ELECTRIC FIELD ANALYSIS IN STRESS CONTROLLED HIGH VOLTAGE CABLES

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ABSTRACT

ELECTRIC FIELD ANALYSIS IN STRESS CONTROLLED HIGH VOLTAGE CABLES

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The terminations and the joints are the basic accessories of the power cables. Power cables require electrical stress control when terminated.

Since there are different types of terminations, the analysis should be done to choose the proper method for electric field control problem at the terminations.

Throughout this study two different types of termination methods are investigated by using the finite element analysis program (ANSYS): Stress Controlled Termination Model with Deflector and Stress Control Tube (SCT). The results are compared with those obtained for a cable without stress control model termination.

The numerical calculations are also compared with the measurements obtained by an experimental model: the electrolytic tank model.

Keywords: the stress controlled cable termination, the deflector model, the stress control tube (SCT), the finite element method, the electrolytic tank experiment.

ÖZ

ELEKTRİK ALAN KONTROLLÜ YÜKSEK GERİLİM KABLOLARINDA ALAN DAĞILIMININ HESAPLANMASI

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Yüksek gerilim kablolarının uygulamada kullanılan en önemli aksesuarları kablo ekleri ve kablo başlıklarıdır. Bu kabloların bağlantı yerlerinde ve uçlarında elektrik alan kontrolü gerekmektedir.

Birçok kablo başlığı çeşidi olduğu için, uygun metodun seçilmesine yönelik olarak elektrik alan kontrol analizleri yapılmalıdır.

Bu çalışma boyunca, iki farklı kablo başlığı modeli sonlu elemanlar analiz programı (ANSYS) kullanılarak incelendi.: Deflektörlü Elektrik Alan Kontrolü ve Elektrik Alan Kontrol Tüpü. İlk olarak, elektrik alan kontrolsüz kablo sonu modeli incelenmiştir ve oluşan sorunlar tesbit edilmiştir. Oluşan elektrik alan sorunlarının üstesinden gelmek için, elektrik alan kontrollü başlık modelleri incelenmiştir.

Sonuçlar, değişik analizler birbiriyle kıyaslanarak tezin sonunda sunulmuştur.

Anahtar Kelimeler: elektrik alan kontrollü kablo bağlantısı, deflektör modeli, elektrik alan kontrol tüpü, sonlu elemanlar metodu, elektrolitik tank modeli

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INTRODUCTION

1.1 Introduction

Power cables are of great importance in power transmission and distribution systems. Terminations and joints are the basic accessories of the power cables. They are required to make connections between lines or to an electrical apparatus. The various aspects are considered while designing the cable terminations and joints because they must possess the same integrity as their associated cables while making the connection both all indoor and outdoor applications.

In cable installation, shielded power cables require electrical stress control when terminated. When the insulation shield is removed from a cable, high potential gradients are concentrated at the cutback point, causing high electrical stress. Electric field enhancement at these points can produce local discharges that could lead to either flashover along the insulation surface or dielectric breakdown causing cable failure. Cable terminations are designed to eliminate the stress concentration at the screen termination to avoid the break-down of the cable. In other words, the electrical field has to be controlled in a cable termination.

Stress distribution control is usually based on geometrical regulation with the stress relief cones, or special materials of high relative dielectric constant. The objective of this work is looking for the cable termination construction with such characteristics that would relieve the electrical stress in as short length as possible. [1]

There is no universal termination or joint. There is a variety of different types of termination and joints each with advantages and disadvantages. [2]

The optimization of cable terminations is achieved by investigating various constructions. [3]

The proper termination method should provide good electrical and mechanical integrity. To design a proper termination, an electric field distribution analysis should be done in the critical regions.

There are several methods for the solution of electrostatic field distribution analysis. These can be summarised as analytical, experimental, free-hand field mapping, analogue methods and numerical methods. [4]

The study in this work is made with numerical solution method and simulation procedure. Although there are several methods for the solution of the problem, it is important first to fully understand the reason of choosing the proper solution method.

- **Analytical:** Analytical methods give exact results by solving mathematical models of physical situations. Difficulties arise for practical problems particularly dealing with the boundary and initial conditions. In some cases, the problems become impossible to represent by analytical method unless it is linear with simple boundary condition.

- **Direct Experimental:** Electric field components in the vicinity of the cable termination can be measured directly. However, the accuracy of the measurement technique is not reliable since the measurement equipment affect the field.

- **Free-Hand Field Mapping:** This is a method of calculating the electric field distribution on the area between the boundaries by successive approximation. Then, equipotential lines are plotted. This method is not preferrable on systems having complicated geometry and mixed dielectrics since the approximations in the calculation approximation lead to inaccurate results.

- **Analogue Methods:** The principle of analogy between different physical problems depends on expressing them by the same mathematical equations. In the study of electric field distribution, the conduction of current between electrodes in an electrolytic tank can be used as an analogue and the equipotential lines are plotted accordingly [5]. Thus, the relative permittivity change of the cable termination model can be simulated by the electrolytic tank analogue model. The results are obtained with adequate accuracy for engineering problems.

- **Numerical Methods:** Most of the engineering problems are solved by using numerical methods. At present, numerical methods are the most powerful design tools with highly developed computer programs. There are two main classes of methods: Finite-difference and Finite-element methods. Numerical methods are particularly used to design electrical equipment.

Design calculations of electrical equipment were originally based on analytically derived formulas. However, as the need arises for materials with better physical limitations and for design optimizations, more sophisticated design tools are required. Numerical methods developed as the basis of design tools since they are capable of modelling accurately complex geometry, non-homogenous regions, different types of excitation and non-sinusoidal quantities that analytical techniques are incapable of. Finite Elements has become the most popular method for many years for the analyses of electromagnetic problems in all types of electrical apparatus. [6]

Originally, the finite element method was developed by some investigators approximating and modelling elastic continua using discrete equivalent elastic bars in the early 1900s. However, modern finite element method was first developed in 1940 by Courant publishing a paper. Courant used piecewise polynomial interpolation over triangular subregions to investigate torsion problems. The next significant step in the utilization of finite element methods was taken by Boeing in the 1950s by using triangular stress elements to model airplane wings. In 1960, Clough made the term "finite element" popular and during the 1960s, investigators began to apply the finite element method to other areas of engineering, such as heat transfer and seepage flow problems. Zienkiewicz and Cheung wrote the first book entirely devoted to the finite element method in 1967. [7]

In this thesis work, a commercially available software, Finite Element Analysis (FEA) Computer Program, ANSYS is used which performs the accurate and fast solution in order to design and optimise field control with user friendly programming.

ANSYS is a comprehensive general-purpose finite element computer program that contains over 100,000 lines of code. ANSYS is capable of performing static, dynamic, heat transfer, fluid flow, electromagnetic analyses. It is in use in many engineering fields, including aerospace, automotive, electronics, and nuclear. ANSYS, being a powerful and impressive engineering tool, has been a leading Finite Element Analysis (FEA) program for well over 20 years. [7]

The program has basic steps in creating and analyzing a model with finite element method. These steps are the preprocessing phase, the solution phase and the postprocessing phase. [8]

Creating a finite element model by defining geometry, mesh controls and meshing the object created form the preprocessing phase. Graphical User Interface (GUI) property of the program offers an extremely wide variety of modelling capabilities. The analysis region is sub-divided into large number of isoparametric regions, called finite elements. In the solution phase, the program applies boundary conditions, initial conditions, loads and solves each node equation to get nodal results. The results are the set of equations that defines the electric potential at nodes of each element. Then, an iterative procedure is followed to solve an associative set of real values along the nodes and the elements at each step. The postprocessing phase contains the commands to display the results by either data files or graphics.

All of the analysis in this work is performed with computer simulations by using the developed program, Ansys.

1.2 The History of Cable Termination Techniques

Power distribution system cable and its accessories manufactured in the 1970s and early 1980s had a life significantly shorter than originally expected. This experience leaded cable suppliers in USA to develop aging tests in order to help produce cable and its accessories with ultimate performance and reliability. The test results provided guidance for key decisions in new designs and processes for cable accessories with development of materials and manufacturing equipment. As a result of this study, protection of the power distribution system is improved. [9]

Traditional skills for terminating and jointing accessories of cables like sweating, plumbing, taping and use of hot poured bitumen compound have been used for many years. However, these traditional techniques are time consuming and require highly skilled personnel, reduced environmental effects. Cable failures and long-term reliability problems occur in the lack of availability of such an elite force with the necessary expertise.

Traditional skills are rapidly disappearing as modern accessories are evolving. Latest developments introduced new materials and application techniques. Modern accessories reduce installation time and furthermore product installation does not rely on the skill of the installer providing improvements on both installation and performance.

Quick and safe installation techniques have been developed depending on the type of the accessory (termination, joint) and the voltage range. [10]

Today, heat shrink systems, cold shrink systems, premoulded rubber accessories and tapes with specialized electrical properties are rapid and reliable methods used for power cable terminations. However, whichever method of terminating is chosen, the requirements of ANSI/IEEE Standard 48 must be met.

IEEE recommended practice for installation, termination and testing of insulated power cable is also used as a guide for installation of electrical cable systems in industrial and commercial applications. [11,12]

1.3 The Basic Structure of Power Cable

The basic structure of a power cable in cross section form is shown in Fig.1.1. In fact, cables are electrically complicated. The basic cable components are the conductor, the electrical insulation (dielectric) and the shielding. There are different types of conductors and insulations. The types of the components are chosen according to the applications specified. [13]

The fundamental concept is the choice of material and size in a power cable design.

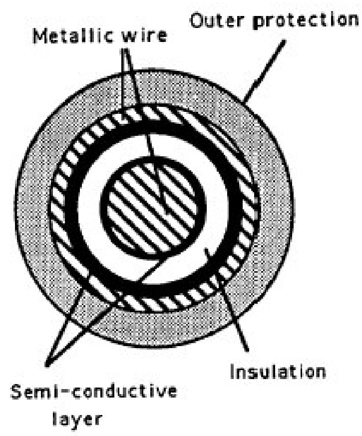

Figure 1.1 Cross Section of a Power Cable

Basically, this assembly is a capacitor with radial symmetry. The metallic core maintained at the high potential constitutes inner electrode surrounded by three polymeric layers. The outer electrode connected to earth-potential is protected by the outer layer from external environment. [14]

Copper and aluminium are the most commonly used metals as conductors. According to the application type of the cable, the conductor is selected. The International Electrotechnical Commission established a standard in 1913 called International Annealed Copper Standard (IACS). This standard specifies the conductivity percentage of copper as 100% where the conductivity of hard drawn aluminium is about 61%. Commonly used power cable conductor is hard drawn aluminium. For insulated conductors, soft copper is used and in overhead applications hard-drawn copper is used because of its higher breaking strength. [13]

The insulation types of cables are Polyethylene (PE), Crosslinked Polyethylene (XLPE), Tree Retardant XLPE (TR-XLPE), Ethylene Propylene

Rubber (EPR),, Polyvinyl Chloride (PVC) and Chlorosulfonated Polyethylene (CSPE). Their properties can be summarized as [2,13]

- **Polyethylene (PE)** is inexpensive produced long chain hydracarbon. It was used in high voltage cable in the past because of its suitable electrical properties. Today, PE is used in cables at 5 kV or less because of its susceptibility to treeing at high voltages.

- **Crosslinked Polyethylene (XLPE)** is operating good impact, abrasion, environmental stress crack resistance and good resistance to corona. The cables from 5 to 46 kV with impulse strength of 2700 V/mil use XLPE.

- **Tree Retardant XLPE (TR-XLPE)** is an improved insulation compound in recent years and is used for medium voltage applications.

- **Ethylene Propylene Rubber (EPR)** is commonly used in medium voltage applications yet can be used for low voltage cables. It has good elastic properties, low temperature resistance, environmental and ozone resistance.

- **Polyvinyl Chloride (PVC)** has good electrical properties and is resistant to flame, moisture and abrasion. However, it is not recommended for temperatures lower than -10ºC because it stiffens as temperatures decline. High dielectric constant and dissipation factor are also disadvantages of the compound. It’s the most common insulation for cables rated at 1000 volts or less.

- **Chlorosulfonated Polyethylene (CSPE)** has a trade name called “Hypalon”. It’s a rubbery polymer having tensile strength and abrasion, oil, chemical resistance that can be rated at 90ºC. Its properties differ depending on the quantity and type of materials comprised.

Shielding in the cable structure is required for making the dielectric field within the insulation symmetrical. Inside the cable, smooth and evenly spaced equipotential lines should be controlled with both conducting and semi-conducting layers. Conducting shield specifications are making the voltage on the side of the insulation the same while smoothing out the surface irregularities of the conductor. Insulation shield makes the voltage on the outside of the insulation ground. Characteristics of the insulation shield are defined in ICEA and AEIC. [13]

1.4 Cable Terminations and Joints

Power cables require termination and joint in the case of connecting the cable to another line or to equipment such as a busbar or a switchgear. Terminations of a power cable are classified as indoor and outdoor application type.

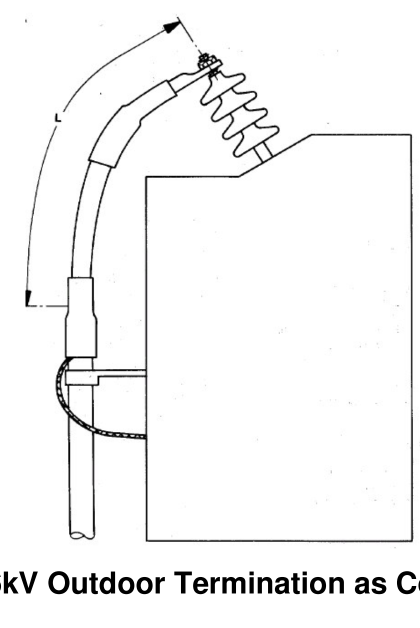

Figure 1.2 7.2 kV-36kV Outdoor Termination as Connection Equipment

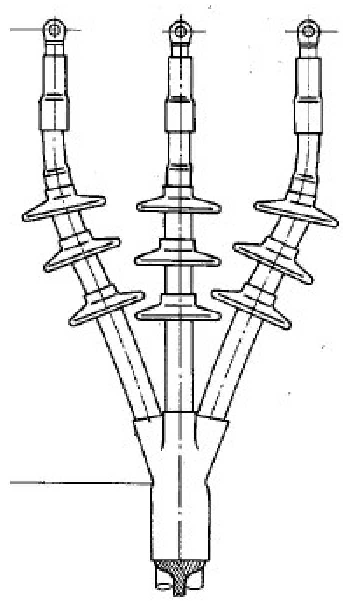

Figure 1.3 7.2 kV-36kV Outdoor Termination as Connection to Overhead Lines

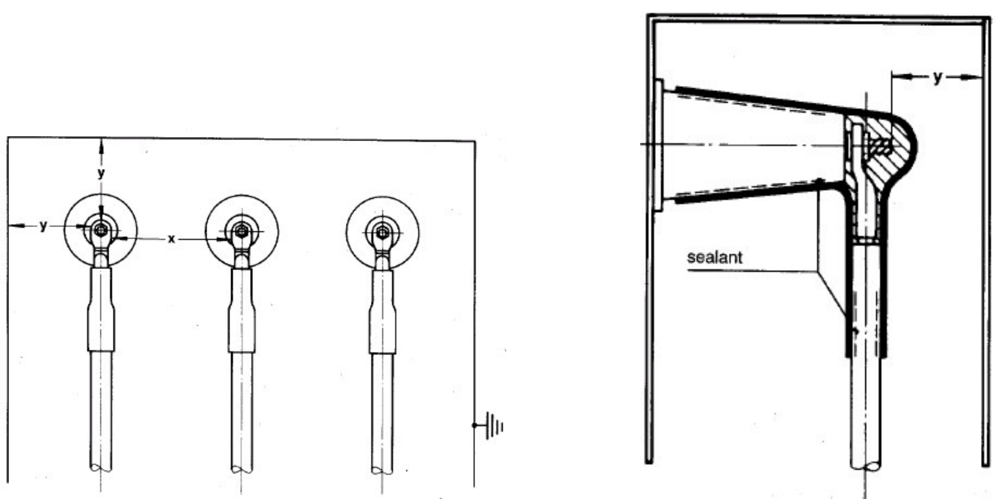

Figure 1.4 7.2 kV-36kV Indoor Termination as Connection to Equipment with Cable Boxes

Termination and joint should provide the performance of the cable integrated both electrically and mechanically. Therefore, installation should be done by choosing the right method and by using proper tools. The requirements are specified in IEEE Standard. 48.

1.5 Requirement of Stress Control on Cable Terminations and Joints

The cable preparation is required for all types of terminations and joints for the application to provide proper electrical and mechanical integrity.

The cable preparation consists of stripping back the metal shielding on the insulation layer at the end of the cable enough distance to make the connection properly. The typical prepared cable is shown in Figure 1.5. [15]

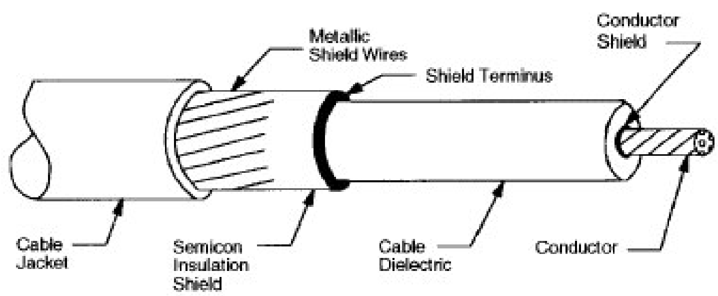

Figure 1.5 The Cable Prepared for Termination

The removal of the shield on the insulation layer changes the radially symmetric capacitor structure of the cable. When the insulation layer of the cable is terminated, there becomes a high stress point at the shield terminus. In addition, high potential gradients are present between the dielectric and the surrounding space. The cable termination without stress control is shown in Figure 1.6.

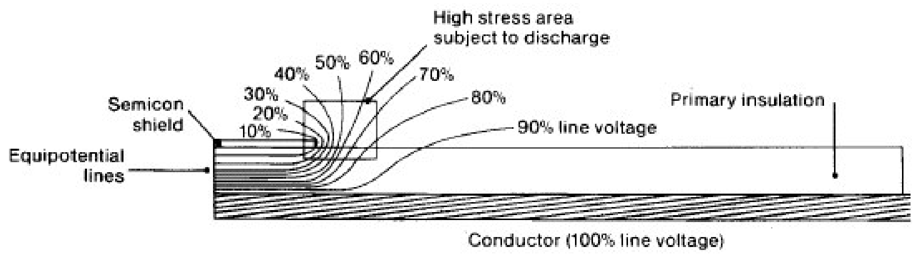

Figure 1.6 The Cable Termination without Stress Control

If stress control is not provided on the shield terminus, premature failure will occur at this point since the stress will be well above than the cable can tolerate. Besides, high stress in this area produces partial discharge and surface corona leading breakdown which shortens the cable lifetime.

The necessary measurements must be taken to reduce the electric stress at the screen termination for long life, high quality operating cables.

There are two kinds of methods for stress relief at the screen termination: the stress cones and the high permittivity materials. [16]

Stress relief methods reduce the high potential gradient by controlling the electrical field.

The traditional method for terminating and jointing stress control is using the stress cones. The stress cones use the geometrical solution by controlling the capacitance in the area of the screen terminus. The curved shape of the stress cones uniformly disperse the equipotential lines which results reduced potential gradient at the surface of the dielectric. The effect of a stress cone at the cable termination is shown in Figure 1.7.

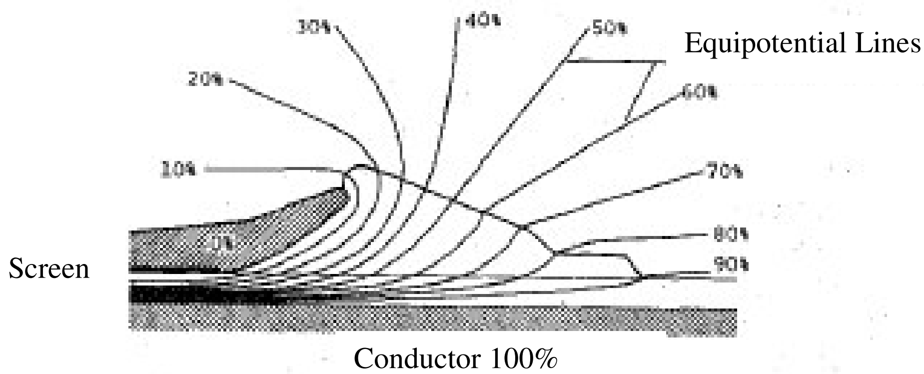

Figure 1.7 The Cable Termination with Stress Control Cone

The installation of stress cones and operation conditions are very important. Stress control does not work properly if the stress cone or its ideal curve is deformed.

The second method of stress control is choosing the material with correct electrical characteristics. Satisfactory stress relief is obtained by a high permittivity layer applied on the cable dielectric. The high permittivity material will refract the electrical field toward the cable end resulting reduced stress at the shield terminus. The effect of high permittivity layer at the cable termination is shown in Figure 1.8.

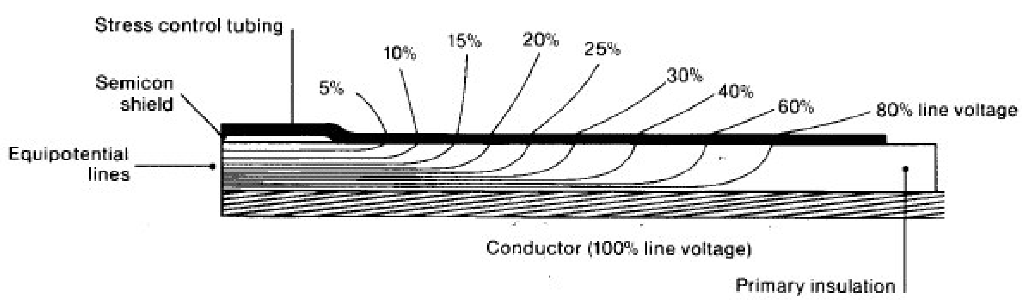

Figure 1.8 The Cable Termination with High Permittivity Stress Control

Stress control method using high permittivity material has some restrictions. The electrical field is refracted when passing from one dielectric to another. The relative permittivities of these materials define the angle of refraction thus, the magnitude of the refraction. As the permittivity increases, the electrical field is refracted far to the end of the layer concentrating at the stress relief tube end which results discharge. Generally this occurs with relative permittivity of the order of 1000 or more [17]

The new stress control method does not depend on the geometry. It is manufactured usually like tubes which is also advantageous for installation. However, the material choice must be done very carefully because inappropriate material can cause discharge. The relative permittivity of the material is the basis of the method. The goal of this study is investigating the performance of this method with different models in order to find the excellent stress control at terminations.

1.6 Contents of the Thesis

This study is divided into six chapters. The introduction and the information about the basic high voltage cable structure, cable terminations, cable joints and electric field controlling constitutes Chapter 1. Chapter 2 outlines the mathematical formulation of the problem and the finite element modelling. In Chapter 3, the simulation procedure of computer analysis is reviewed. The results and evaluation of the simulations are explained in Chapter 4. The effects of different electric field controlling methods are discussed where the result verification of our computer program is also represented. In Chapter 5, the electrolytic tank model is used as an experimental tool for the electric field distribution analysis. Finally, in Chapter 6, conclusion of the study and the future work are covered.

CHAPTER 2

FINITE ELEMENT MODEL OF THE CABLE TERMINATION

2.1 Introduction

In the termination of cables, stress control is achieved by the cable accessories. Cable accessories as terminations and joints must be designed properly for reliable and long term performance.

Analysing the potential and the field distribution in cable termination and joints are the cornerstone of the design process. Then, the material properties for the required performance are chosen according to the analysis results.

Finite element analysis techniques are used for electromagnetic analysis in most of modern engineering problems. With highly developed computers of today, the analysis results are obtained with high accuracy. Simulation of the model demonstrates the performance of the design. Hence, the proper design with long term performance is obtained by using the finite element analysis computer programs.

In this work, the finite element analysis software, Ansys is used in design process. The basic idea is to model the stress control mechanism at the cable termination and joint area.

The numerical model is needed for the analysis of the electric field in the accessories of the cables. The algorithm for the finite element analysis techniques starts with the Maxwell equations used in potential formulations. Then, the Laplace equations for the non-conducting regions and diffusion-like nonlinear equation for the stress control region are defined. Boundary conditions combine these equations. These differential equations are solved by an iterative method to obtain the field distribution of the model. [18]

2.2 Schematic Model of the Cable Termination

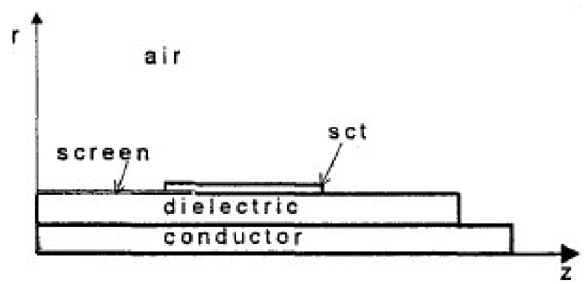

Figure 2.1 The Cable Termination Model with Stress Control Tube

The schematic model of the cable termination is shown in Figure 2.1. Due to the axial symmetry of the model, the electric field distribution analysis is done in only one quarter of the model.

There are five different regions in the model. These regions are: conductor (R_1), dielectric (R_2), screen (R_3), stress control tube (R_4) and air (R_0) constituting the boundaries.

The nonlinear partial differential equation of the numeric model is solved in two-dimensional domain considering the symmetry of the problem. During numerical modelling, the electric potential functions of the model are derived by using boundary conditions. Problems represented by boundary conditioned differential equations are called boundary-value problems. [19]

There are three classes of boundary-value problems. These are Dirichlet problems, Neumann problems and Mixed boundary-value problems.[20]

- **Dirichlet problems** have the potential specified along the boundary such as metallic electrodes.

- **Neumann problems** have the normal derivative of the potential specified along the boundary.

- **Mixed boundary-value problems** use the method of separation of variables. These problems have both the potential specified along some boundaries and the normal derivative of the potential along the rest of the boundaries such as a film covered boundary parts.

2.3 Electric Field Problems

Electric field intensity in a region that electric field exists is defined as;

$$\vec{\mathrm{E}} = \lim_{q \to 0} \frac{\vec{F}}{q} \qquad (\mathrm{V/m}) \qquad \text{(Eq. 2.1)}$$

where F is the force and q is the charge measured in newtons (N) and coulombs (C) respectively.

In an electrostatic field, electric field intensity is defined as;

$$\vec{\mathrm{E}} = -\nabla V \qquad \text{(Eq. 2.2)}$$

where V (Volt) is the electric potential.

The other fundamental field quantity is the electric displacement, D as;

$$\vec{D} = \varepsilon \, \vec{\mathrm{E}} \qquad (\mathrm{C/m^2}) \qquad \text{(Eq. 2.3)}$$

where ε is the permittivity measured in farads per meter (F/m).

The coefficient ε can be written as;

$$\varepsilon = \varepsilon_0 \, \varepsilon_r \qquad \text{(Eq. 2.4)}$$

where ε_0 (F/m) is the permittivity of free space and ε_r is the relative permittivity of the medium.

In addition, for any medium of electrostatics, the electric displacement is represented by;

$$\nabla \cdot \vec{D} = \rho \qquad \text{(Eq. 2.5)}$$

Main relation between the current and the charge densities is expressed by the equation of continuity. The equation of continuity is derived from the principle of conservation of charge.

$$\nabla \cdot \vec{J} = -\frac{\partial \rho}{\partial t} \qquad (\mathrm{A/m^3}) \qquad \text{(Eq. 2.6)}$$

where J is the current density measured in amperes per square (A/m^2), ρ is the charge density measure in coulombs per square (C/m^2) and t is the time.

Substituting (Eq. 2.5) in (Eq. 2.6) results in Ampere-Maxwell equation;

$$\nabla \cdot \vec{J} + \frac{\partial (\nabla \cdot \vec{D})}{\partial t} = 0 \qquad \text{(Eq. 2.7)}$$

Finally, the equation of current density and electric field relationship has great importance in electric field problems while deriving the potential equations;

$$\vec{J} = \sigma(E)\vec{E} \qquad \text{(Eq. 2.8)}$$

where σ (E) is a field dependent conductivity.

2.4 Derivation of the Electric Potential Equations

Substituting (Eq. 2.2), (Eq. 2.3) and (Eq. 2.4) in (eq. 2.7), the nonlinear diffusion-like equation of the electric potential is obtained; [21]

$$\nabla \cdot [-\sigma(E)\nabla V] = \frac{\partial}{\partial}[\nabla \cdot (\varepsilon_0 \varepsilon_2 \nabla V)] \qquad \text{(Eq. 2.9)}$$

where ε_2 is the relative permittivity for the cable insulation material.

By applying the backward Euler method the problem is discretized and (Eq. 2.9) becomes; [18]

$$\nabla \cdot \left[-\left(\sigma(E) + \frac{\varepsilon_0 \varepsilon_2}{\nabla t}\right)\nabla V(t)\right] = -\varepsilon_0 \varepsilon_2 \frac{\nabla^2 V(t+\Delta t)}{\Delta t} \qquad \text{(Eq. 2.10)}$$

where t is the time and Δt is a suitable small time interval.

For the nonconducting regions showing no free charge in the region;

$$\nabla \cdot \vec{D} = 0 \qquad \text{(Eq. 2.11)}$$

The Laplace's equation is satisfied if no free charge is available in the simple medium. Substituting (Eq. 2.3), (Eq.2.4) and (Eq. 2.2) in (Eq.2.11), the Laplace's equation is also satisfied by linear medium potential equation;

$$\nabla \cdot (-\varepsilon_0 \varepsilon_2 \nabla V) = 0 \qquad \text{(Eq. 2.12)}$$

2.5 Numerical Model

The potential equations of all regions are derived.by using the boundary conditions. When the Laplace's equations and diffusion equation are combined;

$$-\nabla \cdot [c(V)\nabla V] - f = 0 \qquad \text{(Eq. 2.13)}$$

$$c(V)=\begin{cases}\varepsilon_0 & \forall K\in R_0\\ \varepsilon_0\varepsilon_i & \forall K\in R_2\\ \sigma(\mathrm{E})+\dfrac{\varepsilon_0\varepsilon_{SCT}}{\Delta t} & \forall K\in R_4\end{cases}$$

$$f=\begin{cases}0 & \forall K\in R_0\\ 0 & \forall K\in R_2\\ -\varepsilon_0\varepsilon_4\dfrac{\nabla^2 V(t+\Delta t)}{\Delta t} & \forall K\in R_4\end{cases}$$

where, K is a regular point in the defined region.

The finite element analysis software needs to get suitable numerical formulation of the given nonlinear partial differential equation for the electric potential calculation. Hence, the original problem is replaced with its variational form of differential equation for the finite element model. The finite dimensional set is represented by a complete basis set and iterative solution is done to get accurate solution.

The variational form is found by constructing the mesh on the model. The solution method obtains nodal values of the variational form on each element. These potentials in vector form are then used in the system solution.

Finally, the system of equations results in the form of;

$$\mathrm{K\,U}=\mathrm{F} \qquad \text{(Eq. 2.14)}$$

where K is a N×N matrix, U is the nodal potential column vector, F is a N vector obtained by finite element method. The software achieves the potential results by using this system of equations. [22]

CHAPTER 3

SIMULATION PROCEDURE

3.1 Introduction

This study investigates and evaluates different types of cable termination models by the finite element analysis computer program, Ansys. The basic steps in simulation procedure steps are explained in this chapter.

The simulations with FEA computer program, Ansys, are demonstrated in three basic steps: preprocessing, solution procedure and postprocessing. [8]

The preprocessing step involves the model properties (geometrical, electrical) input and meshing. In the solution procedure, the boundary conditions are applied and the program solves the nodal potential values of the model. The graphical plotting and reading of the output is done in the postprocessor step to evaluate the results.

The program presents a wide variety of graphical tools to visualize the results. The contour plots are obtained as the output graphics of this study. [23]

The choice of the appropriate parameters is very important to verify the accuracy of the output in the analysis. Otherwise, incorrect results and even errors are obtained in the end of the analysis.

3.2 Simulation Procedure

In this study, the simulation procedure aims to get the electric potential distribution over the model. The simulations are done with the main cable termination models: the deflector and the stress control layer.

First geometrical model of the analyses is the stress control mechanism with deflector at the cable termination as seen in Figure 3.1.

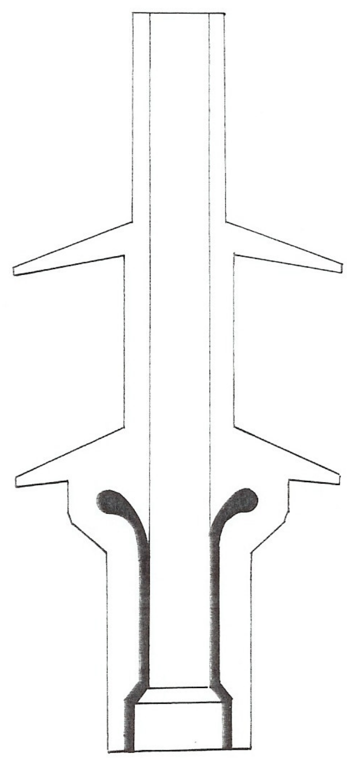

Figure 3.1 The Cable Termination with Deflector Model Geometry

The basic steps of the simulation procedure are done carefully to verify the confidence of the result accuracy

The deflector in the cable termination model has geometrical parameters as shown in Figure 3.2.

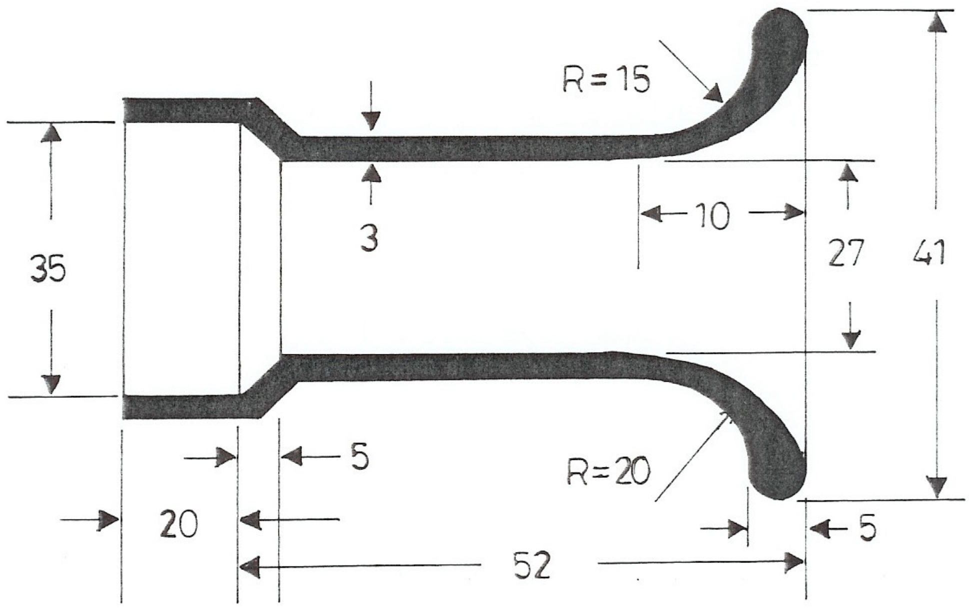

Figure 3.2 The Cable Termination Deflector Model

3.2.1 The Preprocessing

The finite element model of this geometry is created in the preprocessing step. Firstly, model geometry with different material properties is defined. Different materials are indicated in different colours.

The model geometry possesses axial symmetry. Due to the axi-symmetric geometry, only half of the model is used in the analysis where Y axis is the symmetry axis as shown in Figure 3.3.

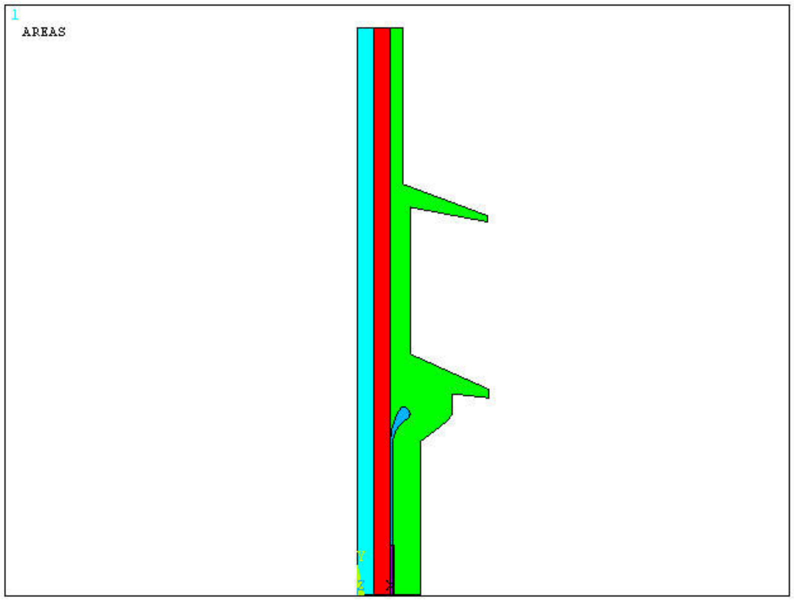

Figure 3.3 The Symmetric Cable Termination Model with Deflector

The next step is meshing. The finite element model is divided into nodes and small areas called elements. The meshing process is automatically generated after specifying the element size and attributes. In order to obtain better meshing, there is the option of mesh modifying. In order to get accurate results from the analysis, the critical areas are remeshed by using the mesh modify tool. Therefore, mesh density is increased without increasing the complexity of the whole model.

The two dimensional axi-symmetric expanded finite element model of cable termination is obtained in the end of the preprocess step as Figure 3.4.

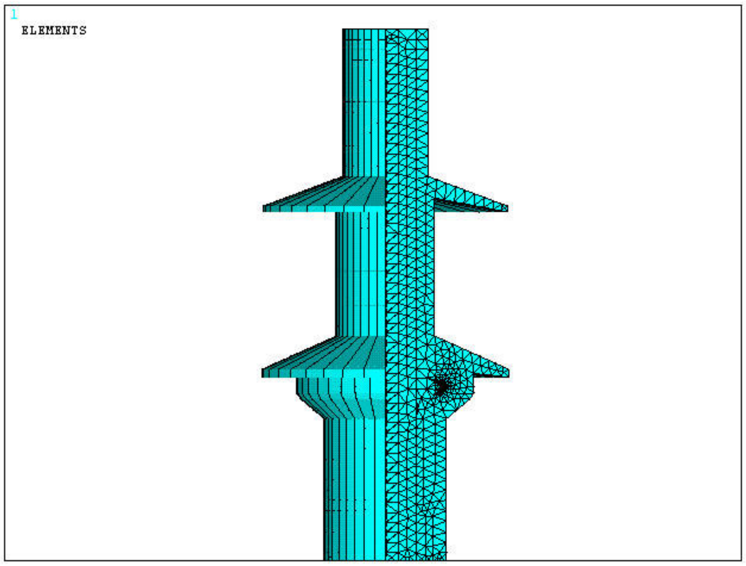

Figure 3.4 The Finite Element Model of Cable Termination

By using different plotting capabilities of the program, the symmetrical model can be observed in every angle of view.

The cable termination model plot is shown in Figure 3.5.

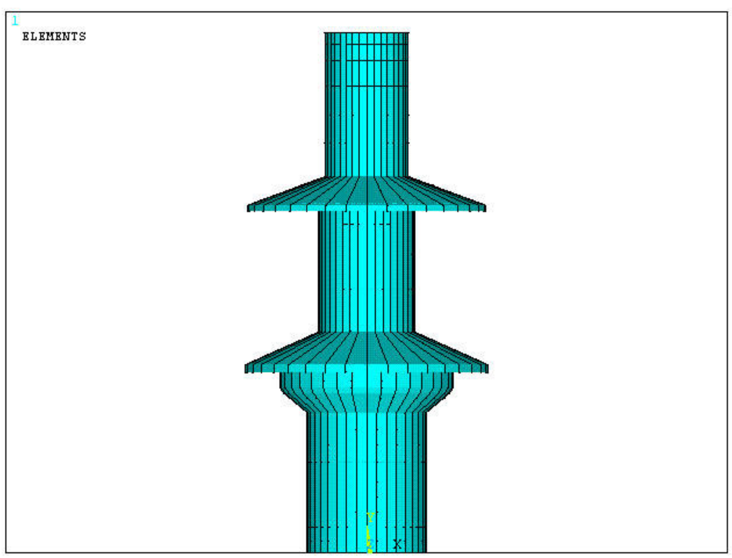

Figure 3.5 The Cable Termination Model

3.2.2 The Solution Process

In the solution process, the preprocessed model is used. Boundary conditions and loads are applied on the model in order to obtain the nodal solutions.

In this study, the results are the set of equations that defines the electric potential at nodes of each element. Then, the electric field distribution is obtained over the model.

This analysis boundary is selected with an outer air region going to infinity to simulate real time application as shown in Figure 3.6. The voltage applied to the cable is 10 kV and the semiconductor layer is grounded for all simulations.

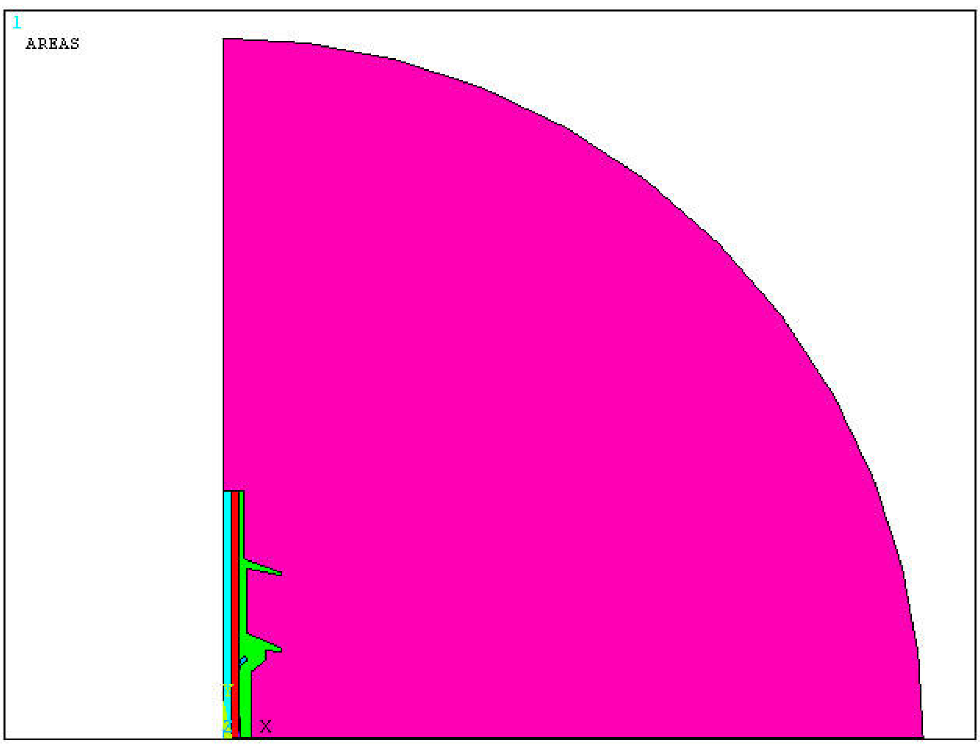

Figure 3.6 The Analysis Boundary of the Cable Termination Model

3.2.3 The Postprocessing

In order to see the graphical display of the analysis results on a plot and read the files of the result data, the postprocessor is used.

The graphic capabilities are important for the analysis of desired design construction. The user must be able to visualize the analysis results properly and understand the analysis. The program includes result contours, sectional view and two dimensional symmetric expansion view properties which are used for the output plots throughout this work.

3.3 Conclusion

During the preprocessor, solution and postprocessor steps, the parameters are chosen for the analysis as described in this chapter.

The FEA program Ansys is a powerful tool for field distribution analysis. The program provides various features for the analysis process and graphical plotting. In the end of the analysis, the result is obtained accurately in a less computing time comparing to the other design tools. [24]

The flow chart of the simulation procedure is given as in Figure 3.7.

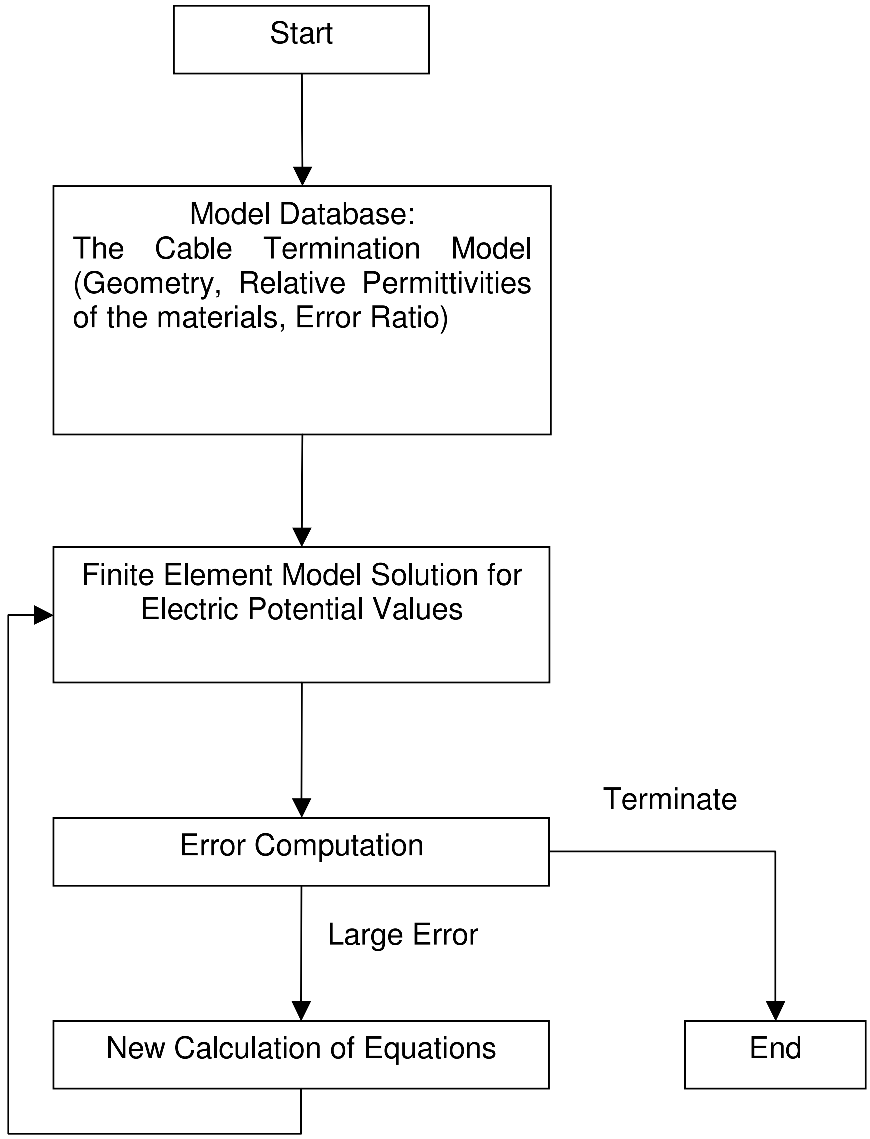

Figure 3.7 The Simulation Flow-Chart

The computation of the result depends on the input data, the types of elements, element shape and size after meshing and the boundary conditions.

However; it is essential that the user understand the basics of the finite element method and the underlying concepts of the analysis to verify the accuracy of the result whichever analysis is demonstrated by using the computer program.

CHAPTER 4

RESULTS AND EVALUATIONS

4.1 Introduction

Different cable termination models are investigated in this chapter. The simulation results demonstrate the electric potential distribution. The results are graphically plotted in order to visualize and understand the problem.

First simulation case in this chapter is the cable termination model without stress control layer. The electric field enhancement at the termination end is observed.

The main cable termination models to be analyzed are the stress control deflector and the stress control tube model. In addition, these models are compared with the numerical model as described in [1] verifying that the finite element analysis computer program (Ansys) results are precise.

Some of the simulation parameter values are fixed in all simulations as;

- The Conductor Potential, V = 10 kV
- The Screen Potential, V = 0 (Ground)
- The Relative Permittivity of the Dielectric (XLPE), ε_r = 2.3

- The Relative Permittivity of the Screen (Semiconductive Material), $\varepsilon_r = 1000$

- The Relative Permittivity of the Outer Protection Layer (Silicone Rubber), $\varepsilon_r = 4$

- The Relative Permittivity of Air, $\varepsilon_r = 1$

4.2 The Cable Termination Model without Stress Control

The first simulation case is the cable termination model without stress control. The electric potential distribution over the model is investigated to observe the requirement for the electric stress control at the cable termination.

The numerical analysis based on the finite element model is formed. The geometrical parameters for the model are taken from a 10 kV 95 mm^2 HV practical cable:

- The Cable Conductor Diameter, D = 13.66 mm

- The Cable Insulator Thickness (XLPE), y = 6.62 mm

- The Cable Screen Thickness, y = 0.7 mm

- The Cable Protection Layer Thickness, y = 10.4 mm – 4.93 mm

The finite element analysis computer program, Ansys used 109797 nodes, 48349 elements, 31 lines, 32 keypoints and 5 areas in this simulation. The data file consisting of the elements needs 28.5 MB, the assembled matrix file for the solution needs 13.625 MB and the result file of the simulation needs 36.125 MB space of the computer.

The result of the numerical simulation is expressed in potential line distribution of the cable termination model as shown in Figure 4.1.

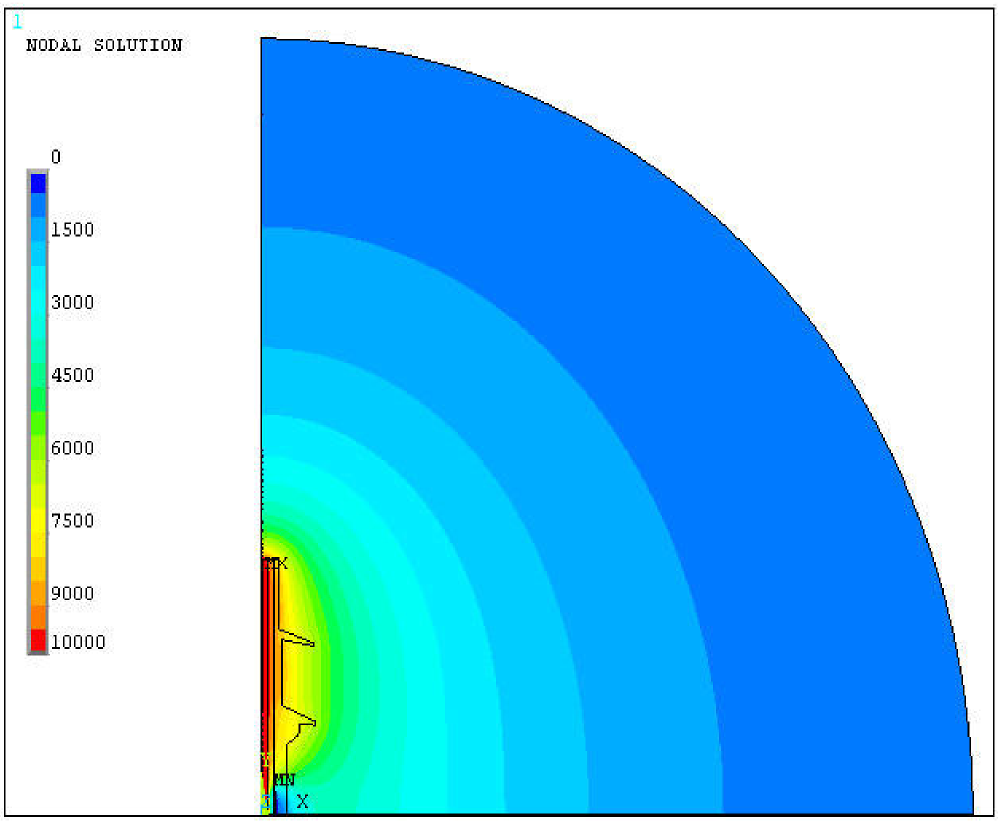

Figure 4.1 The Equipotential Line Distribution of the Cable Termination Model without Stress Control

The equipotential lines are shown in legends with different colours. The legend colour map on the left of the figure expresses the potential values. The red area having 10 kV potential is the cable conductor area. The potential decreases as the air surrounding the model goes to infinity.indicated in blue colour.

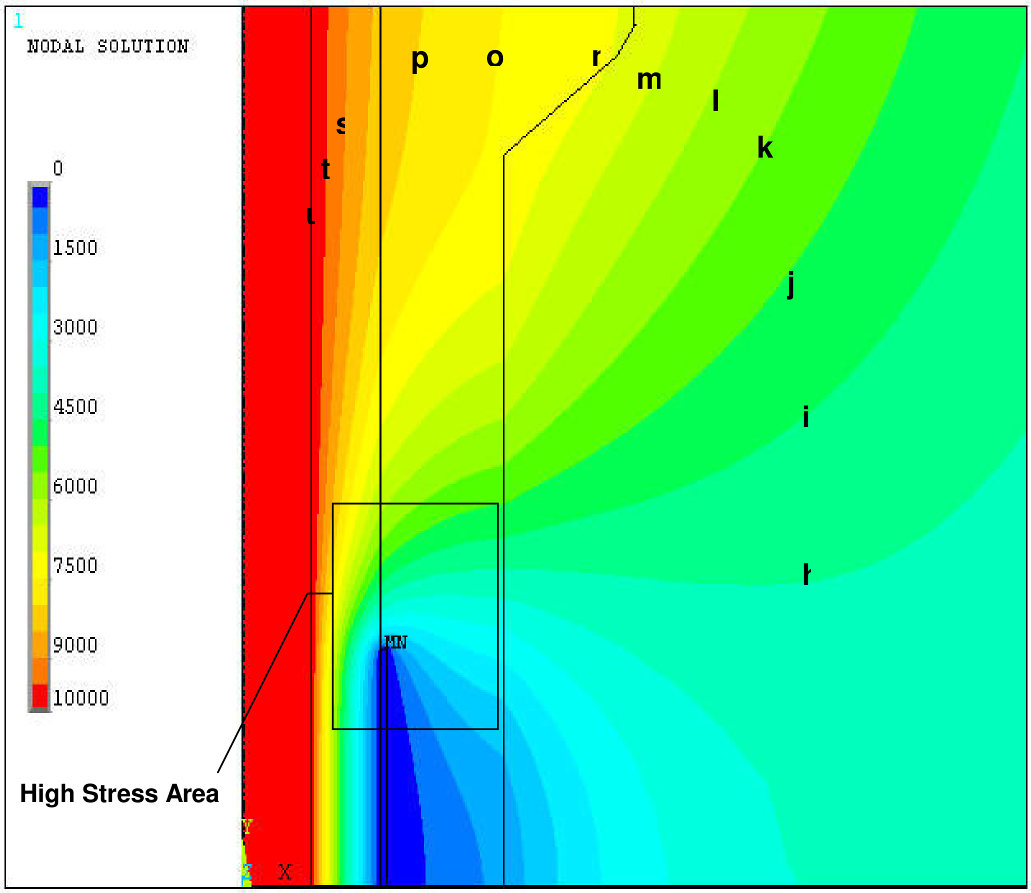

Figure 4.2. The Potential Map of the Cable Termination Model without Stress Control. The legends in kV: a- 0.5, b- 1, c- 1.5, d- 2, e- 2.5, f- 3, g- 3.5, h- 4, i- 4.5, j- 5, k- 5, l- 6, m- 6.5, n- 7, o- 7.5, p- 8, r- 8.5, s- 9, t- 9.5, u- 10.

The potential map of the cable termination model is shown with legends in different colours. The small letters indicate each equipotential line as a result of the simulation process.

When the cable termination model without stress control is numerically simulated, high field concentration is observed at the cable screen terminus area. The field intensity should be reduced to relieve high electric stress at this cutback area. Therefore, the application of electric stress grading material is necessary to achieve satisfactory field control.

The critical points composing the paths are shown on the model as in Figure 4.3.

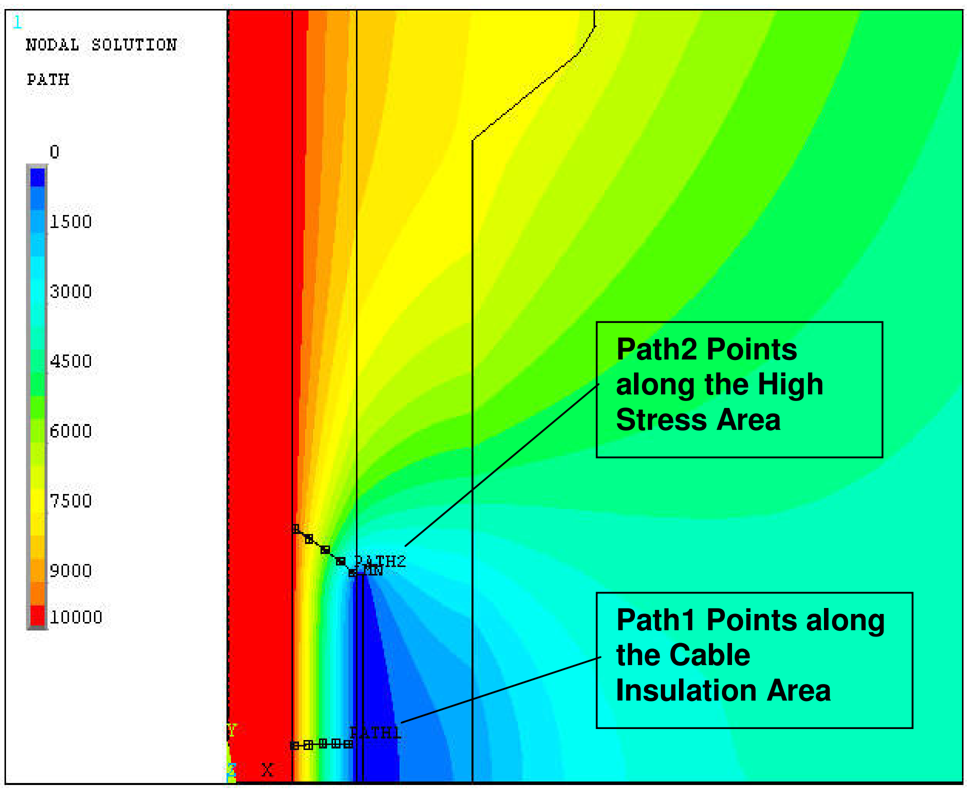

Figure 4.3. The Paths with Critical Points on The Cable Termination Model without Stress Control

Path1 is defined along the cable insulation layer area. The critical points consisting Path1 are chosen between the two boundaries; the cable conductor and the cable insulation screen.

Path2 is defined along the high stress area of the cable insulation screen termination area. Path2 consists of points with the electric field intensity values in the critical screen termination area as in Table 4.1.

Table 4.1. The Path Points defined on the Cable Termination Model without Stress Control

PATH1 (Points in the cable insulation area)		PATH2 (Points in the cable termination area)	
Distance along electric field (mm)	Electric Field Intensity (kV/mm)	Distance along electric field (mm)	Electric Field Intensity (kV/mm)
6.98	2.10	7.08	1.37
8.50	1.73	8.56	1.12
9.96	1.48	10.19	1.10
11.33	1.29	11.81	1.18
12.68	1.16	13.17	4.32

Then, the electric field distribution results are used to observe the effect along the critical paths graphically using MATLAB as shown in Figure 4.4.

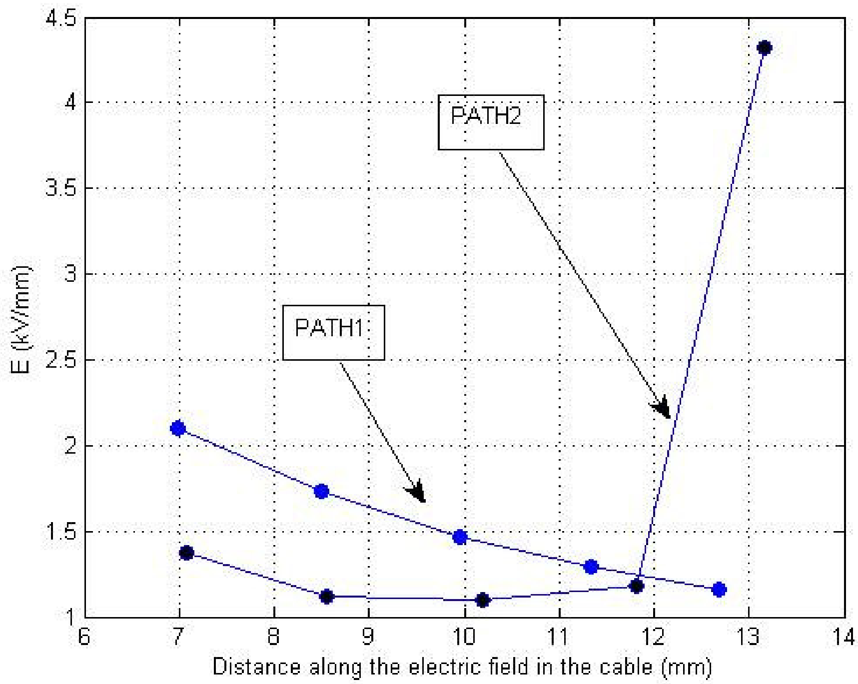

Figure 4.4. Path1 and Path2 Electric Field Intensity Distribution on the Cable Termination Model without Stress Control

Path1 points indicate the normally radial electric field distribution in the cylindrical geometry of the cable. The electric field has the highest value starting from the conductor area and is uniformly decreasing along the cable dielectric. The decrease continues until reaching the cable semiconductive insulation shield where the cable termination is applied.

When there is no stress control in the cable termination, a sharp electric field increase is observed near the semiconductor edge as in Path2. The electric field intensity of the last critical point is observed to be approximately four times greater than the actual value it should be. Thus, the critical path in the area near the interrupted end of the shield indicates the non-uniform field distribution and hence the need for the stress control at this area.

Therefore the termination procedure should be applied around the cable insulation shield where the high electric field is observed. Hence, maximum field intensity in this area is reduced to avoid discharges and following breakdown of the cable dielectric or a flashover along the insulation surface.

4.3 The Cable Termination Model with Deflector

The stress controlled cable termination with the deflector application is the first typical model to be analysed. The numerical model of the deflector is examined with the finite element analysis computer program, Ansys. The software used 36017 nodes, 16995 elements, 45 line, 37 keypoints and 6 areas in this simulation. The computer needed 9.938 MB for the data file consisting of the elements, 4.250 MB for the assembled matrix file in the solution process and 12.562 MB for the result file of the simulation process.

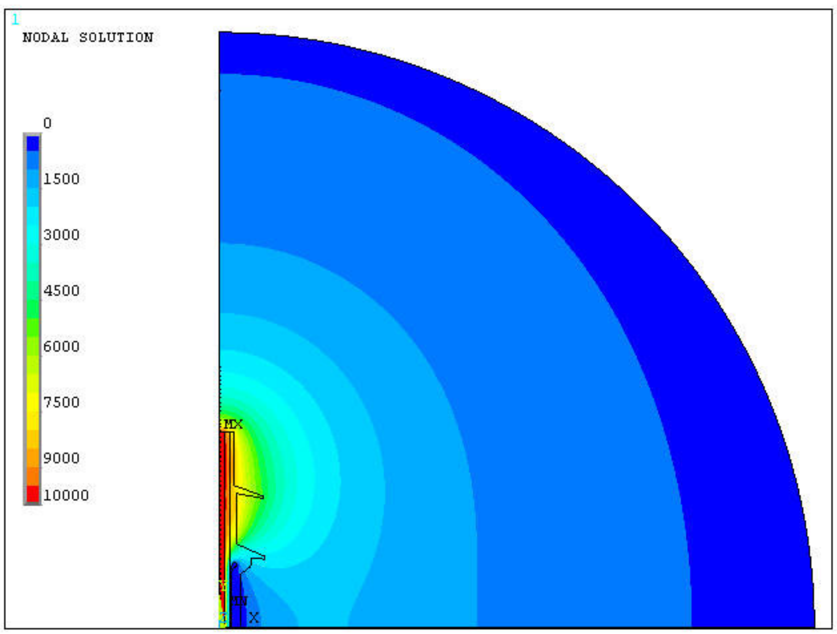

Figure 4.5. The Equipotential Line Distribution of the Stress Controlled Cable Termination Model with Deflector

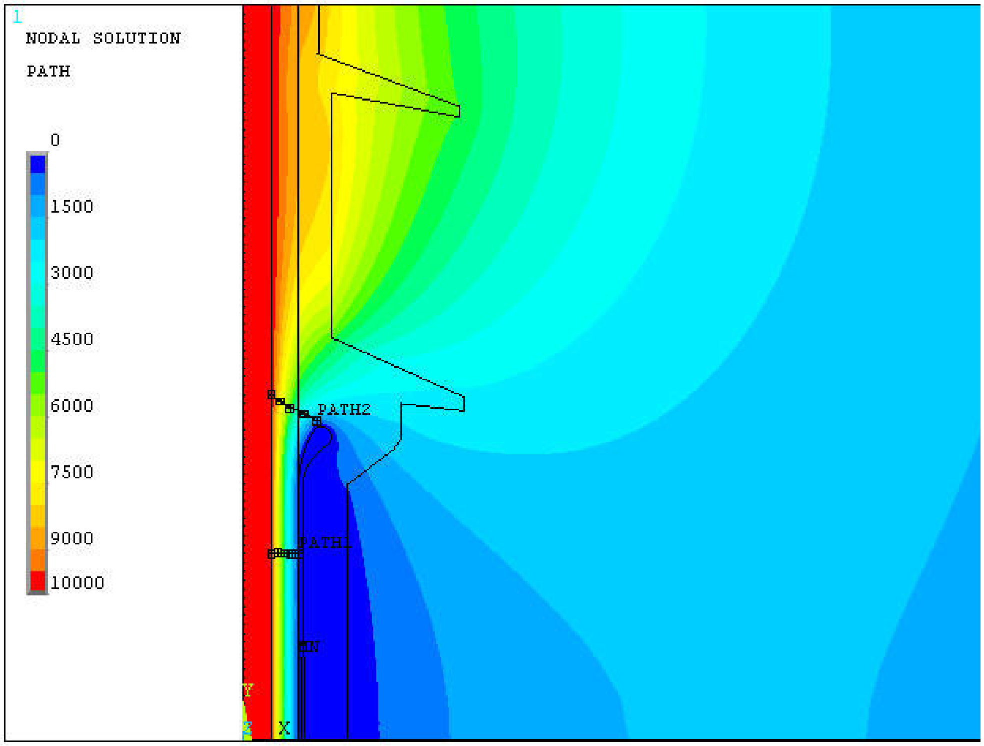

Figure 4.6. The Paths with Critical Points on the Stress Controlled Cable Termination Model with Deflector

After the application of the deflector on the cable shield termination, the electric field distribution is observed. The equipotential lines are uniformly dispersed with the curved deflector shape as observed in Figure 4.6.

The effect of the deflector model is illustrated graphically by choosing the critical points forming Path1 and Path2. The simulation analysis results of the path points are shown in Table 4.2.

Table 4.2. The Path Points defined on the Stress Controlled Cable Termination Model with Deflector

PATH1 (Points in the cable insulation area)		PATH2 (Points in the cable termination area)	
Distance along electric field(mm)	Electric Field Intensity (kV/mm)	Distance along electric field(mm)	Electric Field Intensity (kV/mm)
6.83	2.13	6.83	1.11
8.43	1.73	11.29	0.71
10.04	1.45	14.99	0.37
11.76	1.24	17.70	0.36
13.50	1.11	20.75	0.35

The electric field intensity values of the path points are visualized for better evaluation and understanding by using MATLAB as shown in Figure 4.7.

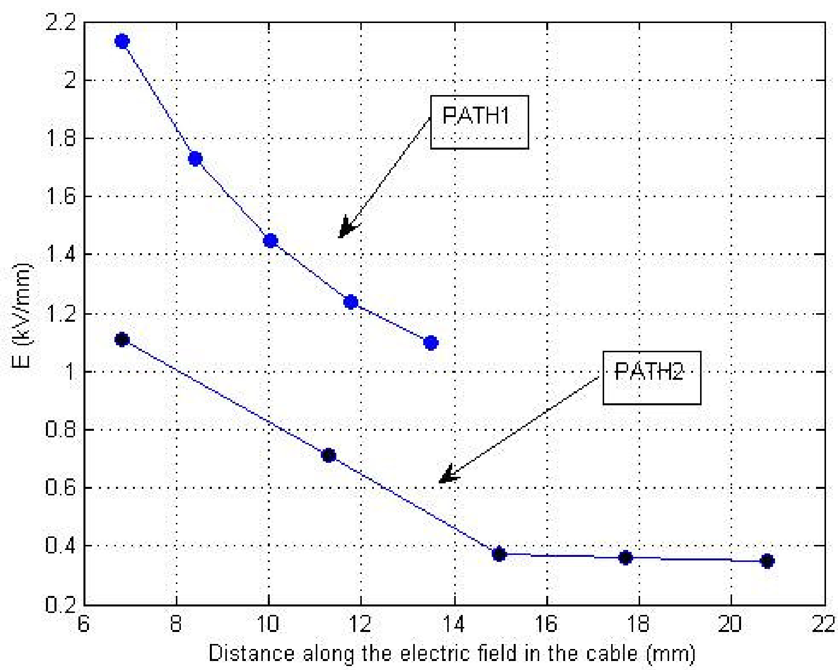

Figure 4.7. Path1 and Path2 Electric Field Intensity Distribution on the Stress Controlled Cable Termination Model with Deflector

The first method of stress control analysed is effective on electric field control as observed from the Figure 4.5. Path2 point field intensities decrease along the electric field at the deflector area. Even at the curvature area, the decrease is many times better than the condition of no stress control at the cable termination.

However, the effectiveness of the deflector technique depends on the perfect geometry of the deflector as well as the quality of the dielectric materials used and the application techniques. The ideal curve is needed for satisfactory results.

4.4 The Cable Termination Model with Stress Control Tube (SCT)

The second stress control method of the cable termination is an additional dielectric layer with high relative permittivity. It is called the stress control tube (SCT) which is applied on the cable insulation screen.

The cable termination model with the stress control tube (SCT) is analysed to observe and evaluate its effect on the electric field distribution. The finite element analysis computer program, Ansys used 120017 nodes, 51737 elements, 38 line, 37 keypoints and 6 areas in this simulation. The data file consisting of the elements needs 30.625 MB, the assembled matrix file for the solution needs 15.062 MB and the result file of the simulation needs 38.812 MB space of the computer throughout the work.

Figure 4.8. shows the equipotential line distribution of the model surrounded with air going to the infinity. The potential map on the left side indicates the electric potential values with different colours.

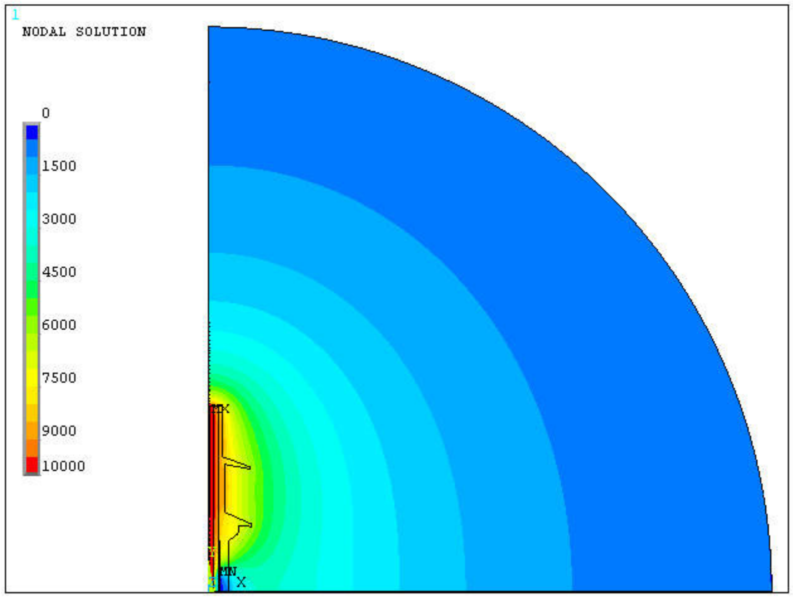

Figure 4.8. The Equipotential Line Distribution of the Cable Termination Model with Stress Control Tube (SCT)

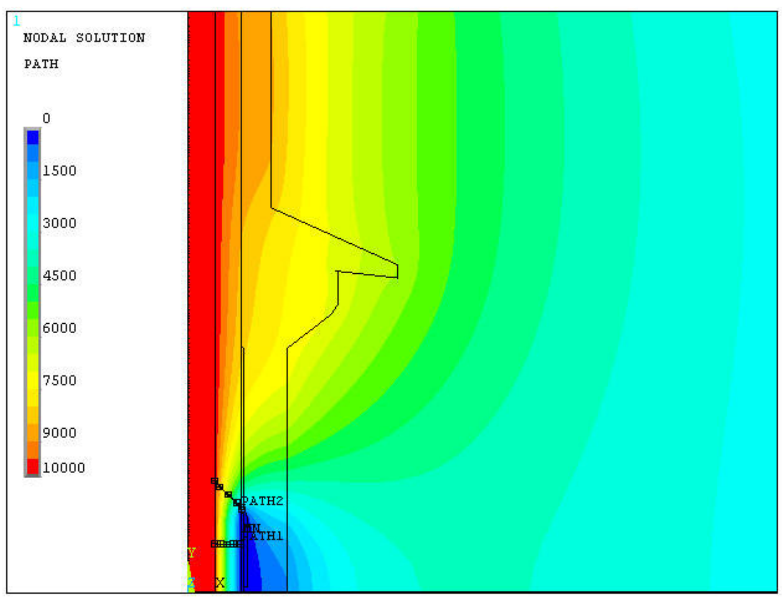

Figure 4.9. The Paths with Critical Points on the Cable Termination Model with Stress Control Tube (SCT)

The critical nodes on Path1 and Path2 are shown in Figure 4.9. Path1 points are chosen along the cable dielectric. The critical points consisting Path1 are chosen to compare the electric field values in the cable insulation area.

Path2 points are chosen on the critical area of the cable termination model with stress control tube (SCT).

The electric field intensity values of the critical nodes are obtained from the simulation program as listed in Table 4.3.

Table 4.3. The Path Points defined on the Stress Controlled Cable Termination Model with Stress Control Tube

PATH1 (Points in the cable insulation area)		PATH2 (Points in the cable termination area)	
Distance along electric field (mm)	Electric Field Intensity (kV/mm)	Distance along electric field (mm)	Electric Field Intensity (kV/mm)
6.83	2.13	6.83	1.02
8.35	1.75	8.11	0.84
9.92	1.48	10.28	0.74
11.66	1.26	12.47	0.66
13.5	1.10	13.79	0.65

To visualize and evaluate the results efficiently, the graphic is drawn using MATLAB as shown in Figure 4.10.

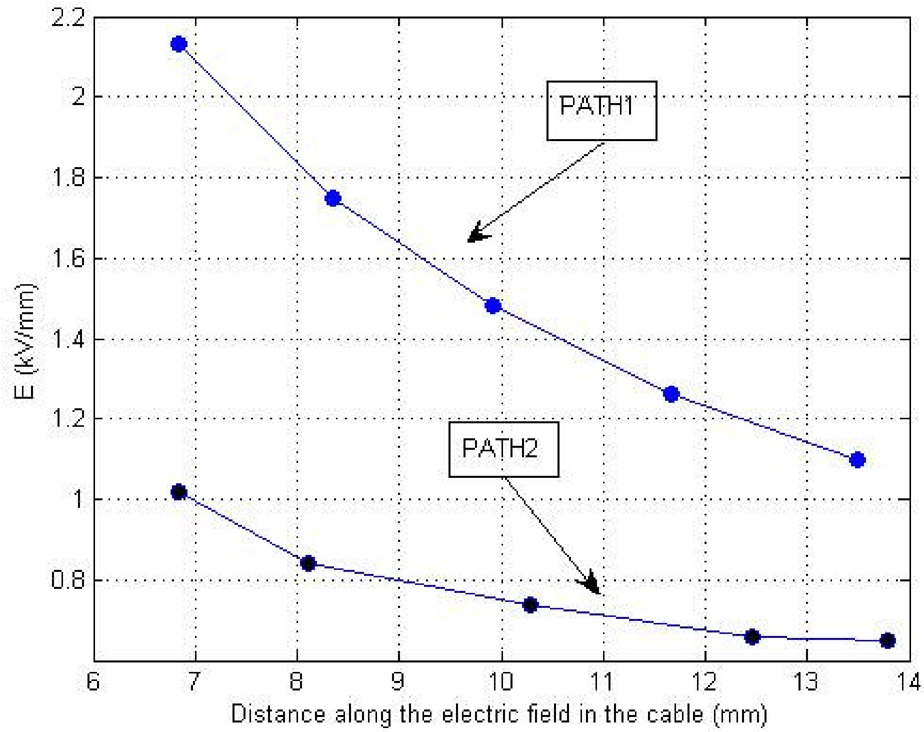

Figure 4.10. Path1 and Path2 Electric Field Intensity Distribution on the Cable Termination Model with Stress Control Tube (SCT)

Path1 plot starts a point with electric field intensity of 2.13 kV and decreases to 1.1 kV along the cable dielectric area. Meanwhile, path2 points are decreasing along the electric field at the cable termination area. The electric field intensity is changing between 1.02 and 0.65 kV on critical Path2 points. Thus, the electric stress is not high at any point of the model with satisfactory field refraction along the high relative permittivity layer called SCT.

The satisfactory stress relief at the cable termination also includes best result in as short length as possible. The electric field at the termination area does not exceed the critical high value with a length of 10 cm in this work. The simulation results are obtained for the cable termination models through this chapter.

4.5 The Comparison of the Cable Termination Models

The electric field intensity values along the cable critical paths are obtained by using finite element analysis program. The cable termination models are compared according to the analysis results shown in Figure 4.11.

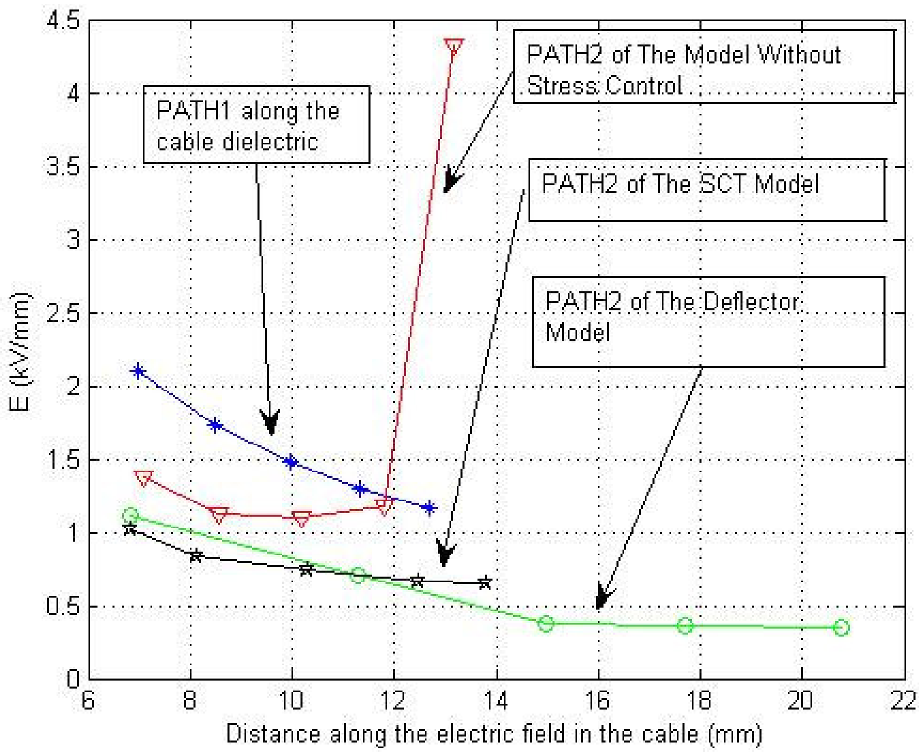

Figure 4.11. The Comparison of the Path1 and Path2 Electric Field Intensity Distribution on the Cable Termination Models

Path1 consist of the critical points showing the electric field intensity decrease along the cable dielectric. The ideal case for the cable termination electric field distribution should be very similar to Path1 without any sharp slopes in the critical areas.

When there is no stress control applied at the cable termination, Path2 has a sharp electric field intensity increase at the cable secreen critical point. This strong electric field at the screen end is reduced with two different cable termination models which are investigated.

First method of the cable termination stress control is the deflector model. Path2 of the deflector model reduces the strong electric field observed at the screen end effectively as shown in the plot.

Second method for effective stress relief at the cable termination is the stress control tube application. The electric field is sufficiently reduced with this model as shown in the Path2 electric field intensities' plot.

The cable termination stress control methods are both effective reducing the strong electric filed intensity as observed. The electric field intensity is decreasing along the critical areas as in the ideal case.

4.6 The Effects of the Stress Control Tube (SCT) Model

The cable termination model with the stress control layer is shown in Figure2.1. The stress control tube application on the cable termination model is investigated considering the physical and material properties. Therefore, the thickness and the relative permittivity effects of the stress control layer are evaluated using the computer program.

In the finite element analysis computer program, the satisfactory model design is done by using APDL (Ansys Parametric Design Language). APDL is a powerful tool to do repeating or complicated operations and calculations. [25]

In the cable termination model; the relative permittivity and the length of the stress control layer are the changing properties. The effect of changes in the properties of the stress control layer is investigated by evaluating the simulations. The simulations solve the model and the electric field distribution over the model is obtained. The analysis result files contain the potentials at each node of the finite element model. Consequently, the output files are evaluated as performance properties to optimize the design.

By using APDL, all the commands are written in the text editors and are executed in a fast way. The changing variables of the model are defined in written commands. In every analysis step, the model is rebuilt according to the changing values of the variables. Then, the results are stored in the output files.

The output files are used to plot three dimensional graphics, representing each axis with the changing variables. The plot is evaluated by finding the critical points and the design is optimized according to this evaluation. Hence, the effects of the changing variables are observed visually.

4.6.1 The Relative Permittivity Effect of the Stress Control Tube Model

The effect of the relative permittivity of the stress control layer applied on the cable termination is analysed. The cable termination model with the stress control tube is written in the text editor. The relative permittivity of the stress control tube is assigned as a variable and is changed in each simulation.

The stress control tube materials with relative permittivity ranging from 5 to 1000 are analysed. The boundaries are defined as the cable conductor potential applied 10 kV and the insulation screen potential as ground.

The results of the analysis are obtained as the equipotential maps using Ansys shown in Figure 4.11.

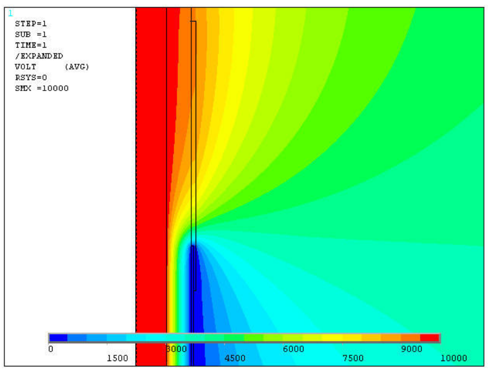

Figure 4.12.a The equipotential map of the SCT model with ε_r= 5

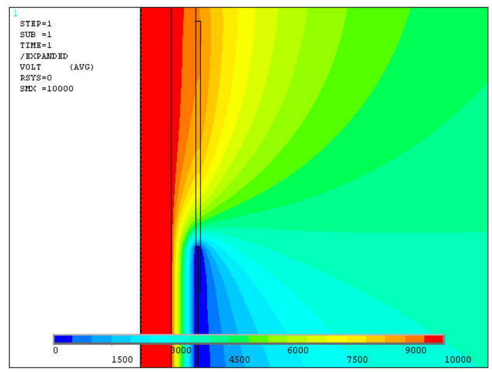

Figure 4.12.b The equipotential map of the SCT model with ε_r= 10

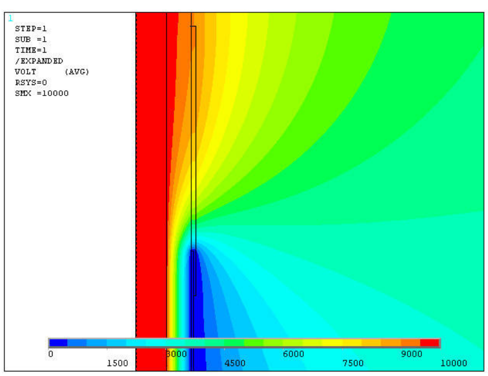

Figure 4.12.c The equipotential map of the SCT model with ε_r= 20

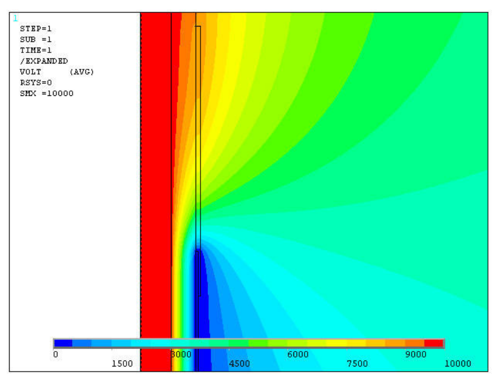

Figure 4.12.d The equipotential map of the SCT model with ε_r= 40

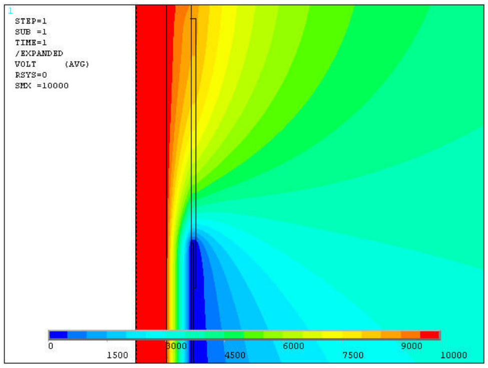

Figure 4.12.e The equipotential map of the SCT model with ε_r= 60

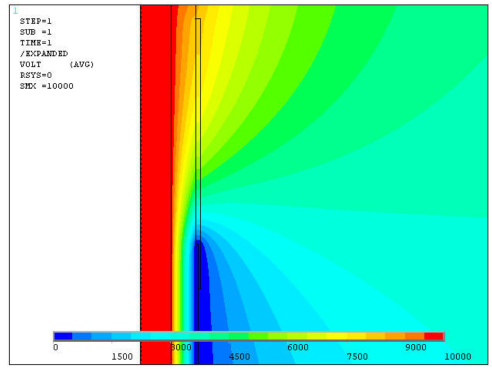

Figure 4.12.f The equipotential map of the SCT model with ε_r= 100

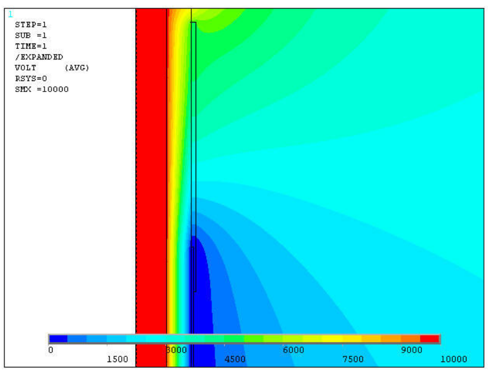

Figure 4.12.g The equipotential map of the SCT model with ε_r= 500

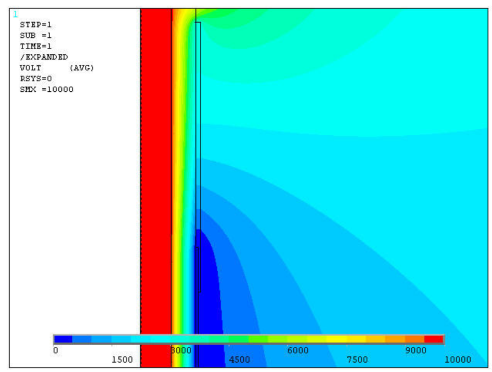

Figure 4.12.h The equipotential map of the SCT model with ε_r= 1000

The increase of the stress control tube relative permittivity is observed to defract the equipotential lines significantly in the screen end area. The maps with relative permittivities ranging from 5 to 40 effectively change the critical area equipotential line concentration. The increase of the relative permittivity greater than 100 (high permittivity) turns out to refract the electrical field in the stress control tube end. For that reason, the increase in relative permittivity should be limited.

The maximum electric field calculated in the critical area of each configuration with changing stress control tube relative permittivity is shown in Table 4.4.

Table 4.4 The Maximum Values of the Electric Field in the Critical Area of the Cable Termination Model with Stress Control Tube for Different Relative Permittivity of the SCT

ε_r **(F/m)**	5	10	20	40	60	100	500	1000
E_{max} **(kV/mm)**	4.9	3.94	3.447	3.447	3.447	3.447	3.447	3.447

The increase of relative permittivity turns out to be effective between 5 and 40. The stress relief is not observed in the screen end area when the relative permittivity is increased greater than 40. Hence, the effect of the stress relief is best achieved by a material with ε_r = 40.

4.6.2 The Thickness Effect of the Stress Control Tube Model

The physical property effect of the cable termination model with stress control tube is analysed. The cable thickness of the stress control tube is assigned as a variable and changes from 1 to 5 mm. The stress control tube relative permittivity is constant (ε_r = 40) in each configuration. Hence, the effect of the stress control layer thickness is analysed.

The boundaries are defined as the cable conductor potential applied 10 kV and the insulation screen potential as ground. The results of the analysis are obtained as the equipotential maps using Ansys shown in Figure 4.12.

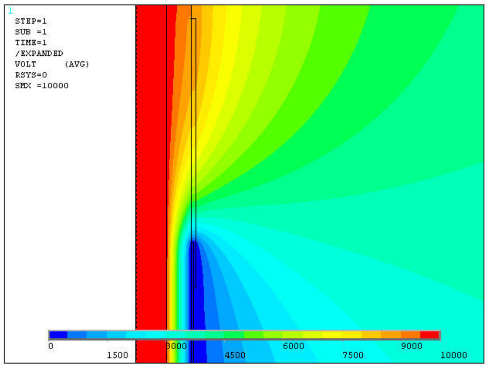

Figure 4.13.a The equipotential map of the cable termination model with 1 mm thick SCT

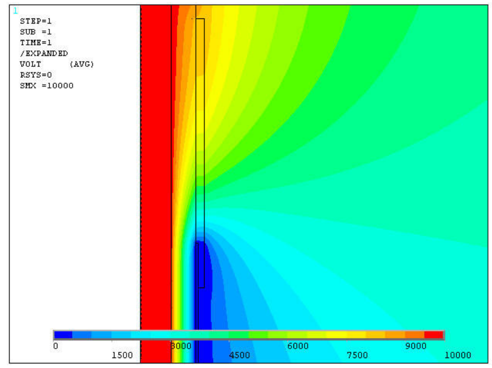

Figure 4.13.b The equipotential map of the cable termination model with 2 mm thick SCT

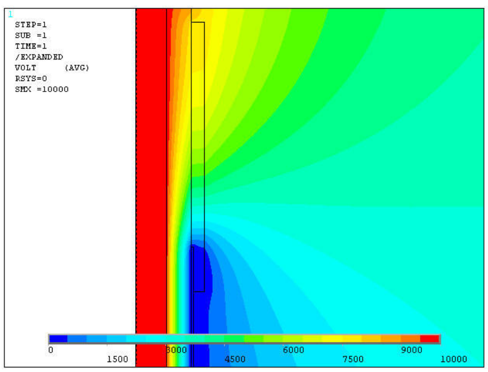

Figure 4.13.c The equipotential map of the cable termination model with 3 mm thick SCT

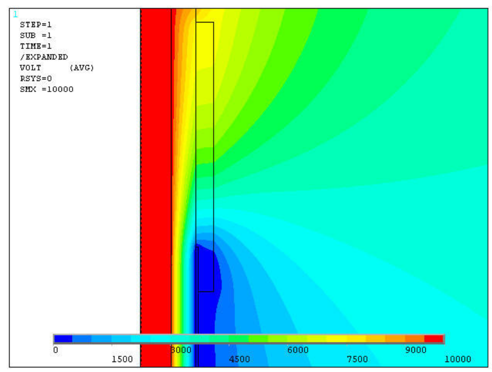

Figure 4.13.d The equipotential map of the cable termination model with 4 mm thick SCT

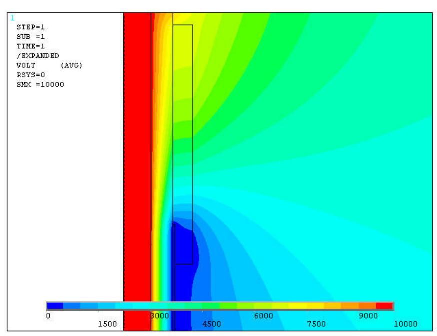

Figure 4.13.e The equipotential map of the cable termination model with 5 mm thick SCT

The equipotential map with different colors indicating corresponding potential values are observed. The analysis results show that the stress control layer thickness effects the equipotential line distribution in the critical area but not very effectively.

The maximum electric field calculated at the critical area of each analysed cable termination model is listed in Table 4.5.

Table 4.5 The Maximum Values of the Electric Field in the Critical Area of the Cable Termination Model with Stress Control Tube for Different Thickness of the SCT (ε_r=40 F/m)

d (mm)	1	2	3	4	5
E_{max} (kV/mm)	3.447	3.4275	3.5023	3.4653	3.4521

Results of numerical models show that for relative permittivity 40, the effect of the stress control layer thickness has no remarkable stress relief effect. The best configuration of the cable termination model with stress control tube turns out to be with 1 mm thickness for cost advantage.

CHAPTER 5

THE ELECTROLYTIC TANK EXPERIMENT

5.1 Introduction

There is a variety of different ways to design the most appropriate cable accessories as termination and joint models. The previous chapters covered the study of different methods for the cable termination electric stress control. Different methods with different material properties are analyzed by indicating both the advantages and the disadvantages through the study. The simulation analysis steps and the results are briefly explained.

The electrolytic tank is an analogue model for the evaluation of the electric field distribution in high voltage dielectrics. [5] In this chapter, the experimental measurement results are obtained to evaluate the electric stress in the cable termination by means of the electrolytic tank.

The most effective cable termination model to be used is selected for this chapter's study.

Firstly, the cable termination model using stress control tube (SCT) of 1 cm thickness with relative permittivity of 40 is analyzed by using the finite element analysis software, ANSYS. Then, this model is used for the design of the electrolytic tank experiment.

The simulation result output is reorganized to give the critical points' electric potential values on the cable. These results are expressed on plots to observe the change in proportional with the changing coordinates of the point.

The first step of the experiment is the experimental setup design as the analogue of the selected cable termination model. The dimension calculations and the design of the tank geometry are obtained with the program code written in MATLAB.

A digital multimeter is used to measure the electric potentials in the electrolytic tank. The experimental results are the measured potential values of the same critical points defined in the numerical programming analysis. The experimental results are expressed in plots to observe the effect better.

In the end of the chapter, the electrolytic tank experiment results are compared with the simulation program results. The experimental result accuracy is checked by using the finite element analysis software ANSYS.

5.2 The Theory of the Electrolytic Tank Analogue Model

The electric field distribution in high voltage dielectics is an analogue of the electrolytic tank model having electrodes across which a voltage is applied. This analogy is based on the Maxwell equations as stated below:

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \text{(Eq. 5.1)}$$

$$\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \quad \text{(Eq. 5.2)}$$

$$\nabla . \vec{D} = \rho \quad \text{(Eq. 5.3)}$$

$$\nabla . \vec{B} = 0 \quad \text{(Eq. 5.4)}$$

In these equations, $\vec{E}$ (V/m) is the electric field, $\vec{B}$ (Tesla) is the magnetic flux density, $\vec{D}$ (C/m^2) is the electric flux density, $\vec{H}$ (A/m) is the magnetic field intensity, $\vec{J}$ (A/ m^2) is the current density and ρ (C/m^3) is the charge density.

In a charge free isotropic dielectric:

$$\rho = 0 \quad \text{(Eq. 5.5)}$$

Then,

$$\nabla . \vec{D} = 0 \quad \text{(Eq. 5.6)}$$

$$\nabla . (\varepsilon \vec{E}) = 0 \quad \text{(Eq. 5.7)}$$

where ε is the permittivity measured in farads per meter (F/m).

In an electrostatic field;

$$\vec{\mathrm{E}} = -\nabla V \quad \text{(Eq. 5.8)}$$

where V (Volt) is the electric potential.

By Ohm's law,

$$\vec{J} = \sigma \vec{E} \quad \text{(Eq. 5.9)}$$

where σ is the conductivity of the medium.

By using the last two equations (9) and (10);

$$\nabla.(\nabla V) = 0 \qquad \text{(Eq. 5.10)}$$

satisfying the Laplace's equation,

$$\nabla^2 V = 0 \qquad \text{(Eq. 5.11)}$$

$$\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} = 0 \qquad \text{(Eq. 5.12)}$$

The equations are applicable for both of the mediums: the electric flux between the electrodes separated by a medium of permittivity ε or a medium of conductivity σ. The solution is the potential equation resulted from Laplace's equation.

As a result, the electrolytic tank having electrodes separated by an insulating medium of permittivity ε is the analogue of the cable having two tubes of current separated by a medium of conductivity σ. By solving the potential equations, the electric field distribution in the electrolytic tank experiment is obtained as the analogue of the cable termination field distribution.

5.3 The Design of the Electrolytic Tank

The design of the cable termination model analogue as an electrolytic tank is the preliminary work of the experimental procedure.

The experiment is done in shallow tank composed of non-conducting walls and base. The cable layer materials having different dielectric properties are represented as steps in the base of the tank. These step angles are calculated proportional with the relative permittivity of the materials. The calculation and the design process are completed using the computer program, MATLAB satisfying sufficient efficiency.

The model is chosen as the cable termination stress control with Stress Control Tube. The relative permittivity of the Stress Control Tube is chosen 40 referring to the optimization result of the previous chapter studies.

The cable termination model properties are considered in design process of the technical program for sufficient efficiency. They are stated as in Table.5.1.

Table 5.1 The Material Properties of the Cable Termination Model

Elements of the Cable Model			
	Relative Permittivity (ε_r)	**Thickness (cm)**	**Area Number**
The Conductor		5.00	1
The Insulation (XLPE)	**2,3**		2
The InsulationScreen		10,00	3
The Stress Control Tube (SCT)	40,0	0,50	4
The Outer Protection (PVC)	4,0	1,00	5
Air	1	10,00	6

The air surrounding the cable is 10,00 cm thick on the cable model having relative permittivity equal to 1.

The tank model dimensions (cm) obtained from the programming as the front view of the tank is shown in Figure 5.1.

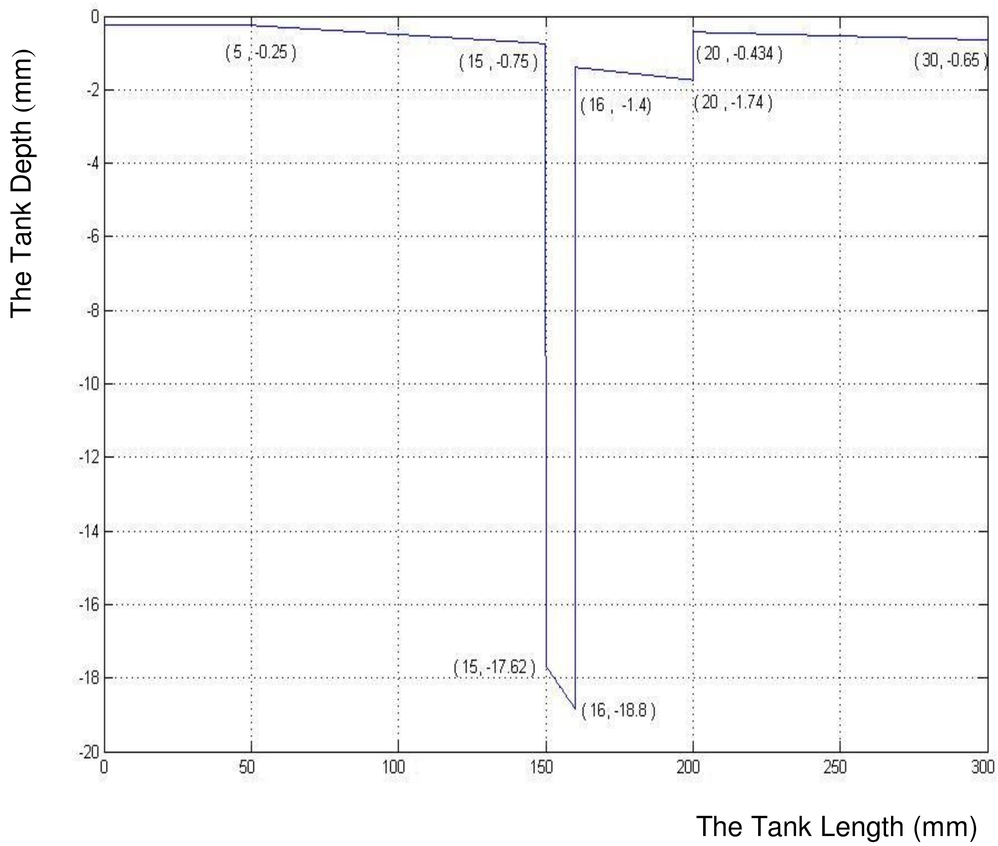

Figure 5.1. The Dimensions of The Tank Front View

The 3D model of the tank obtained as the output of the program is shown in Figure 5.2.

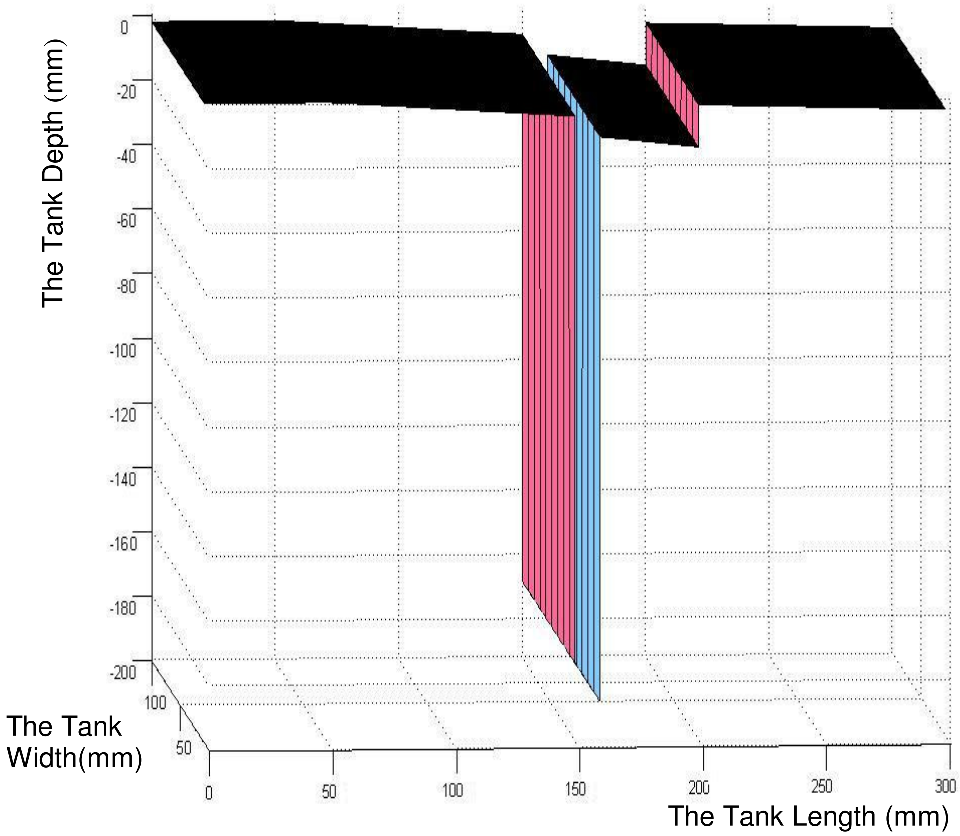

Figure 5.2. The 3D Model of The Tank

The cable termination model conductor area and the insulation screen area are simulated as electrodes in the tank. The silver plate electrodes are chosen as the most satisfactory electrodes to reduce the polarization effect. The electrodes are placed on the tank where the potentials are applied.

In the experiment, 15 V is applied across the conductor area electrode by using a 18 W DC power supply The insulation screen area is grounded by connecting to earth as in the cable termination model. The electrolytic tank prepared for the experiment is made of Perspex with dimensions 30cmx10cmx20cm. The photograph of the tank is shown in Figure 5.3.

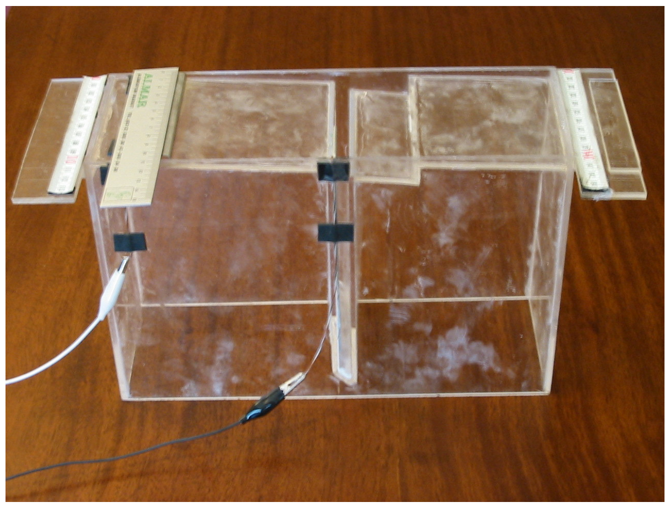

Figure 5.3. The Electrolytic Tank

The tank is constructed by using non-conducting material, Perspex. It is filled with the electrolyte for measurement.

The electrolyte level through the experiment should remain the same for the accuracy of the measurement. Thus, the tank is constructed leak-proof and placed on a smooth surface.

The choice of the electrolyte depends on the desired conductivity. For effectiveness in the measurement, the equipotential displacement effect at the surface of the electroyte should be reduced. Hence, for most of the problems, low conductive electrolyte is required in the experiment. In this experiment, ordinary water is used as the electrolyte.

The measurement process of the experiment is done by using the probe of a digital multimeter. It's manually controlled by moving in equal distances from each critical point. The practical solution for the measurement is achieved by mounting rulers indicating the coordinates on the tank. The photograph of the experimental setup is shown in Figure 5.4.

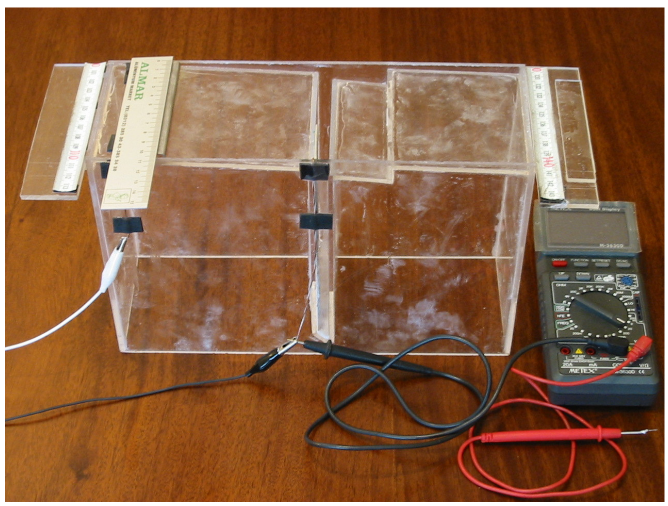

Figure 5.4. The Experimental Setup

The measuring probe is moved on the electrolytic tank longitudinally and then vertically on the electrolyte surface while the other probe of the multimeter is connected to the earth electrode. The potential difference of each location is measured directly and recorded on a table.

The result table of the experiment listing the potential differences of different locations is also considered as the electric stress effect on the locations of the cable termination model.

5.4 The Cable Termination

The numerical model of the cable termination with stress control tube (SCT) is analyzed using the finite element analysis computer program, ANSYS as shown in Figure 5.5.

The analysis model consists of the cable termination layers as: the conductor, the insulation, the insulation screen, the stress control tube, the outer protection and air surrounding the cable model. The design is done for 10 cm long cable termination model.

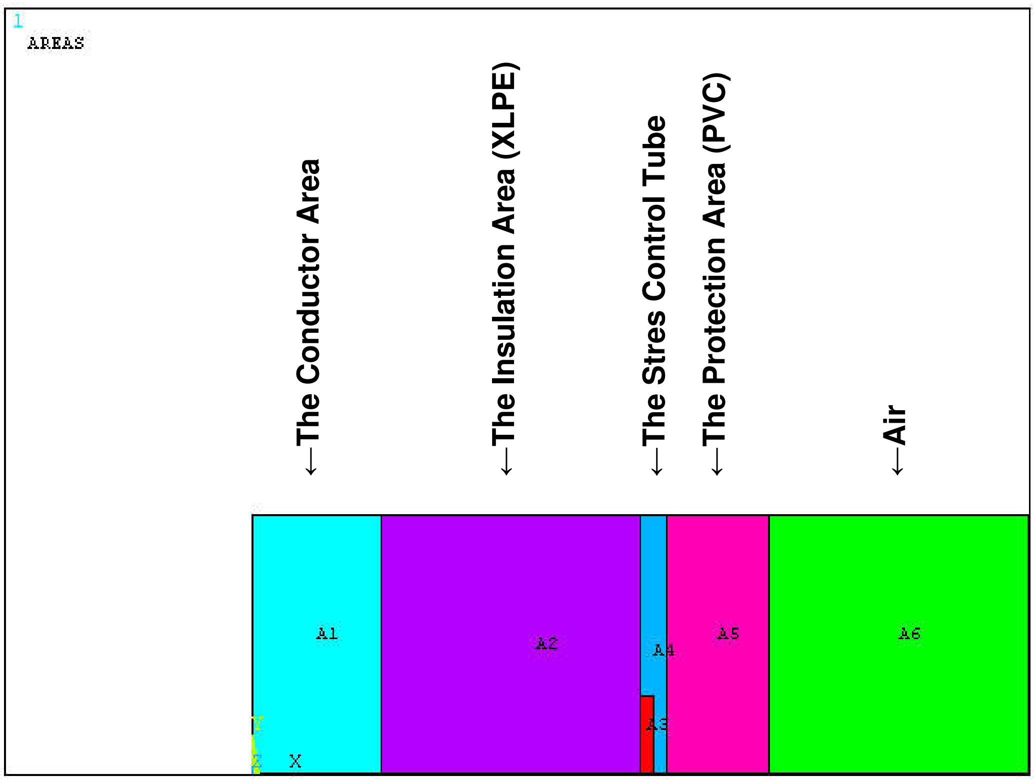

Figure 5.5. The Analysis Boundary of the Axisymmetric Cable Termination Model with SCT

The half of the model is analyzed because of the y axis symmetry. The preprocessing step of the FEA computer program is completed.

The cable termination model areas are expressed in different colours because of the cable layers' different material properties.

The material properties and their assigned area numbers are listed in Table 5.1.

The simulation results are obtained by applying the conductor 15 V and the insulation screen 0 V (ground) potential values in the solution process.

5.5 The Solution of the Electric Field Distribution Obtained by the Finite Element Analysis Computer Program

The analyzed region is divided into isoparametric elements consisting of nodes automatically by the program. Based on the numerical calculations of the model, the electric potential values are listed as node potentials on every element of the analyzed region.

The results and the plots are obtained in the postprocessor step of the program.

The critical points are defined as paths on the analyzed cable termination model. These path points are the nodes of the analyzed region coupling with the result electric potential values.

The paths defined are shown in Figure 5.6.

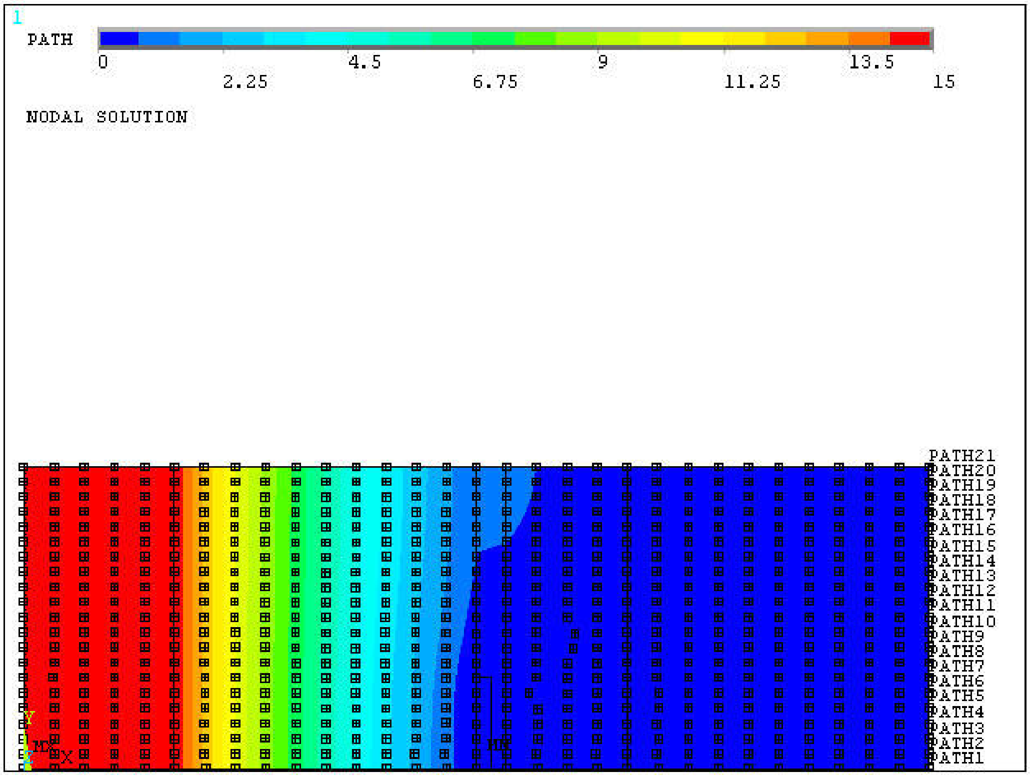

Figure 5.6. The Paths Defined on the Cable Termination Model Obtained by the FEA Computer Program

There are 21 paths composed of horizontally placed 31 nodes. The paths are located with 5 cm vertical distance where the nodes of the same path are located 10 cm horizontal distance between each other.

The output file data of the program is reorganized and listed to form the potential versus distance plots. These plots are collected in one plot to observe the potential change properly as shown is the Figure 5.7.a.

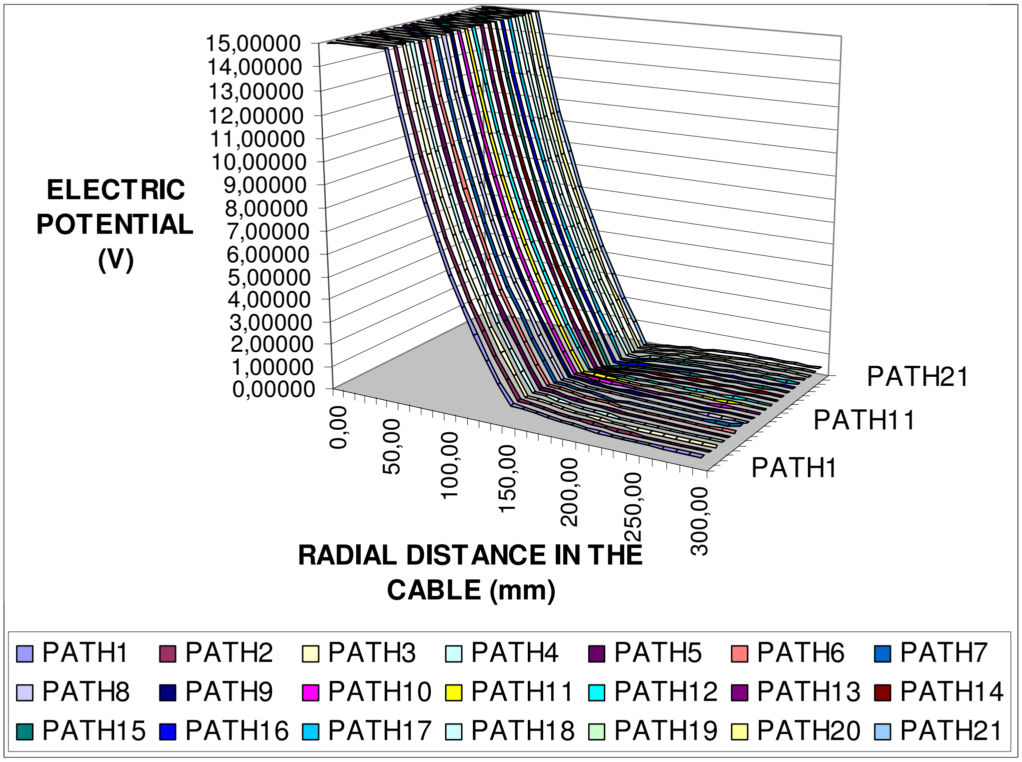

Figure 5.7.a. The Potential Plot of the Paths Defined on the Cable Termination Model Obtained by the FEA Computer Program

The electric potential values are obtained as the output values of each path defined on the model. In the end of the computer analysis, maximum electric potential value is obtained as Vmax = 15 V on the conductor area (positive electrode) while minimum potential value as Vmin = 0V on the screen area (earth) as expected. All other electric potentials receive values between them.

The electric field is stronger on the area between the conductor and the screen. The drop of the potential to the minimum value in a small length causes stress concentration at the end of the screen. However, the stress relief layer designed as stress contol tube (SCT) with relative permittivity of

40 refracts the equipotential lines. This is observed as decrease in the potential values of the SCT area nodes.

The Figure 5.7.b proves the stress control of the cable termination by observing the path nodes around the screen and the SCT intersection area with very small potential values.

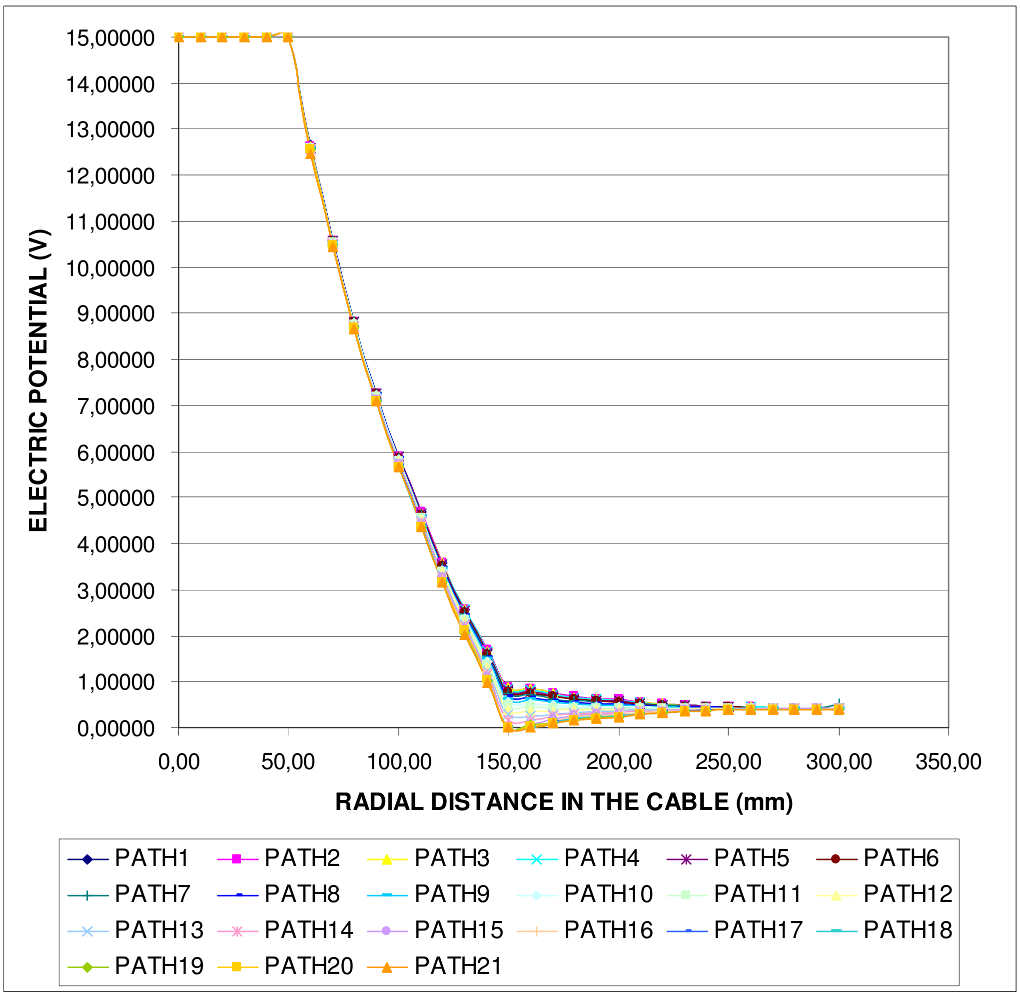

Figure 5.7.b. The Potential Plot of the Path Nodes Defined on the Cable Obtained by FEA Computer Program

5.6 The Electrolytic Tank Experiment Measurement Results

The measurements of the experiment are listed in the output table. This table is used to obtain the potential distribution along the distance chosen as paths. The path nodes' coordinates on the model are the same as chosen ones in the computer programming analysis.

There are 21 paths each consisting of 31 nodes. The potential plot of the experimental measurement is shown in Figure 5.8.a.

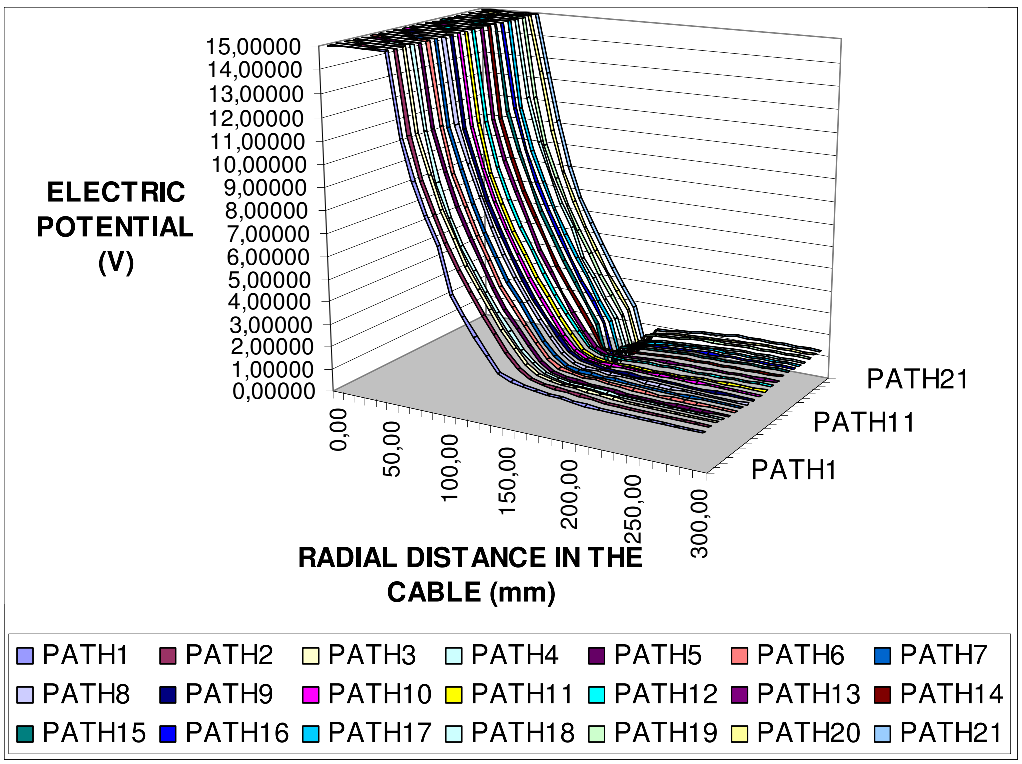

Figure 5.8.a. The Potential Plot of the Electrolytic Tank Experimental Measurement

The potential change between the electrodes forms the path potential lines along the surface of the electrolytic tank. Therefore, the path lines indicate the electric stress at the desired locations.

The measurement nodes of the paths on the potential plots are shown in the Figure 5.8.b.

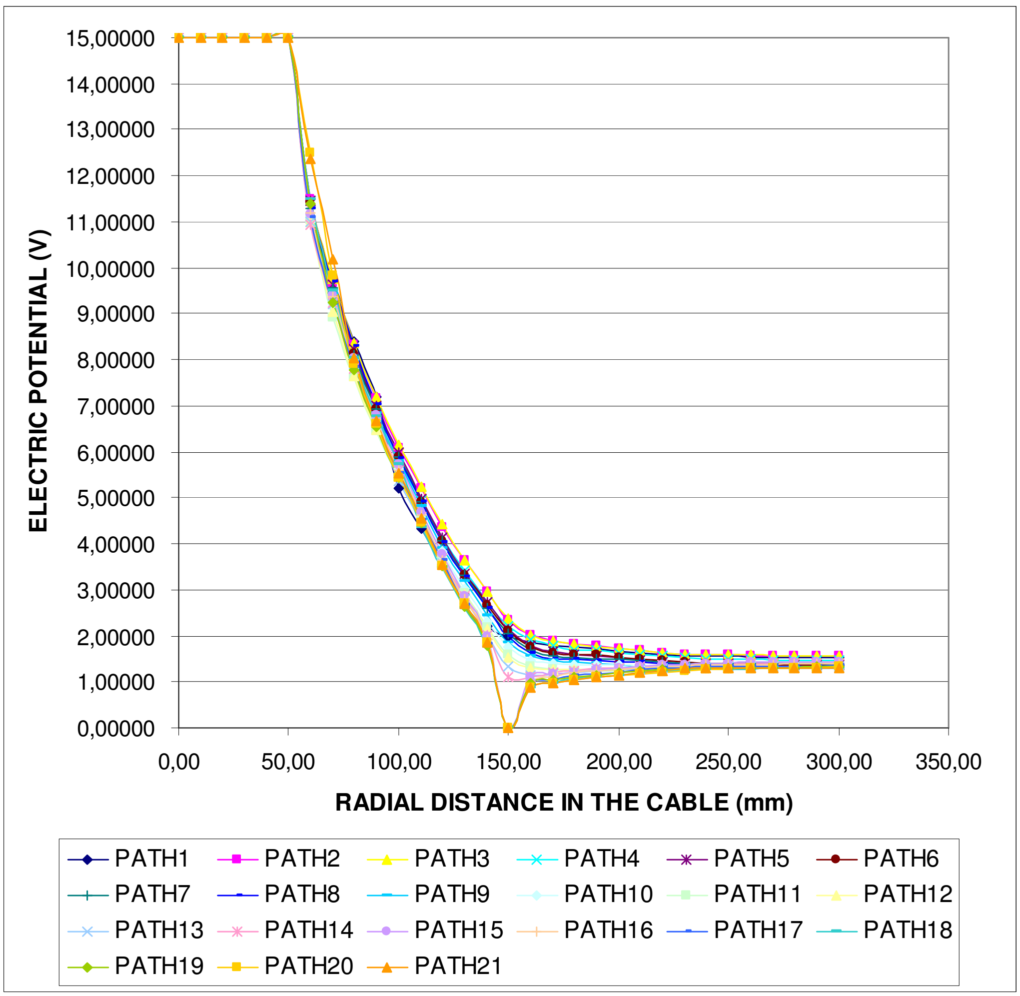

Figure 5.8.b. The Potential Plot of the Electrolytic Tank Experimental Measurement

When the experimental results are compared with the numerical results, the difference is reasonably negligible. Hence, the application of the finite element analysis computer program is proved to be successful.

The electrolytic tank experiment is an old, established method to observe the stress control on the cable termination model. On the other hand, it needs time and too much attention to achieve the output files with less error. Therefore, the finite element analysis computer program is preferred for the electric field control problems.

CHAPTER 6

CONCLUSION

6.1 General

In this study, two different cable termination models are investigated. The electric potential and the field distributions are analysed, the results are evaluated.

Firstly, the cable termination model without stress control is analysed. The high stress area at the cable screen end is studied. High and non-uniform electric fields observed at the screen edge prove the need of the stress control application as indicated by the curves.

Two typical types of the cable termination mechanisms are explored by using the simulation program. The first type is the deflector model. It disperses the concentrating electric field at the termination area with its geometrical structure. The results of the analyses show that the electric field is decreased with the curved geometry of the deflector. The other type of the model is the stress control tube consisting of a layer with high relative permittivity. The stress control layer applied on the cable screen reduces electric field at the termination area successfully.

The stress control tube (SCT) model application is usually done with heat-shrinkable material or as dielectric paste covering the cable insulation screen in today's technology. It is important to avoid air cavities and application defects while termination mechanism is applied for long lifetime of usage and no high skill is needed. However, the deflector model application should be done more carefully since it is based on its ideal geometrical structure. Also, the mold imperfections, curing methods, material quality, bubbles or environmental factors affect the successful application of the deflector. At the same time, the application process needs high skilled working. Hence the overall cost of the method presents an important disadvantage.

As a conclusion, the advantages in the application process and the computer simulation results show that the stress control tube model is a satisfactory and economic solution for electric field control in the cable terminations.

The last chapter covers the analogue model experiment for the evaluation of the electric field distribution analysis. The electrolytic tank experiment is a conventional method used for electric field distribution analysis in dielectrics. The experiment results are compared with the simulation program results to check the numerical calculation done by the software. When the results are compared, the error ratio is negligibly small. Hence, the results of the numerical calculations and analysis done through this work are proved to be reasonably accurate.

6.2 The Future Work

For industrial application, the cable termination stress control tube application method investigation is the future work.

The optimized stress control tube application technique possibly with non linear characteristic material or multiple stress control layers are suggested as the future work for the most satisfactory and economic way of the stress controlled cable termination model.

The application difficulties of the stress control tube such as trapped air between the stress control tube and the cable dielectric, stripping the semiconductor layer and excluding the bubbles are the problems to be solved with more advanced techniques.

REFERENCES

[1] Nikolajevic S.V. , Pekaric-Nad N.M. , Dimitrijevic R.M., “The Influence of Some Construction Parameters on Electric Stress Grading in XLPE Cable Terminations”, 2-5 June 1997 , Conference Publication No.438, CIRED

[2] William A. Thue, “Electrical Power Cable Engineering”, Second Edition, Revised and Expanded

[3] Nikolajevic S.V. , Pekaric-Nad N.M. , Dimitrijevic R.M., “Optimization of Cable Terminations”, April 1997 , IEEE Transactions on Power Delivery , Vol. 12 , No. 2

[4] M. Tuncer Başçıoğlu, “Transient Field Analysis of Underground Cables”, M.Sc.Thesis, METU, 1978

[5] L. L. Alston, “High Voltage Technology” , 1968

[6] Dr T W Preston; “The Finite Element Method as a Computational Tool for Design” GEC ALSTHOM Engineering Research Centre, Stafford

[7] Saeed Moaveni , “Finite Element Analysis”, Theory and Application with ANSYS

[8] Ansys Basic Analysis Procedures Guide, 1994 , Release 5.3 , Swanson Analysis Systems, Inc

[9] Muench F.J., Makal J.M. , DuPont J.P., Hecker, H.A.; Smith, K., “Development and Use of a Testing Regime to Predict Life of Premoulded Rubber Termination and Connection Products Used on Medium Voltage Power Cables”, 23-25 Nov 1993, Third International Conference on Power Cables and Accessories 10kV - 500kV, 1993, Pages:145 – 152

[10] Lothar Heinhold , “Power Cables and Their Application”, 1993 , Siemens Aktiengesellschaft

[11] “IEEE Standard Test Procedures and Requirements for High-Voltage Alternating-Current Cable Terminations”, IEEE Std 48-1990 , 25 April 1990

[12] "IEEE Standard Test Procedures and Requirements for Alternating-Current Cable Terminators 2.5 KV Through 756 KV", IEEE Std 48-1996 , 20 June 1996
[13] W.F.Powers JR., P.E., Southwire Company, "The Basics of Power Cable" , 1994 , Cement Industry Technical Conference
[14]C:Brackeniers, A.Cheenne-Astorino, "A New Family of .M.V. Terminations" , 1993 , Power Cables and Accessories 10kV - 500kV
[15] Jeffry P. Mackevich and John W. Hoffman, Raychem Corporation, "Insulation Enhancement with Heat-Shrinkable Components
[16] Blake A.E., Clarke G.J., Starr W.T. , "Improvements In Stress Control Materials ", 1979 , Transmission and Distribution Conference and Exposition
[17] P.N. Nelson, H.C. Hervig, "High Dielectric Constant Materials For Primary Voltage Cable Terminations" , November 1984 , IEEE Transaction on Power Apparatus and Systems, Vol. PAS-103, No. 11
[18] Egiziano L. ; Tucci V. ; Petrarca C. ; Vitelli M., "A Galerkin Model to Study The Field Distribution in Electrical Components Employing Nonlinear Stress
[19] A. B. J. Reece , T. W. Preston , "Finite Element Methods in Electrical Power Engineering"
[20] David K.Cheng, "Field and Wave Electromagnetics", Second Edition
[21] C.Petrarca, D.Cerbasi, V.Tucci, M.Vitelli, "Numerical Analysis of Performances of Stress Grading Cable Accessories Made of Different Anisotropic Composite Materials" , 2000 , Conference on Electrical Insulation and Dielectric Phenomena
[22] Jianming Jin , "The Finite Element Method in Electromagnetics"
[23] Ellis D., Smith T.F., "Visualization of 3D, Scalar and Vector, Static and Time Varying Fields Using the ANSYS General Purpose Finite Element Program" , 15 Nov 1995 , Visualisation of Three-Dimensional Fields, IEE Colloquium

[24] Steinbigler, H., Haller D., Wolf A., “Comparative Analysis of Methods for Computing 2-D and 3-D Electric Fields” , June 1991 , IEEE Transactions on Electrical Insulation , Volume: 26 , Issue: 3
[25] T. F. Lam , “FEA Applications in DOE and Design Optimization” , 10 Oct. 1997 , Electronic Packaging Technology Conference