Study of the Electric Field Intensity in Bushing Integrated ZnO surge Arresters by Means of Finite Element Analysis

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Abstract

In this paper, the electric field in different types of ZnO surge arresters has been investigated by means of finite element modeling using COMSOL Multiphysics software.
Both conventional and novel built-in-bushing type arresters were studied. Electric field modeling helps the designers to know and consider the important factors affecting the maximum field intensity in the arrester, avoiding too high potential gradients inside and outside the arrester, especially during the transient conditions, a phenomenon which can cause damages to the arrester insulating system that brings it to a premature failure.

Keywords: ZnO, bushing-integrated surge arresters, finite element analysis, electric field intensity

1. Introduction

ZnO-based ceramic varistors have a very steep non-linear voltage-current curve and therefore can support widely varying currents over a narrow voltage range (a factor of 10^{11} while the voltage varies by a factor of approximately three). This phenomenon is termed the varistor effect. At low voltages, the varistor looks like an open circuit. Beyond the breakdown voltage, it limits the voltage between its terminals to a certain amount, protecting the component or the device, which is parallel with it. Because of this excellent nonlinear behavior, ZnO varistors are widely used as the main component of modern surge arresters (Figure 1).

Investigation of the electric field in a ZnO surge arrester and influence of different parameters on its form and intensity is of great importance. In this paper, we have a look at the electric field in ZnO gapless surge arresters.

Finite element is a commonly used method to calculate and analyze the electric field in electric devices and components.

Figure 1. Typical distribution surge arresters.

2. Finite Element Method (FEM)

This is a numerical analysis technique for obtaining approximate solutions to many types of engineering problems. The need for numerical methods arises from the fact that for most practical engineering problems analytical solutions do not exist. While the governing equations and boundary conditions can usually be written for these problems, difficulties introduced by either irregular geometry or other discontinuities render the problems intractable analytically. To obtain a solution, the engineer must make simplifying assumptions, reducing the problem to one that can be solved, or a numerical procedure must be used. In an analytic solution, the unknown quantity is given by a mathematical function valid at an infinite number of locations in the region under study, while numerical methods provide approximate values of the unknown quantity only at discrete points in the region. Although the differential equations of interest appear relatively compact, it is typically very difficult to get closed-form solutions for all but the simplest geometries. This is where finite element analysis comes in. The idea of finite elements is to break the problem down into a large number of regions, each with a simple geometry, *e.g.* triangles.

In the finite element method, the region of interest is divided up into numerous connected subregions or elements within which approximate functions (usually polynomials) are used to represent the unknown quantity. The physical concept on which the finite element method is based has its origins in the theory of structures. The idea of building up a structure by fitting together a number of structural elements was used in the early truss and framework analysis approaches employed in the design of bridges and buildings in the early 1900s. By knowing the characteristics of individual structural elements and combining them, the governing equations for the entire structure could be obtained. This process produces a set of simultaneous algebraic equations. The limitation on the number of equations that could be solved posed a severe restriction on the analysis. The introduction of the digital computers made possible the solution of the large-order systems of equations. Thus the Finite Element Method (FEM) approximates a PDE problem with a problem that has a finite number of unknown parameters. It is the *discretization* of the original problem. This concept introduces finite elements, or *shape functions*, that describe the possible forms of the approximate solution.

Over these simple regions, the "true" solution for the desired potential is approximated by a very simple function. If enough small regions are used, the approximate potential closely matches the exact solution.

Then the advantage of breaking the domain down into a number of small elements is that the problem becomes transformed from a small but difficult to solve problem into a big but relatively easy to solve problem. Through the process of discretizaton, a linear algebra problem is formed with perhaps tens of thousands of unknowns. However, algorithms exist that allow the resulting linear algebra problem to be solved, usually in a short amount of time.

COMSOL Multiphysics can discretize easily the problem domain using triangular elements. Over each element, the solution is approximated by a linear interpolation of the values of potential at the three vertices of the triangle. The linear algebra problem is formed by minimizing a measure of the error between the exact differential equation and the approximate differential equation as written in terms of the linear trial functions.

3. PDE formulation

COMSOL Multiphysics carries out the modeling of static electric fields using the electric potential V. By combining the definition of potential with Gauss' law and the equation of continuity, it is possible to derive the classic Poisson's equation. Specifically, under static conditions the electric potential, V, is defined by the relationship

$$\mathbf{E} = -\nabla \mathbf{V} \qquad (1)$$

Using this together with the constitutive relationship

$$\mathbf{D} = \varepsilon_0\, \mathbf{E} + \mathbf{P} \qquad (2)$$

between **D** and **E**, it is possible to represent Gauss' law as Poisson's equation

$$-\nabla.(\varepsilon_0\, \nabla \mathbf{V} - \mathbf{P}) = \rho \qquad (3)$$

The In-plane Electrostatics application mode assumes a symmetry where the electric potential varies only in the x- and y-directions and is constant in the z-direction. This implies that the electric field, E, is tangential to the x-y plane. Given this symmetry, we solve the same equation as in the 3D case. The Axisymmetric Electrostatics application mode considers the situation where the fields and geometry are axially symmetric. In this case the electric potential is constant in the φ direction, which implies that the electric field is tangential to the r-z plane. Writing the previous equation for ρ in cylindrical coordinates and multiplying it by r to avoid singularities at r = 0, the equation becomes

$$-\begin{bmatrix}\frac{\partial}{\partial r}\\ \frac{\partial}{\partial z}\end{bmatrix}^T \cdot \left(r\varepsilon_0 \begin{bmatrix}\frac{\partial V}{\partial r}\\ \frac{\partial V}{\partial z}\end{bmatrix} - r\mathbf{P} \right) = r\rho \qquad (4)$$

3.1 Boundary Conditions

The relevant interface condition at interfaces between different media for this mode is

$$\mathbf{n_2 \cdot (D_1 - D_2) = \rho_s} \qquad (5)$$

In the absence of surface charges, this condition is fulfilled by the natural boundary condition

$$\mathbf{n \cdot [(\varepsilon_0 \nabla V - P)_1 - (\varepsilon_0 \nabla V - P)_2] = - n \cdot (D_1 - D_2) = 0} \qquad (6)$$

The electric-displacement boundary condition

$$\mathbf{n \cdot D = n \cdot D_0} \qquad (7)$$

specifies the normal component of the electric displacement at a boundary.

The surface-charge boundary condition

$$\mathbf{- n \cdot D = \rho_s \ , \quad n \cdot (D_1 - D_2) = \rho_s} \qquad (8)$$

specifies the surface charge density at an outer boundary or at an interior boundary between two nonconducting media.

The zero charge/symmetry boundary condition

$$\mathbf{n \cdot D = 0} \qquad (9)$$

specifies that the normal component of the electric displacement equals zero.

This boundary condition is also applicable at symmetry boundaries where the potential is known to be symmetric with respect to the boundary.

The electric-potential boundary condition

$$\mathbf{V = V_0} \qquad (10)$$

specifies the voltage at a boundary, which is the upper cap in our modelled surge arrester. Because we are solving for the potential in this application mode, we generally define the value of the potential at some boundary in the geometry.

The ground boundary condition

$$\mathbf{V = 0} \qquad (11)$$

is specifying zero potential, at the lower cap of the arrester.

In axisymmetric models, such as our example, the boundary condition for axial symmetry on the symmetry axis r = 0 is used.

4. Study of the electric field in regular ZnO surge arresters

In the first part of this work we studied, by means of numerous simulations using the axisymmetric modeling, the effect of different parameters on the maximum electric field intensity in a regular distribution zinc oxide arrester, just at the first instant of incidence of a surge. We determined that the maximum field intensity is normally located inside the arrester on the surface of the varistor blocks. This suggests the importance of the insulating coating on the varistor lateral surface. As well, the electric field intensity at some points on the surface of the sheds is higher than the other points in the arrester.

We observe that both the geometry and the materials have influence in this concern, but simulations show that the humidity penetration into the housing has the most important effect on increasing the maximum field intensity, i.e., the field nonuniformity inside the arrester.

5. Bushing-integrated arresters

Based on the results of our previous research work, it is obvious that there is a good compatibility between well lateral insulating coated ZnO varistors and insulating mineral oil. By installation of varistors inside the transformer bushings, we can have an integrated protection against surges. This can give us a better surge protection, because we avoid the supplementary problems related to the pollution and other environmental effects, which are observed in normal surge arresters. As well, the oil improves the electrical and thermal behaviors of the varistors and prolongs their lifetime.

Various researches have shown that the oil-immersed arresters present an excellent thermal stability, even under TOV overvoltages such as those caused by the Ferroresonance. In addition they help to damp these transient overvoltages by dissipating their energy. Thus the bushing-integrated arresters appear to have the following advantages:

- A better thermal dissipation,
- No excessive atmospheric pollution,
- Damping the resonant overvoltages,
- No oxidation of the varistor contacts with the electrodes or metallic spacers,
- No excessive wires and contacts and then lower residual voltages during the lightning strikes.

We can have various designs for the bushing-integrated arresters, depending on voltage and power levels. As examples we propose, two typical designs of Figure 2.

The effect of such integration on characteristics of the electric field at the bushing is very important and has to be considered in the design. For instance the mutual influence of adjacent parts of such internal structure on field distribution has to be carefully investigated. We accomplished this part of work, using COMSOL Multiphysics software.

We analyzed the electrical field inside some designs of the bushing arresters, an example of which can be seen in Figure 3.

Calculations showed that optimized, integrated solutions are possible.

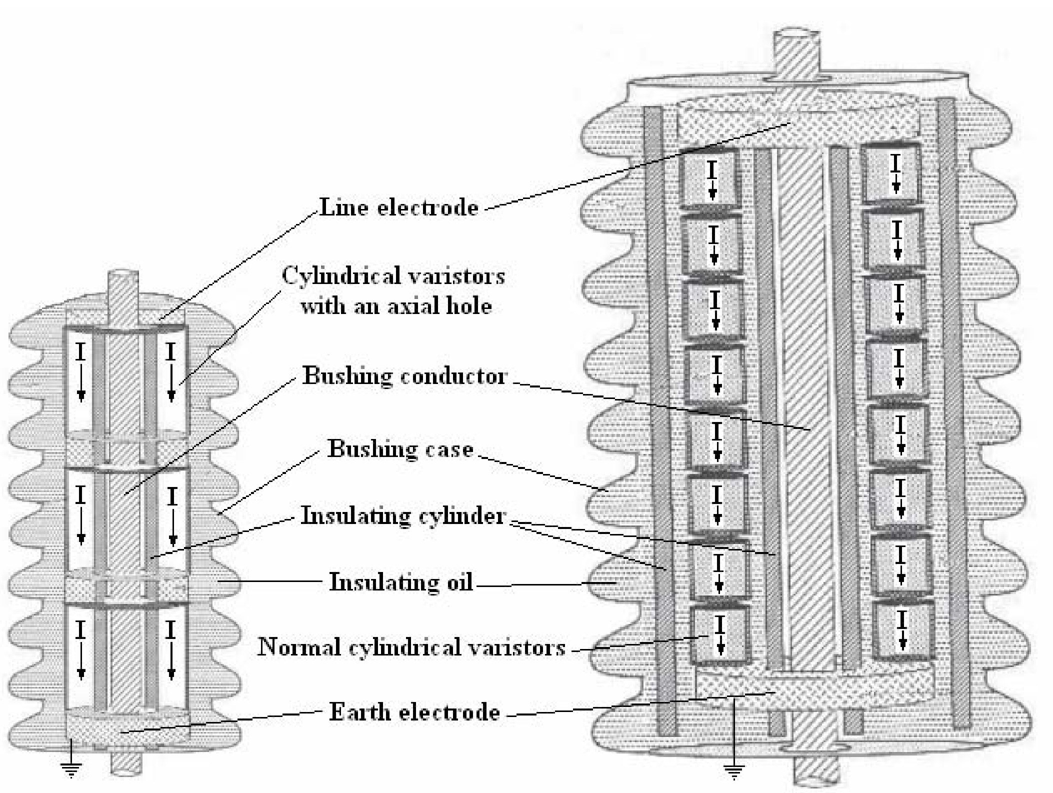

Figure 2. Two possible designs for bushing arresters: medium voltage (left) and high voltage (right).

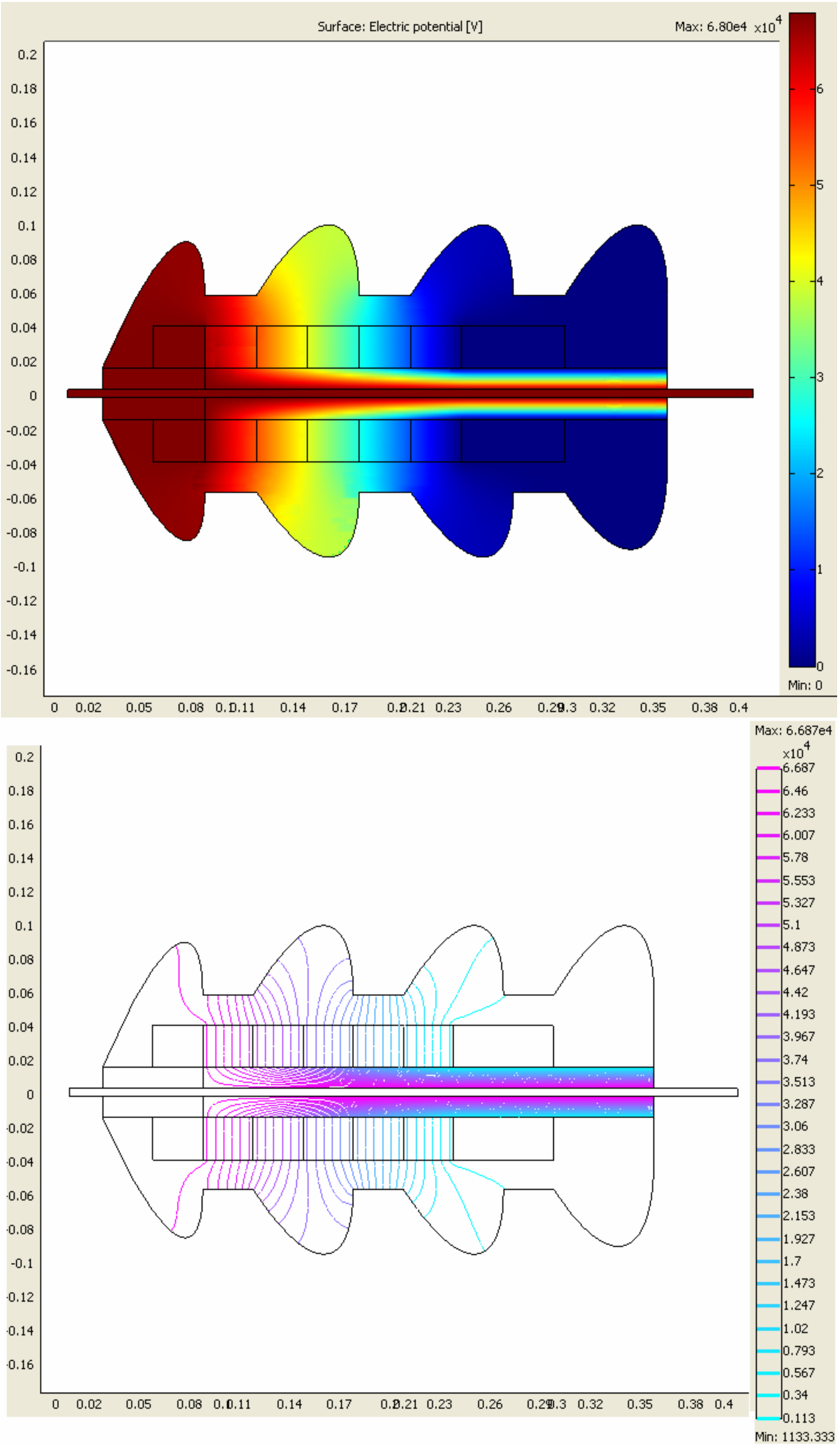

Figure 3. Electric field and potential lines in a medium voltage bushing arrester of the type of Figure 2-left.

6. Conclusions

The electric field inside the regular and bushing-integrated arresters was analyzed in this paper, by means of COMSOL Multiphysics software. We see today the trend of increasing the integration of arresters into the electrical devices. This function will intensify in the coming years. The cost savings and increase in equipment performance and availability will be irresistible to operators, especially in a climate of deregulation and privatization. When protection schemes develop from today's practice of protecting only critical points in the system toward a network with widely distributed protection, insulation coordination can be revised and standards corrected downwards.
In such novel designs, electrical field intensity and configuration have to be verified and investigated attentively, to avoid from future failure in integrated electrical components. Using the powerful COMSOL Multiphysics software is of a great importance in this regard.

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