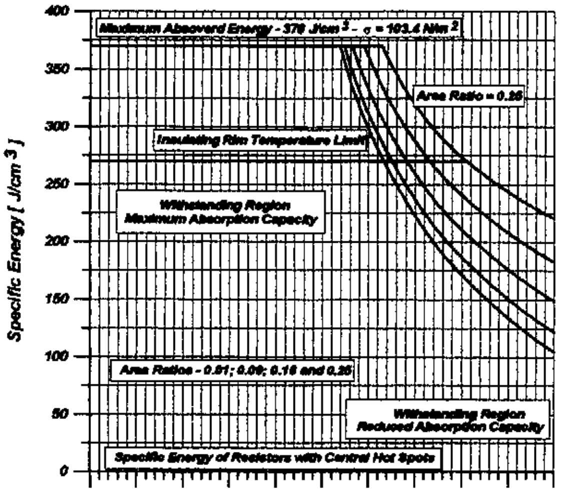

Fig. 2 - Limits for the Specific Energy for a Metal Oxide Resistor with a Central Hot Spot and Insulated by Rim of Organic Material.

II. EVALUATION OF THE ENERGY ABSORPTION CAPACITY

The models used to determine the energy absorption capacity of metal oxide resistors present two basic lines of thinking. The first and more commonly adopted works with the concept of direct measuring of energy through the values of the residual voltage and discharge current, that, in specific when of values of impulse currents of high amplitude claims for a series of precautions. The second, an indirect method, works with the concept of *Withstanding Current*, that to be referred to the common base of absorbed energy claims for a separated measuring of the residual voltage. This should also be carefully carried out under the penalty of resulting in the same errors that can occur in the direct method.

The use of any of these methods and analysis is a testing option linked to the local facilities. The method of *Current Withstanding* is, at first, a little simplified because it does not present any extra measuring difficulties, except when of impulses of current with high amplitude. However, once observed the random nature of the involved phenomenon it is necessary to assume a probability distribution that appropriately represents the behavior of the resistors. The proposed statistical model, for the analysis of the withstanding current, according to *Weibull*, the same extensively used when of the analysis of the dielectric systems withstanding, is also usually adopted to the analysis of the energy absorption capacity. In the moment this model is still able of critics, mainly and probably only due to the lack of data that can support its accuracy in representing the behavior of the resistors regarding to the current and energy stresses.

III. THE ENERGY ABSORPTION CAPACITY - A PROPOSAL FOR TESTING

The model for determining the energy absorption capacity of metal oxide resistors, as proposed, claims for a quite simple testing that uses a low number of testing objects. This is of highest importance when it faces the difficulty that is to order samples in the necessary number for the accomplishment of a wide study.

The method of analysis claims for *40* complete resistors, removed from the production line, or for a complete *120 kV* surge arrester. Once it is working with the one shot energy absorption capacity it is not necessary to determine the surge arrester thermal model to further carry out this testing.

The testing consists of a non-destructive part, related to the measuring, in *5* samples, of the residual voltage. In this case it is necessary to take all cares to avoid errors due to the coupling between the circuits for measuring current and residual voltage. It is recommend taking values of residual voltage for the current levels of *1.5kA*, *3kA*, *5kA*, *10kA* and *20kA*, *8x20* µs shape. Values of reference voltage, before and after the current applications, should be taken and compared. The medium and the maxim limit for the residual voltage, for each of the pre-defined current impulses, are taken as the confidence limit of the average of the results of *5* samples.

With the values of residual voltage for *1.5kA*, *3kA* and *20kA* the parameters for the residual voltage model are computed by *(2)*.

$$U = \frac{k_1}{k_2 - Ln(I)} + k_3 I \qquad (2)$$

where:
U = Residual Voltage, in instantaneous value, in the resistor [V]
I = Current, in instantaneous value, through the resistor [A]
k_1, k_2 and k_3 = Constants of the model.

Once defined the parameters of the residual voltage model it is recommended, to use the model for the discharge current time versus discharge current amplitude stated in *(3)*.

$$\tau = \beta k^{-\frac{1}{\alpha}} \left[\left[\frac{k_1}{k_2 - Ln(I)} + k_3 I \right] I \right]^{-1} \qquad (3)$$

where:
k = Coefficient of proportionality - Standard model
α = Non-ohmic coefficient of the metal oxide resistor - Standard model.
β = Coefficient of proportionality of the current shape.
τ = Time duration of the discharge current.

To define the model shown in *(3)* it is necessary to compute the value of β. This can be accomplished by the second, destructive, part of the testing. The proposed method consists of the application of current impulses, with half sinus shape, or transmission line discharge current, depending on the laboratory facilities.

Generally, the way of failure of the resistors when of the impulse current testing is fragmentation, linked to the starting and development of small cracks associated to the existence of thermal shock due to current concentration in high conductivity channels of small dimensions.

The cracks, at first microscopic, begin in the disk margin of the resistor, a region usually distant from the point of concentration of current. In these tests, failures associated to puncturing, with ejection of metallic particles, in form of metallic vapor, indicate the existence of serious problems in the microstructure of the resistors.

Another type of failure associated to lightning impulses occurs close the edge the resistors, normally by cracking but limited to the areas adjacent to the electrodes. These failures indicate the development of high field stresses in the disk margins. In these cases occurs a modification in the characteristic discharge current time versus discharge current amplitude meaning a further reduction of the energy absorption capacity of the resistors.

The proposed testing method, in spite of recent application when of non-linear resistors, is the *UP and Down Method* with one current impulse per charging voltage level. To the modeling of the discharge current statistical behavior it is proposed the use of the *Symmetric Weibull Distribution*. This allows, by the application of the *Likelihood Method*, to obtain the *Critical Current - $I_{50\%}$* and its *Standard Deviation*.

According to the present experience the resistor withstand the current impulse if no visual failure is observed. The reference voltage measurement after the disk cooling, usually, has been confirming these results.

The control parameter for the testing is the charging voltage of the generator that, at first, should be increased in steps of *10%*. When a resistor fails after an impulse application the charging voltage is reduced of a step. If it supports the impulse application, it should be substituted by a new one that is now submitted to an impulse with the charge voltage increased of a step. The value of the charging voltage step can be modified depending on the results of the testing that, for a better definition, must have at least *5* levels of discharge current applications.

Considering, at least, the results of *35* impulse current applications, the mean values of the currents per level of charging voltage must be determined by standard techniques. With this it is reduced the influence of any further error due to the generator low impedance. From these results and applying the *Likelihood Method* it is computed the *Discharge Critical Value - $I_{50\%}$* and its *Standard Deviation - σ_I*.

$$\beta_{50\%} = k^{\frac{1}{\alpha}} \tau \left[\frac{k_1}{k_2 - Ln I_{50\%}} + k_3 I_{50\%} \right] I_{50\%} \qquad (4)$$

where:
$I_{10\%} = I_{50\%} - 1.29\sigma_I$
τ = Discharge time of the testing current
α = Resistor non-ohmic coefficient (6)
k = Proportional coefficient (7)

$$Z_\beta = \frac{k^{\frac{1}{\alpha}}\tau}{1.29}\left[\left[\frac{k_1}{k_2 - Ln I_{50\%}} + k_3 I_{50\%}\right] I_{50\%} - \left[\frac{k_1}{k_2 - Ln I_{10\%}} + k_3 I_{10\%}\right] I_{10\%}\right] \qquad (5)$$

$$\tau = \kappa^{-\frac{1}{\alpha}}\left[\beta_{50\%} + \eta\sigma\left[\left[\frac{Ln\left[1 - 0.01p\%\right]}{Ln\left[0.5\right]}\right]^{\frac{Ln\left[\frac{\eta}{\eta-1}\right]}{1.39}} - 1\right]\right]\left[\left[\frac{k_1}{k_2 - Ln\left[I_{[p\%]}\right]} + k_3 I_{[p\%]}\right] I_{[p\%]}\right]^{-1} \qquad (11)$$

where:

$I_{[p\%]}$ = Current amplitude with a pre-defined probability of failure

$$E_{Esp} = \frac{\left[\frac{k_1}{k_2 - Ln100} + 100k_3\right]}{U_{MCOV}} 100^{-\left[\left[Ln10\right]^{-1}\left[Ln\left[\frac{\left[\frac{k_1}{k_2 - Ln1000} + 1000k_3\right]}{\left[\frac{k_1}{k_2 - Ln100} + 100k_3\right]}\right]\right]\right]} \qquad (14)$$

$$E_{[0\%]} = \frac{\left[\frac{k_1}{k_2 - Ln100} + 100k_3\right]}{U_{MCOV}} 100^{-\left[\left[Ln10\right]^{-1}\left[Ln\left[\frac{\left[\frac{k_1}{k_2 - Ln1000} + 1000k_3\right]}{\left[\frac{k_1}{k_2 - Ln100} + 100k_3\right]}\right]\right]\right]}\left[\beta_{[50\%]} - \eta Z_\beta\right] \qquad (17)$$

With these data and *(4), (5), (6)* and *(7)* they are computed the values of the *Critical coefficient of proportionality of the current shape - β50%*, and its *Standard deviation - Z_β*.

After considering a correction factor due to the testing impulse shape as stated in *(8)* for half sinus, or in *(9)* for transmission lines discharge currents, with *(10)* it is determined the statistical trend of the *Coefficient of Proportionality of the Current Shape - β.*

$$\alpha = Ln10\left[Ln\left[\frac{\frac{k_1}{k_2 + Ln1000} + 1000k_3}{\frac{k_1}{k_2 + Ln100} + 100k_3}\right]\right]^{-1} \qquad (6)$$

$$k = \frac{100}{\left[\frac{k_1}{k_2 + Ln100} + 100k_3\right]^{Ln10\left[Ln\left[\frac{\frac{k_1}{k_2 + Ln1000} + 1000k_3}{\frac{k_1}{k_2 + Ln100} + 100k_3}\right]\right]^{-1}}} \qquad (7)$$

$$\chi = \frac{2}{\pi} \qquad (8)$$

$$\chi = \frac{\left[\frac{T_{10}}{T_{90}} + 1\right]}{2} \qquad (9)$$

where:

χ= Correction factor applied to the Critical Current and to its Standard Deviation.

T_{10} and T_{90} = Transmission line discharge parameters.

After computing the statistical ratio between the discharge current peak and the discharge time duration *(11)* and considering the residual voltage versus of discharge current characteristic of the tested resistor *(3)* it is possible, according to *(12)*, to compute the energy withstand capacity of the resistor.

$$\beta_{[p\%]} = \left[\beta_{50\%} + \eta Z_\beta\left[\left[\frac{Ln\left[1 - 0.01p\%\right]}{Ln\left[0.5\right]}\right]^{\frac{Ln\left[\frac{\eta}{\eta-1}\right]}{1.39}} - 1\right]\right] \qquad (10)$$

where:

τ= Maximum discharge time of a rectangular impulse current

$\beta_{[50\%]}$ = Coefficient of proportionality of the critical current

$\beta_{[p\%]}$ = Coefficient of a current with a pre-defined failure probability

$I_{[50\%]}$ Critical current amplitude [A]

p% = Pre-defined probability of failure of the resistor

η = Coefficient for the Symmetrical Weibull Distribution equals to 4

$$E_{[p\%]} = \frac{1}{U_{MCOV}}\int_0^\tau u(t) i(t) dt \qquad (12)$$

where:

$E_{[p\%]}$ = Specific Energy for discharge current with a pre-defined failure probability [kJ/kV]

i(t)= Instantaneous current trough the resistor [A]

u(t) = Instantaneous residual voltage of the resistor [V]

U_{MCOV} = Maximum resistor continuous operating voltage [V]

τ= Maximum discharge current time [μs]

For the proposed model, the energy withstand capacity of a metal oxide resistors, for a standard adiabatic heating, is constant and does not depend on the current shape or even amplitude. Therefore, considering rectangular shape impulses it is possible to obtain *(13)* and *(14)*.

The specific energy value computed by *(12)* or by *(13)* and the attached withstanding probability of failure is related to a single current shot application. The choice of a statistical limit for the withstanding energy *(15)* when compared with the lightning arrester design defines the whole system - complete surge arrester - energy withstand capacity as shown in *(16)*.

$$E_{[p\%]} = E_{Esp}\left[\beta_{50\%} + \eta Z\beta\left[\left[\frac{Ln\left[1-0.01p\%\right]}{Ln\left[0.5\right]}\right]^{\frac{Ln\left[\frac{\eta}{\eta-1}\right]}{1.39}} - 1\right]\right] \quad (13)$$

$$pF_{[\%]} = 100[1 - e^{\left[Ln0.5\left[\frac{\left[\left[\frac{E_{[p\%]}}{E_{Esp}}\right]-\beta_{50\%}\right]}{\eta Z_{\beta}}+1\right]^{\frac{1.39}{Ln\left[\frac{\eta}{\eta-1}\right]}}\right]}] \quad (15)$$

where:
pF% = Probability of failure of the resistor

$$pWA_{[\%]} = 100e^{\left[N_C N_{RS} Ln0.5\left[\frac{\left[\left[\frac{E_{A-[p\%]}}{E_{Esp}}\right]-\beta_{50\%}\right]}{\eta Z_{\beta}}+1\right]^{\frac{1.39}{Ln\left[\frac{\eta}{\eta-1}\right]}}\right]} \quad (16)$$

where:
$E_{A\text{-}[p\%]}$ = *Specific energy of the complete surge arrester [kJ/kV]*
$^{P}WA[\%]$ = *Probability of withstanding the energy stresses of the complete surge arrester*
NC = Number of the columns of the compete surge arrester
NRS = Number of series resistors per column of the complete surge arrester

The use of the *Symmetrical Weibull Distribution* to model the dependence between the discharge time duration and the discharge current peak of the impulses, i. e., of a limited distribution, makes possible to define a *"E[0%] Withstand Limit"* as stated in *(17)*.

The key points against this proposed approach are related, first, with choice of *the Symmetrical Weibull Distribution* to model the dependence between the time duration and the amplitude of the current impulses. For this, there is not an answer, mainly, because, in the moment, there is not enough data in this field. The adopted distribution is symmetrical and also limited what seems logical when the involved failure mechanism is associated to the development of microscopic cracks related to the presence of *Hot-Spots* what means a punctual adiabatic heat absorption process. Second, some care must be taken regarding the possible extrapolations of this model mainly due to absence of testing equipment able to apply destructive high current levels. Finally, in the testing range that covers basically discharge times between *500 μs* and *18,000 μs* the developed model and testing procedure seems to be reasonably appropriate.

IV. MODELING OF A COMPLETE ARRESTER – A STUDY CASE

The resistors tested were metal oxide disks with *50 mm* diameter and *22 mm* height for *10 kA – 2.55 kV COV* used in assembling *IEC Class 2* surge arresters up to *228 kV*.

Table I shows some values of residual voltage measured, with *8x20μs* impulse shapes, when of the non-destructive testing of the resistors and used to compute some of the parameters of the resistor model.

Table I – Residual Voltage Testing Results

RESIDUAL VOLTAGE TESTING RESULTS DATA			
Current Level [kA]	*1.48*	*3.10*	*20.7*
Standard Deviation	*0.1*	*0.2*	*0.5*
Residual Voltage [V]	*6630*	*6870*	*8920*
Standard Deviation	*235*	*255*	*280*

With the values of discharge current and residual voltage and with *(2)*, *(6)* and *(7)* they were computed the metal oxide resistor characteristics shown in *Table II*.

Table II – Metal Oxide Residual Voltage Parameters for Mathematical Modeling

METAL OXIDE RESISTOR PARAMETERS	
Logarithmic (2) – k_1 Coefficient	*74,417.71*
Logarithmic (2) – k_2 Coefficient	*18.61*
Logarithmic (2) – k_3 Coefficient	*0.0183*
Non-Ohmic Coefficient - α	*12.64*
Proportional Coefficient - k	*8.13e-46*

For the second part of the testing, the destructive one, a semi-sinus discharge current with *8,700 μs* was applied to *25* disks, one shot per disk, according to the *Up and Down Method* and it was computed the withstanding – failure rate of the resistors as stated in *Table III*.

Table III – Up and Down Testing Method Results

SEMI-SINUS DISCHARGE CURRENT – 8,700 μS				
Level	*Current [A]*	*Discharge*	*Withstand*	*Total*
1	*539*	*1*	*0*	*1*
2	*476*	*4*	*1*	*5*
3	*408*	*5*	*3*	*8*
4	*328*	*1*	*5*	*6*
5	*247*	*0*	*1*	*1*

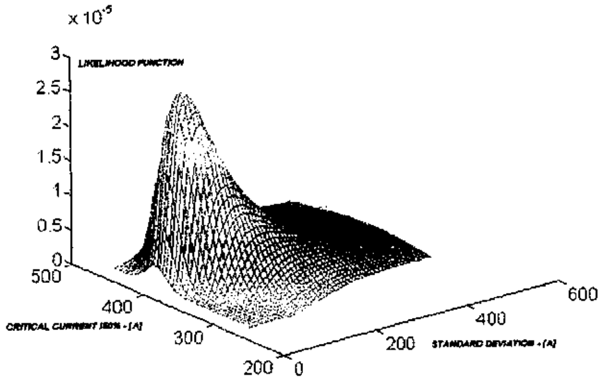

Fig. 3 – Likelihood Function for the Discharge Current Data Shown in Table III and IV

The application of the *Likelihood Method* to the data shown in *Table IV* results in *Fig 3* and *Fig 4* meaning a *Critical current - I50% = 397.56 [A]* and a *Standard deviation* - $\sigma I = 80.9$ *[A]*.

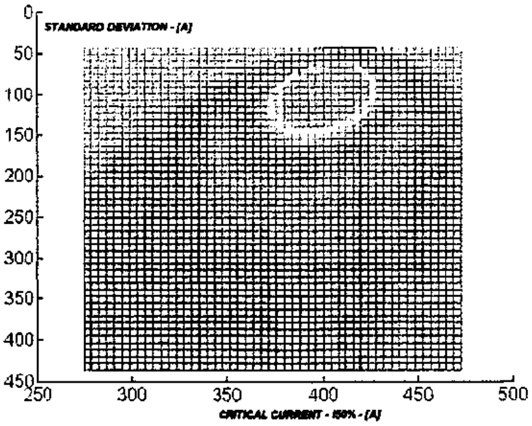

Fig. 4 – Likelihood Function Projection for the Discharge Current Data Shown in Table III

With these values and with the data of *Table I*, *(4)* and *(5)* they are obtained a *Critical coefficient of proportionality of the current shape* - $\beta50\% = 5.528$ and a *Standard deviation* - $Z_\beta = 1.198$.

Both values, related to a semi-sinus wave shape current must be corrected to the standard rectangular shape by *(8)*. This results in a *Critical coefficient of proportionality of the current shape* - $\beta50\% = 3.520$ and a *Standard deviation* - $Z_\beta = 0.763$.

The *Specific Energy [kJ/kV]*, as in *(18)*, and the *Probability of failure of the resistor*, as in *(19)*, are computed considering the values of the *Critical coefficient of proportionality of the current shape* - $\beta50\%$ and of the *Standard deviation* - Z_β *(13)*, *(14)* and *(15)*.

$$E_{[p\%]} = 5.097 + 4.419\left[\left[\frac{Ln[1-0.01p\%]}{Ln[0.5]}\right]^{4.832} - 1\right] \qquad (18)$$

$$pF_{[\%]} = 100\left[1 - e^{-\left[0.6932\left[\frac{\left[\left[\frac{E_{[p\%]}}{1.448}\right] - 3.520\right]}{3.052} + 1\right]^{4.832}\right]}\right] \qquad (19)$$

For a surge arrester with one column of stacked disks, the common assembly of this type of surge arrester, it is possible to use *(20)*, developed from *(16)*.

$$pWSA_{[\%]} = 100e^{-\left[\frac{U_R}{3}\left[0.6932\left[\frac{\left[\left[\frac{E_{[p\%]}}{1.448}\right] - 3.520\right]}{3.052} + 1\right]^{4.832}\right]\right]} \qquad (20)$$

where:

U_R = *Rated voltage of the surge arrester*

Equation (20) can be directly used; it is only necessary to consider the value of the specific energy applied to the arrester obtained by means of any standard transient study. The result of *(20)* is the probability of the surge arrester to withstand the applied stress. From *(20)* it is possible to develop *Fig 5*, that shows a quite simple idea, i.e., the energy withstand capacity of a surge arrester depends on its rating. This means that testing carried out in low rating samples, as for instance, *The Transmission Line Discharge Test*, must be extensive in order to present some statistical meaning.

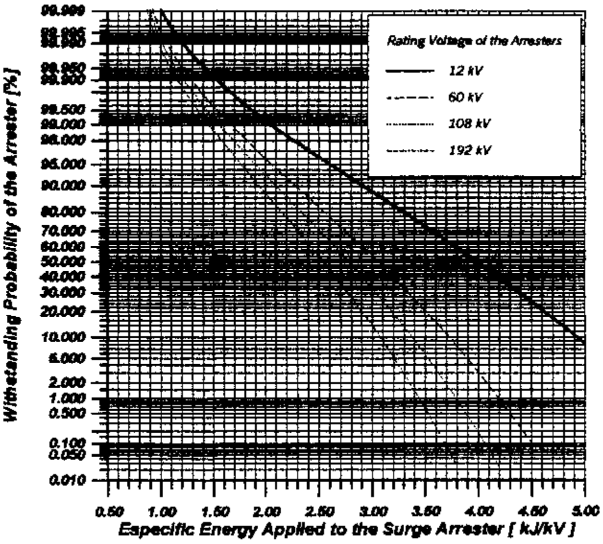

Fig. 5 – Probability of Withstand an Energy Stress of a Complete Metal Oxide Surge Arrester

V. COMMENTS

The developed model for the energy withstanding capability of metal oxide resistors, at least for switching impulses, presents a good laboratory attachment. Direct energy measurements were not able to show a well defined relation among the discharge current peak, the discharge time duration and impulse shape, at least for the current levels of the presented data. However, the discharge current peak versus discharge time duration fitted pretty well with the thermal mechanical modeling assumed for the *Hot Spots*, this means that for this range the model is quite reasonable.

For sure further testing is needed to really define the complete subject mainly regarding metal oxide resistors from other manufactures, but for this specific case the presented model is really a good one.

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