STUDY OF INSULATION COORDINATION IN THE PRESENCE OF MULTIPLE DIELECTRIC MATERIALS

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Abstract

Use of various dielectric materials for insulation is inevitable in high voltage systems. Choosing a particular insulating material (solid, liquid, and gas) depends on various factors like the nature of the system, insulation level required, dielectric strength and thermal & mechanical stress handling capability of the material. Besides the surface break down strength of two material interfaces plays important role in the high voltage design considerations of the system. This paper critically analyses the field stress in high voltage points in presence of multiple dielectric media, in particular on the existing system of Kilo Ampere Linear Injector (KALI – 5000) system.

In this paper, local field enhancement phenomenon due to presence of different solid and liquid dielectrics is evaluated. Mathematical derivations of the percentage increment of field, at the critical point, due to presence of hybrid dielectric materials, are calculated for planar, spherical and cylindrical geometry of the high voltage elements. 2-d simulations of the same to support the mathematical calculations are done using MAXWELL SV software.

INTRODUCTION

This paper is all about local field enhancement of high voltage system due to lack of proper co-ordination of multiple dielectric materials instead of a single dielectric material. the work is inspired by some chronic corrosion leading to damage of a Perspex sheet inside MARX generator of KALI-5000 system. During investigation of the problem it has been found that use of multiple dielectric materials to avoid breakdown may lead to local field enhancement of any high voltage object of a high voltage system. The object can initiate to some other high voltage problems like corona discharge, higher leakage current, local heating etc. for the ease of analysis, some standard geometrical structures resembling to the practical situation is analyzed and simulated. Mathematical derivation is done to find out the range of enhancement of electric field stress at any particular point. The variation of per unit enhancement is also plotted against permittivity ratio of the multiple dielectric, their thickness and position. Simulation of similar structures is also done to support the mathematically derived results. Entire comparative and analytical study is reported in this paper.

THEORETICAL DERIVATIONS AND ANALYSIS

A mathematical approach to find out local field enhancement is attempted in this section. Let us assume that two points having high potential differences between them is separated by a dielectric of relative permitivity of ε_{r1}. Now, another dielectric material of higher relative permitivity value ε_{r2} is inserted in between the high voltage points without increasing the space between them. This is one of the very common practices for the high voltage engineers to avoid the bulk breakdown through the dielectric media. But, in this case, the metal boundary in contact with the lower relative permitivity value, experiences higher electric field stress than previous condition of single dielectric separation.

As far as bulk breakdown through the dielectric is concerned this method helps sometimes if the breakdown strength of the second dielectric is much higher than the previous one. The increased breakdown limit takes care of the added increment in field stress. But, if corona and all other high voltage unwanted phenomena are concerned then this method creates problem by local field enhancement. The above discussion is simplified considering two dielectric materials of different relative permitivity values. But the same inference is true for any number of dielectric materials used (two or more) two separate high voltage points. Below, it has been given, the mathematical explanation of the above mentioned conclusion in a generalized fashion.

Let us consider one object of voltage V is separated from the ground plane using a dielectric material of relative permitivity ε_r. The field experienced by the dielectric material at the metal dielectric juncture is E. Now, n number of dielectric materials of relative permitivity ε_{rn} and thickness t_n is inserted in between. Now the field at the same point of concern has changed to EM. For the ease of calculation let us replace the ground plane with the mirror reflection of the object and the dielectrics about the ground plane. The reflected object will be assigned a voltage of –V. Now, let us consider, the perpendicular distance between object and the ground plane is R and any point P is present on the line joining the object and its mirror image (same as the line perpendicular on the ground plane from the object) at a distance r. hence field strength at P can be defined as

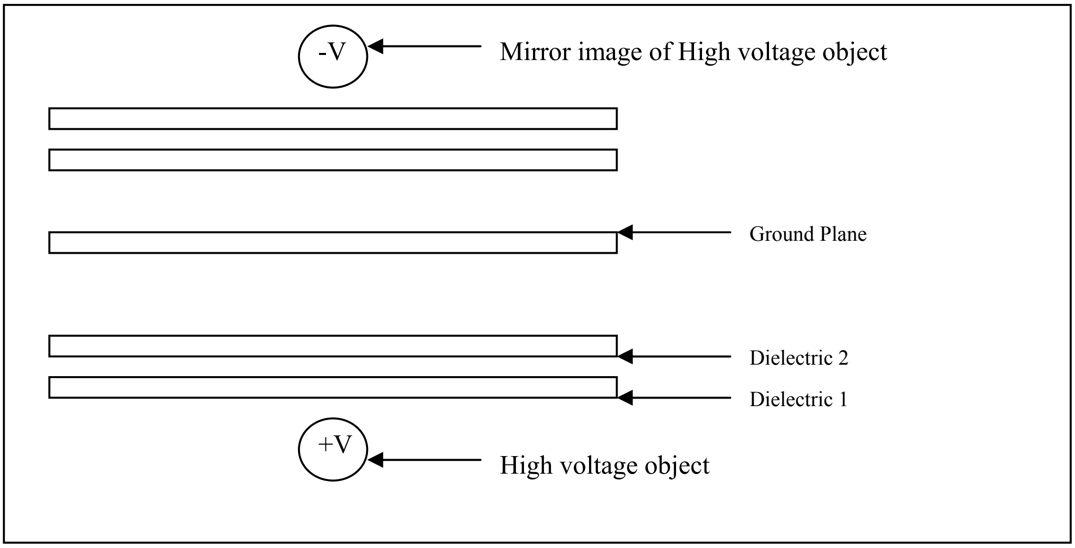

Figure 1: Schematic diagram of high voltage object and ground plane

$$E_r = E(r) - E(2 \bullet R - r) = Q \bullet \{F(r) - F(2 \bullet R - r)\} \quad (1)$$

Where, Q defines the charge accumulation in the high voltage conductor. Hence, we can further write,

$$V = Q_S \bullet \int_{r_c}^{R} F(r) \bullet dr \quad (2)$$

where, r_c is radius of curvature of the high voltage object. In presence of multiple dielectric materials this equation(2) can be re-written as

$$V = Q_M \bullet \left\{ \int_{r_c}^{r_1} F(r) \bullet dr + \int_{r_1}^{r_1+t_1} F_1(r) \bullet dr + \int_{r_c}^{r_2+t_2} F_2(r) \bullet dr + ... + \int_{r_c}^{r_n+t_n} F_n(r) \bullet dr + \int_{r_n+t_n}^{R} F(r) \bullet dr \right\} \quad (3)$$

Where, rn is the distance of the dielectric measured from the object. Considering at all the inter-dielectric boundaries electric field flux density will remain constant, we can write $F_n(r) = \frac{\varepsilon_r}{\varepsilon_{r \cdot n}} \bullet F(r)$ and hence equation (3) can be rewritten as,

$$V = Q_M \bullet \left\{ \int_{r_c}^{R} F(r).dr + \sum_{p=1}^{n} \left(\frac{\varepsilon_r}{\varepsilon_{r \cdot n}} - 1 \right) \bullet \int_{r_p}^{r_p+t_p} F(r).dr \right\} \quad (4)$$

Therefore we can write that at the critical point at distance r_c field E_S with single dielectric of relative permitivity ε_r is

$$E_S = Q_S \bullet \{F(r) - F(2 \bullet R - r)\} = \frac{V \bullet \{F(r) - F(2 \bullet R - r)\}}{\int_{r_c}^{R} F(r) \bullet dr} \quad (5)$$

and the field stress at the same point with multiple dielectric materials E_M is

$$E_M = Q_M \bullet \{F(r) - F(2 \bullet R - r)\}$$

$$= \frac{V \bullet \{F(r) - F(2 \bullet R - r)\}}{\left[\int_{r_c}^{R} F(r) \bullet dr + \sum_{p=1}^{n} \left(\frac{\varepsilon_r}{\varepsilon_{r \cdot n}} - 1 \right) \bullet \int_{r_p}^{r_p+t_p} F(r) \bullet dr \right]} \quad (6)$$

From equation (5) and (6) we can conclude that if $\varepsilon_{rn} > \varepsilon_r$, then $E_M > E_S$. i.e at the critical point the local field enhancement will take place at metal dielectric boundary.

Shape of the high voltage object is going to take significant part in the percentage increment of field enhancement at the most critical points. Considering some standard geometry like infinite plane, infinitely long cylinder and spherical object the calculation is extended. For an infinitely extended high voltage plane object F(r) $=1/\varepsilon\varepsilon_r A$, for an infinitely long high voltage cylindrical object F(r) $=1/2\pi\varepsilon\varepsilon_r r_c$, for a high voltage spherical object F(r) $=1/4\pi\varepsilon\varepsilon_r r_c^2$,

SOFTWARE SIMULATION AND RESULTS

2-D simulations of the above mentioned objects are made using MAXWELL SV software. The enhancement of the electric field intensity at the critical point is observed due to presence of multiple dielectric materials. Simulation is done taking consideration of a practical situation, where high voltage object of 600kV potential is separated from the ground plane using transformer oil dielectric material ($\varepsilon_r \approx 2.3$). The field enhancement at metal dielectric boundary is observed when a perspex sheet ($\varepsilon_r \approx 3.2$) is inserted in between. The simulation window with field distribution is shown below.

DISCUSSIONS

The above analysis is done in context with MARX generator of KALI-5000 1.5 MV, 40 kA, 100 ns pulsed power system. The MARX generator is kept completely inside transformer oil. To further ensure any breakdown from high voltage points inside the MARX chamber, a Perspex sheet of 30 mm thickness is used in between high voltage point and ground. This had increased the breakdown strength of the system but, as a consequence, the high voltage points, having contact with transformer oil, have been subjected to higher electric field strength.

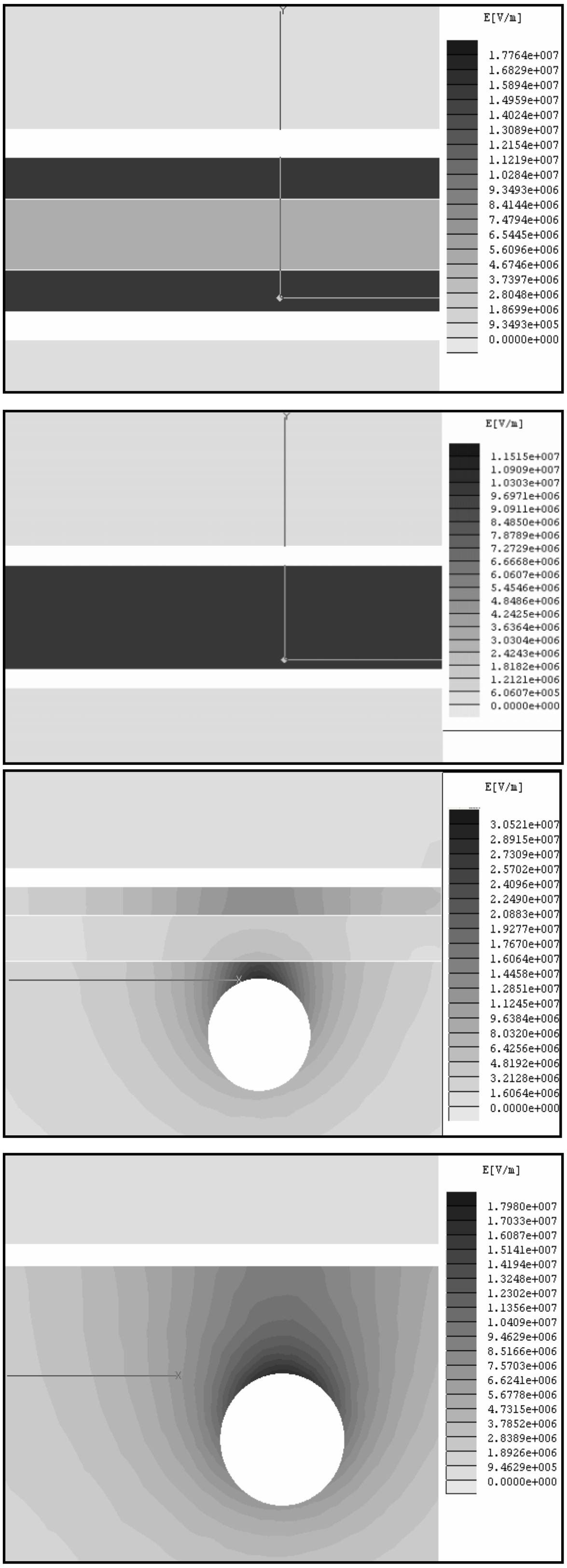

Figure 2: Comparative Field mapping of infinite plane object and infinitely long cylindrical object with single and multiple dielectric materials is shown.

This kind of situation may lead to increased possibility of corona discharge from the high voltage points inside the chamber. According to the above analysis percentage increment of the field stress at the concerned point is a function of thickness of the secondary dielectric material and its relative permittivity. Plot of increment of field with variation of thickness of dielectric and it's ε_r is plotted below for infinite plane and infinitely long cylindrical object.

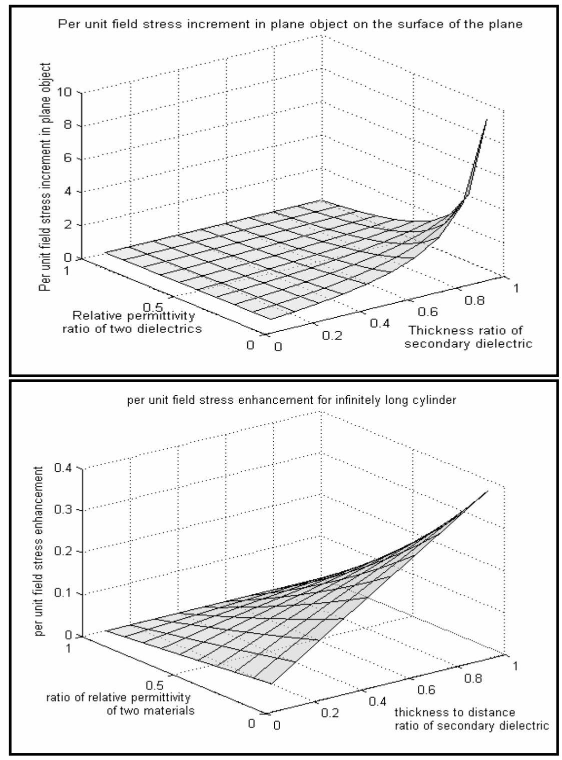

Figure 3: Field stress enhancement with change in permittivity and physical parameters of dielectric material

CONCLUSION

The above discussion leads to the conclusion that selection of dielectric material and their positioning is extremely critical in high voltage engineering point of view. The trades off between better breakdown strength and low relative permittivity, makes the selection further difficult. Position of the dielectric material is also very critical as it can enhance field at a particular point of a big structure. This local field enhancement can damage metallic and dielectric materials of the system leading to further chain breakdown of the total system.