AN APPROACH TO METAL OXIDE ARRESTERS SWITCHING SURGES ENERGY ABSORPTION CAPABILITY EVALUATION

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ABSTRACT:-

This paper deals with considerations regarding metal oxide resistors *"Internal Spots"* and energy absorption capability. In this way the associated mathematical modelling, the related physical-mathematical constraints, some testing results and also testing method, carried out in metal oxide standard production batches are presented and discussed.

Finally, the application of such approach in the *"Surge Arrester Energy Absorption Capability Studies"* related to *"Duty Factor Approach"* statistical characteristic specific aspects are presented and discussed and, as a direct result of this a new method useful to obtain the surge arrester withstand capability probability or even the surge arrester risk of failure is presented.

INTRODUCTION:-

During high voltage system planning studies, among others, it is necessary to deal with aspects related to surge arresters switching surge energy absorption capability that, usually, are verified by standards specified testing procedures, covering, basically, almost all application situations. However, some particular stresses, specifically those resulting in high current short duration as, for instance, among others, that one related to overvoltages due to capacitors switching failures are not efficiently covered.

Generally, all the arresters standard specifications are based on a rule that deals with current peak and energy stress maximum values that, by their turn, are combined in a such way that, virtually, define the arrester energy absorption capability requirements. However, this procedures sometimes results in a multi-column design arrester, usually, over specified mainly due to, fortunately, high current peaks are associated with low energy stresses.

To cover this it was proposed a stress evaluation method based on metal oxide valves current peak versus discharge time withstand characteristic, the so called *Duty Factor Approach - S*, defined, for a generic current shape, as following, by the *Equation-1:/1/*

$$S = \sum_{i=1}^{n} \frac{\Delta T_i}{T_{Max\,i}} \qquad [1]$$

where:

ΔT_i - it discretized square pulse discharge time; and

$T_{Max\,i}$ - maximum discretized square pulse discharge time.

And, finally, that according to *Equation-2* there is a current time dependence as following:

$$I = \alpha \; T_{Max}^{\;-\beta} \qquad [2]$$

where:

α - current wave shape characteristic coefficient; and

β- resistor characteristic coefficient.

At this point it is interesting to note that the above definitions results in a series of mathematical restrictions that must be fulfilled to validate this approach presented and discussed in this paper. It is also convenien to observe that all the attached *Duty Factor Approach* mechanisms and assumptions, with the absence of any kind of testing, can be discussed and assumed as correct but, considering that they claim for a cracking process equivalence, these considerations are difficult to be accepted.

The laboratory testing method results, that are shortly presented and discussed here, are used, basically, to obtain *Equation-2* parameters, that is, the basic *"Discharge Current Time Dependence"* that permits to obtain the related *"Energy Absorption Capability versus Current*

Peak Characteristics", usually useful for surge arrester switching energy absorption capability requirements verification. However, as this testing method must presents statistical bases it is possible, as discussed below, to get a surge arrester withstand probability or even a surge arrester risk of failure.

2. DUTY FACTOR BASIC REQUIREMENTS

Dealing with *Equation 1* and *Equation 2* definitions it is possible to verify that to apply *"Duty Factor Approach"* two mathematical restrictions, resumed as following, must be fulfilled:/2/

I)- "During two different laboratory surge current waves application series the "Duty Factor", to be validated, requires, in a log- log scale, for two parallel straight lines ***Discharge Current Peak - Maximum Allowable Discharge Current Time Characteristic"****; and*

II)- "It is also necessary to show that it is always possible to define a mathematical relationship able to specify both α parameters in a function of a basic one, that is, the related to a rectangular discharge current wave".

In this way, using two usual laboratory surge current generators, that is, *"Transmission Line Discharge Current Generator"* and *"Semi-Sinus Discharge Current Generator"*, it is possible to define a testing method and also an equipment set up aiming, firstly, to verify, both *"Duty Factor"* mathematical restrictions and, finally, also to obtain a metal oxide resistor discharge current withstand statistic data and finally a general surge arrester discharge current and energy withstand model/2-7/

3. DUTY FACTOR APPROACH TESTING PROPOSAL

The metal oxide resistors energy absorption capacity is, usually, verified by the traditional *"Transmission Line Discharge Test"* designed, basically, to provide silicon carbide arrester withstand data.

As verified in practice, this testing, for sure, can be successfully applied to metal oxide arresters. However as these surge arresters are, mainly for high voltage systems, designed in a gapless version they are subjected to a current discharge stress every time the applied voltage is higher than the arrester voltage threshold. Then, in theory, due to the gap filter action absence, it is easy to these surge arresters to be over stressed, for instance, by a continuous current discharges series or even by a high current amplitude low energy surges. A suitable way to verify the above concerns is to apply the *"Duty Factor Approach"*, that results in a metal oxide resistor model that deals with the resistor *"Discharge Current - Time"* characteristic.

The *"Duty Factor"* basic laboratory work is divided in two different tasks:

The first one carried out in a small testing sample batch, containing at least *20* metal oxide resistors per current discharge time per wave shape, and in this case, ideally, it will be interesting to have a full complete data related to, basically, three current discharge time decades has as objective to verify the *"Duty Factor"* mathematical restrictions and to define the *"Critical Discharge Current Characteristic - I 50%"* as shown in *Figure 1*. The *"Up and Down Testing Method"* is presently adopted to perform this test part. /2-4/ In order to reduce testing time, the discharge current sample withstand verification is carried out by visual means.

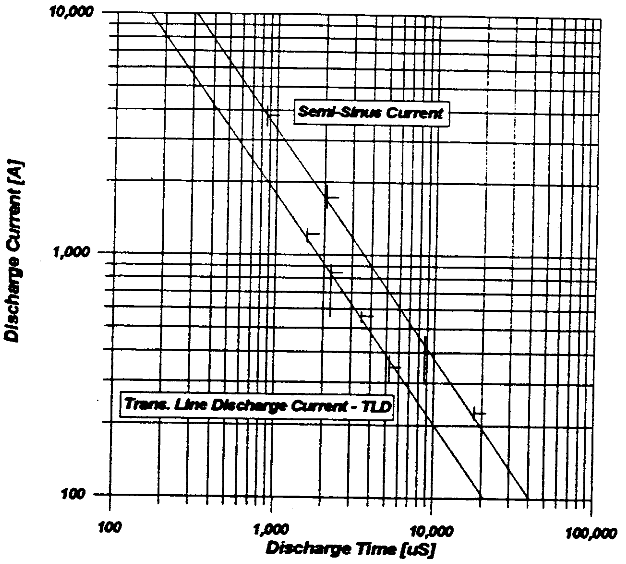

Figure 1 - TLD and Semi-Sinus Critical Discharge Current $I_{50\%}$

After testing both *"Semi Rectangular"* and *"Semi Sinus" "Critical Discharge Current Characteristic - I 50%"* are determinated. Usually, the data point, are obtained by the *"Likelihood Method"* application and, the curve itself, by the *"Least Square Method"*. Finally, to verify the *"Duty Factor Approach"* validation it is necessary to check both characteristics parallelism /1-2-7/ and if, within acceptable limits, it is possible to refer both characteristic parameters to the same basic current wave, that is, to the rectangular one, according to *Equation 3 and Equation 4*. /7/

$$\alpha_{C.TLD} = \frac{\alpha_{90}\left[\beta + \frac{T_{10}}{T_{90}}\right]}{\beta + 1} \qquad [3]$$

$$\alpha_{C.SS} = \frac{\alpha_{ds}\int \sin^{\beta} x \, dx}{\pi} \qquad [4]$$

where:

$\alpha_{C.TLD}$ - *TLD* results computed α coefficient; and

$\alpha_{C.SS}$ - *S.Sinus* results computed α coefficient.

Regarding to *Discharge Current Time* and *Current Amplitude*, that is, to the surge testing basic parameters, it is necessary to verify the *"Transmission Line Discharge Current Generator"* charging voltage, discharge current time ranges that are, basically, attached to the generator's capacitances and inductances and first generator's inductances withstand voltage. Finally, as these parameters result in a lot of set up restrictions the only way is to work, within the pre-defined limits with them but, normally, it is always convenient to obtain a maximum by minimum discharge current time ratio higher than *4*. /2-7/

Considering that the *"Cracking Metal Oxide Phenomena"* is independent of the tested sample number, one can easily assume that once verified for the *Critical Current* - $I_{50\%}$ the *"Superposition Principle Application"* does not need to be verified again. Then, the second laboratory task, using only the *"Semi - Sinus Current Generator"*, due to its statistical characteristics must be carried out in a big testing sample batch containing, roughly, at about *240* metal oxide resistors per current discharge time.

In this case, due to the high sample number the testing procedure can be carried out according to the *"Extended Up and Down Method"* or even according to the *"Multiple Level Method"*.

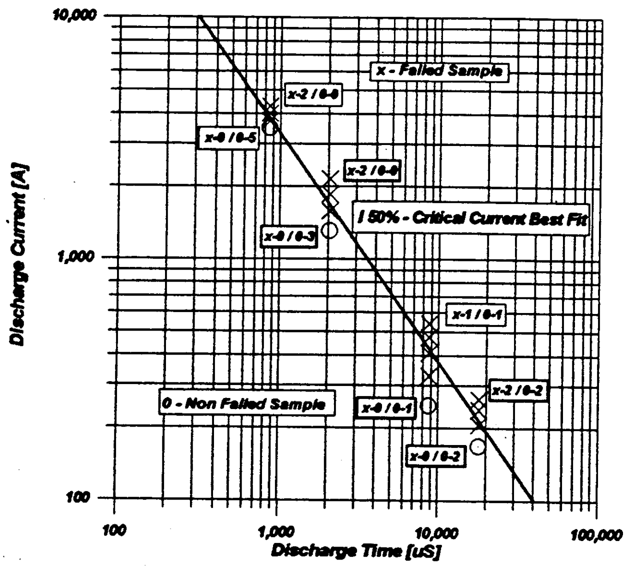

Figure 2 - Withstand Failure Data for Semi-Sinus Discharge Current

To work with the *"Extended Up and Down Method"* involves to divide the original batch in three parts, the first one with *2* samples per testing group, that corresponds to a *30%* discharge current probability, the second one with *3* samples per group, that corresponds to a *20%* discharge current probability and the last one with *7* samples per testing group that, finally, corresponds to a *10%* discharge current probability.

The data statistical evaluation, as previously defined, can be carried out by the *"Likelihood Method"* and by the *"Least Square Method"*.

Once obtained the $I_{50\%}$, this one from the first testing part, $I_{30\%}$, $I_{20\%}$ and $I_{10\%}$ it is possible, for every discharge current time to obtain the best statistical approach and, finally, the metal oxide resistors withstand limits, that means, the surge arrester energy absorption capacity confidence limits. The same can be obtained by the *"Multiple Level Method"* application. In this case, it is recommended to divide the original batch in *8 groups* each one containing *30 samples*.

By the moment, there is not an agreement on which is the better testing method. At first sight, both seem to be suitable for the proposed task. However, the *"Up and Down Method"* can result in a low test sample consume which is an interesting possibility, mainly, facing the standard production metal oxide resistors use. On the other hand, this method requires a resistor withstand visual evaluation, that can be, by any reason, to put in judgement, in spite of, according to the present experimental results, this procedure presents a good agreement to a more sophisticated metal oxide resistors withstand evaluation method.

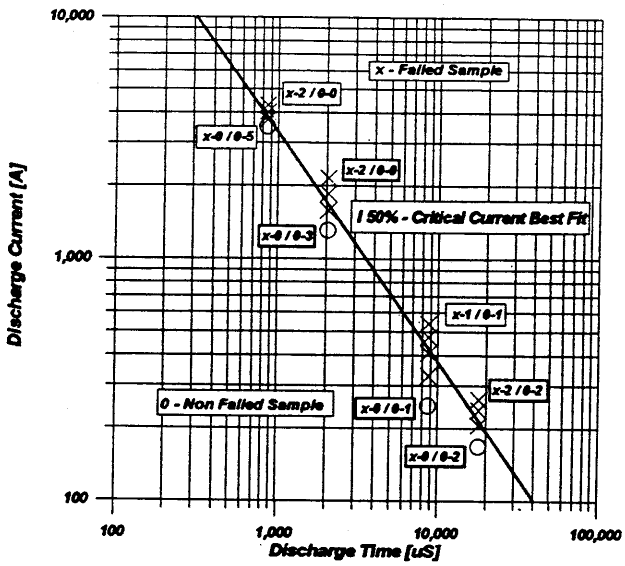

Figure 3 - Withstand Failure Data for Semi-Rectangular Discharge Current

For sure *Figure 2* results, related to a *82* single discharge shot applications */2-7/* can define a metal oxide resistors discharge current withstand capability limit. But, if the obtained results do not have a statistical treatment it is virtually impossible to conclude on a complete high voltage surge arrester discharge current withstand capability. It is interesting to remember that the same comments can be written regarding to *Figure 3* results that are related to a *104* single discharge shot applications.

Finally, it is also important to remember, at this point, that both *Figure 2* and *Figure 3* are related to metal oxide resistors discharge current withstand capacity and according to both the ultimate withstand limit depends on the discharge current wave shape fact not covered by any standard testing method.

4. STATISTICAL DATA TREATMENT

Applying the *Weibull Distribution Approach* and the *Least Square Method* on *Figure 2* and *Figure 3* data and with the *Likelihood Method* results help, depending on the data accuracy, it is possible to obtain a curve set that deals with the current - discharge time dependence and associated probability */9/* Once obtained the above curve set it is necessary first to convert the set to a perfectly, theoretical, rectangular current wave shape using *Equation 4* and, finally, to define the *"Duty - Base Value"*, that is, *S = 1*.[1]

Notes:-

1- Mainly due to laboratory facilities, it is interesting to work with the semi-sinus discharge current wave shape instead of with the semi-rectangular current wave shape.

Using this techniques it is possible to obtain, for each metal oxide resistor type, a curve set similar that one shown in *Figure 4*, related to *Figure 2* and *Figure 3* data.

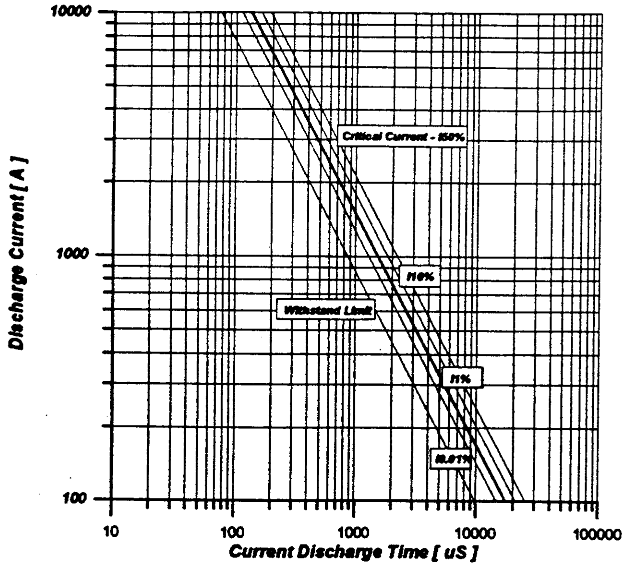

Figure 4 - *Metal Oxide Resistors Rectangular Withstand Characteristics Set*

Reporting to *Figure 4* data it is necessary now only to define the *"Duty - Base Value"* and, in doing this it is necessary to remember two points.

The first one is related to the fact that the above data set intend to model one shot discharge current transient metal oxide resistor differential heating process, and in this way, this model do not cover any associated surge ageing process, that is, in first instance, it is always necessary to take care with multiple discharges.[2] The second one is related to the global surge arrester risk of failure, this one associated to the surge arrester design and assembly, that is, related to metal oxide resistor series and or parallel number and arrangement. In this case it is interesting to observe that to get the same risk of failure a metal oxide distribution surge arrester can deal with a higher individual metal oxide resistor failure probability, that at first sight seems to be a common sense, however using the proposed approach, this can be completely defined and quantified.

Notes:-

2- Dealing with "Duty Approach" definition as stated by Equation-1 and Equation-2 it is possible to work with multiple surges, but as the equivalence is defined in one shot bases the assumed stress is higher then the real one.

According to *Figure 4* curve set, mainly regarding the tested samples, the above discussion, at first sight, can be avoided because there is a reasonable *Current-Time Withstand Margin*. However this is partially correct and basically this is restricted to the switching surge discharge current region. As it is possible to see, from *Figure 4* there is not a so large *Current-Time Withstand Margin* in the lightning surge discharge current region, as it will be necessary in transmission line surge arresters design.

Therefore, in these cases it is necessary to work within a defined current withstand confidence limit and, practical purposes the *0.01%* metal oxide resistors failure characteristic, that now is assigned the value *"Duty - S=1"*, seems to be a reasonable failure probability work limit because, as can easily computed, it results in *99.2% 230kV* surge arrester withstand probability.[3]

Notes:-

3- To correctly define the "Duty Factor Approach" limit, that intends to model a short transient heating phenomena, it is necessary to observe the complete surge arrester thermal model.

5. DUTY APPROACH APPLICATION

As discussed, mainly regarding high current levels, the *"Duty Factor Approach"* can be used to define surge arresters withstand limit and failure risk and in a case of a complete application, covering lightning and switching discharge currents, as shown in *Figure 5* it is convenient and also useful to deal with two *"Duty - S = 1"* curve set.

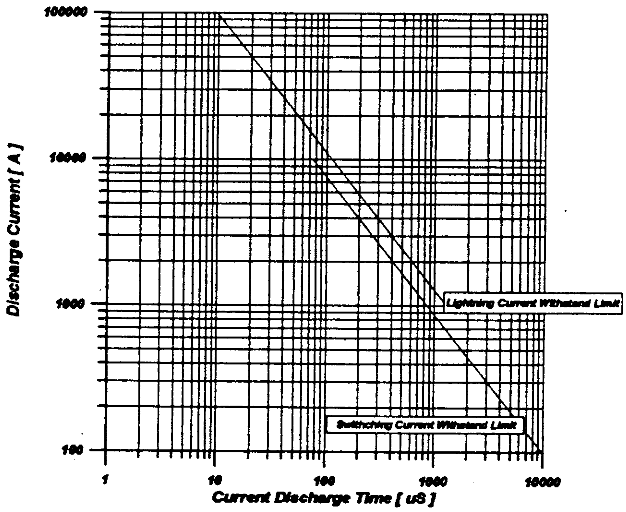

Figure 5 - Metal Oxide Resistors Rectangular Withstand Limits

Now considering *Figure 5* characteristics and *Equation-2*, that is, computing the current *"Duty"*, it is easy to obtain any wave shape and amplitude discharge current stress and, as can be figured, in order to have a correct surge arrester application, this value must be lower than unit.[4]

Notes:

4- To completely to define the correct surga arrester aplication it is also necessary to verify the attached "Specific Energy - [kJ/kV], that is, the long transient heating phenomena and model.

A *"Duty"* value lower than unit means that the surge arrester presents a lower failure risk. By the other hand a *"Duty"* value higher than unit means firstly a failure probability increase, that depending on the case may be acceptable and, finally a necessity of a multi-column arrester application.

Taking into account the proposed evaluation method statistical bases it is possible using *Equation-5*, and *Equation-6*, a suitable simplification of the last one, to compute the relation *"Duty Value - Withstand Probability"* and check if this value is acceptable or not.

$$S = \frac{\alpha_{ps}}{\alpha_{p1}} / [\beta_{p1} - \beta_{ps}] \quad [5]$$

$$S = \frac{\alpha_{ps}}{\alpha_{p1}} \quad [6]$$

where:-

α_{ps}, β_{ps} -Metal oxide resistors model coefficients for *Duty=S* and attached withstand probability *ps*; and

α_{p1}, β_{p1}-Metal oxide resistors model coefficients for *Duty=1* and attached withstand probability *p1*.

Considering that in the proposed model the α parameters follow a *"Weibull Distribution"*, as can be verified, for instance, by *Figure 4* data it is possible to obtain from *Equation-6*, as shown by *Equation-7*, a relation between *"Duty"* and *"Withstand Probability"*.

$$P(\alpha_{ps}) = 1 - 0.5^{[1 + \frac{\alpha_{p1} S - \alpha_{50\%}}{n Z_\alpha}]^m} \quad [7]$$

where:

$P(\alpha_{ps})$ - Current withstand probability related to the α_{ps} coefficient;

$\alpha_{50\%}$ - Critical current α coefficient;

Z_α - α standard deviation; and

S - Computed current "Duty".

In this way, through the current wave shape and amplitude knowledge it is possible to compute the complete surge arrester discharge current *"Duty-S"* and attached *"Withstand Probability"*. Finally, considering, for instance, the current amplitude probability distribution knowledge the complete surge arrester risk of failure can be easily computed.

6. COMMENTS AND CONCLUSIONS

This paper presented a discussion on the *"Duty Factor Approach"* statistical characteristic and suggest some powerful applications. As a net final result of these applications a complete surge arrester withstand verification can be carried out.

Considering the *"Duty"* definition, according to *Equation-1* and *Equation-2* an automatic computation routine for application to any transient digital program can easily implemented the only difficult in fact is to define the metal oxide resistor, that is, to obtain *Equation-2* parameters.

As the *"Discharge current - Time"* characteristic base for *"Duty"* computation is not commonly supplied by manufactures data sheet, a proposed metal oxide resistors testing method useful to obtain all necessary parameters was presented and discussed.

Complementary, the obtained results can be suitably used because, within specific confidence limits, it will be possible to design, to apply, to compare, to define application ranges and to justify and to explain some surge arresters failures.

Finally, the *"Duty Factor Approach"* and the related testing method, as demonstrated and proposed, seems to be a powerful tool in surge arrester energy absorption capacity performance analysis. In this way, even regarding the high number of samples and laboratory hours, it is interesting to apply then to other manufactures metal oxide resistors and also to continue investigating all the attached laboratory aspects.

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