Effect of Stray Capacitance on Surge Arrester Performance

P.Valsalal, S.Usa, K.Udayakumar

***Abstract*— This paper presents the effect of stray capacitance on voltage distribution. The voltage distribution studies during non-conduction and conduction modes of surge arrester are made. This study analyses effect of stray capacitance on non-uniformity in the voltage distribution and utilization factor. As the voltage distribution during non-conduction mode is important for the insulation design, the capacitance distribution for higher rated arrester is studied. The role of stray capacitance during conduction mode is also analysed by computing the residual voltage of arrester for current surges of different front times. The effect of steepness of current surges on voltage distribution is also discussed.**

***Index Terms*— surge arrester, stray capacitance, voltage distribution, FEM, utilization factor.**

I. INTRODUCTION

Metal oxide surge arresters are widely used as protective devices against switching and lightning overvoltages. The physical construction of modern high voltage surge arrester consists of metal oxide discs stacked up inside a porcelain or polymer insulator. The electrical characteristics are determined solely by the properties of the metal oxide blocks, which would degrade due to the power frequency operating voltage applied continuously. The degradation of the arrester is determined considerably by the potential distribution of arresters. The voltage distribution in a metal oxide arrester under normal operating conditions has been observed to be non-uniform due to the effect of stray capacitance [1]. The distribution of stray capacitance not only affects the behavior of metal oxide surge arrester during non-conduction mode (insulation design) but also during the conduction mode. Moreover, in conduction mode, there is an operational delay of the arrester under Very Fast Transient Overvoltage (VFTO). So it is essential to minimize the stray capacitance for better voltage distribution and to decrease the response time of the arrester under VFTO. The different surge arrester ratings of 66, 132, 198, 264, 330 and 396 kV are used for the analysis.

II. VOLTAGE DISTRIBUTION

Non-uniformity of the voltage distribution may be significant factor in reducing the stability or reliability of surge arresters [2]. The unequal voltage grading is influenced by arrester height, height of its installation above the ground, its orientation in space, proximity to other or earthed structures, number, size and location of grading rings and a presence of internal corrective grading circuits or elements [3]. The arrester acts as capacitance in non-conduction mode. The behaviour of metal oxide surge arrester during non-conduction mode is only based on voltage distribution. But during conduction mode, in addition to voltage distribution, computation of initial rise time of the residual voltage is also important for transient study [4].

A. *Voltage Distribution During Non Conduction Mode*

The voltage distribution during non-conduction mode is found using Finite Element Method (FEM). Figure 1 shows the dimensions of 66kV arrester.

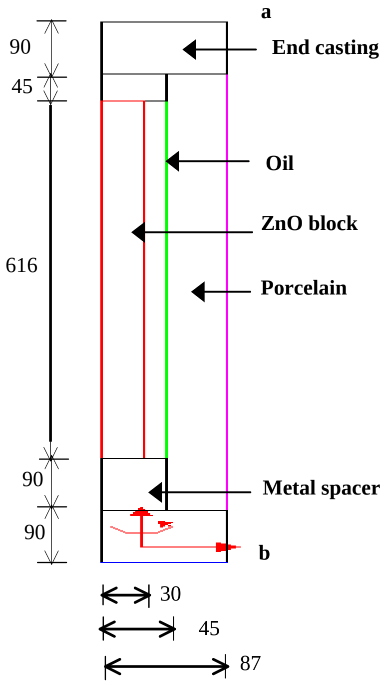

Figure 1 Dimensions of 66 kV arrester (dimensions in mm)

The voltage distribution along the arrester height is computed using FEM based electrostatic field solver. The electrostatic field analysis is carried out in arresters with stacks varying from one to six. The voltage rating for one stack is 66kV. Figure 2 shows the equipotential plot for two (2×66 kV) and six (6×66 kV) stack surge arrester. Figure 3 and Figure 4 show voltage and electrical field plot respectively.

From Figures 2, 3 and 4, it is inferred that voltage distribution is highly non-uniform and electric field is also increased as height of the arrester is increased during non-conduction mode.

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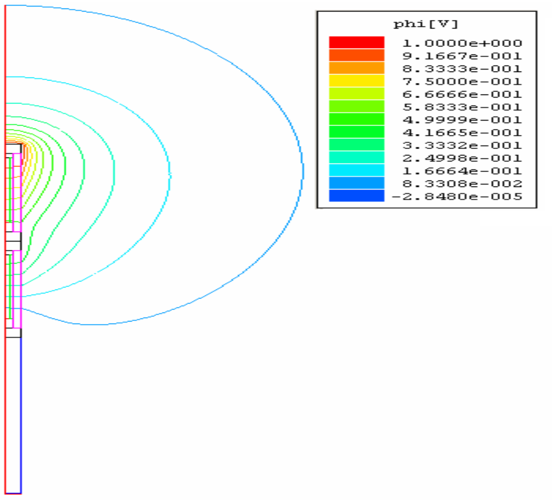

Figure 2 (i) Equipotential plot for 132 kV (2×66 kV) arrester

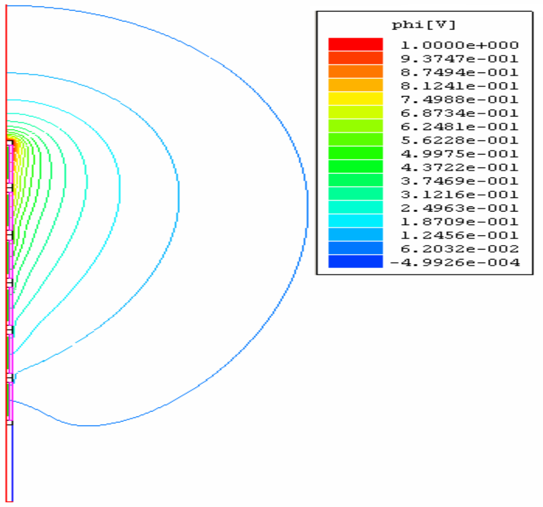

Figure 2 (ii) Equipotential plot for 396 kV (6×66 kV) arrester

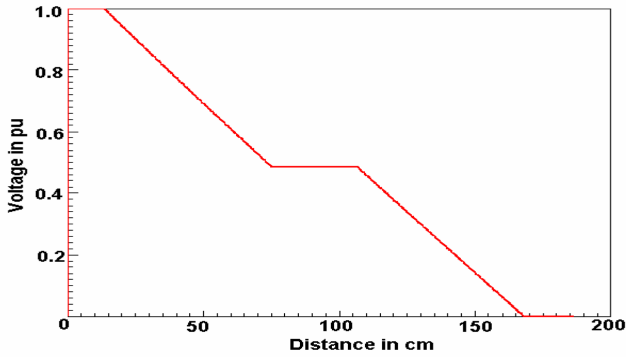

Figure 3 (i) Axial voltage distribution along the 132 kV arrester

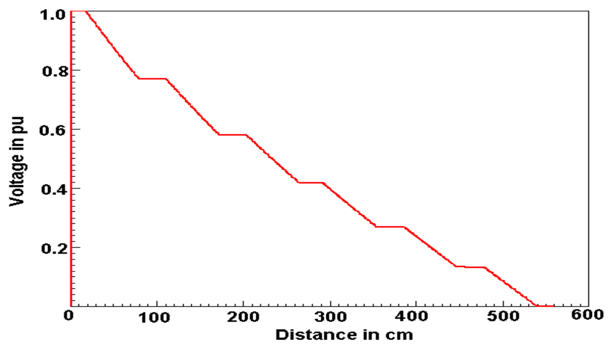

Figure 3 (ii) Axial voltage distribution along the 396 kV arrester

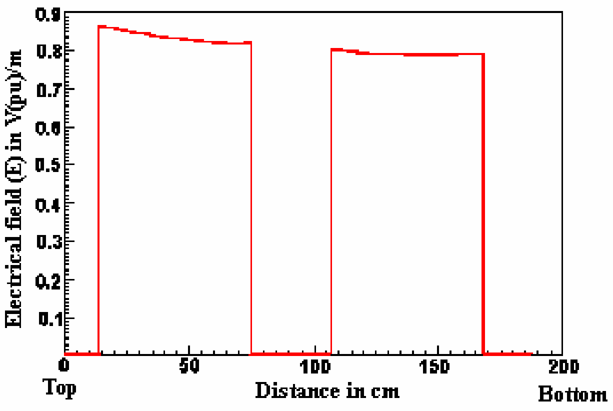

Figure 4 (i) Electrical field along the 132 kV arrester

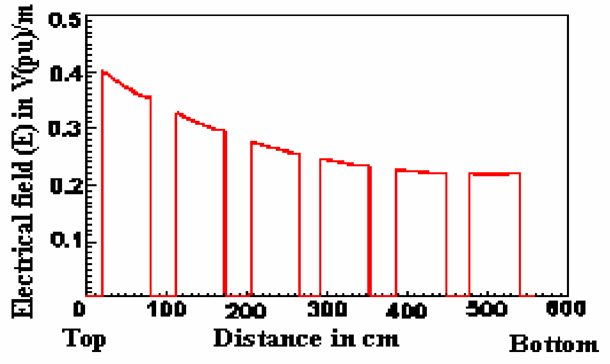

Figure 4 (ii) Electrical field along the 396 kV arrester

The utilization factor (η) is defined by the following relation,

$$\eta = E_{av} / E_{max} \tag{1}$$

One may conclude that the condition E_{max} equal to E_{av} would provide the optimal solution with better utilization of insulation material, which equals to unity for a uniform field. The reduction of utilization factor takes place as the height of arrester is increased as shown in Table I. When the height of the arrester is increased, the value of E_{max} is increased (as shown in Figure 4), thus reducing the value of utilization factor.

Table I
Utilization factor for arresters of different voltage ratings
(1pu = 66kV)

Sl. No	**Voltage (kV)**	**Height (mm)**	**E_{max} (V(pu)/ m)**	**Utilization factor (η)**
1	66	2116	1.65	0.985
2	132	2732	1.72	0.936
3	198	3348	1.84	0.872
4	264	3964	1.99	0.809
5	330	4580	2.12	0.759
6	396	5196	2.41	0.665

The non-uniformity in the voltage distribution is increased due to stray capacitance, which is more for higher rated arresters.

The capacitance plays major role at high frequency current surges. So it is desirable to study the effect of stray capacitance during conduction mode of arrester.

B. Voltage Distribution During Conduction mode

In this mode, a 198 (3×66) kV surge arrester is considered. To predict the dynamic response of the complete arrester, an equivalent circuit is used as per IEC 60099-4 [5] (Figure 5). "**a**, **b** and **c**" are metal flanges of three stack (3×66 kV) arrester. C_{gi} is stray capacitance for i^{th} stack and C_{bp} is block capacitance for arrester. This model for complete arrester assembly with housing is analyzed for different front times (8 µs to 5 ns) using Electro Magnetic Transient Program (EMTP). The residual voltage is computed during conduction mode with conduction of 10 kA, 1/10 µs (Figure 6) and 10kA, 0.005/10µs current surges and it is found that the voltage is distributed non-uniformly. Also it is observed that this non-uniformity increases with steepness of the current surge resulting in higher stress in top unit of arrester.

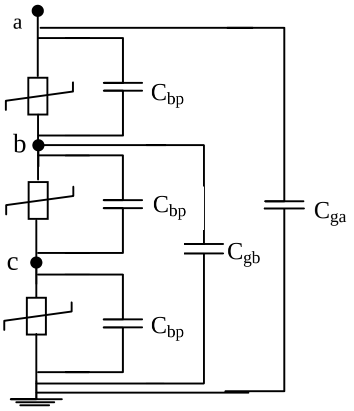

Figure 5 IEC Model (3 stack arrester)

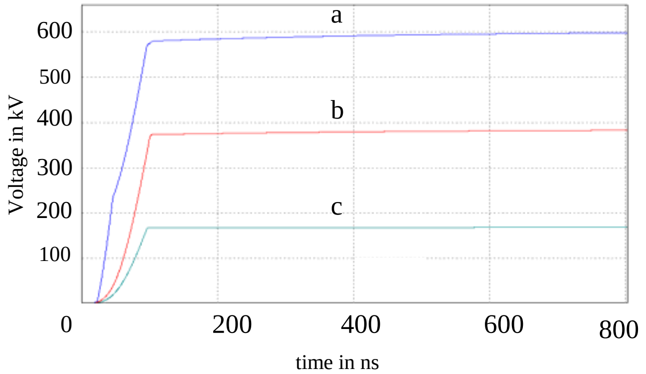

Figure 6 Residual voltage waveforms at the metal flanges (a, b, c) of 198 kV (3×66 kV) during conduction of 10 kA, 1/10 µs current surge

Table II shows the peak value of residual voltage for current surges of 1/10 µs and 0.005/10µs.

Table II
Peak of residual voltage (V_r) for 198kV arrester

SI.No	Voltage at metal flange	V_r	
		1/10 µs	0.005/10 µs
1	**a**	599.70	614.00
2	**b**	384.70	394.80
3	**c**	179.40	181.10

In conduction mode, the non-uniform distribution of voltage depends on both height of arrester and steepness of the current surge. This is due to presence of stray capacitance. So the extraction of stray capacitance is important for the analysis of the arrester.

III. CALCULATION OF STRAY CAPACITANCE

Since the capacitance plays major role in both non-conduction and conduction modes, it is essential to extract the stray capacitance for analysis of the arrester. Moreover, it is essential to decrease the stray capacitance in order to make the voltage distribution more uniform in both the modes.

A. Using Analytical method

Sarma Maruvada et al [6] have given empirical formulae to compute the total stray capacitance for some basic high voltage electrode configurations. This method is limited to configurations which can be approximated as being two dimensional or having cylindrical symmetry.

The stray capacitance C_g of any object is regarded as being composed of two capacitance values, $C_g = C_\infty + C_p$, where C_∞ is the capacitance of the object well above the ground and C_p is the additional capacitance due to the proximity to the ground.

$$c_\infty = 2\pi\varepsilon_0 (a+b+c)/3 \qquad (2)$$

$$C_p = \pi\varepsilon_0 a \{ (a/4\Delta) + \ln(1+c/\Delta) \} \text{ ; for a vertical cylinder} \qquad (3)$$

where

$$\left.\begin{array}{l} \text{a: the (horizontal) length} \\ \text{b: the horizontal width (a = b)} \end{array}\right\} \text{ of the object}$$

c: height
Δ: the smallest distance between the object and ground

Since the exact physical dimensions are not taken accurately in the empirical formula, an attempt has been made to find the capacitance values using FEM.

B. Using Analytical method

A FEM package is used to compute the capacitance distribution (block and stray). Two dimensional axi-symmetry Electrostatic field solver of Maxwell FEM package is used to compute the arrester block and stray capacitance. The problem formulation is done as prescribed in IEC 60099-4 International Standard Part 4 [5]. By solving the Laplace equation $\varepsilon\nabla^2 V(r,z)=0$ with appropriate boundary conditions, the block capacitance and the stray capacitances are computed from the energy stored in the system.

Using the FEM, the stray capacitance distribution is calculated for arresters rating from 66 kV to 396 kV and is compared with the stray capacitance calculated using empirical formula (Equation 2 and Equation 3). Table III shows the stray capacitance values obtained by both the methods.

TABLE III
Stray Capacitance for different voltage rating

Voltage rating (kV)	C_{gt} using Analytical method (pF)	C_{gt} using FEM (pF)	Error (%)
66	2.48	2.100	-18.09
132	4.04	4.58	11.79
198	5.22	6.78	23.00
264	6.17	8.86	30.36
330	6.97	10.78	35.34
396	7.64	14.61	47.70

From Table III it is observed that the percentage error increases with the voltage rating of the arrester.

The non-uniformity in the voltage distribution can be quantified using distribution factor. The Distribution Factor (DF) is defined by the following equation

$$\mathrm{DF} = \sqrt{\frac{C_{gt}}{C_{bt}}} \qquad (4)$$

where,

C_{gt} is total stray capacitance and
C_{bt} is total arrester capacitance with housing.

The height of the arrester increases with voltage rating. As height increases with voltage rating, there is an increase in C_{gt} and decrease in C_{bt}. As a result, the DF increases with voltage rating indicating the more non-uniform voltage distribution. Figure 7 shows the increase in distribution factor with voltage rating.

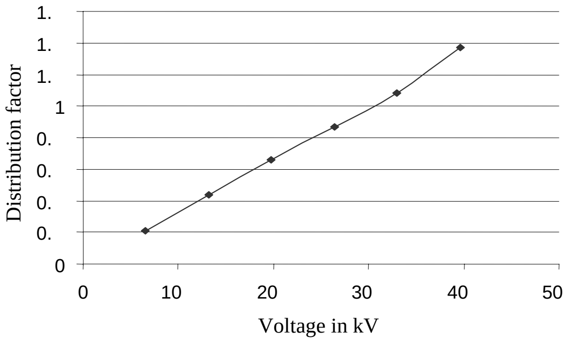

Figure 7.Increase in distribution factor with voltage rating

The voltage distribution analysis during non-conduction and conduction modes is made. The non-uniformity in the voltage distribution depends on stray capacitance. This stray capacitance effect is more for higher rated arresters for both the modes and also steepness of current surge while conduction.

IV. CONCLUSION

The voltage distribution is computed for different arrester ratings using FEM and it is found that the voltage distribution is highly non-uniform. This non-uniformity increases as height/rating of arrester is increased, due to presence of stray capacitance. There is a reduction of utilization factor with higher rating of the arrester. So the non-uniformity in the voltage distribution has to be considered in the design stage of surge arrester. In conduction mode, in addition to the non-uniformity in the voltage distribution, there is an operational delay due to stray capacitance as steepness of the current surge is increased. The accurate value of stray capacitance is extracted using FEM. From the analysis it is observed that, the stray capacitance plays major role in surge arrester during both non-conduction and conduction modes. So it is essential to incorporate the accurate value of stray capacitance for the study of high rated arresters.

REFERENCES

[1] Jinliang He, Rong Zeng, Shuiming and Zhicheng Guan, ‘Potential distribution analysis of suspended-type Metal-oxide surge arresters’, IEEE Transactions on Power Delivery, Vol.18, No.4, October, pp 1214-1220, 2003.

[2] Kumar U. and Mogaveera V, ‘Voltage distribution studies on ZnO arresters’, IEE Proc.-Gener. Transm. Distrib., Vol.149, No.4, July, pp 457-462, 2002.

[3] Alame N. and Melik G., ‘Axial voltage and gradient distribution of metal oxide surge arresters’, Proceedings of the 3rd International conference on properties and applications of dielectric materials, July 8-12, Tokyo, Japan, pp.1149-1151, 1991.

[4] P.Valsalal, “Modelling of metal oxide arrester for very fast transients”, Ph.D dissertation, Anna University, Chennai, Tamilnadu, India, Jan 2006.

[5] IEC 60099-4 International Standard Part 4, Metal oxide surge arresters without gaps for A.C. systems.

[6] Sarma Maruvada.P, and Hylten-Cavallius. N, ‘Capacitance calculations for some basic high voltage electrode configurations’, IEEE Transactions on Power Apparatus Systems, Vol. PAS-94, No.5, September/October, pp. 1708-1713, 1979.

BIOGRAPHIES

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