Development of the Selection Procedure of an Insulating Foam for Its Application in Gas Insulated Transmission Lines, Demonstrated Using Syntactic Foam

by

Harshada Ganesh Pendse

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Graduate Supervisory Committee:

George Karady, Chair
Keith Holbert
Raja Ayyanar

ARIZONA STATE UNIVERSITY

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ABSTRACT

Due to increasing integration of renewable resources in the power grid, an efficient high power transmission system is needed in the near future to transfer energy from remote locations to the load centers. Gas Insulated Transmission Line (GIL) is a specialized high power transmission system, designed by Siemens, for applications requiring direct burial or vertical installation of the transmission line. GIL uses SF_6 as an insulating medium. Due to unavoidable gas leakages and high global warming potential of SF_6, there is a need to replace this insulating gas by some other possible alternative. Insulating foam materials are characterized by excellent dielectric properties as well as their reduced weight. These materials can find their application in GIL as high voltage insulators. Syntactic foam is a polymer based insulating foam. It consists of a large number of microspheres embedded in a polymer matrix.

The work in this thesis deals with the development of the selection procedure for an insulating foam for its application in GIL. All the steps in the process are demonstrated considering syntactic foam as an insulator. As the first step of the procedure, a small representative model of the insulating foam is built in *COMSOL Multiphysics* software with the help of *AutoCAD* and *Excel VBA* to analyze electric field distribution for the application of GIL. The effect of the presence of metal particles on the electric field distribution is also observed. The AC voltage withstand test is performed on the insulating foam samples according to the IEEE standards. The effect of the insulating foam on electrical parameters as well as transmission characteristics of the line is analyzed as the last part of the thesis. The results from all the simulations and AC voltage withstand test are observed to predict the suitability of the syntactic foam as an insulator in GIL.

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CHAPTER 1.

A BACKGROUND ON GAS INSULATED TRANSMISSION LINES (GIL) AND SYNTACTIC FOAM

1.1 Background of Gas Insulated Transmission Lines

The inclusion of increasing number of renewable resources in the existing power system will result in some basic changes in power transmission system in the near future. These renewable generators are generally located far away from the metropolitan areas. The energy is then transferred from these remote locations to the load centers through high power transmission systems. Such high power transmission systems have already been installed in developing countries like China and India to transfer several giga watts of energy over a long distance of 1000 km or more. These long transmission lines require very high towers (typically 70-80 m) and a large number of conductor bundles [2]. This type of assembly is difficult to construct for every geographical location. The Gas Insulated Transmission Lines (GIL), developed by Siemens AG, can be proven as one of the possible alternatives to deal with the above mentioned problem.

Gas Insulated Transmission Lines (GIL) technology is mainly used for high power transmission for special applications requiring direct burying or vertical installation. GIL is an optimized adaptation of the Gas Insulated Switchgear (GIS) technology for long distance applications. The conductor in GIL is placed inside the earthed outer conducting enclosure and the space between the two is filled with the insulation gas under pressure. Support insulators are used to maintain the position of the conductor. The sliding contacts are provided to help in case of thermal expansion. Thermal, mechanical and dielectric factors are generally considered for dimensioning of GIL [1-2]. GIL is divided into small gas compartments throughout its length. It mainly uses SF_6 or a mixture of SF_6 and N_2 under high pressure for electrical insulation [3]. The constructional features of GIL can be seen from the Figure 1.1. The figure is used with the permission of ©Siemens AG.

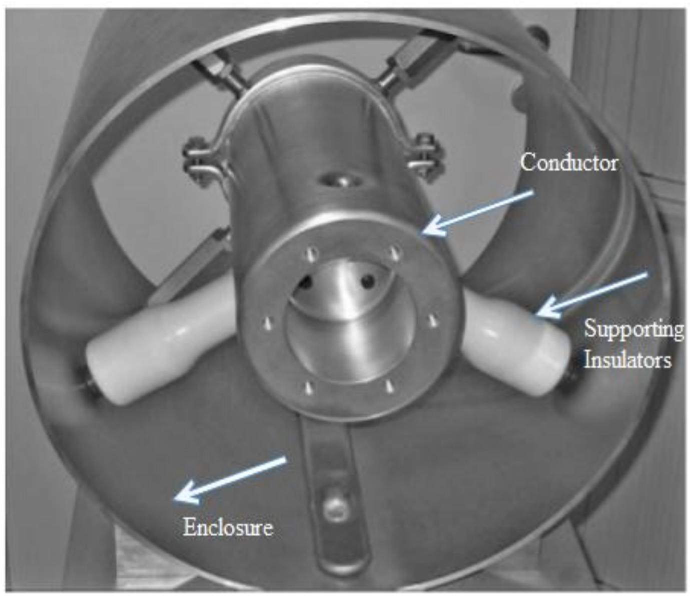


Figure 1.1 Construction of Gas Insulated Transmission Line [2]

The advantages of GIL are as follows:

- Low losses because of the larger cross section of conductors
- Low dielectric losses
- Ratings of 2000 A for single circuit and directly buried applications
- Horizontal, vertical or slanted installation possible in above ground, tunnel, directly buried or submarine environment

- Immune to weather conditions: ice, snow, wind, pollution
- No visual impact, no audible noise
- Low electromagnetic interference.

For a single phase GIL with enclosures solidly bonded at each end, there exists a series inductance and capacitance to earth for each phase. Coupling between the phases can be neglected considering the screening effect of the enclosures of the GIL assembly. The enclosure and conductor of GIL are designed to have large cross section. Because of this, the series resistance per phase is generally low for GIL. The value of shunt conductance per phase too, is insignificant. For 50 Hz, the values of electrical parameters of GIL at 400 kV, 2000 MVA are given in Table 1.1. Along with this, these values are compared with that of overhead lines (OHL) and XLPE cables (2 per phase), both operating at 400 kV with thermal rating of 2000 MVA [5].

Table 1.1 Comparison of Electrical Parameters of GIL, OHL and XLPE Cable Operating at 400 kV

	GIL	OHL	XLPE cable (2 per phase)
Current rating (A)	3000	3000	3000
Transmissible Power (MVA)	2078	2000	2000
Dielectric losses (W/m)	-	2.4	15.0
AC resistance (μΩ/m)	6.7	20	6.0
Inductance (nH/m)	162	892	189
Capacitance (pF/m)	68.6	13	426

Similar transmission capacities as stated in Table 1.1, may also be obtained from some other geometrical configurations. Thus, all the figures represented in the Table 1.1 are for indication purpose [5]. The specifications of the overhead line, GIL and the transmission cable are specified in Appendix A**.**

From Table 1.1, it can be observed that the inductance of GIL is less than that of the overhead transmission line almost by the factor of 5.5. In a meshed system, GIL can be used in parallel with a regular overhead transmission line to share the total power transferred. In general, the power flow across two buses is given by the equation,

$$P = \frac{V^2}{X} Sin(\delta) \tag{1.1}$$

Where, V is the magnitude of the voltage, δ is the phase angle between the sending and the receiving end voltage and X is the reactance of the transmission line. The resistance value is assumed to be very small for the derivation of the above formula. Because of the lower inductance, GIL when constructed in parallel with an overhead line carries a greater share of transmitted power. When a GIL with reactance X_{GIL}, is constructed in parallel with a transmission line with reactance X_{OHL} , the resultant inductance will be $X_{Eq} = \frac{X_{OHL} X_{GIL}}{(X_{OHL} + X_{GIL})}$ and the total power transferred is $P = \frac{V^2}{X_{Eq}} \sin(\delta)$. Now, the total power carried by the GIL in the above mentioned scenario will be given by,

$$\frac{P_1}{P} = \frac{X_{OHL}}{X_{OHL} + X_{GIL}} \tag{1.2}$$

Thus, by substituting X_{OHL} =5.5 X_{GIL} in Equation (1.2), it can be concluded that the GIL carries almost 85% of the total power when constructed in parallel with the overhead line [5].

When the line loading of GIL is exceeded than the natural loading of the line, the voltage at the receiving end starts decreasing. The capacitor charging current of the line may reduce the actual useful power transmitted across the line within thermal limits. This can be improved using reactive power compensation. In GIL, the reactive compensation is not needed till the length of 100 km [5].

Steady state stability is mainly related to the ability of the system to return back to its original operating condition following a small disturbance such as load variation or switching operation. Steady state stability of the system is mainly affected by the control system of the network and thus, GIL has negligible effect on it. The transient stability of the system increases with the decrease in inductance of the transmission line [5]. Thus, inclusion of GIL increases transient stability of the system due to smaller value of inductance.

Electromagnetic field of GIL

To protect general public and the person working on the maintenance of a transmission line, there are some international guidelines on electromagnetic field limitations. As seen from Figure 1.1, the construction of GIL is such that the Aluminum enclosure is grounded. Because of the solidly grounded enclosure system, inverse current gets induced in the low impedance enclosure, thereby reducing the total electromagnetic interference. This screening remains effective in case of transient conditions too.

When GIL has a single phase enclosed design and the enclosures are solidly bonded at each end, the circulating currents in the enclosure will try to reduce the external magnetic field of the GIL. However, the magnetic field is not completely nullified as a result of the spatial disposition of the three phases in the system. This is represented in Figure 1.2. The comparison between RMS values of magnetic flux density, at 1 m above the ground level, for a GIL, a transmission cable and an overhead line is given in the Table 1.2. All the values are calculated for the transmitted power of 2000 MW. All the lines are 400 kV lines and with 3000 A current carrying capacity [5].

Figure 1.2 The Flat Formation of Phase Distribution of GIL

Table 1.2 Comparison of RMS Values of Magnetic Flux Density for GIL, Overhead Line and XLPE Cable at 1 m Above Ground Level

B (μT)	Distance from the central axis (m)			
	0	10	20	30
Overhead line	42.0	36.5	21.0	10.8
GIL Flat formation	5	0.25	0	0
XLPE cable 1 per phase Flat formation	109	11	2.9	1.3
XLPE cable 2 per phase Flat formation	13.2	0.74	0.19	0.08

The first GIL operating at 400 kV was installed in Schluchsee, Germany in 1975 for a hydropower pumping storage plant. The longest GIL till date is installed at PP9 in Saudi Arabia in 2004 which is 17 km long line connecting 8 blocks of power plant to a substation operating at 400 kV. Another GIL installation in Japan connects Tokai Substation to the Shin-Nagoya Power substation through a tunnel based installation of 9.9 km [2]. Table 1.3 summarizes some of the other worldwide installations of GIL [2].

Table 1.3 GIL Installations Across the World [2]

Place	Operating voltage	Place	Operating voltage
Joshua Falls, USA	145 kV	Bowmanville, Canada	550 kV
Palexpo, Switzerland	220 kV	Baxter Wilson Power Plant	550 kV
Sai Noi, Thailand	550 kV	Hams Hall, UK	420 kV
Xiluodu, China	550 kV	Cairo North, Egypt	245 kV

1.2 Motivation for the Research

GIL primarily uses SF_6 or a mixture of SF_6 and N_2 at high pressure as an insulator, filled in between the conductor and the enclosure. Small sections of Aluminum enclosure and conductor are welded together on the site location to build a long length GIL. SF_6 is then filled in the gap at the pressure of 8 bars. When the line length increases, gas leakages through the enclosure system becomes unavoidable. When GIL is used over longer lengths, maintaining gas pressure becomes very important for reliable operation. This requires additional care and safety units to restrict gas leakages throughout the length of the GIL. In addition to that due to high global warming potential of SF_6, it has been listed as a greenhouse gas in Kyoto Protocol in 1997. SF_6 is about 23000 times more harmful than CO_2. The survey of the present situation of environmental implications caused by SF_6 is given in the paper by WG 23-02 [24]. The clearance from the authorities and governments for the projects dealing with SF_6 has become increasingly difficult over the years due to the restrictions on the use of SF_6. Therefore, different attempts are being made to replace SF_6 by some other insulating material.

One option to deal with this problem is to replace SF_6 by some other insulating gas such as N_2, CO_2 or air, at a very high pressure to maintain sufficient dielectric strength for the reliable operation of the transmission line. But the gas leakages throughout the length of the line will affect the gas pressure and thus leading to unreliable operation of the transmission system. Liquid insulating materials too, will face the same leakage problem. Moreover, the weight of the assembly will increase as a result of the high density of the liquid insulators. Another option is to use solid insulating material to fill up the gap in between the enclosure and the conductor. In general, polymer based solid insulators possess very high value of relative permittivity which increases capacitance and dielectric losses in the transmission line. The behavior of the line insulated with the solid insulation will be very similar to transmission cables.

The other feasible alternative to this solution is to use an insulating foam material for this particular application of high voltage transmission line. The relative permittivity of the foam insulating materials is comparatively lower than that of the solid insulating materials. This makes it different than the regular transmission cables. The foam insulating material is characterized by reduced weight and compact design. Polyurethane foam is a foam insulating material which is widely used in low voltage applications [10]. The open cell structure of the voids in Polyurethane foam affects its long term performance as an insulator. Syntactic foam is a new type of insulating material consisting of hollow microspheres embedded inside the polymer matrix. The special characteristic of this foam is the closed cell structure. The properties such as high dielectric strength, low density and good mechanical strength make this foam a potential alternative for the replacement of SF_6 from GIL. Syntactic foam is already in use for the cable termination units of the high voltage transmission cables as an insulator [7]. Therefore, this type of insulating foam can be a possible solution for the application of GIL which will solve the problem of gas leakage as well as won't increase capacitance of the line when compared to the transmission cables.

1.3 Literature Review

Syntactic foam consists of a polymer matrix (called binder) and a number of hollow microspheres mixed with the binder. Inclusion of hollow microspheres makes the material lightweight, at the same time keeping the specific strength high [9]. According to the American Society for Testing and Materials (ASTM), syntactic foam is a material consisting of hollow sphere fillers in a resin matrix [8]. The density of the syntactic foam goes down to 0.65 g/cm^3 which helps in attaining a compact and lightweight design [11].

The microstructure of the syntactic foam can be observed with the help of a scanning electron microscope (SEM) picture as shown in Figure 1.3. Scanning electron microscope is generally used for the resolution in the range of nanometers. Being a non-conductive material, the syntactic foam sample is coated with carbon before observation with SEM in order to avoid charging of the sample by electron beam during microscopy. The foam in the picture consists of glass microspheres with diameter in the range of 20-120 μm. The spherical microspheres and polymer matrix can be clearly observed from the Figure 1.3.

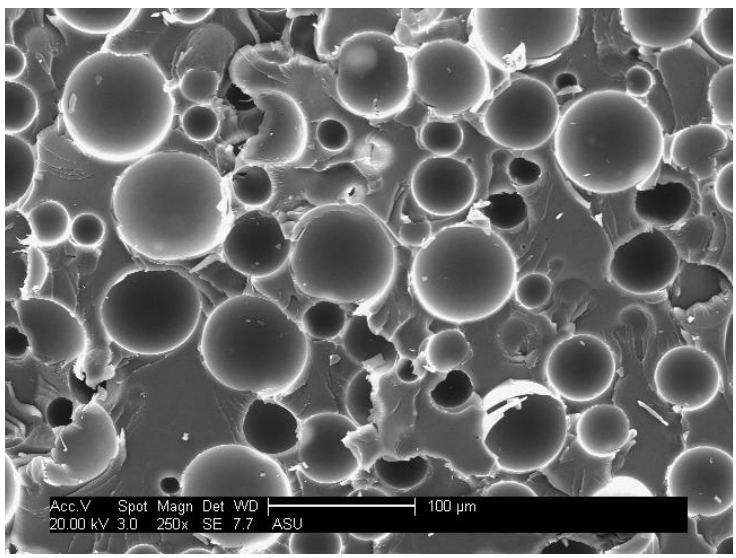


Figure 1.3 The SEM Picture of Epoxy-Resin Matrix, Glass Microsphere Based Syntactic Foam

In general, the spherical microspheres have diameters in between 1-50 μm, wall thickness between 1-4 μm, bulk density 70-500 kg/m3 and apparent density 50-500 kg/m3 [12]. In some cases, hollow macro spheres (diameter 1-100 mm) are also used as a filler material.

The syntactic foam can be widely differentiated in two basic types, two-phase syntactic foams and three-phase syntactic foams. If the microspheres are closely packed in the matrix material, the foam is two-phase syntactic foam. During the process of manufacturing of the syntactic foam, air gets trapped inside the matrix material. Sometimes the resin can't penetrate through the cluster of microspheres leading to air entrapments. This type of syntactic foam is classified as a three-phase syntactic foam. Two-phase syntactic foams exhibit good mechanical properties but the dielectric constant and loss coefficient of the three phase syntactic foam are lower than the two phase syntactic foam. The moisture absorption is higher in case of three-phase syntactic foam because of the presence of open source voids [13].

The usual polymer foam consists of randomly distributed air voids with different shapes and sizes scattered all around the foam. These voids are visible to the naked eye. Unlike this, air remains trapped inside the glass walls of hollow microspheres in case of syntactic foam. The uniform shape of the hollow microspheres gives the foam a homogenous structure. The porosity of the foam is in the microscopic range. Apart from that, syntactic foam possesses many advantages over the conventional polymer foam such as reduced weight, excellent mechanical strength, and reduced cost, good impact behavior and damage tolerance [14]. The excellent mechanical properties of the syntactic foam are contributed by the resistivity of the microspheres to the compressive forces [15]. The compressive properties of the foam depend on the characteristics of the microspheres used. On the other hand, the tensile properties of the foam are influenced by the matrix material used [18]. The presence of air voids during production of the foam can alter the properties of the foam depending on the shape and size of the voids.

Syntactic foam exhibits a closed cell structure making it hydrophobic and reducing the chances of moisture absorption. The total moisture absorption in syntactic foam mainly depends on the resin-microsphere interface and concentration or size of the microspheres. For the microsphere concentration of 67% or less by volume, the water absorption is insignificant and is independent of the density of the microspheres [16]. The absorption increases rapidly with the increase in presence of cavities. This property of the syntactic foam makes it a potential insulator for outdoor applications. The impact of water absorption on dielectric properties of the syntactic foam was studied by keeping the foam samples immersed in deionized water at 50°C for 50 hours [17]. Four different types of filler microspheres were used for the test. The microspheres were manufactured with various combinations of untreated or silane-coated glass surfaces, different alkali ion concentration in the glass walls and diameters ranging between 40 μm to 60 μm. It was observed that for the foam samples with untreated microspheres the increase in weight was more than 2.5% while for the silane-coated microsphere samples, the increase in weight was less than 2% of the original value. The silane-coating provides a chemical bonding between the epoxy resin matrix and the microspheres. This reduces the water ingress. The dielectric properties such as permittivity and loss factor of the foam increase for the samples with untreated microspheres and with high alkali ion concentration. With the low concentration of the alkali ions used, the washout rate also reduces. Thus, syntactic foam with rightly chosen microspheres can be used for the submarine applications too.

The ageing behavior of the syntactic foam due of the effect of temperature and humidity is observed in [19]. The hydrothermal ageing of epoxy based syntactic foam with polymeric microspheres was observed by climatic chamber and pressure cooker storage method. The characteristics like breakdown strength and dielectric constant were observed throughout the ageing process. It was observed that the water intake is higher in case of pressure cooker method than the climatic chamber method due to higher temperature. Addition of silica particles to the matrix material decreases the residual water in the foam. The dielectric constant of the foam increases with the ageing time. The breakdown strength decreases over the period of time due to hydrothermal ageing. The overall study shows good hydrothermal behavior of the syntactic foam in terms of water intake and its effect on dielectric constant. Thus, it can be easily used for the outdoor applications.

The syntactic foam, in general, is characterized by a low dielectric constant. By using appropriate inorganic microsphere configurations, the loss tangent factor of the syntactic foam can be reduced. Thus, dielectric losses can be reduced by using appropriate syntactic foam. The effect on the value of permittivity of the syntactic foam because of the elastomeric or silane coating on the microspheres is observed in [20]. The permittivity of the foam is measured by dielectric spectrograph for the frequencies from 10^{-1} to 10^{7} Hz. It was observed that for the frequencies greater than 1 Hz, the elastomeric or silane coating doesn't have any effect on the permittivity of the foam. At lower frequencies, the complex permittivity reduces because of the nanometer coatings of the microspheres. The effect of varying humidity on the syntactic foam samples with 50% volume concentration of microspheres and with diameter 65 μm is studied in [11]. Three foam samples, one stored at 80% humidity at 80°C, one stored at ambient temperature and the other stored at 80°C in dry condition were tested by dielectric spectrography. It was observed that the relative permittivity and loss factor remain unaffected by the humid conditions.

High strength, thermal and environmental stability, low shrinkage and high water resistance are few of the properties that make epoxy based syntactic foam superior over other matrices. The effect of varying degree of volume fraction of microspheres on tensile strength of syntactic foam is observed in [14]. The microspheres used are of the same sizes but of different densities from 220, 320, 380, 480 kg/m^3. It was observed that the tensile strength of syntactic foam with all the types of microspheres showed decreasing tensile strength when volume percentage was increased from 30 to 60%. It was observed that the specific strength of the low density microspheres almost remains unaffected by the degree of volume fraction.

Moreover, the thermal expansion coefficient of the epoxy based syntactic foam is lower than the plain epoxy. This coefficient further reduces with the increase in microsphere concentration. For any particular percentage of the microspheres, this coefficient remains constant for the temperature rise till almost

370^{o}C. Thus, even for the higher working temperatures, the probability of generation of air voids because of thermal expansion is very low.

Syntactic foam can be used as a replacement to the conventional dielectric insulators because of its lightweight structure, low material cost and good electrical insulation properties. The variation in size and concentration as well as different material for microspheres or the polymer matrix helps in getting desired insulation and mechanical properties according to the required application. It is important to study the performance of the syntactic foam under long term electric stress before its probable use as a dielectric insulator. The long term stability of the foam with polymer coated microspheres is investigated in [11]. The syntactic foam with 40% concentration of the microspheres with diameter 40 μm doesn't undergo electrical breakdown for the electric stress of 20 kV/mm and 25 kV/mm for the time duration of 1000 hours. The dielectric strength increases as compared to the foam with microspheres of diameter 95 μm, as a result of reduced discharges inside smaller microspheres. The long term stability of the foam is greatly affected if the electric stress for the analysis or the size and concentration of the microspheres is increased. The breakdown strength of the foam can be improved by addition of silica particle to the matrix material.

The partial discharge activity of the syntactic foam material has been studied under non-uniform and uniform field studies in [21] and [22]. The sample used for the experimental study was of 2 mm thickness, made up of epoxy resin matrix with 40% concentration of microspheres. When a high voltage is applied to the foam, the partial discharge activity starts from the amplitude of few picofarads coulombs at the voltage of 27 kV. The amplitude then remains unaffected as the voltage magnitude is increased till a sudden rise in the discharge activity is observed. After a certain voltage this "step" activity recurs with lesser time interval and breakdown through the foam takes place.

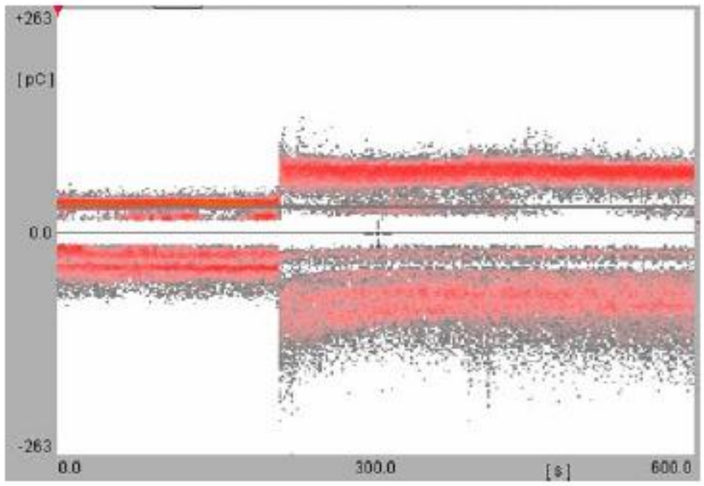


Figure 1.4 Rise of the Partial Discharge Activity [21]

Under uniform field stress, the partial discharge starts at 30 kV at about 10 pC and it remains constant over increasing voltage magnitude till 36 kV. The intensity of partial discharges increases to a very high value at 52 kV. The partial discharges initiates in inhomogeneous fields inside the foam like air voids or cavities inside the microspheres. These discharges are inhibited by some local limitations as a result of which the amplitude remains constant. When a syntactic foam sample is observed by scanning electron microscope after the partial discharge test, the material doesn't show any signs of deterioration. The field stress increases as soon as breached between two dielectrics occur and breakdown takes place. Thus, under uniform field stress, the breakdown does not occur because of the erosion of the material. It occurs because of the dielectric breakdown of the matrix material.

1.4 Objective and Scope of Research

It can be seen from the literature review that there has been a lot of investigation related to the dielectric properties of various types of insulating foams describing different aspects such as long term stability, effect of humidity or temperature on dielectric permittivity and partial discharge behavior in uniform and non-uniform field stress. But there is no guideline about the selection procedure of insulator foam for the special application related to the high voltage transmission line. The primary objective of the thesis is to establish the first step of this guideline by developing a computer based model of the insulating foam to analyze electric field distribution for the application of transmission line. In addition to this, a study of dielectric breakdown properties and effect of the insulator on transmission characteristics of the transmission line are the secondary objectives of the thesis. Since syntactic foam can be a probable alternative as explained earlier, all the steps of the selection procedure are demonstrated with syntactic foam as an example. The suitability of the syntactic foam for the application of GIL is also evaluated.

As the primary objective of the thesis, a small model of the insulating foam is developed in *COMSOL Multiphysics* software for an epoxy based syntactic foam consisting of glass microspheres with 40% concentration by volume and with random radii ranging from 30-60 μm. The randomness in the structure was introduced with the help of the *Microsoft Excel VBA* coding. Various approximations were made while modeling the foam given the intricate structure of syntactic foam. The base electric field is assumed to be the maximum field that exists inside the Gas Insulated Transmission Line operating at 400 kV for considering pessimistic scenarios for the simulations. The variation of the maximum and the minimum value of the calculated electric field with respect to the base electric field are analyzed and probability of breakdown through the foam is evaluated with the help of the numerical analysis of the results. Also, effect of metal impurities on the electric field distribution is also analyzed.

After modeling the foam using *COMSOL Multiphysics*, AC voltage withstand tests are conducted on syntactic foam samples in the practical environment. The epoxy-based syntactic foam with the same configuration as that of the one considered for the computer model is used for carrying out the test. The test sample thicknesses are taken as 3 mm, 3.5 mm and 4 mm. The test is conducted according to the IEEE standard for high voltage testing. The foam samples are immersed in the transformer oil at the time of breakdown voltage test. The effect of sample thickness on breakdown voltage of the syntactic foam is also studied.

As the last part of the thesis, the effect of the insulating foam on the electrical parameters of the line is studied. The detailed constructional features of Foam Insulated Transmission Line (FIL) operating at 400 kV are described first. The inductance, capacitance and resistance are calculated for the designed FIL. The transmission line is modeled with the help of the distributed parameters model. The power voltage characteristics are plotted for the simplified two bus system connected with FIL to get the load characteristics of the line. The maximum power that can be transferred with FIL is calculated keeping in mind the voltage operating limits. The no-load characteristics are also plotted to observe the Ferranti effect.

1.5 Thesis Outline

Chapter 1 provides the background of the Gas Insulated Transmission Line, motivation for the research, the literature review of the syntactic foam and the objective of the thesis.

Chapter 2 deals with the primary objective of the thesis i.e. computer simulation model of syntactic foam in *COMSOL Multiphysics*. The functionality of the software, different steps involved in building the simulation model, the analysis of the results is explained in this chapter.

Chapter 3 deals with explanation of the test procedure and results for the high voltage breakdown test for the syntactic foam samples.

Chapter 4 deals with the calculation of electrical parameters such as resistance, inductance and capacitance of the transmission line. The maximum power that can be transferred through the line under voltage stability conditions is estimated in the chapter.

Chapter 5 includes all the important conclusions from the study and it refers to the other steps that can be considered for the selection process.

CHAPTER 2.

DEVELOPMENT OF THE SYNTACTIC FOAM MODEL FOR ELECTRIC FIELD SIMULATION STUDIES

As the first step of the selection procedure of insulating foam for its application in Gas Insulated Transmission Lines, the electric field distribution is analyzed for the estimated base electric field stress. Thus, to study electric field distribution through the insulating foam, a small representative model is designed in *COMSOL Multiphysics* software based on finite element analysis (FEM) method. For syntactic foam, the main constituent dielectric components are air, epoxy resin and glass. The composite nature of the dielectric leads to an uneven electric field distribution even with the application of uniform electric field. The following chapter describes the steps involved in building an insulating foam model by modeling syntactic foam. For the model developed, the results of the field distribution are analyzed to discuss suitability of syntactic foam as an insulator. The effect of the presence of a metal particle in the dielectric medium is also evaluated as a part of the study.

2.1 Introduction to the *COMSOL Multiphysics* Software

COMSOL Multiphysics software helps in modeling and solving engineering and scientific problems through its user controlled environment. For solving the equations involved in the model, finite element method (FEM) is used with the help of variety of numerical solvers available with the software. All the steps involved in building insulating foam model, such as geometry, materials, mesh, solver settings are recorded with the help of sequences. Partial differential equations (PDE) forms the basis of all the scientific and engineering studies involved in *COMSOL Multiphysics* software [23]. The electric, magnetic and electromagnetic fields can be simulated for static and low frequency applications by solving differential forms of Maxwell's equations for the initial and boundary conditions. The equations are solved using the finite element method with numerically stable edge element discretization. The results are represented by the electric and magnetic fields plots in the graphics window. The current and voltages can also be plotted with the help of user defined settings. The output can be analyzed in two dimensional or three dimensional environments [24].

The work flow in the module is described by the following steps: definition of geometry, selection of materials, definition of boundary conditions, definition of finite mesh elements, selection of solver and visualization of results. These steps are accessed through the desktop guided user interface [23]. The Electrostatic interface from the *AC/DC module* is selected for the following simulation of syntactic foam. Frequency domain analysis at 60 Hz frequency is used to get the electric field distribution for the AC voltage applied.

2.2 Basic Syntactic Foam Structure

The syntactic foam generally consists of glass microspheres with diameters in the range of 60-120 µm. The microspheres are scattered randomly inside the epoxy resin matrix. The wall thicknesses of these microspheres lie between 1-

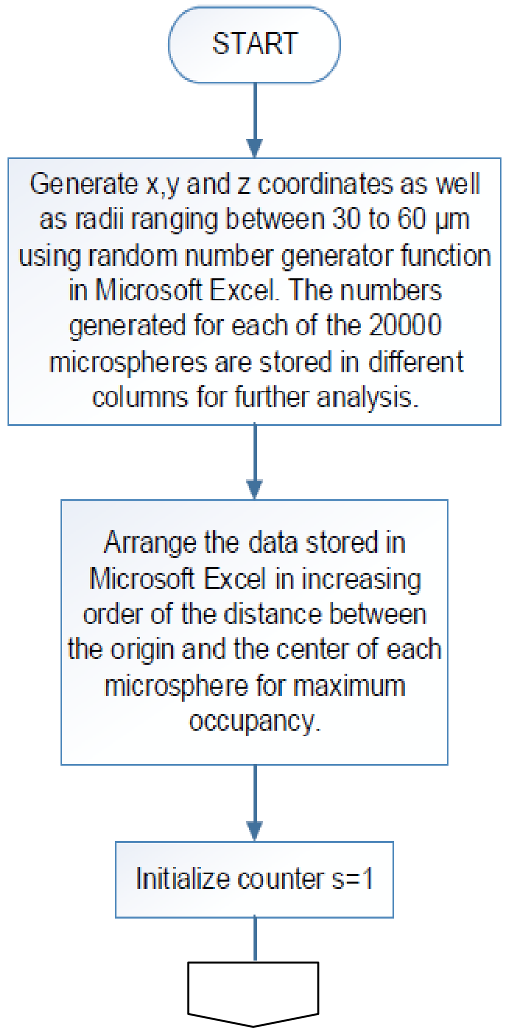
5 µm. The development of the syntactic foam model for studying electric field distribution consists of three main parts,

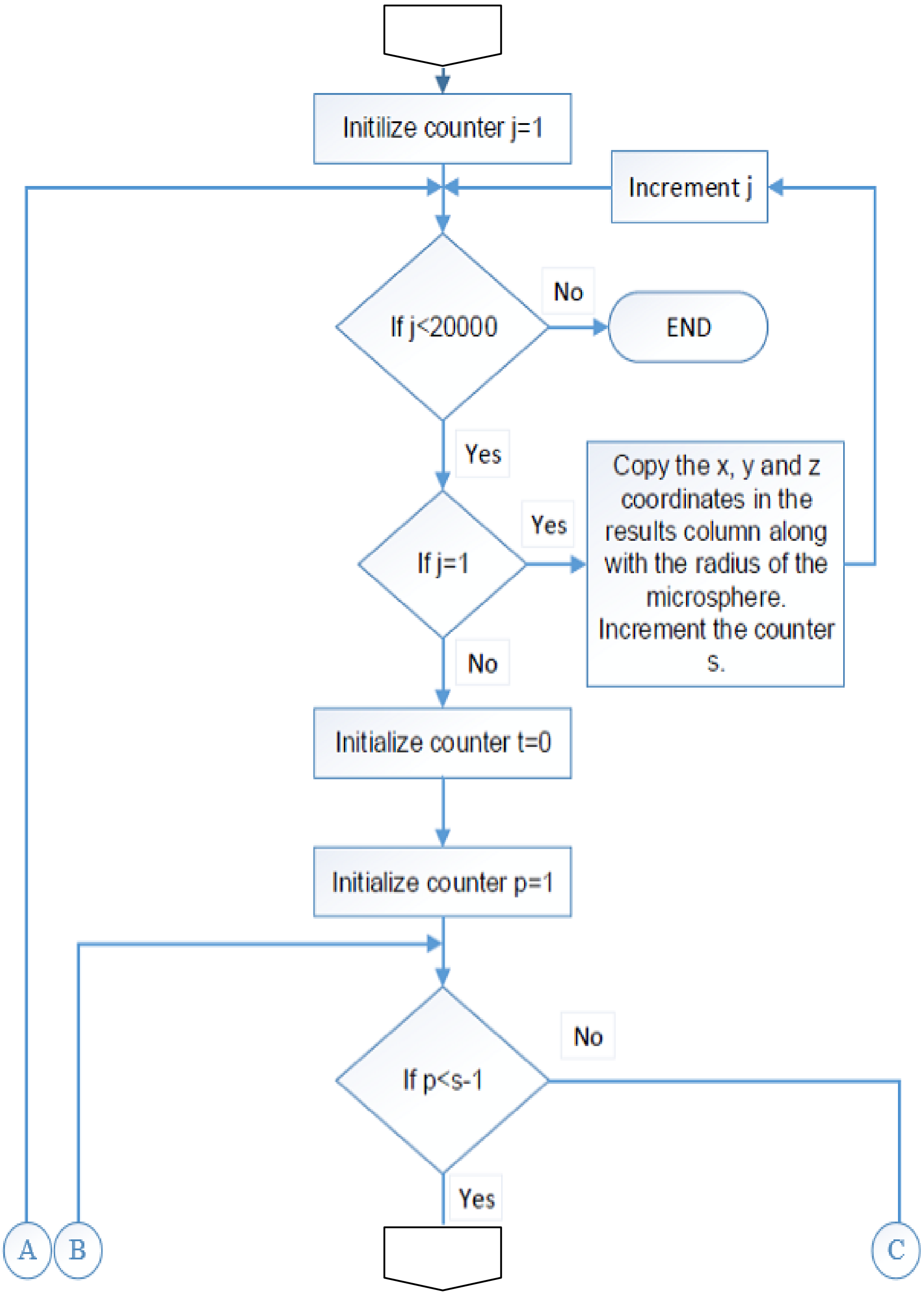
1. Development of the *Microsoft Excel Visual Basic* program to generate random coordinates for microspheres
2. Constructing intricate geometrical components of the syntactic foam system in *AutoCAD*
3. Solving the model in *COMSOL Multiphysics* to plot electric field distribution and voltage profiles.

1. Development of the *Microsoft Excel Visual Basic* Code

To make the model as realistic as possible, there has to be randomness in the composition of the component elements. This randomness is introduced in the model with the help of *Microsoft Excel Visual Basics (VBA)* macros. The *VBA* program gives random coordinates of the microspheres inside the specified shape of the foam model. As syntactic foam is manufactured by mechanically mixing glass microspheres with the resin material, the locations of microspheres are generated such that no two microspheres intersect with each other. The microspheres are allowed to form a cluster by touching each other, considering the practical possibility of the case. According to the general size of the microspheres, each microsphere is given a random radius between 30 to 60 µm for the simulation purpose. The wall thickness of the microspheres is maintained at 1 µm. The filling degree of the foam plays a crucial role in determining mechanical and electrical properties of the microspheres. Here, the filling degree is maintained in between

35-40% of the matrix volume. The flowchart of the program is described in the Figure 2.1.




Initilize counter j=1
Increment j
If j<20000
No
END
Yes
If j=1
Yes
Copy the x, y and z coordinates in the results column along with the radius of the microsphere. Increment the counter s.
No
Initialize counter t=0
Initialize counter p=1
If p<s-1
No
Yes
A
B
C

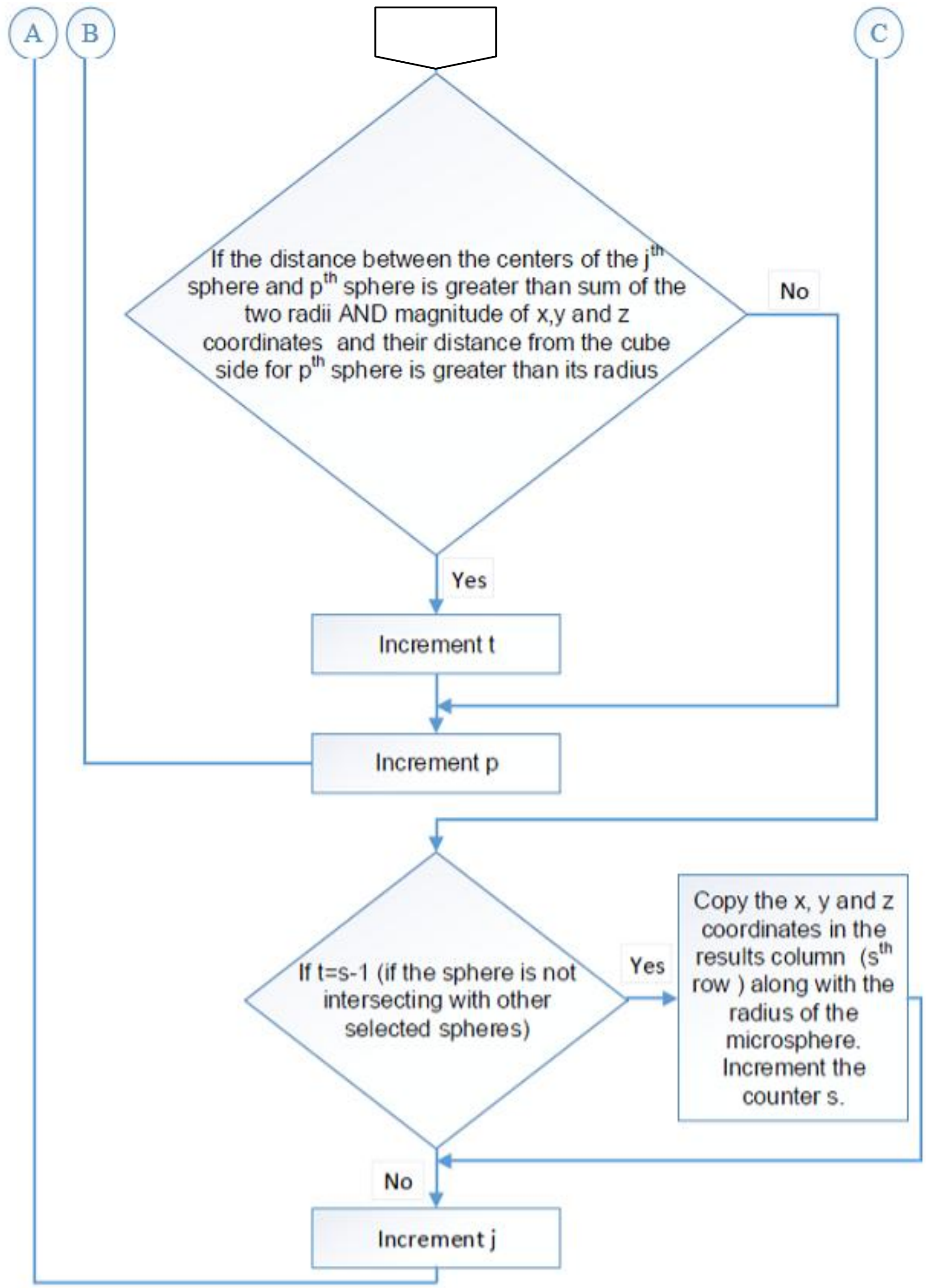


Figure 2.1 Flowchart for the Program for Determining Coordinates of the Spheres

2. The geometrical model construction in *AutoCAD*

The main challenge about the development of a model for syntactic foam is the large number of elements involved in the geometry of the structure. These large number of microspheres with diameters in micrometers and 1 µm wall thicknesses are impossible to construct manually, even for a cubical model as small as 250 µm. Because of this limitation to construct all the microspheres at the same time, specialized *CAD* software, *AutoCAD* 2014 is used for construction of this complicated geometry.

AutoCAD is equipped with a feature which enables it to read commands from the script file and to generate geometrical figures in the work-plane. With the output coordinates and radii of the microspheres calculated by the *Excel VBA* code, the script file can be generated for *AutoCAD*, with the command *SPHERE*. With the help of the other script file with same center coordinates, another range of concentric spheres can be generated for the simulation of glass walls. After creating the entire geometry in *AutoCAD*, it can be exported in as an '*.iges'* file which can be directly imported in *COMSOL Multiphysics* through the *CAD Input Module*.

3. Solution for the electric field distribution in *COMSOL Multiphysics*

The solution of the electric field distribution problem for the considered syntactic foam model can be found with the help of *COMSOL Multiphysics*. After the model is imported through *CAD Input Module*, the material properties are assigned to the various elements in the model. The important property with respect to the electric field distribution is the relative permittivity of the material with respect to air. Since the analysis is done at the supply frequency of 60 Hz, electric permittivity is kept constant with respect to the change in frequency. The various materials and their dielectric permittivity considered for the model is given in Table 2.1.

Table 2.1 Relative Electric Permittivity of the Constituent Elements

Material	Relative permittivity
Aluminum electrodes	1
Epoxy resin matrix	3.5
Glass walls of microspheres	5
Air inside the microspheres	1

After assigning the material properties, the physics settings are finalized for the model. The solution is obtained with the help of finite element analysis. Finite element analysis method is used in a wide variety of engineering problems such as solid mechanics, dynamics, heat problems, fluids and electrostatic problems. Finite element analysis cuts a structure into several elements (pieces of the structure). This process results in a set of simultaneous algebraic equations. The behavior of electric field is based on the nature of electrodes (uniform and non-uniform). Finite element method uses the concept of piece-wise polynomial interpolation. By connecting the elements together, the electric field quantity becomes interpolated over the entire structure in piece-wise fashion. In this method, indeterminate structures are solved [27].

In electrostatics, Maxwell's equations and constitutive equation reduce to the following form,

$$\nabla \times E = 0 \tag{2.1}$$

$$\nabla \cdot D = \rho \tag{2.2}$$

$$D = \varepsilon E \tag{2.3}$$

Where, E is the electric field intensity, D is the electric displacement, ρ is the space charge density, ε is the dielectric permittivity of the material. Based on Eq. (2.1), electric field intensity is introduced by the negative gradient of the electric scalar potential, V, in following form

$$E = -\nabla V$$

Substituting equations (2.2) and (2.3) in (2.1) Poisson's scalar equation is obtained as

$$-\nabla \cdot (\varepsilon \nabla V) = -\nabla \cdot (\varepsilon_0 \varepsilon_r \nabla V) = \rho$$

Where, ε_0 is the permittivity of free space and $\varepsilon_r = \varepsilon_r$ (E, x, y, z) is the relative permittivity. If the permittivity ε_r is constant such as in the isotropic dielectrics,

$$\Delta V = -\rho\varepsilon$$

For space charge free ($\rho = 0$) fields, field is expressed by Laplace's equation as $V = 0$. In this study, solution of the problem is obtained from solution of Laplace's equation in rectangular coordinates.

$$\nabla^2 V = \frac{\partial^2 V}{\partial^2 x} + \frac{\partial^2 V}{\partial^2 y} + \frac{\partial^2 V}{\partial^2 z}$$

V= Breakdown voltage on the upper electrode,

V = 0 Volt (ground) on the lower electrode,

∂V/∂n = 0 on all other outer boundaries and on the symmetry axis.

After setting up the physics conditions for the module, meshing is done to solve the above equations at those many points in the geometry. Once meshing is done AC analysis is done by adding frequency domain study to the model and solving the system for 60 Hz frequency.

2.3 Calculation of the Electrode Potential for the Syntactic Foam Model

For a 400 kV standard GIL, standard dimensions of the enclosure and conductor are given in Table 2.2 [2].

Table 2.2 400 kV GIL Dimensional Parameters

Operating Voltage Level (kV)	400
Conductor Outer Diameter (mm)	180
Conductor thickness (mm)	10
Enclosure Inner Diameter (mm)	500
Enclosure thickness (mm)	10

Since it is very difficult to build the syntactic foam structure for the entire volume enclosed by the 400 kV GIL, some smaller models are built in *COMSOL* to study electric field distribution. Now, the GIL consists of two concentric metallic cylinders insulated with the insulating gas, SF_6. When the support insulators are neglected for the simplified case, the electric field distribution is coaxial. It is very high in the vicinity of the conductor and then the value decreases in radially outward direction towards the enclosure. Figure 2.2 and Figure 2.3 show the plots for electric field intensity (V/m) and electric potential (V) simulation of simplified GIL model in *COMSOL*. The maximum electric field was calculated to be 4.39 kV/mm.

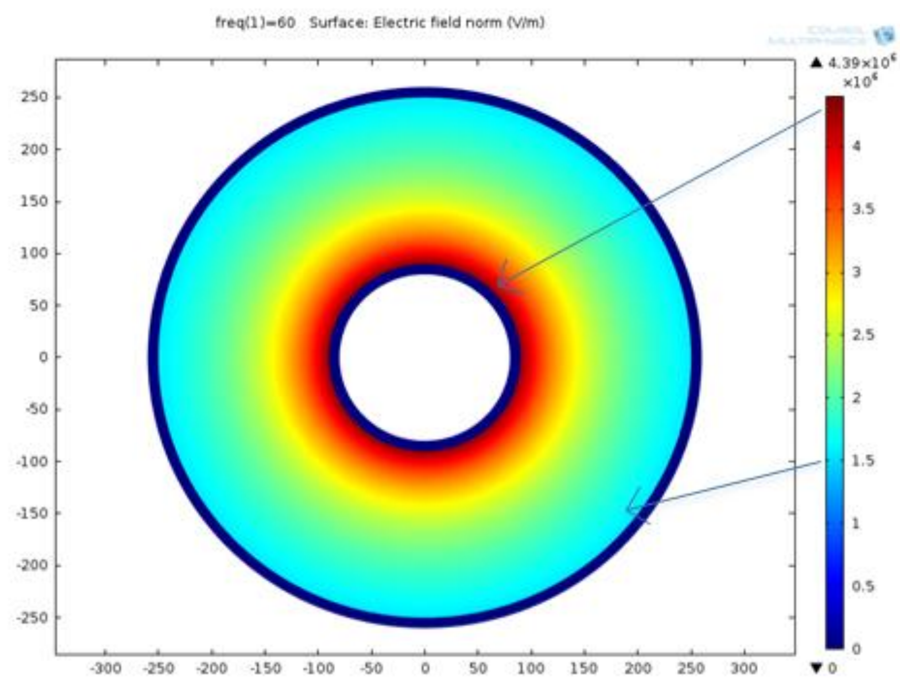


Figure 2.2 Electric Field Distribution of 400 kV GIL

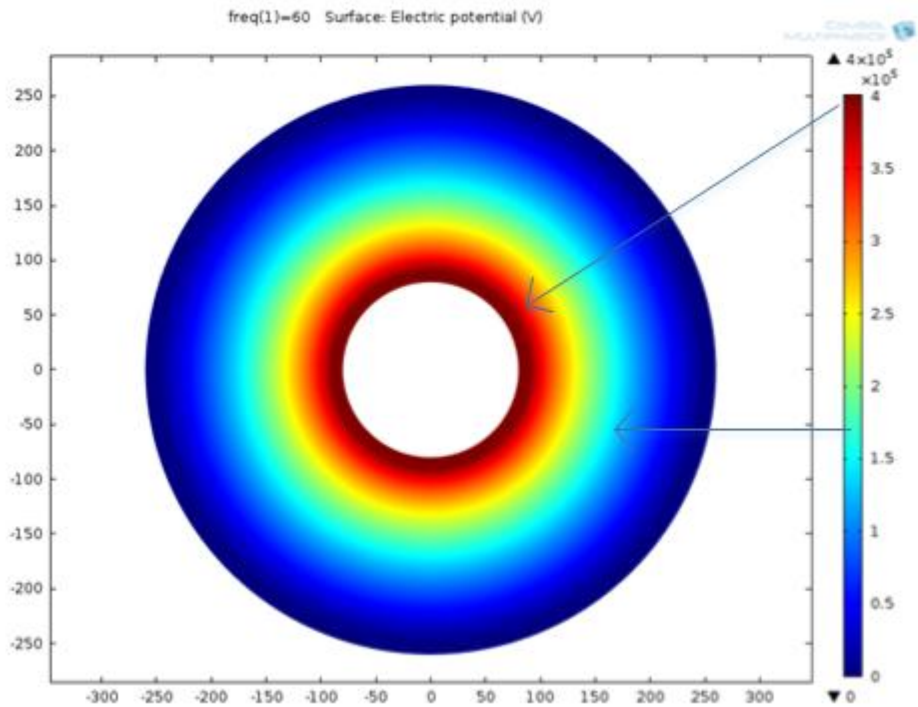


Figure 2.3 Electric Potential Distribution of 400 kV GIL

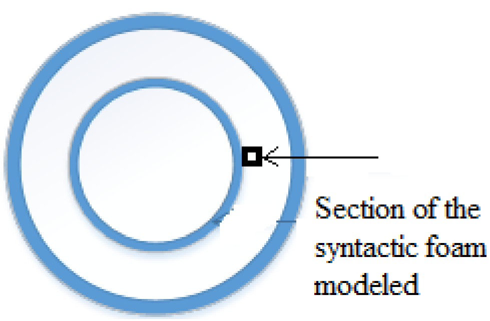


Figure 2.4 The Section of the Syntactic Foam Modeled

For the smaller scale model of the syntactic foam, a cubical/ rectangular section is modeled in between two parallel plate electrodes. In case of a parallel plate electrode configuration, the electric field generated in between the two electrodes is uniform. Thus, the base value of the field for these models is always maintained equal to the maximum value of the coaxial field of the simplified GIL model i.e. 4.39 kV/mm. The idea of simulating a smaller section of syntactic foam in the transmission line is made clear with Figure 2.4. The relationship between applied voltage and the magnitude of the electric field intensity in case of parallel plate electrodes is given by,

$$E = \frac{V}{d} \tag{2.4}$$

Where, V is the voltage applied to the high voltage electrode when the other electrode is grounded and d is the distance between the electrodes. Thus, the voltage applied to the Aluminum electrode for the simulation purpose is calculated using Equation (2.4).

2.4 The Cubical Model of Syntactic Foam with Side 250 µm

As a first step to analyze electric field distribution for the syntactic foam, a cubical model is built in *COMSOL Multiphysics*. The side of the cubical section is designed to be 250 µm. The voltage of 1598 V is applied to the Al electrode to keep the base voltage stress at 4.39 kV/mm. The conditions are assumed to be ideal with no contaminating particles and absence of air bubbles. The model is represented in Figure 2.5. The maximum value of field stress observed inside the cubical section is 6.35 kV/mm. This value is almost 2 times the value of breakdown strength of air. For understanding the overall behavior of the electric field distribution for syntactic foam, the distribution for the y-z planar surface at x=100 µm is plotted and is shown in Figure 2.6.

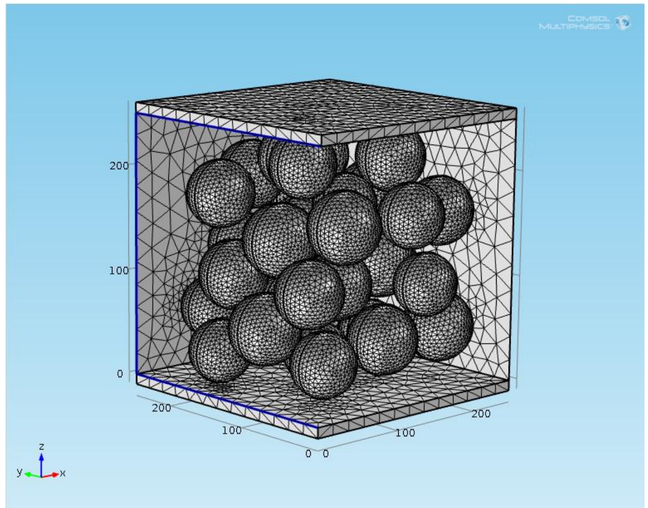


Figure 2.5 The Meshed Cubical Model of Syntactic Foam of Side 250 μm

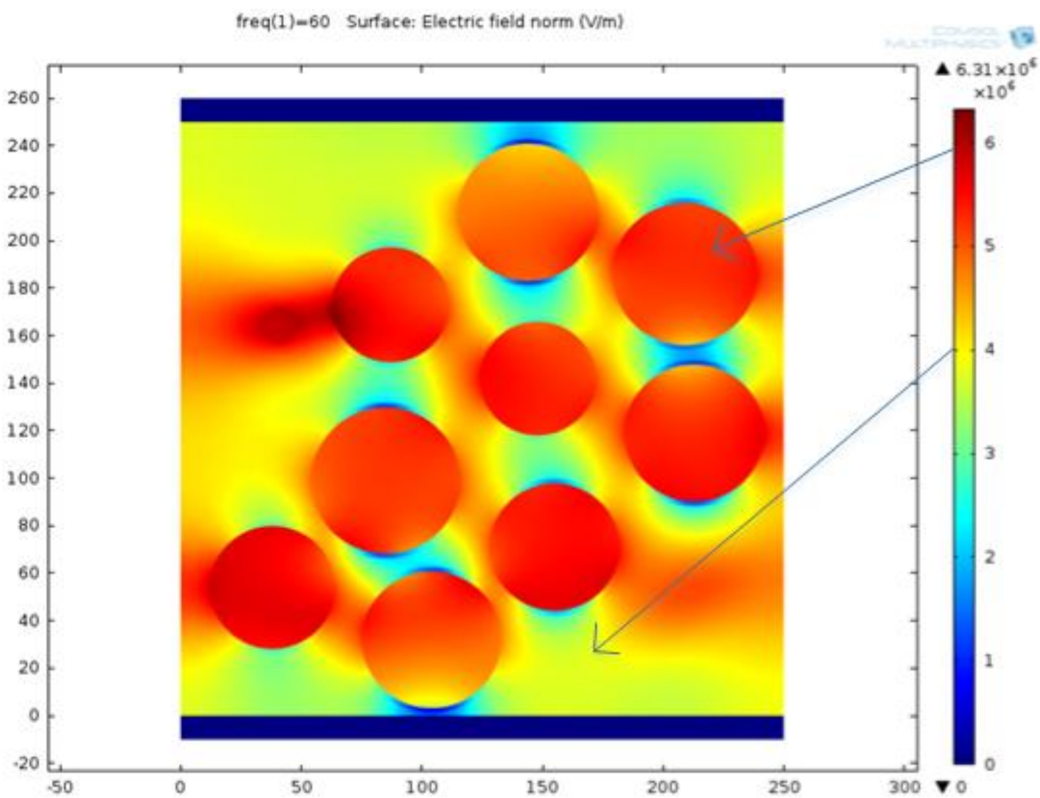


Figure 2.6 The Electric Field Distribution for the *y-z* Planar Surface at x = 100 μm

For the base electric field applied, the field distribution is not uniform as expected. The maximum field value for the section is observed to be 6.31 kV/mm which is 42.14% higher than the base value. This is because of the interaction of the dielectric materials having different values of dielectric permittivity. The electric field gets concentrated inside the spherical microspheres because of the low dielectric constant of air. The distribution for the epoxy resin matrix is highly non-uniform in the vicinity of the microspheres. The value is considerably low near the microspheres along the direction of electric field. On the other hand, for the plane parallel to the Al electrodes (perpendicular to the direction of the electric field), the electric field is very high.

The presence of really high electric field inside the glass microspheres might lead to gas discharges if sufficient pressure is not maintained for the air filled inside the microspheres. But, since the air inside the microspheres is trapped by the glass walls, in the worst case scenario, the gas discharges remain confined to the area inside the microspheres. The glass being an inorganic dielectric gets least affected by it. Thus, the breakdown can be initiated in the epoxy resin matrix considering high values of electric field stress. If the local value of electric field stress exceeds the breakdown strength of the epoxy resin, it will deteriorate the matrix eventually causing breakdown inside the syntactic foam.

2.5 Approximation of the Microspheres

The detailed modeling of syntactic foam requires a high performance system with very high Random Access Memory (RAM) and computational speed for computing field distribution by *COMSOL Multiphysics* due to its intricate structure at the microscopic level. The availability of such a system for the simulation purpose is not always possible due to high costs involved. Therefore, in order to make a large scale model, some simplifications are necessary such that the new field distribution is as same as the original one.

The geometrical construction of foam involves construction of two concentric spheres for the hollow part and the glass walls. Simplification can be done by modeling the microspheres by a single sphere with dielectric constant 1.57. The value of the dielectric constant is obtained by trial and error method such that the new model's field distribution pattern in almost similar to the original model and the variations in electric field stress values are within the acceptable limits. This new idea is implemented on a smaller 250 µm model with same coordinates and same radii of the microspheres as were considered for the previous model. The distribution pattern is observed by analyzing and comparing various planar surfaces of the two models. The electric field distribution for the y-z plane at x = 100 µm (same as the one described in Figure 2.6) with the new model is shown in Figure 2.7.

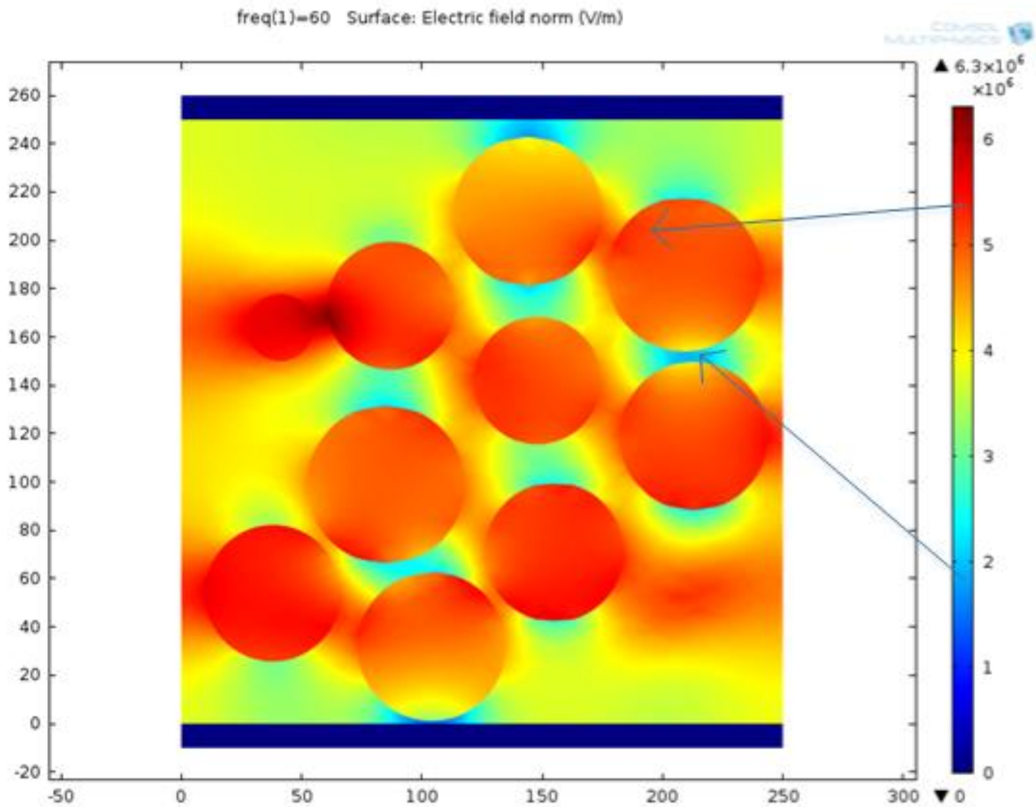


Figure 2.7 Electric Field Distribution of the *y-z* Plane at x= 100 μm for the Approximated Model

Along with this, data is extracted for the magnitude of calculated electric field along the direction of applied field, from the upper electrode to the lower electrode, for various x, y coordinates for both the original and approximated models. This data is then analyzed in *Microsoft Excel* for better comparison of the two models. The analysis is also done for the planar surfaces parallel to the electrodes (perpendicular to the applied field). The graphs comparing field intensities of the two models are shown in Figure 2.8.

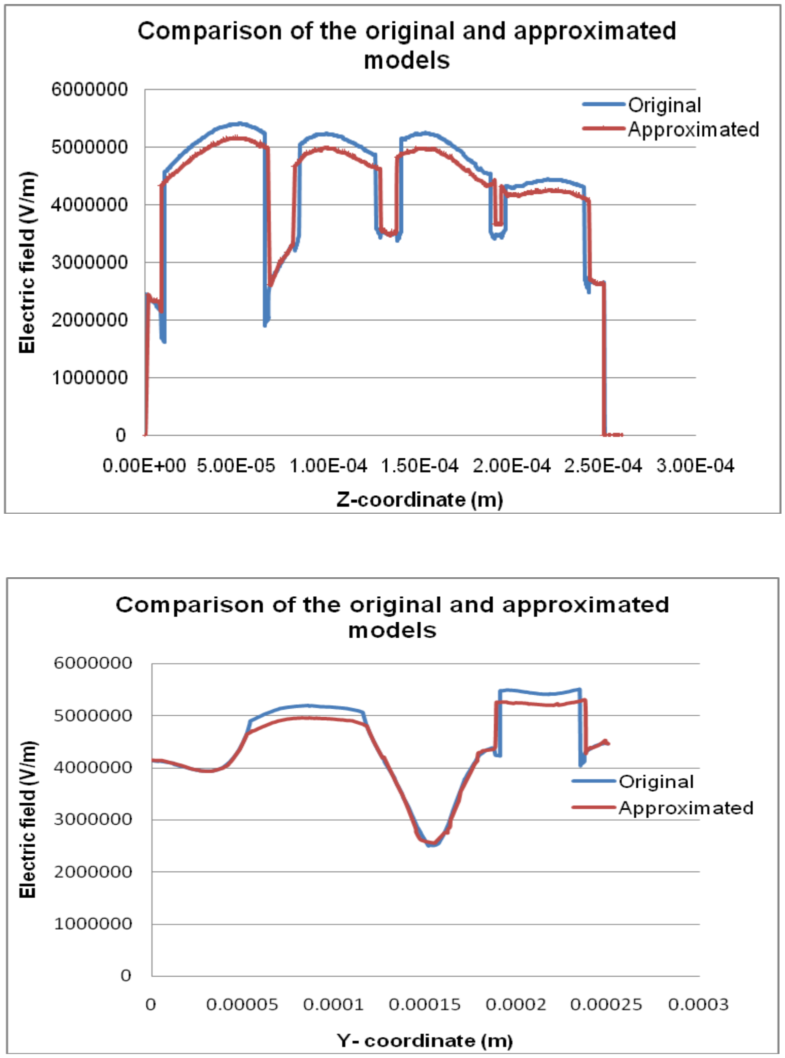


Figure 2.8 Comparison of the Electric Field Stress of the Original and Approximated Models Along the Direction of Electric Field and Perpendicular to It.

It can be clearly observed from all the graphs that electric field distribution of the approximated model closely follows the distribution observed in original model of syntactic foam. The field value changes at the microsphere-resin interface and inside the microsphere. The value observed at the interface is higher than the actual field. Therefore, the new model gives pessimistic results which won’t be harmful for further analysis. The value observed inside the microspheres is 2.5 to 5% lower than the actual value which is within acceptable range. As stated earlier, the stress on the epoxy resin and the microsphere-resin interface is more important to predict the suitability of syntactic foam. Thus, the model can be used for further analysis of the foam.

2.6 The Larger Cubical Model of Size 1 mm

With the help of the approximations stated above, a larger cubical model is built with side measurement of 1 mm. The size of the microspheres is allowed to vary from 30 µm to 60 µm in radius. The voltage applied to the electrode is calculated such that the base electric stress remains 4.39 kV/mm. The meshed cubical model is shown in Figure 2.9 and the effective electric field distribution for the y-z plane at x = 500 µm is shown in Figure 2.10.

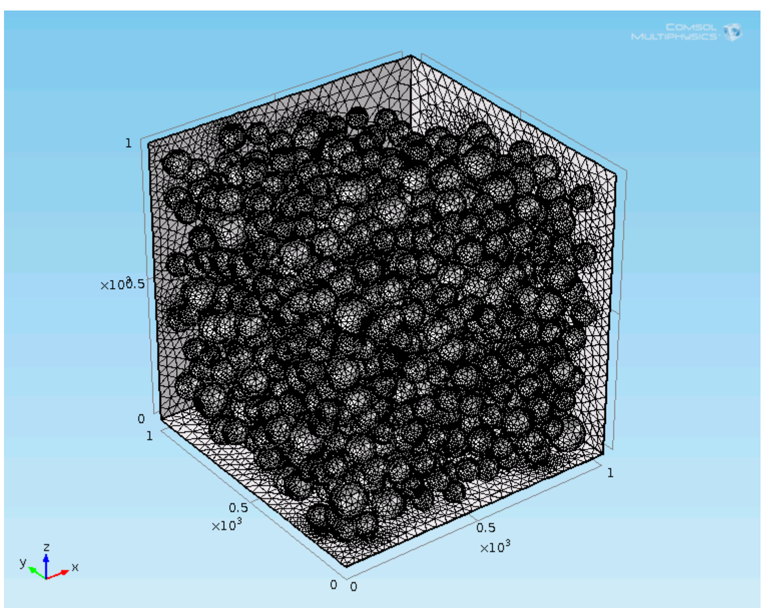


Figure 2.9 Meshed Cubical Model of Side 1 mm

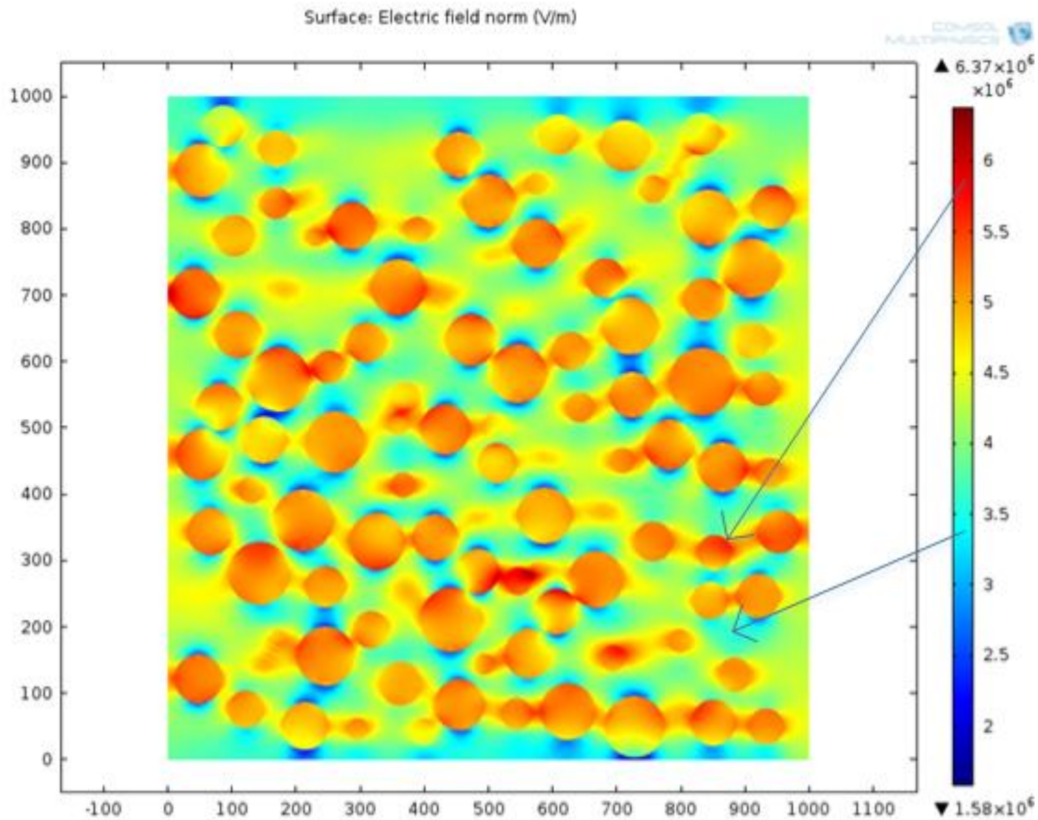


Figure 2.10 The Electric Field Distribution of the *y-z* Plane at x= 500 μm

The pattern of electric field distribution was observed to be similar to that of the model discussed in the previous section. The electric field gets concentrated inside the microspheres and near the vicinity of the microspheres, in perpendicular direction to the electric field applied. After observing field distribution for different cases for the cubical model developed and analyzing the data in *Excel*, it was observed that the average percent of increase in the magnitude of electric field than the base value is 45.1% for all the cases considered. This value is 2.12 times higher than the breakdown strength of air.

The breakdown strength of pure epoxy resin is around 16 kV/mm, which is 5.33 times as that of air [28]. From all the simulations performed for the ideal case scenario of syntactic foam, it can be observed that the electric field concentration inside the epoxy resin matrix ranges between 5-5.5 kV/mm. The field needed for the breakdown of epoxy resin is almost 3 times of the magnitude of the field observed in the simulations. Also, the air filled inside the microspheres at high pressure, restricts the gas discharges inside the microspheres. Thus, it can be concluded from the developed computer analysis of syntactic foam, that syntactic foam is suitable insulating foam for the application of transmission lines with the safety factor of more than 3.

Thus, the basic methodology that should be used for the construction of insulating foam model for application in transmission line is explained above. This is done with the help of the developed syntactic foam model. Ability to change parameters used in the above model makes it generic. For example, for the other type of syntactic foams, with different matrix material or different type of microspheres, the relative permittivity assigned to the components in the *COMSOL Multiphysics-Materials* section can be varied before plotting electric field distribution. Also, for the general insulating foams, the *Excel VBA* program can be modified to incorporate other shapes and sizes of the filler material by varying range of the random radii generated or removing the condition of separated microspheres. Therefore, along with syntactic foam, other types of insulating foams can be also be modeled with the same method by incorporating some minor modifications in the modeling technique. This will be useful in order to verify first step of the foam selection method for a transmission line.

But, under practical circumstances, many factors like air voids, presence of impurities come in the picture. The effect of these impurities on the electric field distribution is studied in the following section.

2.7 Impact of Impurities on Electric Field Distribution of Syntactic Foam

Presence of metal particles in the foam

For Gas Insulated Lines, assembly of the component elements takes place on the on-site location by joining all the factory built units within a mobile clean room [5]. For GIL, the welding procedures taking place on-site, might lead to formation of small metal particles. These metal particles might result in a continuous PD in case of floating components when these particles are discharged periodically [25]. In case of GIL, if these particles are in the region of low electric field, which are expected to be near the enclosure surface, the electric field is not appreciably affected.

In case of syntactic foam insulated lines too, the assembly of the factory built parts has to be done on the on-site location. Syntactic foam is generally prepared with the help of thermosetting resins according to US patent 4595623 [26]. The mixture can be heated to make the thermosetting plastic to flow. The mixture can then be cooled down to get the solidified syntactic foam. The small pieces of enclosure and conductor can be brought on the site location with solidified syntactic foam in the gap. The two sections of the line can be welded together and foam from the two sections can be fused together by positional heating to connect them. This is shown in Figure 2.11. The presence of metal particle in case of syntactic foam can be more harmful than in case of GIL. This will have an effect on the long term performance of the syntactic foam as an insulator. The presence of such metal particles will result in local concentration in the electric field and this leads to partial discharges which will eventually form electrical trees and thus reducing life of the dielectric [27]. The critical size of these metal particles ranges between 2-10 mm. Generally the particles are of the shape of metal flakes [27].

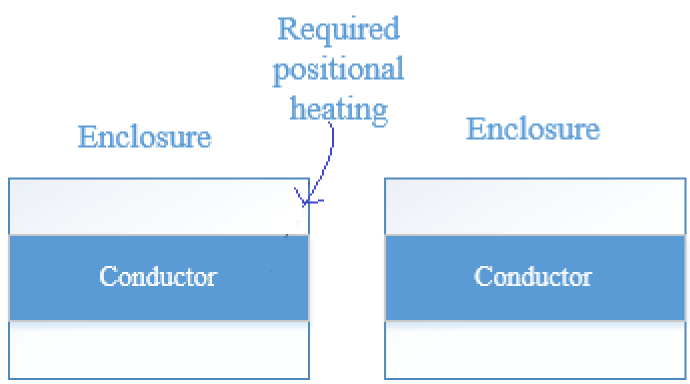


Figure 2.11 The Positional Heating of the Syntactic Foam

The effect on the electric field distribution because of the presence of metal particles is analyzed by modeling a cubical section of syntactic foam of side 2 mm in between two Aluminum electrodes. The cylindrical metal particles with length 1.5 mm and 2 mm and radius varying between 40 to 50 µm are simulated inside the cubical section. The base electric field for the model is maintained at

4.39 kV/mm, which is the maximum field stress observed in 400 kV GIL model. The voltage applied to the high voltage electrode, *V*, is determined by the formula,

$$E = \frac{V}{d}$$

Where, *E* is the base electric field and *d* is the distance between the electrodes. The electric field is calculated by assigning floating potential to the cylindrical metal particle in *COMSOL Multiphysics*. The increase in the value of the electric field stress is studied with respect to the deviation from the base electric field applied. Three cases are simulated for the metal particle along vertical, horizontal direction and along the diagonal of the cubical section.

- Vertical position of metal particle

Figure 2.12 shows the cross sectional view of model of syntactic foam with metal particle placed vertically in the middle of the cubical section. The radius of the particle is varied from 40 μm to 50 μm and the effect on the electric field distribution is observed. The electrodes are placed along the *x*-*y* plane of the Figure 2.12 and thus, the direction of the base electric field is along *z* direction. Figure 2.13 shows electric field distribution along the plane passing through center of the cylinder of diameter 100 μm.

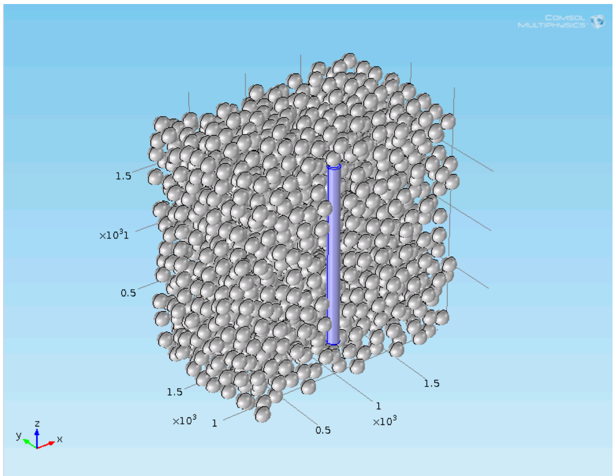


Figure 2.12 The Model of the Syntactic Foam With Metal Particle Placed Vertically at the Center of the Cubical Section of Side 2 mm

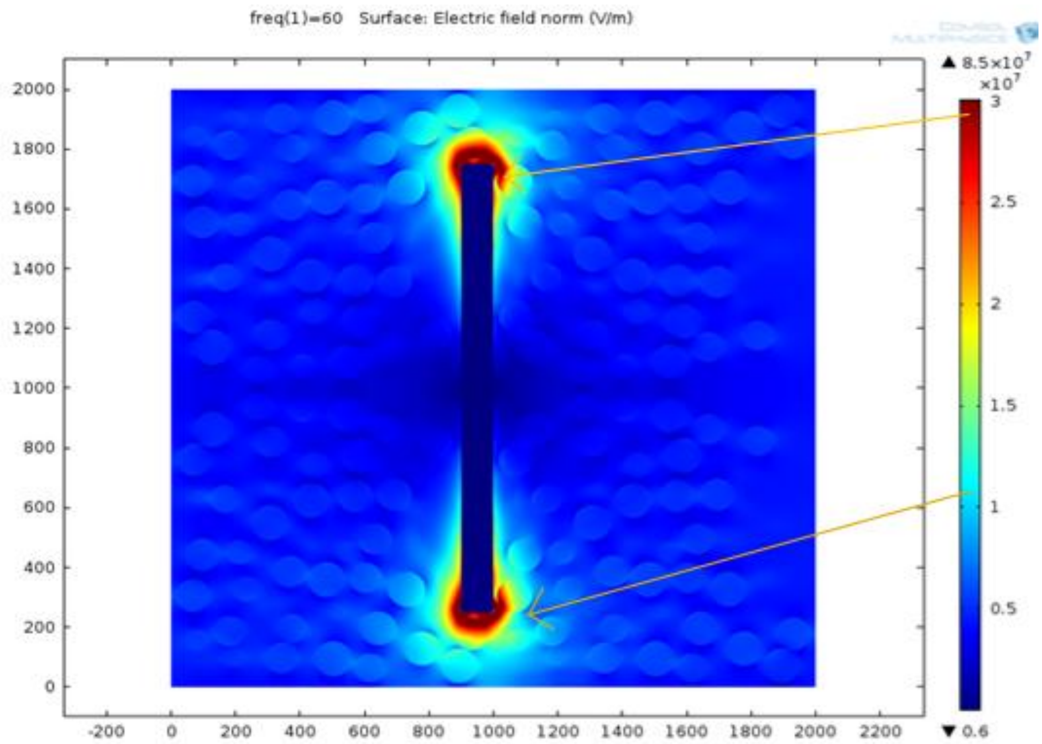


Figure 2.13 The Electric Field Distribution Along the Plane Passing Through the Center of the Metal Particle Placed Vertically in the Cubical Section of 2 mm

The electric field gets concentrated near the top and the bottom edges of the metal particle due to its sharpness. The magnitude of the maximum field is 87 kV/mm which is 19.8 times the base electric field applied for a particle of 50 μm radius. For various points in the *x-y* plane, data points for the calculated electric field are collected along the vertical line, in the direction of the electric field (from upper electrode to the lower electrode), and are analyzed in *Excel*. It is observed that the field magnitude is almost 18 times the original electric field for the 50 μm model and 11.5 times the original electric field for the 40 μm model at the edge of the metal particle. On the other hand, the maximum electric field decreases to 2.2 times the original field magnitude for the 50 μm case and 2 times the original field in case of 40 μm case at the distance of 150 μm from the center of the base of the metal particle in *x-y* plane. The *Excel* datasheet is attached in Appendix C.

Thus, when a metal particle is placed perpendicular to the electrodes or in the direction of the electric field, the field distribution will lead to partial discharges in the epoxy resin matrix. This behavior is due to the fact that electric field intensity magnitude at the top and bottom edges of the metal particle, at the base value of 4.39 kV/mm, being 5 times higher than the breakdown strength of epoxy resin. Also, this magnitude of electric field increment varies greatly with the diameter of the metal particle.

- Horizontal position of the metal particle

Figure 2.14 shows the cross sectional view of the syntactic foam model with metal particle placed horizontally (parallel to the electrodes) inside the cubical section of side 2 mm. The electrodes are placed in the *x*-*y* plane of the Figure 2.14 and thus, the direction of the base electric field is along *z* direction. The size of the metal particle is varied between 40 μm and 50 μm by radius. The curving radius is kept at 10 μm at the edges of the cylinder.

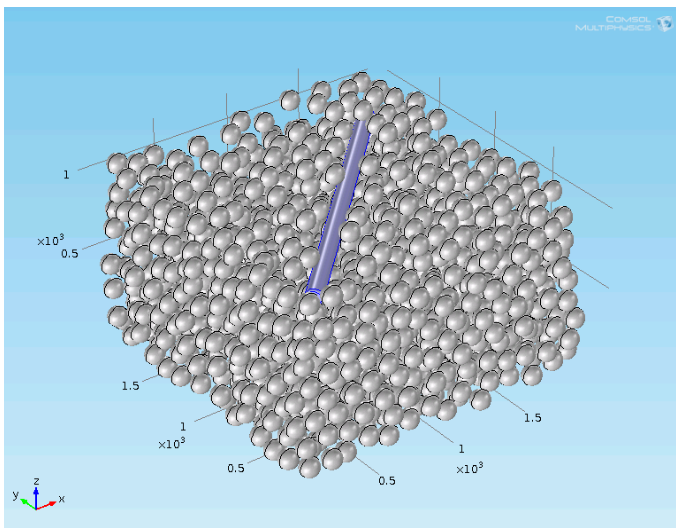


Figure 2.14 The Model of the Syntactic Foam With Metal Particle Placed Horizontally at the Center of the Cubical Section of Side 2 mm

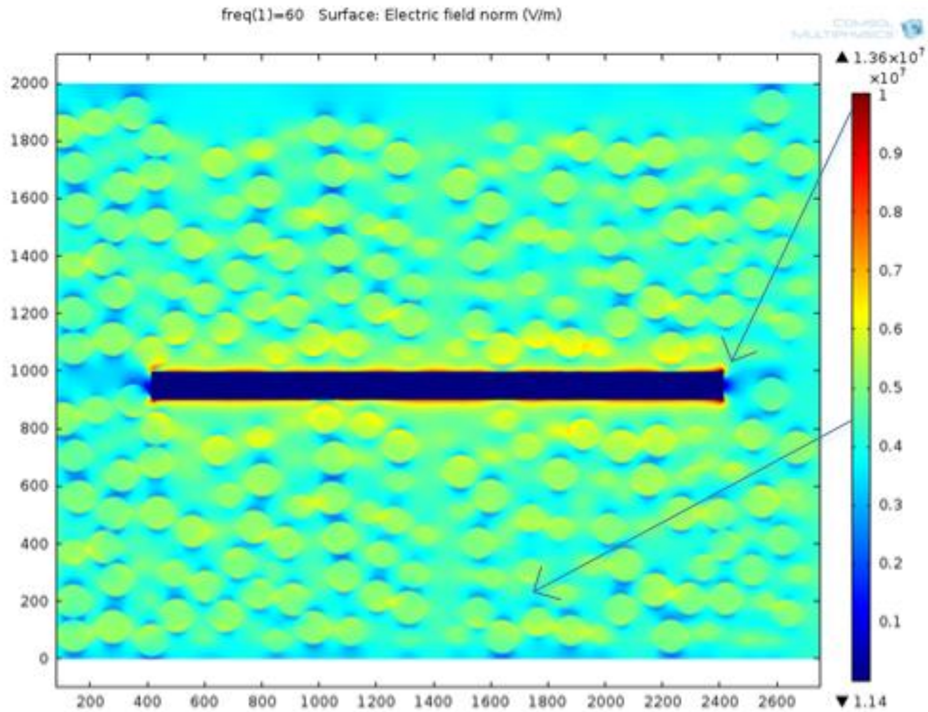


Figure 2.15 The Electric Field Distribution Along the Plane Passing Through the Center of the Metal Particle Placed Horizontally in the Cubical Section of Side 2 mm

The electric field distribution along the horizontal plane passing through center of the metal particle is shown in Figure 2.15. It can be observed here too, that the electric field gets concentrated along the edges of the metal particle. The maximum electric field observed in case of metal particle simulated with 50 μm radius is 13.7 kV/mm. This value is 4.56 times as that of the breakdown strength of air. This observed electric field value is much lower than that of the previous case where particle was aligned in the direction of the electric field. When magnitude of the electric field intensity for the 40 μm and 50 μm cases is compared with the original field distribution, it was observed that the field increases by 1.8-2 times the original field near the edge of the metal particle for both the cases. Since this value of field concentration is less than that of the breakdown strength of epoxy resin matrix, any partial discharge activity is avoided inside the epoxy resin matrix. Also, this increase is not appreciably affected by the size of the metal particle. Thus, this position of the metal particle will not affect the long term breakdown characteristics of the syntactic foam.

- Particle placed along the diagonal of the cubical section

Figure 2.16 shows the cross sectional view of the syntactic foam model with the metal particle placed along the diagonal of the cubical section. The electrodes are placed in the *x*-*y* plane of the Figure 2.16 and thus, the direction of the base electric field is along *z* direction. The particle has radius of 50 μm and the length of the particle is 2 mm.

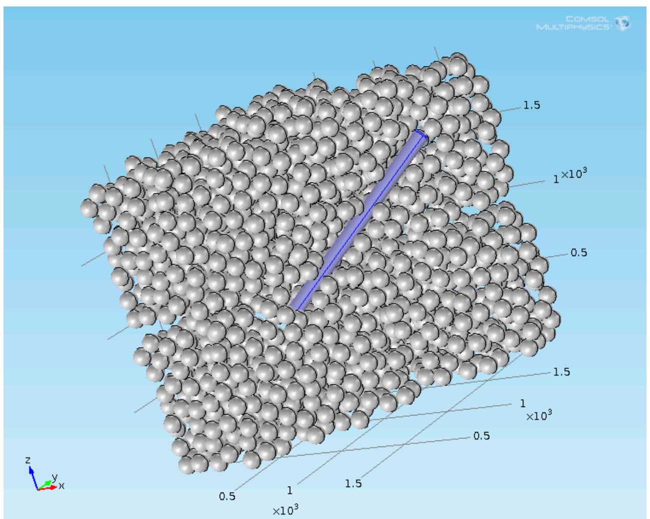


Figure 2.16 The Model of the Syntactic Foam With Metal Particle Placed Along the Diagonal of the Cubical Section of Side 2 mm

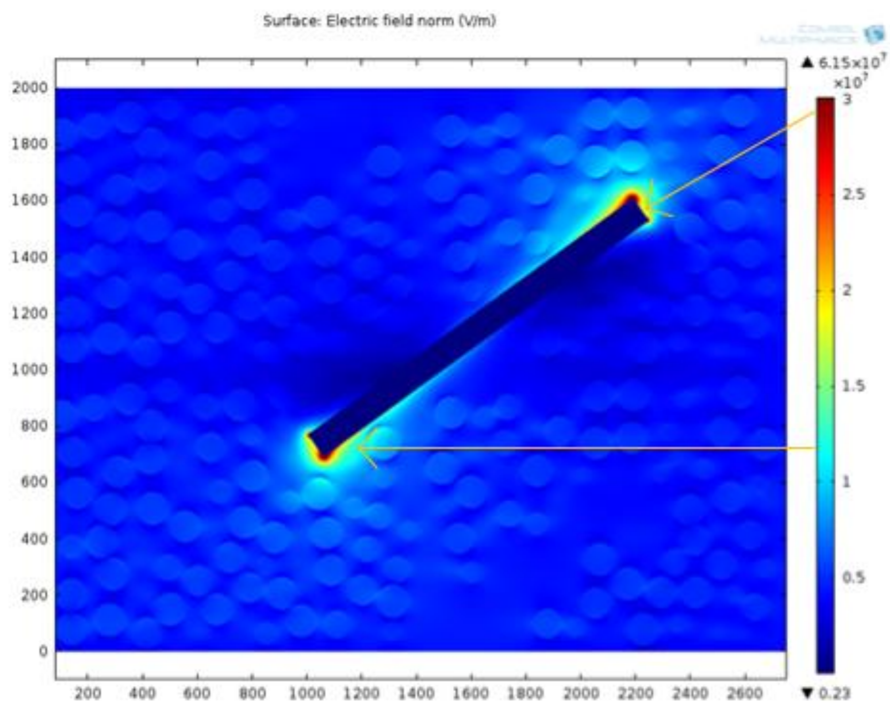


Figure 2.17 The Electric Field Distribution Along the Plane Passing Through the Center of the Metal Particle Placed Horizontally in the Cubical Section of Side 2 mm

The electric field distribution along the diagonal plane is shown in Figure 2.17. The maximum electric field observed in the above case is 61 kV/mm. This value is almost 12 times higher than the original field near the edge of the metal particle, when metal particle of 50 µm radius is included in the model. The data points for the calculated electric field intensity along vertical lines (from upper electrode to the lower electrode), for different points in the *x-y* plane are collected and analyzed in *Excel*. It is observed that the field value reduces to 2-2.5 times the original value when moved towards the center of the particle from the flat ends.

Thus, for this position of the metal particle, the foam will have some partial discharges in the vicinity of the metal particle near the flat edges of the simulated cylindrical particle.

Therefore, the position of the metal particle with respect to the direction of electric field is very important in determining the effect of metal particle on the performance of the syntactic foam. When the particle is along the direction of electric field, the effect is the worst. These high values of electric field will cause partial discharge in the epoxy resin matrix and this will lead to breakdown through the resin matrix due to deterioration of the dielectric as observed in the first case and third case. Also, the highest magnitude of electric field is observed near the edge of the cylindrical metal particle in all the three cases. If the edges are smoother than the cases considered, the effect on the field magnitude will be reduced.

It is important to consider that for all the simulations performed for the presence of metal particles, the base electric field is maintained at 4.39 kV/mm. This value is the maximum value of the electric field observed in 400 kV GIL as seen from Figure 2.1. Thus, these simulations capture the most pessimistic scenario of having metal particle in the region of the transmission line with maximum field. The effect of the metal particle will be less damaging in any other area of the transmission line.

Thus, this chapter describes the first step of the insulating foam selection procedure for application in transmission lines. As a part of the first step, a complete model of the transmission line is developed in *COMSOL Multiphysics*. The electric field distribution in the 400 kV GIL is observed to be coaxial, with maximum field magnitude concentrated near the conductor of the GIL assembly. The magnitude of the maximum field is 4.39 kV/mm which is 1.46 times that of the breakdown strength of air. This maximum value of electric field is considered to be the base value for further analysis of insulating foam. For all the simulation models, the voltage applied to the high voltage electrode, *V*, is calculated by using the relation, $E = \frac{V}{d}$ where *E* is the base electric field and *d* is the distance between the electrodes.

For simplification of the modeling technique and due to the limitations about the technical specifications of the computer system, the microspheres inside the foam are modeled with a uniform material with relative permittivity 1.57 to combine the effect of glass walls and the air inside the microsphere. The electric field distribution obtained by this method is found to be very similar to the original distribution with offset magnitude of less than 5%. For the developed 1 mm cubical section of the syntactic foam, the electric field magnitude deviates from the base electric field by 40-45% for different test models analyzed. The field magnitude required for breakdown through epoxy resin matrix is almost 3 times the maximum magnitude of the field observed in the simulation. Thus, the calculated field concentration in the epoxy resin matrix is not sufficient to cause electric breakdown through the foam. Thus, syntactic foam, in the pure form, can be used an insulator for transmission lines with a safety factor of 3.

The methodology developed for modeling syntactic foam in the above section can be used for modeling other types of insulating foams too, for application in transmission lines. The model developed for syntactic foam is a generalized model. For modeling some other type of insulating foam with different material, the relative permittivity value for the component elements can be changed to take into account effect of altered material components. The size of the generated microspheres can be varied by changing the range of radii that the *Excel VBA* program uses to generate a random number. Moreover, the condition of separated microspheres can be removed for the foams other than syntactic foam to accommodate various shapes and sizes of the voids.

The on-site welding procedures may lead to formation of metal particles in form of metal flakes with size varying between 2-10 mm during the assembly of different sections of the transmission lines. Thus, as a part of the analysis of the computer based model of the insulating foam, the effect of metal particles on electric field distribution is also observed. For this purpose, a cylindrical metal particle with length 1.5-2 mm is modeled inside a cubical section of the insulating foam, which is syntactic foam in this case, of length of the side being 2 mm. It was observed that for the base electric field of 4.39 kV/mm, the electric field distribution is greatly affected by the position of the metal particle. The effect is most damaging for the case with particle positioned in direction of the applied field (along z direction). The field goes as high as 19 times the base electric field near the top and bottom edges of the particle. This field, which is almost 5 times the breakdown strength of epoxy, will lead to partial discharges inside the epoxy matrix, thus affecting the long term performance of the system. On the other hand, when a particle is placed perpendicular to the direction of the applied field (in x-y plane), the effect is not damaging as the concentrated field is just 2 times the base electric field and is less than the breakdown strength of epoxy resin. Thus, existence of the metal particle inside syntactic foam model can be dangerous in some cases.

All the simulations are performed with the pessimistic scenario based on application of base electric field, which is the maximum field that exists in 400 kV GIL as explained in section 2.3. The alignment of metal particle along the direction of electric field near the conductor surface has very less probability. But, for a safer operation of the transmission line, these particles should be removed before building the assembly of the line. For this purpose, while joining the two sections together, conductors should be welded first. Then the particles near the conductor region should be removed. After that the thermosetting matrix of syntactic foam should be heated and then the enclosures should be welded. This procedure will make sure that there are no particles near the conductor region. The effect of metal particles on insulating foams other than syntactic foam can be verified with the same model, but by changing few parameters as explained earlier.

CHAPTER 3.

EXPERIMENTAL IDENTIFICATION OF ELECTRICAL BREAKDOWN STRENGTH OF SYNTACTIC FOAM

The first step of the selection procedure of insulating foam for application of transmission lines is explained in chapter 2. This step is related to the development of a computer based model of the insulating foam and analysis of electric field distribution for possible breakdown. As the second step of the procedure, it is very important to conduct a study of the dielectric insulator's behavior under power frequency AC voltage and lightning impulse voltage in practical environment. Also, the study of the effect of partial discharges is necessary. This chapter concentrates on the explanation of the test procedure and setup that is used to carry out AC voltage withstand test on the insulating foam considered. This is explained with syntactic foam samples similar to the chapter 2. As the second part of the chapter, the results from breakdown tests are analyzed and discussed.

3. 1 AC Voltage Withstand Test

The loss of dielectric property of the solid insulating material as a result of electric field greater than a certain magnitude is called dielectric breakdown. This critical magnitude of electric field is called as breakdown strength of the solid insulating material [28]. Breakdown voltage gives the maximum value of voltage that the material will be able to withstand.

Dielectric strength of the solid dielectric materials depends on many factors such as electrode configuration, thickness of the insulating material, electrode material, air voids or other defects in the material and temperature and humidity at the time of experiment. The breakdown occurs in the area where electric field gets concentrated. These weak spots in the insulating material generally decide the breakdown strength of the solid material.

3. 2 Test Procedure

AC withstand voltage is the prospective value of AC voltage that the material will be able to withstand under specified experimental conditions. This test voltage can either be a peak voltage or a RMS value of the AC voltage according to the IEEE standard for high voltage testing. The RMS value of the voltage can be obtained by dividing its peak value by square root of two [28]. In general, for testing purpose, the frequency of the applied voltage lies between 45-60 Hz [29]. This frequency can be altered for the apparatus-specific tests. The positive and negative half cycles of the applied voltage should ideally be equal, with peak to RMS value within $\pm 5\%$ of square root of two. The wave shape can be varied from pure sinusoidal to some other type of wave shape for the special cases involving test objects with non-linear impedance. The test voltage should be measured for the withstand test with the uncertainty of less than 3% of the peak or RMS value [30].

The voltage shall be applied to the test object starting at a value sufficiently low to prevent any effect of over-voltages due to switching transients. The voltage should be raised with a rate such that the accurate reading of the measurement instrument can be recorded and the test object is not subjected to the prolonged stress at the test voltage. This is achieved by keeping the rate of rise at 2% of the test voltage per second after 75% of the estimated final test voltage. The test is generally carried out over the period of 60 seconds. The test voltage is generally maintained for the test duration and then reduced. The abrupt removal of test voltage might result in switching transients which may affect the breakdown voltage value. The errors caused due to corona and stray capacitance can be reduced by using suitably dimensioned electrodes and guard circuits [30].

3. 3 Description of the Test

As discussed above, the electrical breakdown voltage test is carried out on syntactic foam samples to determine breakdown strength of the foam. For the test, the samples manufactured by *Engineered Syntactic Foam, Boston, USA* are used. The samples are made up of epoxy-based syntactic foam with glass microspheres with diameters in the range of 60-120 μm. The total volume occupied by the microspheres is 40% of the matrix volume for all the samples under consideration. The impact of the variation in sample thickness on dielectric breakdown strength of the foam is observed for the samples with thicknesses 3, 3.5 and 4 mm. Tests were performed at the room temperature.

The test was performed by immersing syntactic foam samples in transformer oil filled vessel to prevent partial discharges and corona through air during the test procedure as seen from the Figure 3.1. Before starting the test, the tendency of the test sample to absorb the oil is tested, since absorption of insulating oil can alter the breakdown strength of the sample. For this, each sample is kept immersed in transformer oil for 24 hours period. The recorded weight of the sample changed from 17.2 grams to 17.6 grams after oil immersion (average). The negligible change in weight of the sample before and after oil immersion indicated that oil does not penetrate through the epoxy based syntactic foam samples and the dielectric strength will not be appreciably affected by the test procedure.

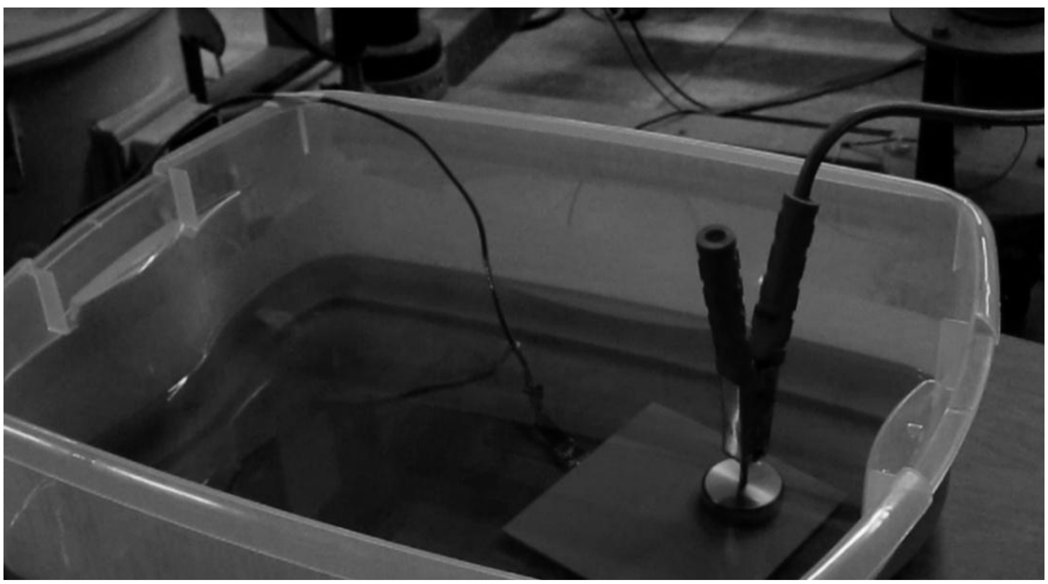


Figure 3.1 The Electrode Configuration for the AC Voltage Withstand Test

The test is performed according to the IEEE standard 4-1995. The test is performed at 60 Hz power frequency. The voltage applied to the sample is increased at an estimated rate of 0.8 kV/sec to permit accurate readings till the breakdown occurs. The breakdown strength is calculated by dividing the breakdown voltage with the thickness of the sample. Electrodes are designed according to the ATSM standards, with one cylindrical electrode with size 51 mm in diameter, 25 mm thick with edges rounded to 6.4 mm radius. The other electrode is plate shaped. Both the electrodes are made up of stainless steel.

The tests are conducted in High Voltage Laboratory on the fifth floor of ERC. The test voltage is applied with the help of an AC transformer with rating 120 V/100 kV, 5 kVA. The breakdown voltage is measured with the help of potential transformer by connecting a voltmeter on the secondary side of the voltage transformer. The measured voltage is multiplied with the accurate turns ratio to get the voltage on the primary side of the transformer. The calculated voltage on the primary side is then divided by the thickness of the sample to get the breakdown voltage of the syntactic foam sample. The test setup can be seen from Figure 3.2. The connection diagram can be seen from Figure 3.3.

Figure 3.2 The Test Setup for AC Voltage Withstand Test

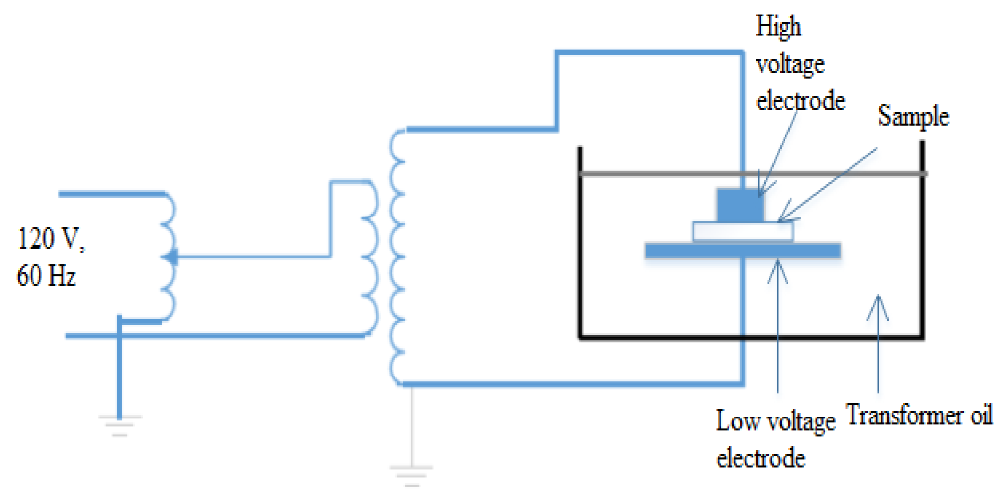


Figure 3.3 The Connection Diagram of the Dielectric Breakdown Test

The high voltage is applied to the upper cylindrical electrode. The lower plate-shaped electrode is grounded as seen from Figure 3.3. The test is performed by varying the electrode locations at six different positions for single test sample. The gap of 1-2 minutes is maintained in between two readings and oil is stirred after every experiment to make sure that the readings are not affected by the by products of oil degradation. The electrodes are cleaned after every six readings. The experiment is repeated for all the six samples of varying thicknesses.

3. 4 Results and Discussions

In order to calculate the electrical breakdown strengths of syntactic foam, experiments are performed in High Voltage Lab at Arizona State University. The AC voltage withstand tests are performed on readily manufactured epoxy based syntactic foam samples with 40% concentration of glass microspheres. The results of the breakdown test on the syntactic foam samples with thicknesses 3 mm, 3.5 mm and 4 mm are listed in Table 3.1, Table 3.2 and Table 3.3 respectively.

Table 3.1 Breakdown Voltage Stress for the Syntactic Foam Sample with Thickness 3 mm

Sample 1

Voltage on Secondary side of PT	Primary voltage	Breakdown Strength	Average breakdown strength	Standard deviation
78.6 V	47.16 kV	15.72 kV/mm	15.71 kV/mm	0.199
77.8 V	46.86 kV	15.62 kV/mm		
80.2 V	48.122 kV	16.04 kV/mm		
79.1 V	47.46 kV	15.82 kV/mm		
76.6 V	46.14 kV	15.38 kV/mm		
78.5 V	47.1 kV	15.7 kV/mm		

Sample 2

Voltage on Secondary side of PT	Primary voltage	Breakdown Strength	Average breakdown strength	Standard deviation
79.2 V	47.52 kV	15.84 kV/mm	15.29 kV/mm	0.3850
77.2 V	46.32 kV	15.44 kV/mm		
78.4 V	47.04 kV	15.68 kV/mm		
74.2 V	44.52 kV	14.84 kV/mm		
75.1 V	45.06 kV	15.02 kV/mm		
74.6 V	44.76 kV	14.92 kV/mm		

Table 3.2 Breakdown Voltage Stress for the Syntactic Foam Sample with Thickness 3.5 mm

Sample 1

Voltage on Secondary side of PT	Primary voltage	Breakdown Strength	Average breakdown strength	Standard deviation
83.6 V	50.16 kV	14.33 kV/mm	13.81 kV/mm	0.498
77.2 V	46.32 kV	13.23 kV/mm		
77.1 V	46.26 kV	13.21 kV/mm		
84.3 V	50.38 kV	14.45 kV/mm		
82.1 V	49.26 kV	14.07 kV/mm		
79.3 V	47.58 kV	13.59 kV/mm		

Sample 2

Voltage on Secondary side of PT	Primary voltage	Breakdown Strength	Average breakdown strength	Standard deviation
78.4 V	47.04 kV	13.44 kV/mm	13.25 kV/mm	0.140
77.6 V	46.56 kV	13.30 kV/mm		
76.2 V	45.72 kV	13.06 kV/mm		
77.5 V	46.5 kV	13.28 kV/mm		
78.1 V	46.86 kV	13.38 kV/mm		
76.4 V	45.84 kV	13.09 kV/mm		

Table 3.3 Breakdown Voltage Stress for the Syntactic Foam Sample with Thickness 4 mm

Sample 1

Voltage on Secondary side of PT	Primary voltage	Breakdown Strength	Average breakdown strength	Standard deviation
88.2 V	52.92 kV	13.23 kV/mm	13.00 kV/mm	0.205
87.4 V	52.44 kV	13.11 kV/mm		
85.2 V	51.12 kV	12.78 kV/mm		
86.6 V	51.96 kV	12.99 kV/mm		
88.1 V	52.86 kV	13.21 kV/mm		
84.6 V	50.76 kV	12.69 kV/mm		

Sample 2

Voltage on Secondary side of PT	Primary voltage	Breakdown Strength	Average breakdown strength	Standard deviation
90.6 V	54.36 kV	13.59 kV/mm	13.27 kV/mm	0.169
87.5 V	52.50 kV	13.12 kV/mm		
88.2 V	52.92 kV	13.23 kV/mm		
87.3 V	52.38 kV	13.09 kV/mm		
89.2 V	53.52 kV	13.38 kV/mm		
88.3 V	52.98 kV	13.24 kV/mm		

It can be observed from the results that the average breakdown strength of the syntactic foam samples is 15.5 ± 1.08 kV/mm for 3 mm samples, 13.53 ± 0.95

kV/mm for 3.5 mm samples and 13.14 ± 0.45 kV/mm for 4 mm samples. When these values are compared with the breakdown strength of air which is 3 kV/mm, the breakdown strengths are approximately 5.15, 4.51 and 4.38 times higher for 3 mm, 3.5 mm and 4 mm samples respectively. The slight variation of the dielectric strengths in case of samples with equal thicknesses is supported by the fact that the microspheres are randomly distributed in the foam samples. The samples used for the tests are derived from different batches of syntactic foam manufactured by the supplier. Thus, the weak points causing electrical breakdown can be varied in case of two samples with equal thicknesses.

Figure 3.4 shows the relationship between sample thickness and the breakdown strength of the syntactic foam. It can be observed that the dielectric strength of the foam samples reduces with the increase in thickness of the foam samples. The exponential nature of the curve specifies that the breakdown strength almost remains constant after the sample thickness greater than 4 mm.

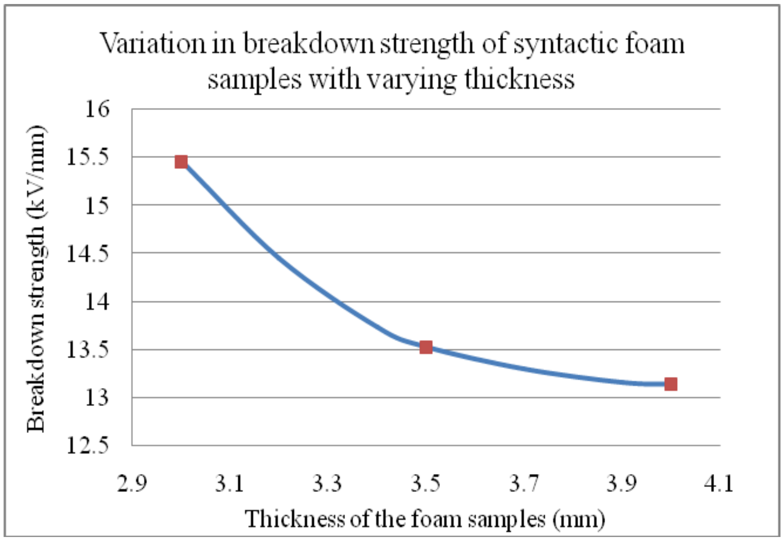


Figure 3.4 The Effect Varying Sample Thicknesses on Breakdown Strength of Syntactic Foam

Thus, it can be observed from the tests that the breakdown strength of the syntactic foam samples, for the given test conditions, remains constant at 13 kV/mm. Since the source voltage is limited to 100 kV in the High Voltage Laboratory, samples with higher thicknesses are not considered for the breakdown test. However, while completing the second step of the foam selection procedure for transmission lines, AC voltage withstand tests should be performed on the samples with higher thickness as a part of the practical studies for better understanding of the dielectric properties of the insulating foam.

CHAPTER 4.

ELECTRICAL PARAMETERS AND LINE CHARACTERISTICS OF A FOAM INSULATED TRANSMISSION LINE (FIL)

The first two steps of the selection procedure of insulating foam for the application of transmission lines, involving computer simulation model and practical testing of dielectric properties of the foam are explained in chapter 2 and 3 respectively. Another important aspect of the evaluation of suitability of any insulating foam in high voltage transmission lines is to analyze its effect on the transmission characteristics of the line. This study is demonstrated with syntactic foam as an example. The first part is carried out by calculating electrical parameters such as inductance, capacitance and resistance for the line. The line is then modeled with equivalent Π model for distributed parameters. The maximum power transfer capacity of this new line with syntactic foam as an insulator is calculated by plotting power-voltage curves for the simple two bus system with a single load, a single transmission line and a single generator, by keeping the voltage at the receiving end within acceptable limits.

4.1 Basic Constructional Details of Syntactic Foam Insulated Transmission Line

The assembly of the proposed Foam Insulated Transmission Line (FIL) is similar to that of the Gas Insulated Transmission Line (GIL). It consists of an Aluminum conductor enclosed within an Aluminum enclosure. The two cylinders are insulated from each other with the help of syntactic foam. The dimensions of the enclosure and conductor are selected such that the use of the dielectric material is optimal. In general, for coaxial systems, this optimization is achieved when the ratio of $\ln\left(\frac{r_3}{r_2}\right)$ is maintained at 1, where r_2 is the outer radius of the conductor and r_3 is the inner radius of the enclosure [35]. The enclosure of the transmission line is solidly grounded. The thickness of the enclosure and conductor can be customized based on the current carrying capacity requirement of the application. The general construction of the FIL is represented in Figure 4.1.

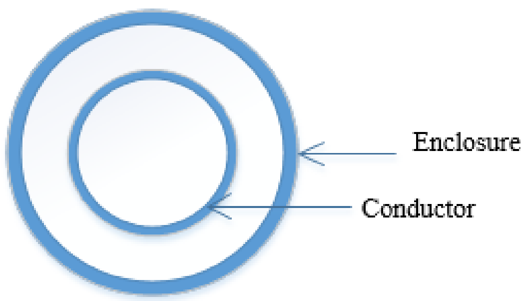


Figure 4.1 Basic Construction of FIL

For calculation of electrical parameters of the line, the voltage level of FIL is considered to be 400 kV. The dimensions of the enclosure and conductor are given in Table 4.1.

Table 4.1 Typical Dimensional Data of 400 kV FIL

Operating Voltage Level (kV)	400
Conductor Outer Diameter (mm)	180
Conductor thickness (mm)	10
Enclosure Inner Diameter (mm)	500
Enclosure thickness (mm)	10

4.2 Calculation of Electrical Parameters

It is necessary to calculate electrical parameters such as inductance, capacitance and resistance to study transmission characteristics of FIL. As the constructional features of FIL are similar to GIL, the formulation used for the calculation of electrical parameters for GIL is also applicable to Foam Insulated Transmission Line, with dimensions as mentioned in Table 4.1.

The inductance of the line is the addition of the self inductance of the conductor, the inductance of the enclosure and the inductance in between the conductor and the enclosure [31]. Considering r_1 as the inner radius of the conductor, r_2 as the outer radius of the conductor, r_3 as the inner radius of the enclosure and r_4 as the outer radius of the enclosure, the inductance of the conductor can be given by [31],

$$L_C = \frac{\mu_0}{2\Pi} \ln\left(\frac{r_2}{GMR}\right) \tag{5.1}$$

Where, μ_0 is the dielectric permeability of the air. The geometric mean radius (GMR) of the conductor is given by,

$$\ln(GMR) = \ln(r_2) - \frac{r_1^4}{\left(r_2^2 - r_1^2\right)^2} \ln\left(\frac{r_2}{r_1}\right) + \frac{\left(3r_1^2 - r_2^2\right)}{4\left(r_2^2 - r_1^2\right)}$$

The inductance of the insulated gap between the enclosure and the conductor is given by,

$$L_S = \frac{\mu_0}{2\Pi} \ln\left(\frac{r_3}{r_2}\right) \tag{5.2}$$

The inductance of the enclosure is given by,

$$L_e = \frac{\mu_0}{2\Pi}\frac{1}{\left(r_4^2 - r_3^2\right)}\left(\frac{r_4^4}{\left(r_4^2 - r_3^2\right)}\ln\left(\frac{r_4}{r_3}\right) - \frac{\left(3r_4^2 - r_3^2\right)}{4}\right) \tag{5.3}$$

The capacitance of the line is derived from the expression for coaxial cables similar to GIL [31].

$$C = \frac{2\Pi\varepsilon_0\varepsilon_r}{\ln\left(\frac{r_3}{r_2}\right)} \tag{5.4}$$

Where, ε_0 is the dielectric permittivity of the free space, ε_r is the relative permittivity of the dielectric medium. The relative permittivity of the epoxy resin based syntactic foam is 2.3 at 40% concentration of the hollow glass microspheres [32]. The resistance of the line is calculated using resistivity of the pure aluminum which is 2.68*10 $^{(-8)}$ Ω-m at 20^{0}C [33]. Total resistance is obtained by adding the resistance of the enclosure and conductor. The calculated resistance, inductance and capacitance are as shown in the Table 4.2.

Table 4.2 The Calculated Values of Inductance, Capacitance and Resistances

Voltage Level	Inductance (mH/km)	Capacitance (μF/km)	Resistance (mΩ/km)
400 kV	0.2113	0.125	6.7149

These values are less than that of overhead lines and underground XLPE cables as given in Table 4.2. The appreciable increase in the value of capacitance of the FIL is because of the presence of solid dielectric with higher ε_r instead of SF_6 with ε_r equal to unity.

4.3 Distributed Parameters Model of Transmission Line

In general for the transmission lines with length greater than 250 km, the parameters are not lumped together, but are considered distributed for the line model. Due to the high value of capacitance involved, transmission cables too, are represented by distributed parameters model for the length more than a few km.

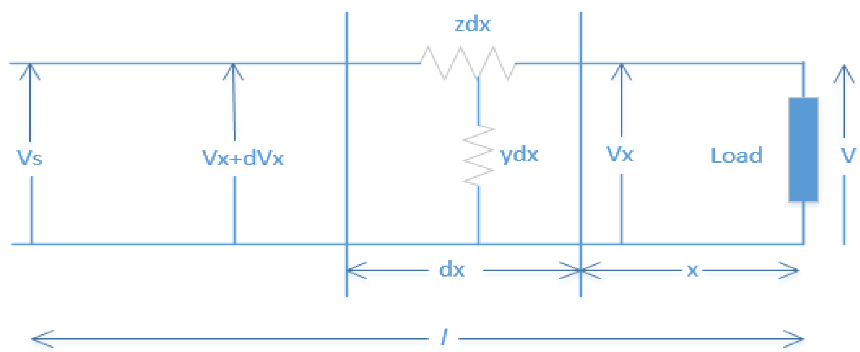


Figure 4.1 Schematic Diagram of Long Line

Figure 4.1 shows single phase and neutral return of the transmission line. It represents an elemental section of the line with length *dx* units, which is assumed to be at a distance *x* units from the receiving end of the line with series impedance $z{\cdot}dx$ and shunt admittance $y{\cdot}dx$. For the above model, the voltage V_x at can be represented by

$$V_x = C_1 e^{\gamma x} + C_2 e^{-\gamma x} \quad (5.5a)$$

$$I_x = \frac{C_1}{Z_C} e^{\gamma x} + \frac{C_2}{Z_C} e^{-\gamma x} \quad (5.5b)$$

Where $\gamma = \sqrt{(R + jX)(G + jB)} = \alpha + j\beta$ is the propagation constant,

$Z_C = \sqrt{\frac{(R + jX)}{(G + jB)}} = R_C + jX_C$ is the characteristic impedance of the line,

$C_1 = \frac{1}{2}(V + Z_C I)$,

$C_2 = \frac{1}{2}(V - Z_C I)$,

R, *X*, *G* and *B* are resistance, reactance, conductance and shunt susceptance of the line per unit length respectively,

V, *I* are the receiving end voltage and current [33].

Thus, V_x can be written as

$$V_x = \frac{1}{2}(V + Z_C I)e^{\gamma x} + \frac{1}{2}(V - Z_C I)e^{-\gamma x} \tag{5.6a}$$

$$I_x = \frac{1}{2}\left(\frac{V}{Z_C} + I\right)e^{\gamma x} - \frac{1}{2}\left(\frac{V}{Z_C} - I\right)e^{-\gamma x} \tag{5.6b}$$

Or

$$V_x = \frac{V}{2}\left(e^{\gamma x} + e^{-\gamma x}\right) + \frac{Z_C I}{2}\left(e^{\gamma x} - e^{-\gamma x}\right) \tag{5.7a}$$

$$I_x = \frac{V}{2Z_C}\left(e^{\gamma x} - e^{-\gamma x}\right) + \frac{I}{2}\left(e^{\gamma x} + e^{-\gamma x}\right) \tag{5.7b}$$

This can be represented as,

$$\begin{bmatrix} V_x \\ I_x \end{bmatrix} = \begin{bmatrix} \cosh \gamma x & Z_C \sinh \gamma x \\ \frac{1}{Z_C} \sinh \gamma x & \cosh \gamma x \end{bmatrix} \begin{bmatrix} V \\ I \end{bmatrix} \tag{5.8}$$

In vector form, where the bar at the top of the variable represents a phasor quantity and a variable without a bar represents the magnitude of the vector, the voltage at any point at a distance *x* units from the receiving end is given by,

$$\bar{V}_x = \bar{V} \cosh \bar{\gamma} x + \bar{Z}_C \bar{I} \sinh \bar{\gamma} x \tag{5.9}$$

4.4 AC Power Flow for the Two Bus System with a Distributed Parameter Model of Transmission Line

For a simple two bus model with an AC source feeding an AC load with real power P and reactive power Q through a series impedance of $R+jX$ as seen from the Figure 4.2 , the AC power flow has fairly direct analytical solution [34]. This is explained as follows. If V is the magnitude of the load voltage for the above mentioned case, the solution can be obtained by solving the quadratic equation,

$$V^4 + \left(2(RP+XQ)-V_S{}^2\right)V^2 + \left(R^2+X^2\right)\left(P^2+Q^2\right)=0 \qquad (5.10)$$

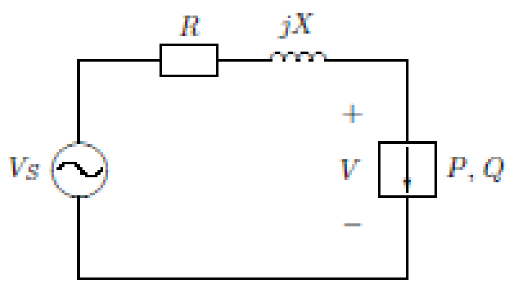


Figure 4.2 Power Transfer in Simple Two Bus AC System

The Equation (10) can be represented in terms of ρ as the ratio of $\frac{V}{V_S}$, which is the ratio of magnitude of receiving end voltage to the sending end voltage. After normalizing the above equation by $r=\frac{R}{V_S{}^2}$ and $x=\frac{X}{V_S{}^2}$, Equation (10) becomes,

$$\rho^4 + \left(2(rP+xQ)-1\right)\rho^2 + \left(r^2+x^2\right)\left(P^2+Q^2\right)=0 \qquad (5.11)$$

In general for the above equation, V_S and V are represented in kV, P is represented in MW, Q is represented in MVAr and r and x are represented in 'inverse MVA'.

Thus, the solution for the above quadratic equation is given by,

$$\rho^2 = \frac{1}{2}\left(1 - 2\lambda \pm \sqrt{1 - 4\left(\lambda + \mu^2\right)}\right) \tag{5.12}$$

Where $\lambda = rP + xQ$ and $\mu = xP - rQ$

This solution can be extended for the long transmission line analysis of length l units [36]. From Equation (9), in vector form, the voltage at the sending end can be written as

$$\bar{V}_S = \bar{V}\cosh\bar{\gamma}l + \bar{Z}_C\bar{I}\sinh\bar{\gamma}l \tag{5.13}$$

For simplicity, substituting $\bar{W} = \cosh\bar{\gamma}l$ and $\bar{Z} = \bar{Z}_C\sinh\bar{\gamma}l$ and then multiplying by $\bar{V}^*$ on both sides,

$$\bar{V}_S\bar{V}^* = \bar{W}V^2 + \bar{Z}\bar{I}\bar{V}^* = \bar{W}V^2 + \bar{Z}\bar{S}^* \tag{5.14}$$

Multiplying this equation by its conjugate,

$$V_S^2V^2 = \left(\bar{W}V^2 + \bar{Z}\bar{S}^*\right)\left(\bar{W}^*V^2 + \bar{Z}^*\bar{S}\right) = W^2V^4 + 2\operatorname{Re}\left(\bar{W}\bar{Z}^*\bar{S}\right)V^2 + Z^2S^2 \tag{5.15}$$

After normalization of Z by $z = \frac{Z}{V_S^2}$ and then dividing Eq. (15) by V_S^4 and representing ρ as the ratio of $\frac{V}{V_S}$ i.e. the ratio of magnitude of load voltage to the supply end voltage,

$$W^2\rho^4 + \left(2\operatorname{Re}\left(\bar{W}\bar{z}^*\bar{S}\right) - 1\right)\rho^2 + z^2S^2 = 0 \tag{5.16}$$

If the real and imaginary parts of $\left(\bar{W}\bar{z}^*\bar{S}\right)$ are separated as $\lambda - j\mu$, the solution of the quadratic equation is given by,

$$\rho^2 = \frac{1}{2W^2}\left(1 - 2\lambda + \sqrt{\left(1 - 2\lambda\right)^2 - 4W^2z^2S^2}\right)$$

$$= \frac{1}{2W^2}\left(1 - 2\lambda + \sqrt{1 - 4\lambda + 4\lambda^2 - 4\left(\lambda^2 + \mu^2\right)}\right)$$

$$= \frac{1}{2W^2}\left(1 - 2\lambda + \sqrt{1 - 4\left(\lambda + \mu^2\right)}\right) \tag{5.17}$$

Now,

$$W^2 = \sinh^2 \alpha l + \cos^2 \beta l = \frac{\cosh 2\alpha l + \cos 2\beta l}{2} \tag{5.18}$$

$$\overline{W}\overline{z}^* = \frac{\overline{Z}_C^{\ *}}{V_S^{\ 2}} \sinh \overline{\gamma}^* l \cosh \overline{\gamma} l$$

$$= \frac{1}{2V_S^{\ 2}}\left(R_C - jX_C\right)\left(\sinh 2\alpha l - j \sin 2\beta l\right)$$

$$= \frac{R_C \sinh 2\alpha l - X_C \sin 2\beta l}{2V_S^{\ 2}} - j\frac{R_C \sin 2\beta l + X_C \sinh 2\alpha l}{2V_S^{\ 2}} = r^* - jx^* \tag{5.19}$$

Multiplying by $\overline{S}$,

$$\lambda - j\mu = \overline{W}\overline{z}^* \overline{S} = \left(r^* - jx^*\right)\left(P + jQ\right) = r^* P + x^* Q - j\left(x^* P - r^* Q\right) \tag{5.20}$$

Thus, the solution for the quadratic equation can be obtained from

$$\rho^2 = \frac{1}{2a^*}\left(1 - 2\lambda \pm \sqrt{1 - 4\left(\lambda + \mu^2\right)}\right) \tag{5.21}$$

Where, $r* = \dfrac{R_C \sinh 2\alpha l - X_C \sin 2\beta l}{2V_S^{\ 2}}$

$$x^* = \frac{R_C \sin 2\beta l + X_C \sinh 2\alpha l}{2V_S^{\ 2}}$$

$$a^* = \frac{\cosh 2\alpha l + \cos 2\beta l}{2}$$

In case of a long transmission line, the additional term at the start $\dfrac{1}{2a^*}$, captures the Ferranti effect when the line is lightly loaded. For the short lines, the values for αl and βl are quite low giving similar results as that of the lumped parameter model.

4.5 The Power-Voltage Curve for the Transmission Line

The voltages at all the buses in the system should be maintained within prescribed limits under normal operating conditions for maintaining voltage stability in the system. To study voltage stability, the relationship between the transmitted power (P) and the voltage at the bus (V) should be observed during steady state analysis. For any PQ bus in the system, the PV curve gives the dependence of the bus voltage magnitude on the active power load when increased from zero to the maximum possible value. It is observed that the voltage at the load bus reduces when power transfer is increased. But after a critical point of power transfer, the voltage collapses. This maximum value of the power that can be transferred is known as 'maximum loadability' of the line. For practical purposes, only the power transfer till this maximum limit gives a stable operating point. PV curve helps in determining the voltage stability margin i.e. how far the operating point can be shifted before the voltage collapses. The standard voltage limit for stable operation is maintained at $\pm 5\%$ of the deviation from the operating value.

The system under consideration is the simple two bus system with one generator and one load bus which is connected with the help of the transmission line which uses syntactic foam as an insulator. The power-voltage curves for the system are plotted with the help of Equation (5.21).

1. No-load characteristics

The capacitance of the Foam Insulated Lines plays an important role in determining the no-load characteristics. When lightly loaded, the capacitance of the line might lead to over-voltage at the receiving end due to the Ferranti effect. The characteristics are plotted for 200 km and 300 km using distributed parameters for long line. The plot in Figure 4.3 clearly indicates 9% increase in voltage at the receiving end for the line of length 200 km. On the other hand, the voltage increases by about 20% if the line length is increased to 300 km. Therefore, additional compensation is needed if Foam Insulated Lines are used for lengths greater than 75 km.

2. Effect of varying line length with a constant power factor load

As the application of this syntactic foam insulated line is for transmission, the power-voltage characteristics for the load with constant power factor of 0.8 pf lagging can be observed in Figure 4.3. It is observed that the line loadability limit reduces with the increase in line length. At 5% dip in the operating voltage, the power that can be transferred through the line is 1323 MW for a 200 km long line and 1400 MW for the 300 km long line when just the voltage stability conditions are under consideration. This higher value of power transferred for longer line is the result of effective higher capacitance of the line.

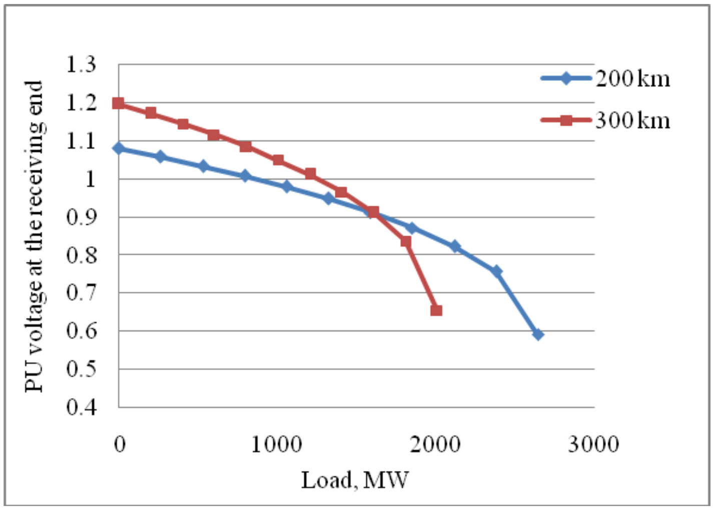


Figure 4.3 Power-Voltage Characteristics with a Constant Power Factor Load of 0.8, Lagging for 400 kV

3. Effect of loads with varying power factors at a constant line length

The power factor of the load connected at the receiving end of the line plays an important role in determining the maximum power transfer capacity. This is studied from the power-voltage curves by varying power factor of the load at receiving end bus from 0.8 lagging to 0.8 leading. The transferred power at the point where the voltage drops to 95% of its sending end value is determined from the graphs. It is observed that for the leading power factor loads the power transfer capacity is higher than that of the lagging power factor loads. But, this condition might lead to undesirable overvoltage in the lightly loaded conditions. Figure 4.4 and 4.5 shows the power voltage curves for a 200 km and 300 km long lines. For the voltage stability limit considered, the maximum load that the system will be able to take at unity power factor is 3760 MW and 3500 MW for 200 and 300 km lines resp. The transfer capacity reduces from this value to 35.18% for a 200 km line and 40% for a 300 km line when load power factor is varied from unity pf to 0.8 lagging.

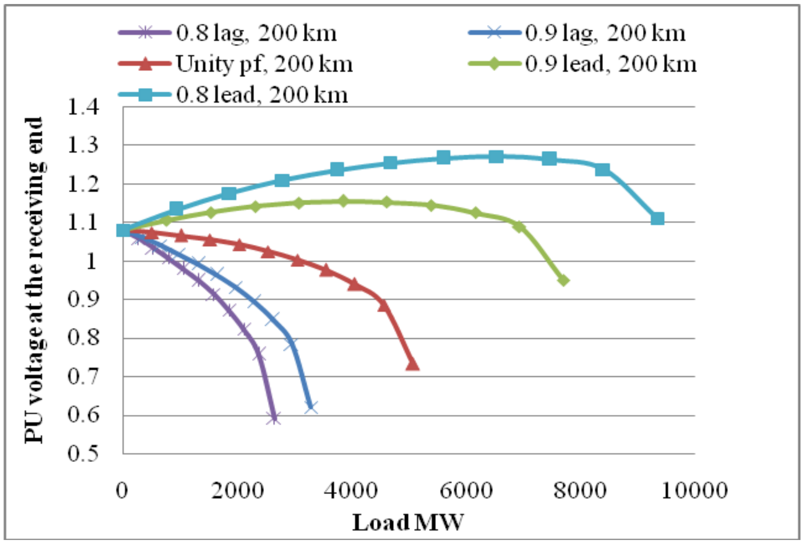


Figure 4.4 Power-Voltage Curve for Varying Power Factors for 400 kV, 200 km

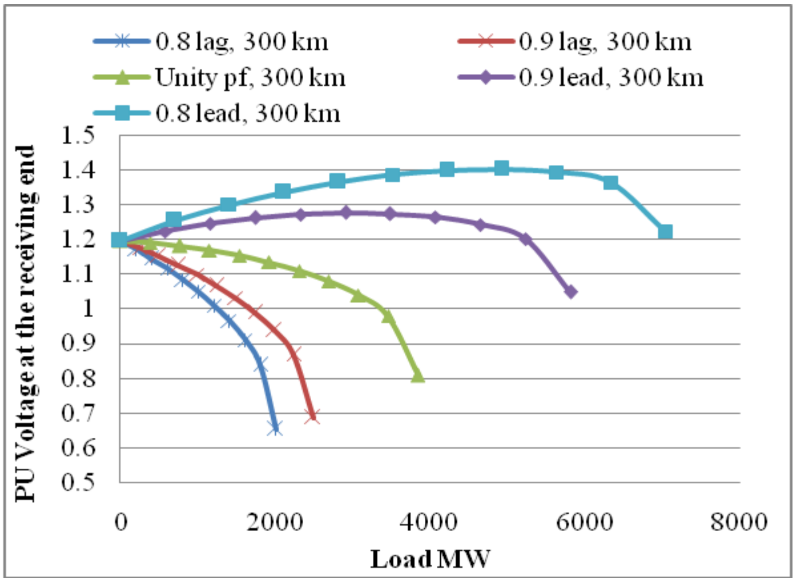


Figure 4.5 Power-Voltage Curve for Varying Power Factors for 400 kV, 300 km

Thus, due to comparatively higher value of capacitance involved, reactive power compensation is required under light load conditions when syntactic foam is used as an insulator for the transmission line. Under various load conditions too, the power transfer capacity of the line can be increased with the help of appropriate reactive power compensation by the voltage at the receiving end within $\pm 5\%$ of that of the sending end voltage. The maximum value allowable power transferred under different conditions can get reduced by the thermal limitations of the transmission system. Thus, in addition to the voltage stability condition, the thermal limitation should also be taken under consideration for calculation of allowable current carrying capacity of the line.

CHAPTER 5.

CONCLUSIONS AND FUTURE WORK

5.1 General Conclusions

Because of the possibility of gas leakages in the long length Gas Insulated Transmission Lines (GIL) and proven high global warming potential of SF_6 gas, there is a need for a replacement of the insulator in GIL. Insulating foam forms a good alternative option as a SF_6 replacement, given its relatively low dielectric constant as compared to the solid insulators as well as its reduced weight. Syntactic foam is a type of insulation foam with high weight to strength ratio and good insulation properties at high voltage.

The work presented in this thesis describes the first few steps of the selection process of insulation foam for the application in GIL. As the first step of the selection process, a methodology for the development of the computer based insulation foam model in *COMSOL Multiphysics* is explained to analyze electric field distribution through the foam for the application of transmission line. This is done by developing a model of syntactic foam and simultaneously evaluating suitability of syntactic foam as an insulator in GIL. The developed model also uses inputs from softwares like *AutoCAD* and *Microsoft Excel VBA*.

As the second step of the selection process, the procedure for the AC voltage withstand test for the samples of insulation foam is explained. These tests are performed on syntactic foam samples with varying thicknesses. The dielectric strength of the syntactic foam is calculated. After evaluation of dielectric properties, the steps to study the impact of the new insulation foam on electrical parameters of the transmission lines is described in the fourth chapter.

Some of the important conclusions from the studies are as follows:

- The basic model for a 400 kV GIL is developed in *COMSOL Multiphysics* and electric field distribution is calculated from the model. It is observed that the electric field distribution in GIL is coaxial and the maximum magnitude of electric field appears near the conductor. The value of this field is 4.39 kV/mm which is 1.46 times the breakdown strength of air. For further analysis of the insulation foam models, this value of field is taken as a base value.
- Due to intricate structure of the insulating foam, instead of building large models of the foam insulated transmission lines, smaller sections of the insulating foam are built in *COMSOL Multiphysics* software in between two Aluminum electrodes. The voltage applied to the high voltage electrode, V, for the simulation purpose is calculated by using formula,

  $$E = \frac{V}{d}$$

  Where, E is the base electric field and d is the distance between the electrodes.
- The syntactic foam mainly consists of hollow glass microspheres embedded inside the epoxy resin matrix. Due to complexity of the geometry and high costs involved in the required technical specifications of the computer systems, the foam is modeled with an approximation of modeling glass microsphere with a material with relative permittivity of 1.57. This value of relative permittivity is obtained by trial and error method. The maximum value of the

electric field inside the microspheres for the approximated model is observed to be 6.3 kV/mm. When this value is compared with the original model, the magnitude variation is found to be less than 5% of the original value. Thus, this approximation is considered valid for further analysis of the syntactic foam.

- With the approximation stated above, a cubical section of syntactic foam with side 1 mm is modeled with microspheres with radii ranging between 30-60 μm. It is observed that the electric field gets concentrated inside the microspheres and along the perpendicular direction to the applied field in the vicinity of the microspheres. For the base electric field of 4.39 kV/mm, the highest magnitude of the field observed is 6.37 kV/mm. This value is 42-45% higher than the base value for various models designed. This value is 2.12 times higher than the breakdown strength of air.
- The high pressure air inside the microspheres does not allow discharges inside the microspheres. Also, the breakdown strength of pure epoxy resin is 16 kV/mm, which is 5.33 times as that of air. The calculated maximum stress inside the epoxy matrix of syntactic foam is 5-5.5 kV/mm. Thus, under ideal circumstances, syntactic foam can be used as an insulator in GIL with the safety factor of 3.
- This method of modeling syntactic foam can also be used to model other types of insulating foams too. The other material components can be modeled by assigning different relative permittivity values in the *Materials* section of *COM-*

SOL. The input range of the sphere radii in *Exce*l program can be changed to vary microsphere size. Also, for all the insulating foams other than syntactic foam, the condition of separated microspheres can be removed from the *Excel* program.

- The on-site welding procedure of the enclosure and conductor assembly may lead to formation of metal particles of size 1.5-10 mm in length and in the shape of metal flakes. The effect of presence of metal particle on electric field distribution is observed by simulating a cylindrical metal particle with length 1.5 mm or 2 mm, and with radii 40-50 μm. The base electric field for the simulation is maintained at 4.39 kV/mm as explained earlier. The damage done by the metal particle highly depends on the orientation of the metal particle with respect to the electric field applied. When the metal particle is along the direction of the applied field, the field concentration near the flat edges of the cylinder shoots up to 18-19 times the field observed in the original model without metal particle. Since this field is almost 5 times higher than the breakdown strength of the epoxy resin, partial discharge activity will start. When the metal particle is aligned perpendicular to the applied field, the field concentration drops to 2-2.5 times the original field magnitude without the metal particle, thus not causing any discharges.
- Therefore, though very unlikely, the presence of metal particles in the syntactic foam can be hazardous for the long life of the insulator and thus, questioning the suitability of the syntactic foam as an insulator particular situation.

Thus, these metal particles should be removed from the assembly of Foam Insulated Transmission Lines. One of the solutions for this problem is welding the conductor before positional heating of syntactic foam matrix or welding of the enclosure. Thus, the removal of metal particles in the vicinity of the conductor is possible.

- The same method of analysis of metal particles can be used for other type of insulating foams too, by making appropriate changes in properties of material components and the shapes or sizes of the filler material.
- When syntactic foam samples with 40% concentration of glass microspheres are tested for AC breakdown strength according to the IEEE high voltage test standard 1995, it was found that the breakdown strength reduces with the increasing thickness of the test samples. The calculated dielectric strength of the syntactic foam is 13 kV/mm. The thickness of the foam samples is limited to 4 mm given the limitation of 100 kV test voltage. In actual practice, the test should be performed on the samples with higher thicknesses.
- The inductance, capacitance and resistance of the transmission line insulated with syntactic foam are calculated as a third part of the process. The capacitance of the line is appreciably increased to 125 nF/km. This brings down the critical length for reactive compensation to 75 km. For the simplified two bus system considered, the no load voltage increases by 9% for a 200 km line and by 20% for a 300 km line. The maximum power transfer capacity of the line is

1323 MW for 200 km line and 1400 MW for 300 km line when power factor at the receiving end is 0.8 lagging.

5.2 Future Work

The work done in the thesis explains a few steps related to the selection process of insulating foam as an insulator for Gas Insulated Transmission Line (GIL). All the steps in the process are explained considering syntactic foam as an insulator. The suitability of syntactic foam for its application in GIL is also evaluated. But, there are some more points that can be taken into consideration for improvements in the procedure already developed as well as for the extension of the selection procedure to study other aspects of transmission line insulated with insulating foam material.

- For the computer based syntactic foam model, all the glass microspheres were approximated by a uniform material with dielectric constant 1.57, in order to keep the required computer specifications low. With the higher technical specifications of the computer system, the study can be made more detailed and exact electric field distribution under all the considered conditions can be plotted and studied. Also, instead of developing a smaller cubical model of syntactic foam, a complete coaxial structure can be built in *COMSOL* similar to the original GIL model.
- The study of effect of impurities on electric field distribution in the syntactic foam can be extended from metal particles to air voids and dust particles. Al-

so, for metal particles, the length and diameter can be varied and its effect can be analyzed.

- Instead of using foam samples of thickness ranging between 3 mm to 4 mm, samples with higher thicknesses can be used to carry out AC voltage withstand test. Also, the study can be extended for various tests like partial discharge test and impulse voltage breakdown tests under varying temperature and humidity conditions.
- The current carrying capacity of the line can be estimated with the help of the development of the thermal model for the system. If the line current carrying limit is thermally limited, then the calculated power transfer capacity of the line can be modified accordingly.

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APPENDIX A

SPECIFICATIONS OF GIL, OVERHEAD LINE AND XLPE TRANSMISSION CABLE, ALL OPERATING AT 400 kV FOR COMPARISON OF THE ELECTRICAL PARAMETERS

Table 1.1 compares electrical parameters of the Gas Insulated Transmission Line, the overhead line and the transmission cable all operating at 400 kV with the rating of 2000 MVA. The details about the specifications of the overhead line and the transmission cable used for the comparison are given in the following section.

The values given for GIL correspond to a directly buried, single-phase GIL with conductor diameter 280 mm and enclosure inner diameter 630 mm. The enclosures are assumed to be solidly grounded. The depth of laying is 1050 mm and axial spacing between phases 1300 mm. The soil conditions are an ambient temperature of 15°C and a thermal resistivity of 1.2 KmW^{-1}. The continuous thermal rating is determined by the maximum soil temperature, which is limited to 60°C [5].

The overhead line characteristics correspond to a 420 kV French line with 3 x 570 mm^2 phase and two earth wires. The cable solution proposed for achieving the 3000 A rating, uses two cables per phase with conductor section of 2000 mm^2 inter axial distance of the two trefoils is 1800 mm. The soil conditions are an ambient temperature of 15°C soil thermal resistivity of 1.2 KmW-1 and a depth of laying to the top of the cables of 1050 mm. The rating was achieved using standard practice of IEC 60287 where the conductor temperature was 90°C and thermally stabilized backfill was used.

APPENDIX B

EXCEL VBA CODE USED FOR THE SYNTACTIC FOAM MODEL

Module 1

```
Sub Test1()

'5000 different numbers are generated in order to get 8
numbers which will be able to fit the criterion. These num-
bers are generated via random umber generator of Excel.
These numbers are stored in different columns. 1: x coordi-
nate 2: y coordinate 3: z coordinate 4: magnitude of the
vector

For k = 1 To 30000
    m = Int((3000 - 0 + 1) * Rnd + 0)
    n = Int((500 - 0 + 1) * Rnd + 0)
    l = Int((3000 - 0 + 1) * Rnd + 0)
    'o = Int((60 - 35 + 1) * Rnd + 35)
    Cells(k, 1) = m
    Cells(k, 2) = n
    Cells(k, 3) = l
    Cells(k, 4) = Sqr(Cells(k, 1) ^ 2 + Cells(k, 2) ^ 2 +
                  Cells(k, 3) ^ 2)
    Cells(k, 5) = 60
Next k
End Sub
'After calculating the coordinates for these numbers, they
are sorted manually using Excel commands for sheet 1 by in-
creasing order of the magnitudes of the vectors just to get
optimal outcome. These different set of ordered coordinates
is used for the further analysis.
```

Module 2

```
Sub Test1()
s = 1
For j = 1 To 20000
    If j = 1 Then
        Cells(s, 7) = Cells(j, 1)
        Cells(s, 8) = Cells(j, 2)
        Cells(s, 9) = Cells(j, 3)
        Cells(s, 10) = Cells(j, 5)
        s = s + 1
    Else
        t = 0
        For p = 1 To s - 1
            If  Sqr((Cells(p, 7) - Cells(j, 1)) ^ 2 +
                (Cells(p, 8) - Cells(j, 2)) ^ 2 + (Cells(p,
                9) - Cells(j, 3)) ^ 2) > (Cells(p, 10) +
                Cells(j, 5)) _
               And (Abs(Cells(j, 1) - 500) > Cells(j, 5)) _
               And (Abs(Cells(j, 1)) > Cells(j, 5)) _
```

```
                And (Abs(Cells(j, 2) - 500) > Cells(j, 5)) _
                And (Abs(Cells(j, 2)) > Cells(j, 5)) _
                And (Abs(Cells(j, 3) - 500) > Cells(j, 5)) _
                And (Abs(Cells(j, 3)) > Cells(j, 5)) Then
                t = t + 1
            End If
        Next p
        If t = s - 1 Then
            Cells(s, 7) = Cells(j, 1)
            Cells(s, 8) = Cells(j, 2)
            Cells(s, 9) = Cells(j, 3)
            Cells(s, 10) = Cells(j, 5)
            s = s + 1
        End If
    End If
Next j
End Sub
```

Module 3

```
Sub Test1()
For i = 1 To 48
    Cells(i, 12) = 4 / 3 * 3.14 * Cells(i, 10) ^ 3
Next i
For i = 1 To 48
    If i = 1 Then
        Cells(1, 13) = Cells(i, 12)
    Else
        Cells(1, 13) = Cells(1, 13) + Cells(i, 12)
        If Cells(1, 13) > 37500000 Then
            Cells(2, 13) = i
           Exit For
        End If
    End If
Next i
End Sub
```

APPENDIX C

EXCEL DATA ANALYSIS FOR ELECTRIC FIELD DISTRIBUTION

The various models of syntactic foam are developed in *COMSOL Multiphysics* as a part of analysis of the electric field distribution. The effect of having metal particles inside the foam model is further analyzed in Microsoft Excel, by collecting data points for the calculated field values along the vertical lines from upper electrode to the lower electrode and then plotting it in Excel for metal particles of radius 40 µm to 50 µm.

- When the metal particle is placed along the direction of applied
  - For the vertical line passing through the edge of the metal particle

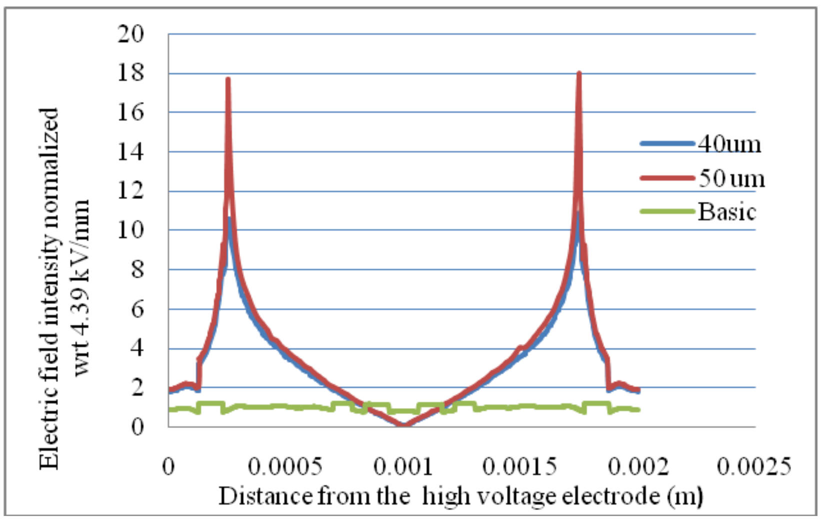

Figure C1. The Comparison of the Electric Field Distrbution Along a Straight Line In the *z* Direction With *x*= 900 µm and *y*= 950µm for the 2 mm Cubical Model Developed

  - For the vertical line passing at a distnace of 150 µm from the center of the metal particle.

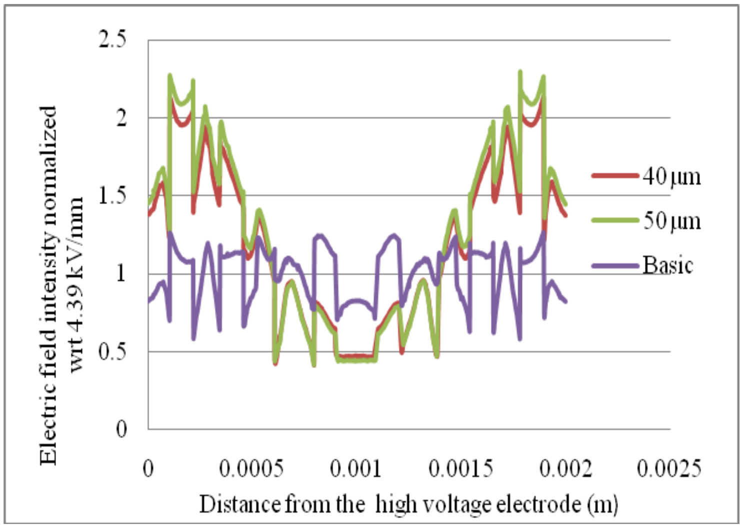

Figure C2. The Comparison of the Electric Field Distrbution Along a Straight Line In the *z* Direction With *x*= 1100 µm and *y*= 1100 µm for the 2 mm Cube

- When the metal particle is placed along the diagonal of the cubical section modeled
  - For the vertical line passing through the edge of the metal particle

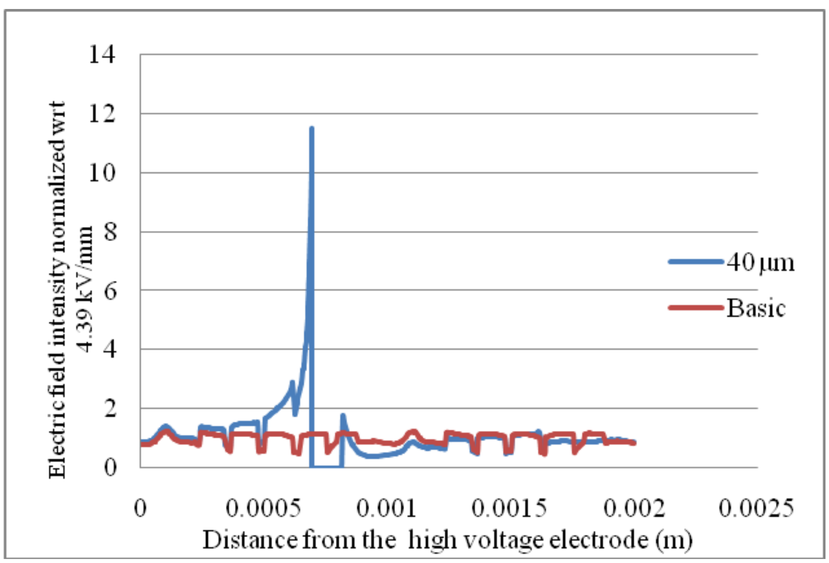

Figure C3. The Comparison of the Electric Field Distrbution Along a Straight Line in the *z* Direction With x= 750 µm and *y*= 750 µm for the 2 mm Cube

▪ For the vertical line passing thought the central part of the cylindrical particle

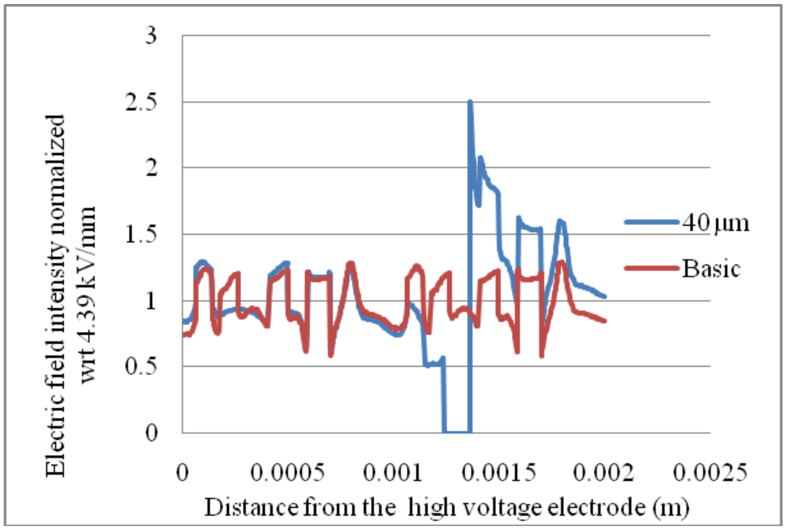

Figure C4. The Comparison of the Electric Field Distrbution Along a Straight Line in the *z* Direction With *x*= 1300 µm and *y*= 1300 µm for the 2 mm Cubical Model