“THERMAL MODELING OF BUSBAR CONFIGURATION BY FINITE ELEMENT TECHNIQUE”

Major Project Report

Submitted in Partial Fulfillment of the Requirements for the Degree of

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(Electrical Power System)

By

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CERTIFICATE

This is to certify that Major Project Report entitled “Thermal Modeling of Busbar Configuration by Finite Element Technique” submitted by Mr.Jugal Lotiya (10Meee22), towards the partial fulfillment of the requirements for the award of degree in Master of Technology (Electrical Engineering) in the field of Electrical Power Systems of Nirma University is the record of work carried out by him under our supervision and guidance. The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

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Abstract

Busbar systems are often employed as a riser for power distribution in large buildings. In electrical power distribution, busbar is a strip of copper or aluminum that conducts electricity within a switchboard, distribution board, substation or other electrical power apparatus. The use of busbar technology is increasing to realize connections within power supply systems in answer to the need of compactness. The temperature rise of busbar systems is a vital factor which limits the maximum continuous current the busbar can carry and is responsible for failure of insulation and higher losses if exceeded which affects its performance.

The dissertation is dealing with thermal analysis such as temperature field, heat flux and heat transfer in industrial Busbar system. The integrated problem on heat conduction and radiation-convective heat exchange describes the temperature regime in current carrying busbars of power electrical apparatus. The joule heating effect is described by conservation laws for electrical current and energy. The computation approach employs the finite element technique to solve the three dimensional electric field distribution problem and thermal analysis. Numerical as well as experimental solution has been carried out and compared. Simulation as well as three dimensional geometry has been developed and modeled by using software program ANSYS Multiphysics.

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Nomenclature

h .... coefficient of Heat Transfer

λ .... thermal conductivity [$\frac{W}{m^{\circ}C}$]

γ .... Stefan-Boltzmann constant

ϵ .... emittivity of the body

$\overrightarrow{D}$ .... electric flux density [C/m^2]

$\overrightarrow{E}$ .... electric field potential[v/m]

$\overrightarrow{B}$ .... magnetic flux [T or W/m^2]

$\overrightarrow{H}$ .... magnetic field [A/m]

$\overrightarrow{J}$ .... current density [A/m^2]

ρ .... electric charge density [C/m^3]

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Chapter 1

Introduction

1.1 Background

The efficient, reliable and economical design of power apparatus has been a standard demand of researchers and engineers since the very beginning of electrical engineering. Busbar systems are today widely employed in the industrial environment for electrical energy distribution. The main advantages of these devices are linked to their modularity that enables fast and easy installation, plant modification and maintenance. They may be used in a variety of configurations ranging from vertical risers, carrying current to each floor of a multi-storey building and to bars used entirely within a distribution panel. Several manufacturers in the market propose busbar systems from a few to thousand amperes. Their design seems to be quite easy and for a long time, thanks to the experimental knowledge, different types and sizes have been designed using scalar rules.

In any electrical circuit some electrical energy is lost as heat which, if not kept within safe limits, may impair the performance of the system. This energy loss, which also represents a financial loss over a period of time, is proportional to the effective resistance of the conductor and the square of the current flowing through it. A low resistance therefore means a low loss; a factor of increasing importance as the magnitude of the current increases. Designing for low loss uses more conductor material but leads to a lower working temperature, more reliable operation and since the cost of lifetime energy losses is far greater than the cost of first installation, lower lifetime costs. The capacities of modern-day electrical plant and machinery are such that the power handled by their control systems gives rise to very large forces. Busbars, like all the other equipment in the system, have to be able to withstand these forces without damage. It is essential that the materials used in their construction should have the best possible mechanical properties and are designed to operate within the temperature limits laid down in IEC 60439-2 and IEC 60439-6 or other national or international standards.

1.2 Busduct System

Busduct systems are defined in the NEC 368.2 as a grounded metal enclosure containing factory mounted, bare or insulated conductors, which are usually copper or aluminum bars, rods, or tubes. Generally three types of busduct system is used:
1. Non-segregated phase Busduct
This consists of three phase bus-bars in a common metal enclosure made of steel or aluminum. The enclosure provides safety for the operating personnel and reduces chances of faults. The busduct shall be factory assembled or site fabricated if facilities are available. The enclosure is effectively grounded.

2. Segregated phase busduct
This type is similar to non-segregated phase busduct except that metal or insulation barriers are provided between phase conductors to reduce chances of phase to phase faults. The metal barriers are preferred.

3. Isolated Phase Busduct
In this construction each phase conductor is housed in a separate non-magnetic enclosure. The bus-duct is made of sections which are assembled together at site to make complete assembly. The enclosures are generally round or square in shape and are of welded construction. The enclosures of all phases are usually supported on a common steel structure.

1.2.1 Cooling Arrangement for Busduct System

Very often busduct carry extremely high current ranging from 10kA to 30kA. Since the generation voltage normally is about 11kV to 16kV and the generator ratings are quite high, i.e up to 500 MVA, fabricated aluminium round conductors/channels are used as phase conductors and these are surrounded by outer earthed aluminium enclosures to prevent accidents and reduce external magnetic fields due to high phase currents. To keep the cost of such busducts low, lower cross-section conductors may be used provided the temperature rise is controlled within the specified limits. For safe and reliable operation following types of cooling arrangement are used:

1. **Air natural cooling**

In this method, heat generated by the conductor and enclosure is dissipated adequately through the enclosure by the phenomenon of heat transfer during natural air cooling and no external means of cooling is envisaged.

2. **Forced air cooling**

Conventional cooling through external sources is not possible since the busducts are closed and if blowers are kept inside the busducts, then the motors driving the fan must get power supply. For reasons of safety and reliability no power supply connections are permitted inside the busduct. And in this case, reluctance motors used which run due to magnetic field generated by the phase conductor.

1.3 Literature Survey

In this Reference [1] numerical and analytical approaches for the study of busbar systems are analyzed and compared. In the first part of this paper, the multi conductor model (MC) is presented for studying a general busbar system and the equation are formalized for current-driven and voltage-driven problems. Afterward, the MC method has been applied for solving a current- driven problem related to an industrial busbar system. The evaluation of current distribution and electrodynamic forces of the system has been compared with the one obtained by using a classical finite-element method. In the second part, an analytical approach for evaluating the electrodynamic forces is presented. The adjacent massive conductors configuration considered in the IEC standard 865/93 is fully detailed and the nonadjacent massive conductors configuration, not considered in the standard, has been developed.

Reference [2] presents a two dimensional coupled magneto-fluid-thermal finite element analysis model is presented for the evaluation of electrical heating and natural convection for busbar trunking system. The power frequency harmonic magnetic field, eddy currents and power loss of an air-insulated busbar trunking system are calculated firstly, then the Joule heat is coupled into the fluid field analysis as heat generation load. Thermal field is directly coupled with fluid field: Investigations show that there is a best midterm space between busbars that can make the temperature rise lowest. The bigger the size of shielding, the lower the temperature rise of busbar. Experiment results prove that this model can approximately simulate the thermal field of air-insulated busbar trunking system.

This publication [3] is deals with the experimental validation of a numerical model for the steady-state analysis of multi conductor busbar systems. The computational approach employs the finite element technique to solve the two-dimensional electromagnetic field problem and deduce a complex impedance matrix. Such a matrix, inserted in the circuit equations, enables prediction of the system behavior. The analysis has been developed on an industrial three-phase busbar system having three conductors per phase, considering different supply conditions. The experiments have confirmed the validity of the proposed model.

Paper [4] discusses general model of busbar systems taking into consideration skin and proximity effects and any possible connection of sub conductors. The proposed approach is based on a finite element electromagnetic field computation to deduce the impedance matrix and on a successive network analysis to predict the device behavior. This technique can be used for simulating busbar systems under periodic operating conditions even if the supply quantities are affected by a significant harmonic content. The method is based on the assumption of linearity of the system, which is usually verified except under some short circuit conditions in presence of ferromagnetic enclosures.

Paper [5] deals A dynamic finite element analysis (FEA) method has been shown in earlier research to accurately predict the mechanical response of power system substation busbar structures during short circuit faults. However, the dynamic method is computationally intensive and time consuming. A static finite element analysis is much faster than the dynamic analysis although it is not as accurate. This paper presents a procedure to scale the forces in a static FEA to provide reasonably accurate results. The proposed procedure accounts for the natural frequency and electrical damping of the busbar structure. It is hoped that the proposed method will be useful in allowing substation engineers to quickly check their preliminary design, reserving the dynamic finite element analysis for final design checkout.

Paper [6] demonstrates modeling of the busbars and the magnetic field in an aluminum reduction cell. The methodology presented is focused on a series of fast and effective numerical calculations, where in the initial state the busbars of the reduction cell are represented by an equivalent resistance network. The analysis relies on calculating a complete finite element model with different wave forms imposed on the liquid fluid interface for magnetohydrodynamic stability calculation purposes. Principles of the approach are presented and results from a reduction cell analysis are shown.

Paper [7] presents tutorial on calculating the temperature of naturally and liquid-cooled dc bus is presented. Estimation of time constants allow the calculations of time-varying bus temperatures, while the determination of span constants is helpful in calculating heat gradients along busbars.

Paper [8] describes three-dimensional eddy-current field model for calculating the eddy-current losses in a compact bus duct system is proposed. The temperature rises in the compact bus duct system, including both the long linear section and connecting unit, are evaluated using finite-element method when solving the governing thermal equations. The contact resistance between copper conductors and the corresponding temperature rises are measured in the test also. The computations are validated by test results and the results confirm the proposed algorithm is accurate and practical.

1.4 Objective of Dissertation

Busduct system is more and more used to realize connections within power supply systems in answer to the need of compactness. The main objective of the dissertation is to develop accurate numerical model for industrial busbar system by considering **temperature rise**.

The integrated problem on heat conduction and radiation-convective heat exchange describes the temperature regime in current carrying busbars of power electrical apparatus. Beside steady-state conditions, the transient thermal regime of busbar has an important influence upon whole power supply system from thermal behavior point of view.

The main goal is to optimization of busbar configuration through temperature rise test and Hence, a three dimensional thermal analysis of busbars connections, using a specific software package based on Finite Element Method, has to be computed. From 3D thermal modeling and simulations, the thermal condition such as temperature rise and heat loss for the busbar has to be computed. This allows a better correlation between protection characteristics of the busbar design.

1.5 Technique and Methodology

By revolution in the computer technology has led to development of numerous computational techniques for solving many engineering problems. As mathematical modeling become an integral part of analysis of engineering problems. In this dissertation, Numerical technique such as **Finite Element Technique** is employed because it is one the most flexible and versatile method for solving engineering problems. Finite element method offers a way to solve wide variety of complex continuum problems by sub-dividing item into a series of simpler interrelated problems.Essentially, it provides a consistent technique for modeling whole system as assemblages of discrete part or finite element.

Any real-life system studied by simulation techniques (or for that matter by any other OR model) is viewed as a system. A system, in general, is a collection of entities which are logically related and which are of interest to a particular application. There are variety of commercial FEA software packages available in market. However, no software has the capability to meet the complete analysis requirements of a design. Therefore, some firms use one or more CAE software depending on their requirements. Some companies also develop their own customized version of commercial software to meet their requirements provided by the commercial software.

In this dissertation, the simulation is introduced with **ANSYS 14.0 Workbench**. The core product of Ansys Inc is its ANSYS Multiphysics/Structure mechanics module. This code is based on the finite element method and is capable of performing static (stress) analysis, thermal analysis, modal analysis, frequency response analysis, transient simulation and also coupled field analysis. The **ANSYS multiphysics** can couple various physical domains such as structural, thermal and electro magnetics. Many researchers and engineers prefer this module because of its parametric language known as Ansys Parametric Design Language (APDL). For determination of Temperature field, thermal-electric field analysis is carried out with complete solution in ANSYS Workbench 14.0

1.6 Outline of the thesis

Chapter 1 introduces the background of industrial busbars system, based on it, literature survey has carried out, different techniques and Methodology is explained in brief. The objectives to the work done are defined.

Chapter 2 gives the introduction of the Finite Element Method. In which its History, the Different Approaches and material properties(linear and Non-linear), general boundary conditions has explained. After it the various range of analysis and introduced in brief, the thermal problem with Conduction, Convection and Radiation has described.

Chapter 3 deals the fundamental background of Electromagnetics analysis. In which, Electrostatic field and Magnetostatic field is explained. This chapter is mainly focused on Steady-state Electrical conduction in which steady state electrical potential, total current density as well as Joule loss and Joule heating has explained in detail.

Chapter 4 gives the introduction of ANSYS multiphysics software. In which how the FEM analysis carried out in ANSYS 14.0 Workbench platform is mention with flowchart. The general modules of analysis based on FEM is explained in sequence. This chapter is shows how to simulation can be done, define material properties, boundary conditions and to assign the all parameters for respective analysis.

Chapter 5 discusses about the Experimental test in which temperature rise test is explained. In this chapter, electrical and thermal results are carried out and compare it with simulation results. The variation of temperature rise test values with simulation results has been indicated.

Chapter 2

Introduction to Finite Element Method

2.1 Introduction

The finite element method is a numerical analysis technique for obtaining approximate solutions to a wide variety of engineering problems. Although originally developed to study stresses in complex airframe structures, it has since been extended and applied to the broad field of continuum mechanics. Because of its diversity and flexibility as an analysis tool, it is receiving much attention in engineering schools and in industry. In more and more engineering situations today, it is necessary to obtain approximate numerical solutions to problems rather than exact closed-form solutions. For example, we may want to find the load capacity of a plate that has several stiffeners and odd-shaped holes, the concentration of pollutants during nonuniform atmospheric conditions, or the rate of fluid flow through a passage of arbitrary shape. Without too much effort, we can write down the governing equations and boundary conditions for these problems, but we see immediately that no simple analytical solution can be found. The difficulty in these three examples lies in the fact that either the geometry or some other feature of the problem is irregular or arbitrary. Analytical solutions to problems of this type seldom exist; yet these are the kinds of problems that engineers are called upon to solve.

2.2 History

Finite Element Analysis (FEA) was first developed in 1942 by R. Courant, who utilized the Ritz method of numerical analysis and minimization of variational calculus to obtain approximate solutions for vibration systems. Shortly thereafter, a paper published in 1956 by Turner, Clough, Martin, and Topp established a broader definition of numerical analysis.

By the early 70's, FEA used only on expensive mainframe computers generally owned by the aeronautics, automotive, defense, nuclear industries and the scope of analyses was considerably limited. Finite Element technology was further enhanced during the 70's by such people as Zeinkiewicz and Cheung, when they applied the technology to general problems described by Laplace and Poisson's equations. Mathematicians were developing better solution algorithms, the Galerkin, Ritz and Rayleigh-Ritz methods emerged as the optimum solutions for certain categories of general type problems. Later, considerable research was carried out into the modeling and solution of non-linear problems, Hinton and Crisfield being major contributors.

2.3 Different Approach

One of the advantage of the finite element method is the variety of ways in which one can formulate the properties of individual elements. There are basically three different approaches.

2.3.1 Direct Approach

The first approach to obtaining element properties is called the **Direct Approach** because its origin is traceable to the direct stiffness method of structural analysis. Although the direct approach can be used only for relatively simple problems, because it is the easiest to understand when meeting the finite element method for the first time. The direct approach suggests the need for matrix algebra in dealing with the finite element equations. Main advantage of this approach is that an easy understanding of technique and essential concept is gained without much mathematical illustration. In solving a problem using the direct approach, first, the elements are defined and then their properties are determined. Once the elements have been selected, direct physical relationship are used to established element equation in terns of concerned variables. Finally, elements equations for various elements or members are combined to generate a system of equations which are solved for unknowns.

2.3.2 Variational Approach

Element properties obtained by the direct approach can also be determined by the **Variational Approach**. The variational approach relies on the calculus of variations and involves maximize or minimize a functional. A functional is a quantity whose value depends on entire shape of some functions rather than a number of discrete variables. Functional involves unknown functions and the aim of calculus of variation is to find condition which are imposed when integrals attains stationary values.

It can be observed in variational approach that function that is extreme of the functional is also solution of the corresponding operator equations. Also it is easy to prove the existence of a solution and the condition involved at the interfaces can be easily tackled. Variational formulation has also got the advantages that more complex boundary conditions can be modeled. Moreover, the functional contains lower order derivatives than the differential operator and the problem may posses reciprocal variational formulation.

The main task in using variational principle is to find variational function for the particular problem concerned. It may be possible to find functional for most problems in engineering. However, mathematical manipulations may be required to get the functional, if a classical variational functional is not available for the problem concerned. These mathematical manipulations, whenever required, make the approach more complex. Depending on problem, functional could be an integrated quantity which may be characteristic of the problem.

Knowledge of the variational approach is necessary to work beyond the introductory level and to extend the finite element method to a wide variety of engineering problems. Whereas the direct approach can be used to formulate element properties for only the simplest element shapes, the variational approach can be employed for both simple and sophisticated element shapes.

2.3.3 Weighted Residuals Approach

A third and even more versatile approach to deriving element properties has its basis in mathematics and is known as the weighted residuals approach. The weighted residuals approach begins with the governing equations of the problem and proceeds without relying on a variational statement. In FEM using weighted residuals approach, the domain considered is first discretized with suitable elements. Then, general functional behavior of dependent field variable is assumed so as to approximately satisfied given differential equations over elements. Initially, approximation is applied over each element and subsequently this approximation is substituted into the original differential equation and assembled for whole domain. Approximation results in some error called a 'residual', which is required to vanished in some average sense over the entire solution domain. Resulting system of equation is solved after substitution of boundary conditions to get approximate solution.

This approach is advantageous because it thereby becomes possible to extend the finite element method to problems where no functional is available. The method of weighted residuals is widely used to derive element properties for nonstructural applications such as heat transfer and fluid mechanics.

2.4 Boundary Condition

The choice of the boundary conditions not only influences the final solution, but can further reduce the analysis domain. The boundary conditions that can be imposed form three main groups:

- **Dirichlet condition**

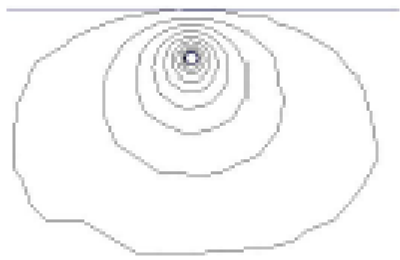

Figure 2.1: Dirichlet boundary condition

This condition is assigning by fixing a determined value of the potential on a given boundary curve. In this way, this curve is characterized by a constant value of the potential, then the equipotential lines result tangential to such a boundary. In other words, no line crosses that boundary. The Dirichlet condition can be expressed as:

$$\phi(r) = f(r) \tag{2.1}$$

if $f(r) = \theta$ this condition is named homogeneous condition;
if $f(r) > \theta$ is known as inhomogeneous condition.

- **Neumann condition**

This condition is assigned by fixing the normal derivative of the potential on a given boundary curve. In other words, the lines crosses the boundary in a known way.
The Neumann condition can be expressed as

$$\frac{\partial\phi(r)}{\partial n} = g(r) \tag{2.2}$$

These boundary conditions are particularly useful in structures characterised by one or more symmetry axes. The analysis is accomplished only on a part of the total structure, imposing the Dirichlet or the Neumann conditions on the symmetry axis itself.

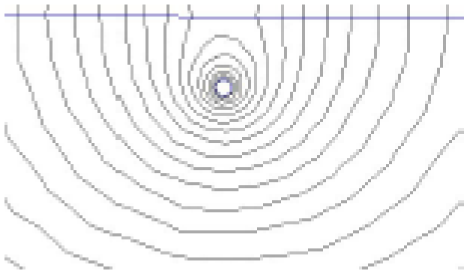

Figure 2.2: Neumann boundary condition

2.5 Thermal Problems

Heating is a very frequent phenomenon on electromagnetic devices and in many situations, the evaluation of temperature is necessary to avoid overheating in structures. In our area, there are different sources of heat such as, Joule effects by eddy and conducting currents, magnetic hysteresis and also mechanical friction. There are three different ways of that heat is transmitted:

- **Conduction**
- **Radiation**
- **Convection**

2.5.1 Thermal Conduction

Conduction is a process where the heat is transmitted inside a body or between different bodies having physical contact. The basic equation describing thermal conduction is (Fouriers equation)

$$c.\frac{\partial T}{\partial t} + \nabla(-\lambda \nabla T) = Q \tag{2.3}$$

where:

- c is the thermal capability
- λ is the thermal conductivity
- T is the temperature
- Q is the thermal source volumetric density

2.5.2 Thermal Convection

Convection occurs when a fluid has contact with a heated solid body. There will be a constant movement where the heated particles will be replaced by cooler ones. The main effect, heat is transmitted from the body to the fluid by the following equation (Newtons equation):

$$\lambda.\frac{dT}{ds}.n = -h.(T - T_a) \tag{2.4}$$

where:

- h is the coefficient of heat transfer by convention
- λ is the thermal conductivity
- T is the temperature at the heated wall
- T_a is the temperature of the fluid at a point far from the wall

The quantity h depends on the fluid properties, velocity and geometry. In practical applications, h is difficult to evaluate and it is normally determined experimentally.

2.5.3 Radiation

Normally for convection and conduction, at least two materials must be present in the system. This is not the case for radiation. A body emits electromagnetic waves. This radiation can reach another body. Part of these waves will be reflected and part will be absorbed by this second body. This last portion will be transformed into thermal energy. A body at temperature T radiates energy to another at temperature T_a involving it, according to the following expression:

$$\lambda\frac{dT}{ds}.n = \varepsilon.\gamma.(T^4 - (T_a)^4) \tag{2.5}$$

where:

- γ is the Stefan-Boltzmann constant
- ε is the emittivity of the body

2.6 Demerits of Finite Element Method

Some demerits of FEM are as follow:

- Close-form expression in terms of problem parameters are not available in FEM. Numerical solution is obtained at one time for specific problem case only. Hence, unlike analytical solution, there is no advantage of flexibility and generalization.

- Large amount of data is required as input for mesh used in terms of nodal connectivity and other parameters depending of the problem.

- Experience, good engineering judgement and understanding of physical problems are required in FEM modeling. Poor selection of element type or discretization may lead to fault result.

2.7 Range of Analysis

- **Magnetostatic Analysis**
  Magnetic analysis is used to design or analyze a variety of devices such as solenoids, electric motors, magnetic shields, permanent magnets, magnetic disk drives, and so forth. Generally the quantities of interest in magnetostatic analysis are magnetic flux density, field intensity, forces, torques, inductance and flux linkage.

- **Transient Electromagnetic Analysis**
  Transient magnetics allows performing transient or steady state AC analysis designing for a variety of DC or AC devices such as electric motors, transformers, and so forth. Generally the quantities of interest in transient magnetics analysis are time functions of magnetic flux density, field intensity, external, induced and total current densities, forces, torques, inductance, and flux linkage.

- **Time-Harmonic Electromagnetic Analysis**
  Time-harmonic electromagnetic analysis is used to analyze magnetic fields caused by alternating currents and, vice versa, electric currents induced by alternating

magnetic fields (eddy currents). This kind of analysis is useful with different inductor devices, solenoids, electric motors, and so forth. Generally the quantities of interest in harmonic magnetic analysis are electric current (and its source and induced component), voltage, generated Joule heat, magnetic flux density, field intensity, forces, torques, impedance and inductance.

- **Electrostatic Analysis**

  Electrostatic analysis is used to design or analyze a variety of capacitive systems such as fuses, transmission lines and so forth. Generally the quantities of interest in electrostatic analysis are voltages, electric fields, capacitances, and electric forces.

- **Current Flow Analysis**

  Current flow analysis is used to analyze a variety of conductive systems. Generally the quantities of interest in current flow analysis are voltages, current densities, electric power losses (Joule heat).

- **Thermal Analysis**

  Thermal analysis plays an important role in the design of many different mechanical and electrical systems. Generally the quantities of interest in thermal analysis are temperature distribution, thermal gradients, and heat losses. Transient analysis allows you to simulate transition of heat distribution between two heating states of a system.

- **Stress Analysis**

  Stress analysis plays an important role in design of many different mechanical and electrical components. Generally the quantities of interest in stress analysis are displacements, strains and different components of stresses.

Chapter 3

Electromagnetic Analysis

3.1 Introduction

For building a busduct model and simulate its electromagnetic behavior, we need to deal with a set of equations named after Maxwell and to solve them. It should be mentioned that most practical problems in electromagnetic cannot be solved purely by means of analytical methods, e.g. radiation caused by a mobile phone near a human head, shielding of an electronic circuit by a slotted metallic box, etc. In many of such cases, numerical methods in electromagnetics can be applied in an efficient way to come to a satisfactory solution. In this chapter, we have introduced the basics of electromagnetism in the frame of Maxwell's equation, steady state electric and magnetostatic field system.

3.2 Maxwell's Equations

In electromagnetics, Maxwell's equations are a set of four equations, developed by James Clerk Maxwell, that describe the behavior of both the electric and magnetic fields as well as their interactions with matter.
Maxwell's four equations express respectively, how electric charges produce electric fields (Gauss' law), the experimental absence of magnetic monopoles, how currents and changing electric fields produce magnetic fields (the Ampere-Maxwell law), and how changing electric fields produce electric fields (Faraday's law of conduction).

Table 3.1 describes these equations in differential form.

Name	Differential form
Gauss's law for electricity	div $.\overrightarrow{D} = \rho$
Gauss's law for magnetism	div $.\overrightarrow{B} = 0$
Faraday's law of induction	curl $\overrightarrow{E}$= -$\frac{\partial}{\partial t}$ $\overrightarrow{B}$
Ampere's law (with Maxwell's extension)	curl $\overrightarrow{H}$= $\overrightarrow{J}$ + $\frac{\partial}{\partial t}\overrightarrow{D}$

Table 3.1: Maxwell equations in Differential Form

where,

$\overrightarrow{D}$[C/m^2] denotes the electric displacement also called the electric flux density,

$\overrightarrow{E}$[v/m] is the electric field,

$\overrightarrow{B}$[T or W/m^2] is the magnetic flux,

$\overrightarrow{H}$[A/m] is the magnetic field,

$\overrightarrow{J}$[A/m^2] is the current density,

ρ [C/m^3] is free electric charge density. Together with the material equations:

$$\overrightarrow{D} = \overrightarrow{E}.\varepsilon \tag{3.1}$$

$$\overrightarrow{B} = \overrightarrow{H}.\mu \tag{3.2}$$

$$\overrightarrow{J} = \overrightarrow{E}.\kappa \tag{3.3}$$

Maxwell's equations describe the behavior of the electromagnetic fields. ε, μ and κ hold the material properties. Usually, they are scalars which depend of course on the location and maybe on the field strength and the time. Gauss' law for electricity is displayed as integral form and in differential form in table 3.1 . In integral form, it states that the electric flux out of any closed surface is proportional to the total charge enclosed within the surface. In differential form, the divergence of the electric flux density gives a measure of the source density. Gauss's law for magnetism is displayed as integral form and in differential form in table 3.1 . In integral form, it states that the net magnetic flux out of any closed surface is always equal to zero. As the divergence of a vector field is proportional to the source density, Gaussfs law for

magnetism in differential form states that no free magnetic charges exist.
Faraday's law of induction states (same table) that the line integral of the electric field around a closed loop is equal to the negative of the rate of change of the magnetic flux through the area enclosed by the loop. This line integral is equal to the generated voltage or electro-motive-force (emf) in the loop,so Faraday's law is the basis for electric generators. It also forms the basis for inductors and transformers. Finally, Ampere's law states that the line integral of the magnetic field around a closed loop is equal to the sum of a) the rate of change of the electric flux and b) the conduction and impressed current density through the area enclosed by the loop.

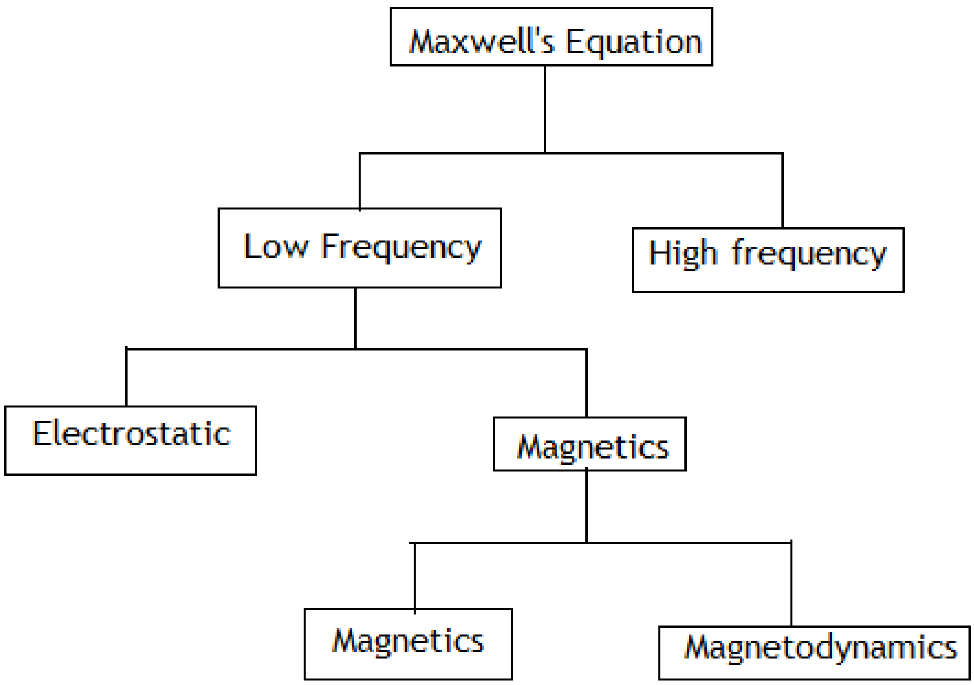

Figure 3.1: Classification of Maxwell equation

3.3 Electrostatic and Magnetostatic Fields

In general, there are two classes of electromagnetic fields can be described:

- The time independent static
- Time varying fields

They can be scalar and vector fields. A typical scalar field for example is the electrostatic potential distribution V(x,y,z) between charged electrodes; and the magnetic field intensity H(x,y,z) surrounding a current carrying conductor is a typical vector field. We have to distinguish between the slow and fast varying electrical current flow field with regard to the geometrical dimensions of the current carrying conductor.

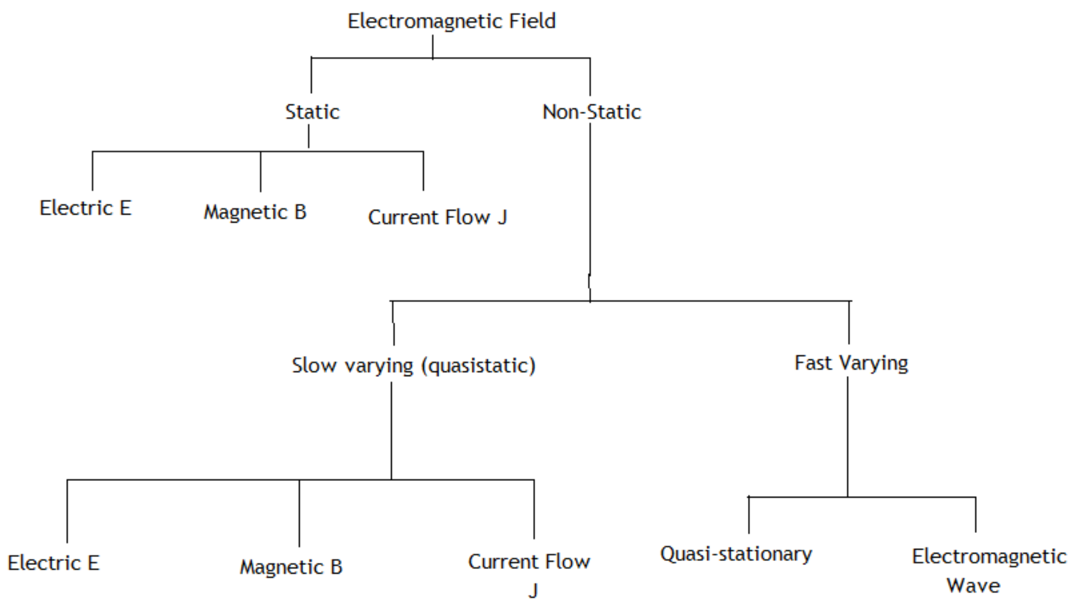

Figure 3.2: Classification of Electromagnetic field

The slow varying fields are understood to be fields not leading to current redistributions. This means that there are no eddy current effects as the dimensions of the current carrying conductor are smaller than the penetration depth of the field. The currents at those frequencies are distributed as in the DC case, uniformly over the whole surface of the conductor. Eddy current effects are considered in the fields with fast varying time dependence, due to the low frequency being treated as quasi-stationary. High frequency fields, as focussed on antenna problems and leading to the electromagnetic waves.

Most of the physical issues in energy engineering can be described by quasistatic phenomena. Slowly varying and periodic fields up to 10 kHz are considered to be quasi-stationary. Electrical energy devices such as motors, actuators, induction furnaces and high voltage transmission lines are operated at low frequency.

Typical examples of quasi-static fields are the fields excited by coils in rotating electrical machines and transformers. Inside these conductors the displacement current is negligible and the magnetic field H outside the coil is exclusively excited by the free current density J. For those quasi-static fields, Amperes law is applicable:

$$J = \nabla \times H \tag{3.4}$$

Deciding whether the displacement current can be neglected or not, depends on the wavelength λ of the problem considered in the frequency domain. If it is large compared to the physical dimensions of the problem L, the displacement current is negligible. the field problem can be considered as quasi-static. For this class of problem, the interesting fields vary slowly and can be periodic. So, three categories of problems are distinguished:

- Static
- Slowly varying transient
- Time-harmonic eddy current

In time-harmonic problems sinusoidal varying field quantities is assumed. In theory, a time-harmonic solution is only valid for linear systems as a sinusoidal excitation does not yield a single frequency response in the non-linear case.
In order to analyze the electromagnetic fields, there are two general approaches

a. High-frequency electromagnetic analysis
   This type of analysis calculates the propagation properties of electromagnetic fields and waves in a given structure. High-frequency electromagnetic field analysis simulates the electromagnetic phenomena in a structure when the wavelength of the signal is of the same order of magnitude or smaller than the dimensions of the model. The high-frequency band ranges from hundreds of MHz to hundreds of GHz. In this case, the analysis can also classified into two following catagories:

- time-harmonic analysis
- modal high-frequency analysis

b. Low frequency electromagnetic analysis

For low-frequency problems, or one can say quasi-static problems, the displacement current in Maxwell's equations is ignored. Therefore, charge accumulation and capacitance effects are excluded. This approach is valid when the working wavelength is much larger than the geometric dimensions of structure or the electromagnetic interactions are not obvious in the system. Otherwise, the full set of Maxwell's equations must be solved (high frequency analysis).

In this category the different types of analysis can be followed: static magnetic analysis for analyzing magnetic fields caused by direct current (DC) or permanent magnets, harmonic magnetic analysis for analyzing magnetic fields caused by low frequency alternating current (AC) or voltage and finally transient magnetic analysis which analyze magnetic fields caused by arbitrary electric current or external field that varies over time. Some applications of low frequency electromagnetic analysis are in transformers, electric motors, magnetic imaging systems etc.

3.4 Electro-static field

The two fundamental laws governing these electrostatic fields are Gausss law and Faradays law. In terms of the electric (scalar) potential V, E is expressed as

$$E = -\nabla V \tag{3.5}$$

or

$$V = -\int E.dl \tag{3.6}$$

The Poissons equation as:

$$\nabla \epsilon . \nabla V = -\rho \tag{3.7}$$

or if ϵ is constant:

$$\nabla^2 V = -\frac{\rho}{\epsilon} \tag{3.8}$$

When $\rho = 0$, this equation becomes Laplaces equation:

$$\nabla^2 V = 0 \tag{3.9}$$

3.4.1 Electric Potential

In classical electromagnetism, the electric potential (a scalar quantity denoted by V and also called the electric field potential or the electrostatic potential) at a point within a defined space is equal to the electric potential energy (measured in joules) at that location divided by the charge there (measured in coulombs). The electric potential at a specific location in the electric field is independent of q_t. That is to say, it is a characteristic only of the electric field that is present. The electric potential can be calculated at a point in either a static (time-invariant) electric field or in a dynamic (varying with time) electric field at a specific time, and has the units of joules per coulomb, or volts. There is also a generalized electric scalar potential that is used in electrodynamics when time-varying electromagnetic fields are present. The electric potential created by a point charge Q, at a distance r from the charge (relative to the potential at infinity), can be

$$V = \frac{Q}{4\Pi\epsilon r} \tag{3.10}$$

3.4.2 Current Density and Continuity Equation

Current density is defined as the current flowing in unit area when the area is held normal to the flow of charges. It is a represented by J. When a steady state current is passing through a conductor, the current density is uniform if conductor has uniform cross-section.

$$J = \frac{\Delta I}{\Delta S} \tag{3.11}$$

The direction of J is such that maximum number of charges cross the macroscopic surface in that orientation. Consider different orientations for the microscopic surface. Normal drawn microscopic surface under this orientation gives the direction of current density vector.

$$J = \frac{dI}{ds} \tag{3.12}$$

$$dI = \overrightarrow{J}.\overrightarrow{d}s \tag{3.13}$$

Net out flow of current per unit volume is negative of time rate of charge per unit volume. The continuity equation explains the law of conservation of charge as well as continuity of current.

$$divJ = -\frac{\partial\rho}{\partial t} \tag{3.14}$$

$$\nabla J = -\dot{\rho} \tag{3.15}$$

According to law of conservation of charge, charge can be neither created nor destroyed.Same charge keeps flowing.Existing charge can not be destroyed and new charge can not be created.The divergence of J gives net outflow of current per unit volume.

3.4.3 Joule loss and Heating

Joule heating, also known as ohmic heating and resistive heating, is the process by which the passage of an electric current through a conductor releases heat.Joule heating is referred to as ohmic heating or resistive heating because of its relationship to Ohm's Law. It forms the basis for the myriad of practical applications involving electric heating. However, in applications where heating is an unwanted by-product of current use (e.g., load losses in electrical transformers) the diversion of energy is often referred to as resistive loss. According Joule's law Heat energy is proportional to I^2, R and t. Heat energy $\propto I^2$ R t

$$Energy = \frac{I^2}{R} t J_1 \tag{3.16}$$

where J_1 is called joule's constant. We know the Power

$$P = I^2 R = \frac{V^2}{R} = VI \tag{3.17}$$

multiply and divide with volume, it will be

$$P = EJVolume \tag{3.18}$$

where,

E= $\frac{V}{l}$ is the electric field intensity and J=$\frac{I}{A}$ is the current density. Since E and J are in same direction,

$$P = (\vec{E}.\vec{J})Volume \tag{3.19}$$

$$P = \int (E.J)dv \tag{3.20}$$

The energy dissipated per second is volume integral of dot product of vector E and J.Heat produced by the conductor is due to collision of electrons inside the conductor.

3.5 Magneto-Static Field

A magnetic field is a mathematical description of the magnetic influence of electric currents and magnetic materials. The magnetic field at any given point is specified by both a direction and a magnitude (or strength); as such it is a vector field.The magnetic field is most commonly defined in terms of the Lorentz force it exerts on moving electric charges. There are two separate but closely related fields to which the name 'magnetic field' can refer: a magnetic B field and a magnetic H field.

The basic laws of magnetosttic fields are Amperes law, and the law of conservation of magnetic flux. In terms of the magnetic (vector) potential A

$$B = \nabla \times A \tag{3.21}$$

Applying the vector identity

$$B = \nabla \times \nabla \times F = \nabla(\nabla . F) - \nabla^2 F \tag{3.22}$$

Poissons equation for magnetostatic fields

$$\nabla^2 A = -\mu J \tag{3.23}$$

When J=0, this equation becomes Laplaces equation:

$$\nabla^2 A = 0 \tag{3.24}$$

3.5.1 Magnetic Flux Density

The magnetic flux per unit area is called magnetic flux density.The magnetic flux through a given surface is proportional to the number of magnetic B field lines that pass through the surface. This is the net number, i.e. the number passing through in one direction, minus the number passing through in the other direction.

For a uniform magnetic field B passing through a perpendicular area the magnetic flux is given by the product of the magnetic field and the area element. The magnitude and direction of B due to the current carrying conductor is given by Bio-savart's law.

$$B = \frac{d\phi}{ds} \tag{3.25}$$

on integrating

$$\phi = \int_s B.ds \tag{3.26}$$

3.5.2 Magnetic Field Intensity

Magnetostatic deals with magnetic field produced by steady state current. Steady current flowing through a straight conductor produces magnetic field in the form concentric circle. The intensity of this magnetic field is given by Bio-Savart's law.

$$H = \int \frac{\overrightarrow{Idl} \times \overrightarrow{r}}{4\Pi r^3} \tag{3.27}$$

3.5.3 Magnetic field boundary condition

Boundary conditions play a key role for solving partial differential equations. They determine the form of the basis set used in the expansion of the general solution. The sets of eigenvalues and basis functions can be either continuous or discrete (or a combination) depending on the nature of the boundary conditions. We will need boundary conditions when we solve Maxwells equations for waveguides, reflection coefficients and Snells law. For the magnetic field, an integration path is constructed along the same lines as the one used to determine the boundary condition on the electric field. Note that the equations governing E and H are similar except that the one for H has a non-zero right-hand side. If the current density is zero over the region of interest, then there is really no distinction between the two and one can say that the tangential magnetic fields must be equal across a boundary. However, if a surface current exists on the interface, there may be a discontinuity in the tangential fields. The boundary condition is given by

$$\hat{n} \times (H_1 - H_2) = K \tag{3.28}$$

where, K is the surface current density.

Chapter 4

Modeling and Simulation

4.1 Introduction of ANSYS

Today's technology and business environment is rife with competitive challenges, customer requirements and financial pressures. This combination of factors has resulted in the need to find new methods for engineering more innovative products and manufacturing processes while minimizing costs and time to market. Virtually every industry now recognizes that a key strategy for success is to incorporate computer-based engineering simulation early in the development process, allowing engineers to refine and validate designs at a stage where the cost of making changes is minimal.

ANSYS is the original (and commonly used) name for a Multiphysics, general-purpose finite element analysis software. ANSYS Multiphysics are self contained analysis tools incorporating pre-processing (geometry creation, meshing), solver and post processing modules in a unified graphical user interface. At ANSYS,the possibilities for most complex design challenges through fast, accurate and reliable simulation. The technology enables organizations to predict with confidence that their products will thrive in the real world. Figure 4.1 shows the flowchart for finite element analysis using this software. ANSYS is a general purpose finite element modeling package for numerically solving a wide variety of problems. These problems include: static and dynamic structural analysis (both linear and non-linear), heat transfer and fluid problems, as well as acoustic and electro-magnetic problems. The ANSYS Multiphysics software is a general-purpose analysis tool allowing a user to combine the effects of two or more different yet interrelated physics, within one unified simulation environment. In this chapter, we have followed the sequence of analysis, demonstrate Electric-Thermal Couple analysis for typical busduct system.

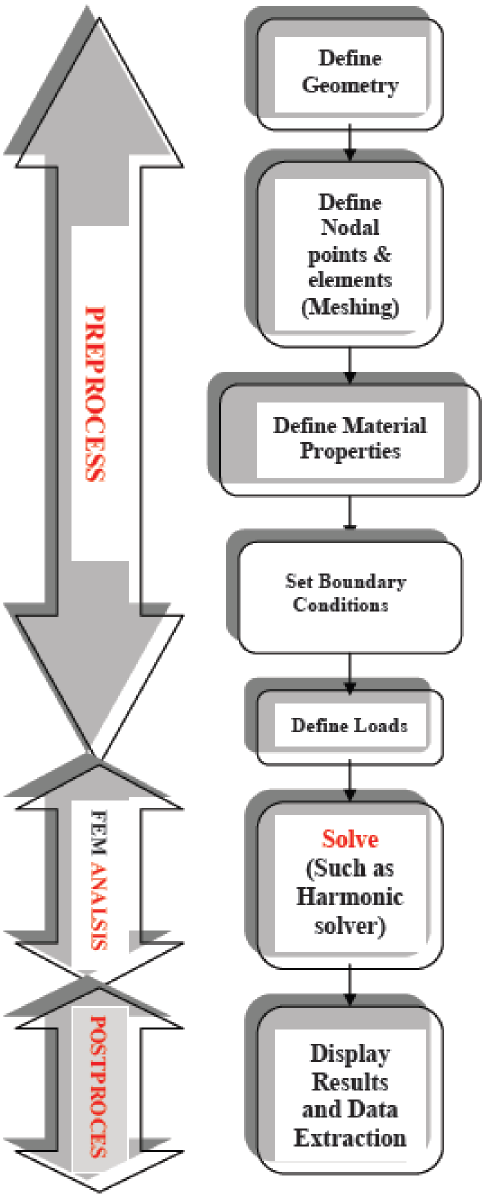

Figure 4.1: Flow chart of FEM analysis using ANSYS

Now, we come to the busbar simulation using Finite Element Method with the simulation tool ANSYS. As shown in figure 4.1, the task sequence in an ANSYS simulation has some main parts which are essentially the same no matter how your simulation project looks like:

a. Geometry Modeling

b. Setting up material properties(such as permeability,resistivity,conductivity etc)

c. Meshing

d. Application of loads and degrees of freedom. Deciding what boundary conditions have to be fulfilled.

e. Numerical solving: This gives us the solution for every nodes or elements(discrete)

f. Postprocessing: Visualization of element solution and data export

4.2 Geometry and Material properties

A conductor body is characterized as a body that can carry current and possible excitation to the system. Solid CAD geometry is used to model solid source conductors. In solid conductors, such as busbars, the current can distribute non-uniformly due to bar position changes, hence the program performs a simulation that solves for the currents in the solid conductor prior to computing the electric as well as magnetic field.
Here, typical 2000 mm long busduct system having copper conductors with bakelite supports has been introduced. The busduct consists of Copper bars, Bakelite insulation for busbar supports and grounded metallic enclosure of structure steel. Fig 4.2 and fig 4.3 shows three dimensional geometry of busduct system with enclosure and along with bakelite supports respectively. Fig 4.4 and fig 4.5 shows busbars arrangement with respect to phase position in which four buses per phase has been arranged. Table 4.1 and Table 4.2 shows the dimension of busduct system and material properties respectively.

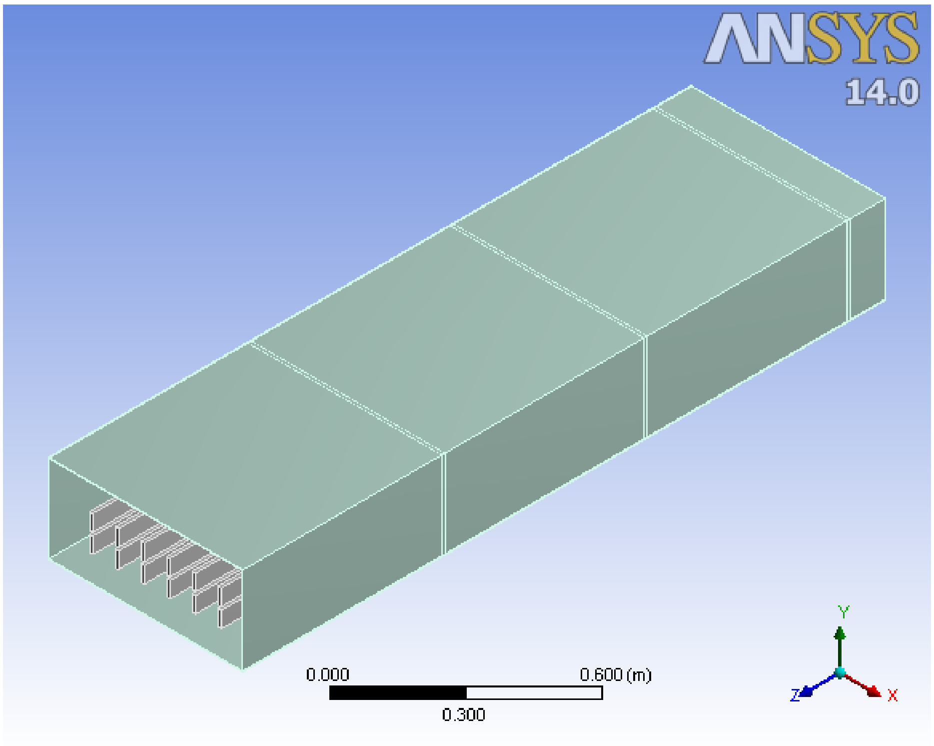

Figure 4.2: Three dimensional view of Busduct System

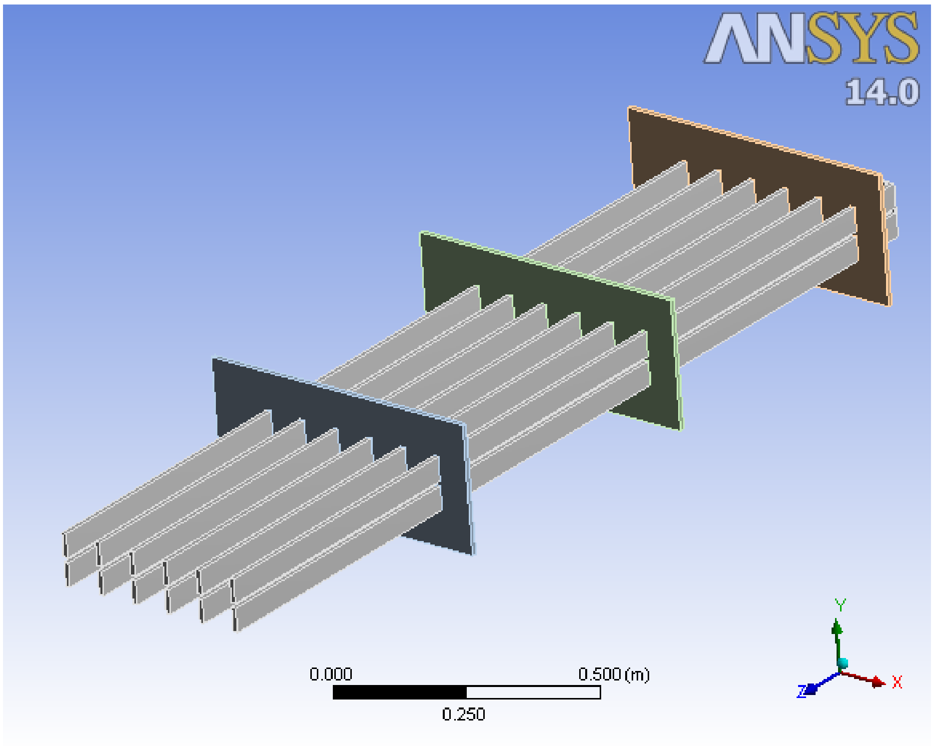

Figure 4.3: Busduct System along with Bakelite supports

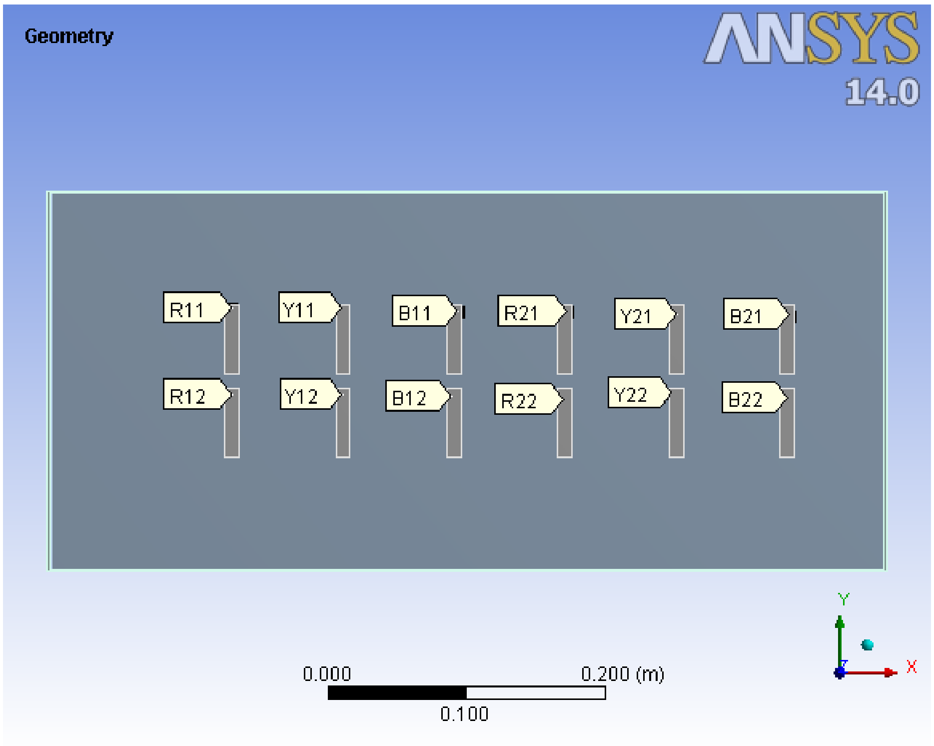

Figure 4.4: Busbar arrangement with respect to phase position

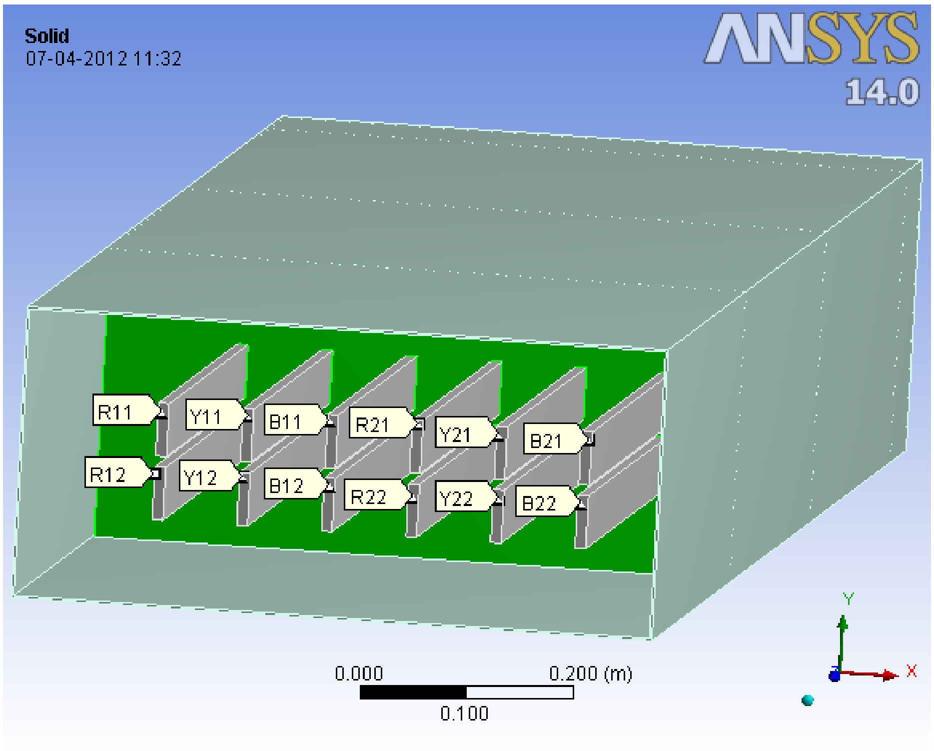

Figure 4.5: Phase position of buses along with Enclosure

Sr. no	Parameters	Material	Values
1	Enclosure	Structure steel	270mm x 600mm x 2000mm
2	Busbars	Copper alloy	50mm x 10mm x 4 bus per phase
3	Bus Supports	Bakelite	270mm x 600mm x 10mm

Table 4.1: Dimension of Busduct system

Sr. no	Parameters	Material	Values
1	Density	Structural Steel	7850 kg m^{-3}
2	Specific Heat	Structural Steel	434 J $kg^{-1}C^{-1}$
3	Isotropic resistivity	Structural Steel	1.7e-007 (Ohm m)
4	Isotropic Relative Permeability	Structural Steel	10000
5	Density	Copper Alloy	8300 kg m^{-3}
6	Coefficient of Thermal Expansion	Copper Alloy	1.8e-005 C^{-1}
7	Specific Heat	Copper Alloy	385 J $kg^{-1}C^{-1}$
8	Isotropic Thermal Conductivity	Copper Alloy	401 W m^{-1} C^{-1}
9	Isotropic Resistivity	Copper Alloy	1.694e-008 (ohm m)
10	Isotropic Relative Permeability	Copper Alloy	1
11	Density	Bakelite	1300 kg m^{-3}
12	Isotropic Thermal Conductivity	Bakelite	1.4 W m^{-1} C^{-1}
13	Specific Heat	Bakelite	820 J $kg^{-1}C^{-1}$

Table 4.2: Material Properties of Copper Alloy, Bakelite and Structural Steel

4.3 Meshing and Element types

Meshing is the process in which geometry is spatially discretized into elements and nodes. This mesh along with material properties is used to mathematically represent the stiffness and mass distribution of structure. Here, we have applied Patch conforming meshing. This is a meshing technique in which all faces and their boundaries (edges and vertices) [patches] within a very small tolerance are respected for a given busduct. Patch conforming meshing is invariant to loads, boundary conditions, Named Selections, results or any scoped object. That is, when we change the scope of an object, there is no need to re-mesh. The Patch Conforming Tetra mesh method provides Support for three dimensional inflation, Built-in pyramid layer for conformal quad-tet transition and Built-in growth and smoothness control. We can try to create a smooth size variation based on the specified growth factor.

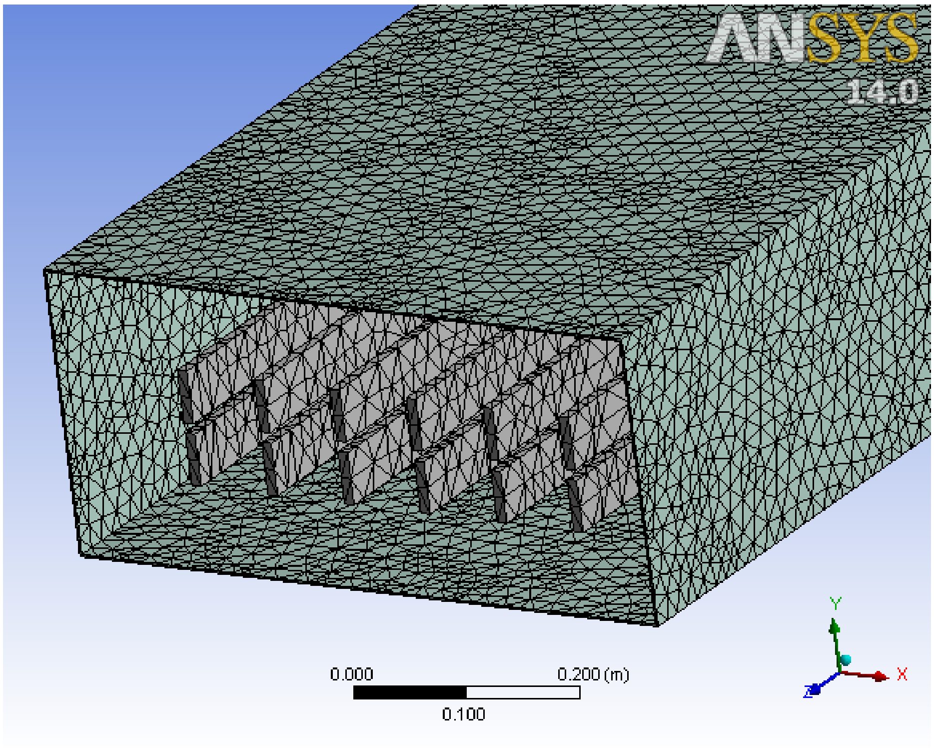

Figure 4.6: Patch conforming tetrahedron meshing over Enclosure

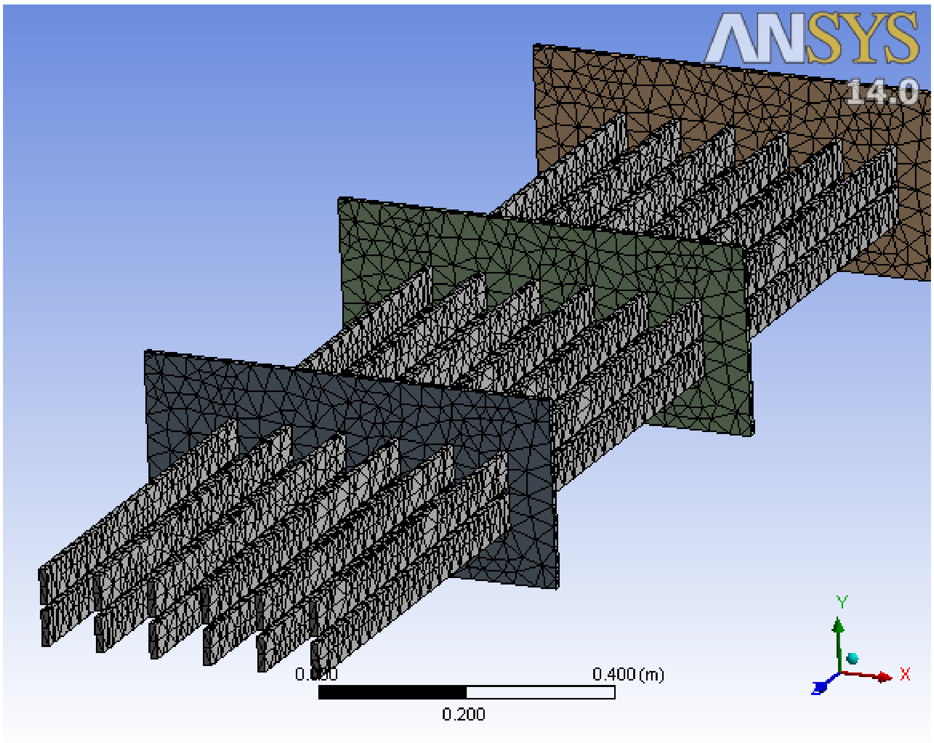

Figure 4.7: Patch conforming tetrahedron meshing along with busbar supports

The busduct is meshed with the SOLID 232 element, three dimensional 10-node, tetrahedral current-based electric element. The element has one degree of freedom, voltage at each node and is based on the electric scalar potential formulation. It is applicable to the low frequency time-harmonic quasi-static electric field analysis. Fig 4.6 and Fig 4.7 shows Patch conforming Tetrahedron Meshing over Enclosure and bakelite supports along the buses respectively.

4.4 The load

After having defined the simulation geometry along with the material properties and having defined the finite element mesh along with the boundary conditions, we have to define the loads. A three phase current, say 2500 Ampere(rms) per phase is applied on every node of solid conductors. Furthermore, to terminate heavy current, ground potential is provided at one of the end of each busbar. Coupling degrees of freedom into a set causes the results calculated for one member of the set to be the same for all members of the set.

For thermal analysis, the results are imported from the steady-state electrical analysis. As per input parameters, internal heat generation and convection is applied from all bodies. Fig 4.8 shows the thermal boundary condition is applied as convection. The natural air Convection is applied on every busbar surfaces such that the internal heat generation is dissipated on surface to directly atmosphere.

4.5 Numerical Solver

The main goal of this dissertation is to find the temperature at every node of busduct system. The electrical-thermal analysis has been carried out. A thermal-Electric Conduction analysis allows for a simultaneous solution of thermal and electric fields. This coupled-field capability models joule heating for resistive materials. For Electric-

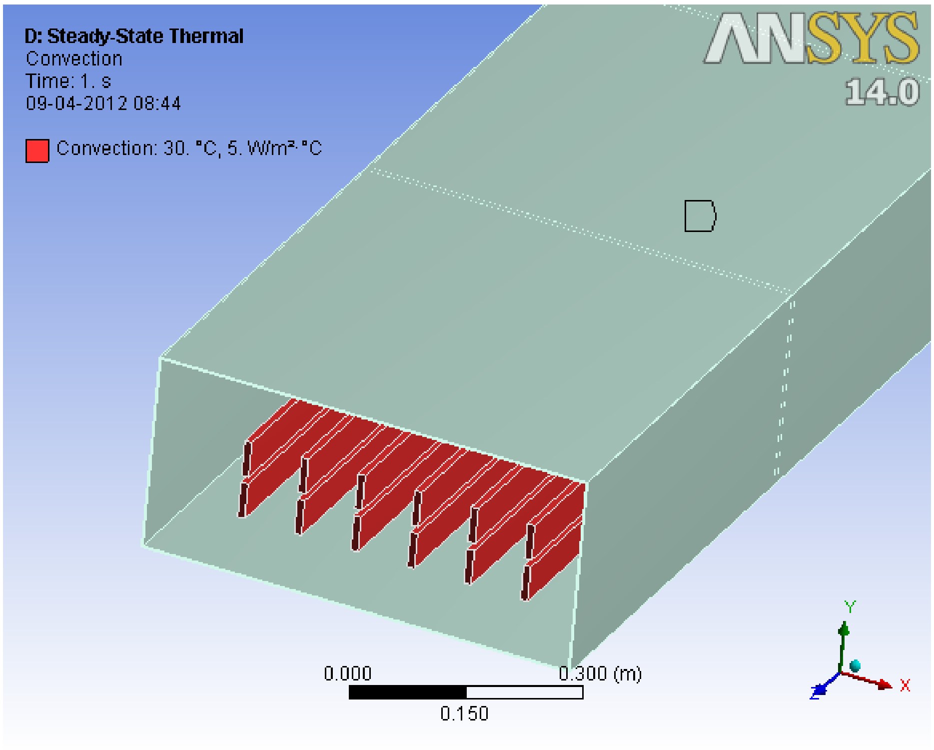

Figure 4.8: Thermal Boundary condition

thermal analysis, The basic controls are:

- Step Controls
- Nonlinear Controls
- Output Controls

4.5.1 Step Controls

Step Control used to specify the end time of a step in a single or multiple step analysis. Multiple steps are needed if to be change load values, the solution settings or the solution output frequency over specific steps. Typically We do not need to change the default values.

4.5.2 Nonlinear Controls

Typical thermal-electric problems contain temperature dependent material properties and are therefore nonlinear. For both thermal and electrical effects are available and include Heat and Temperature convergence for thermal effects and Voltage and Current convergence for electric effects. The Program Controlled option for Nonlinear Formulation defaults to the Quasi option but the full option is used in cases when a Radiation load is present or when a distributed solver is used during the solution.

4.5.3 Output Controls

Output Control allow to specify the time points at which results should be available for postprocessing. A multi-step analysis involves calculating solutions at several time points in the load history. However, we may not be interested in all of the possible results items and writing all the results can make the result file size unwieldy. We can restrict the amount of output by requesting results only at certain time points or limit the results that go onto the results file at each time point.

4.6 Post Processing

After building the model and obtaining the solution, it is need to show solution which defined before solving. To show it, we should perform post processing. Post processing means reviewing the results of an analysis. It is probably the most important step in the analysis, because one is trying to understand how the applied loads affect the design, how good the finite element mesh is, and so on. In ANSYS, two postprocessors are available to review the results: POST1, the general postprocessor, and POST2, the time-history postprocessor. Via the post processor of ANSYS, it is possible to plot or visualize the results at Nodal as well as element based solution.
Figure 4.9 shows the total current density distribution and in Figure 4.10 shows the total joule heating distribution over the busbars. Based on couple analysis, figure 4.11 and figure 4.12 shows temperature distribution along with busbars and on enclosure respectively.

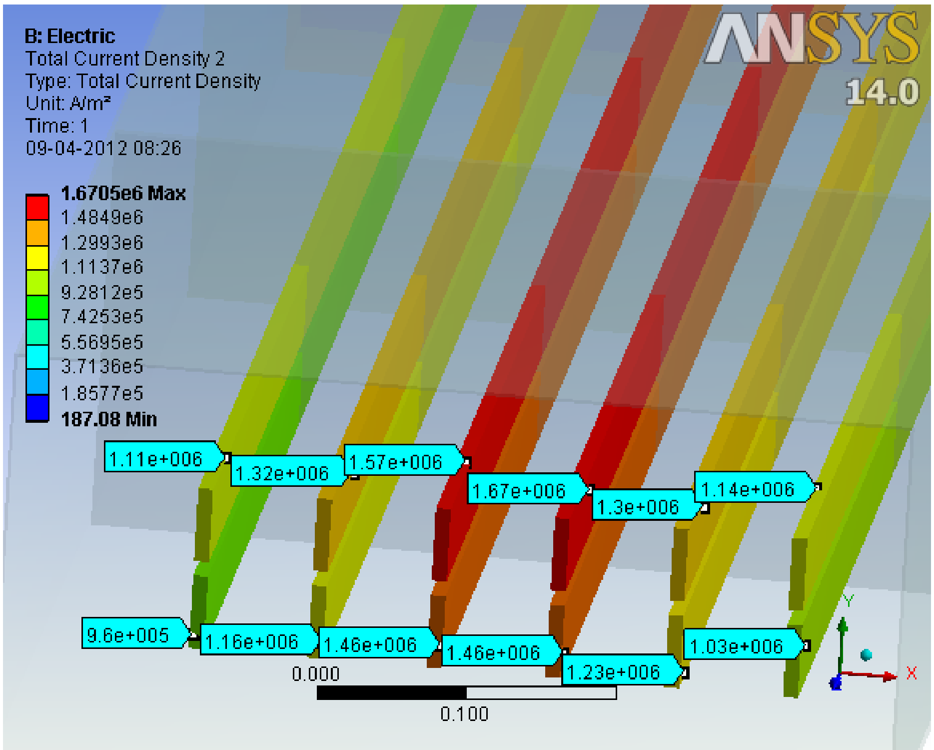

Figure 4.9: Total Current Density distribution over the busbars

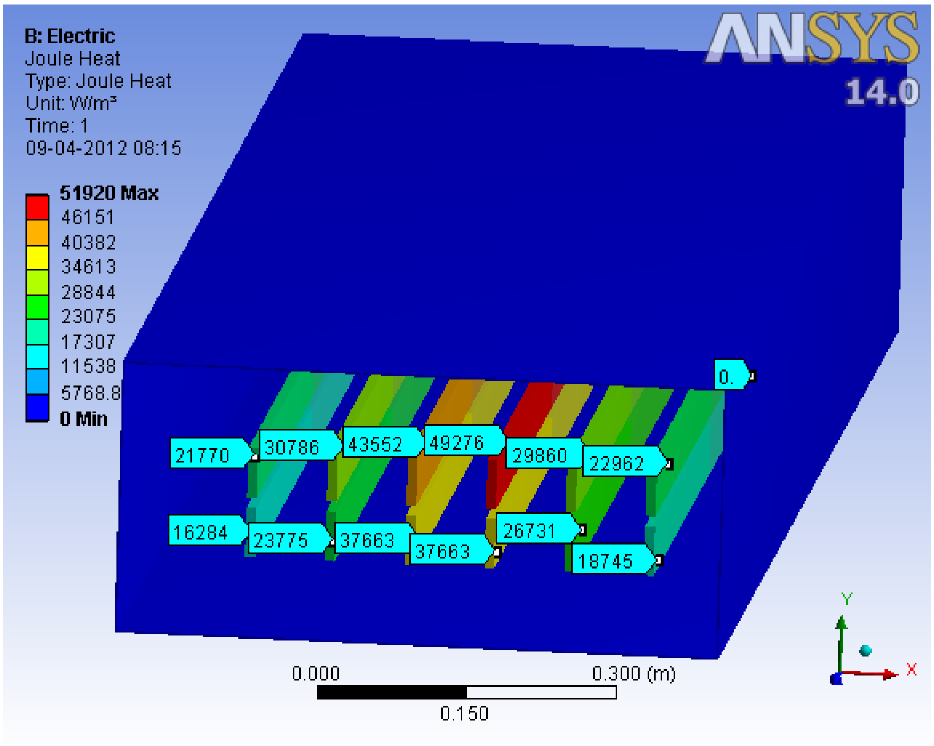

Figure 4.10: Joule Heating distribution

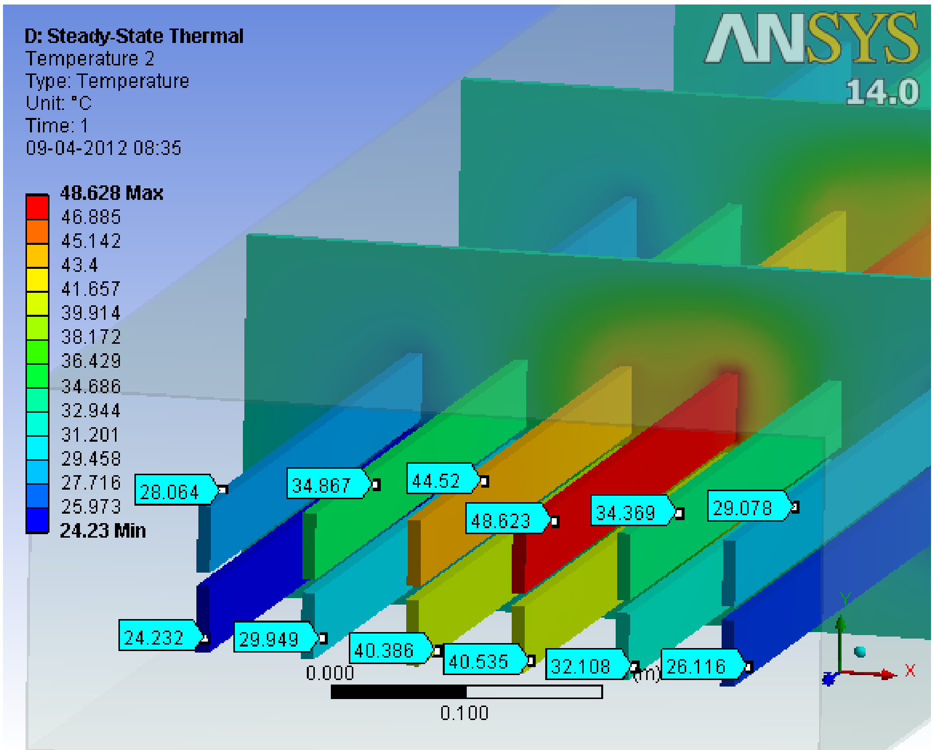

Figure 4.11: Temperature Distribution over the busbars

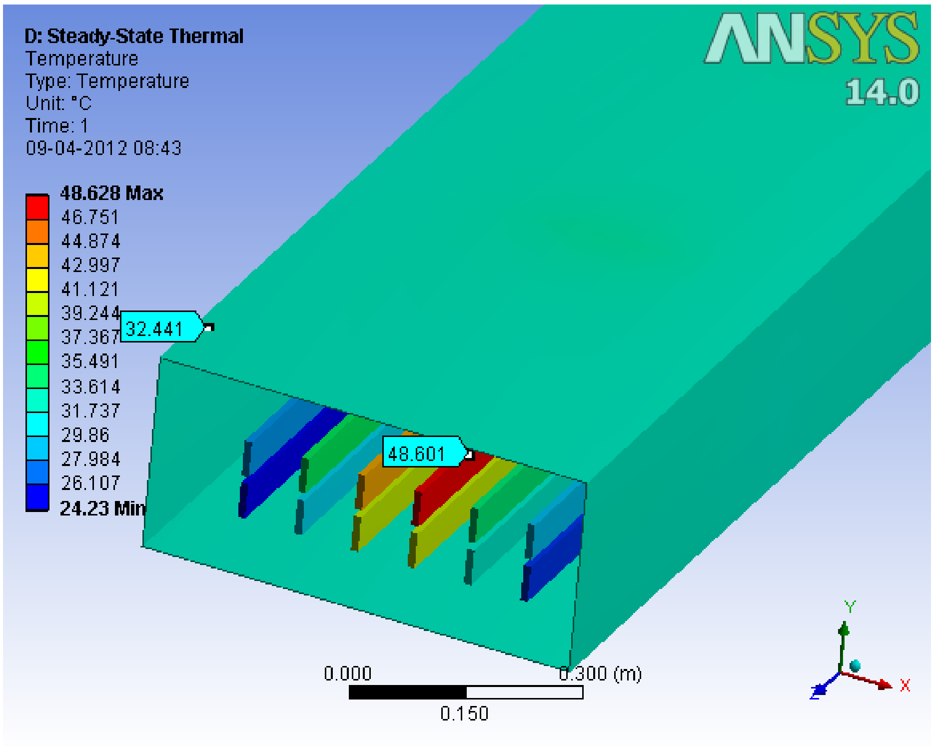

Figure 4.12: Temperature Distribution on Enclosure along with busbars

Here, we have simulated two more configurations and solved electrical-thermal couple analysis and evolute electrical as well as thermal simulation values. In both configuration, two busbars per phase has been arranged. Both configurations have same dimension and material properties but the phase position and busbar position is different. The material properties of Copper alloy, Bakelite supports and Structural steel encloser is the same as mentioned in table 4.2.

Table 4.3 shows the dimensions for both configurations of given busduct system.

Sr. no	Parameters	Material	Values
1	Encloser	Structure steel	270mm x 600mm x 2000mm
2	Busbars	Copper alloy	100mm x 10mm x 2 bus per phase
3	Bus Supports	Bakelite	270mm x 600mm x 10mm

Table 4.3: Dimension of new configurations

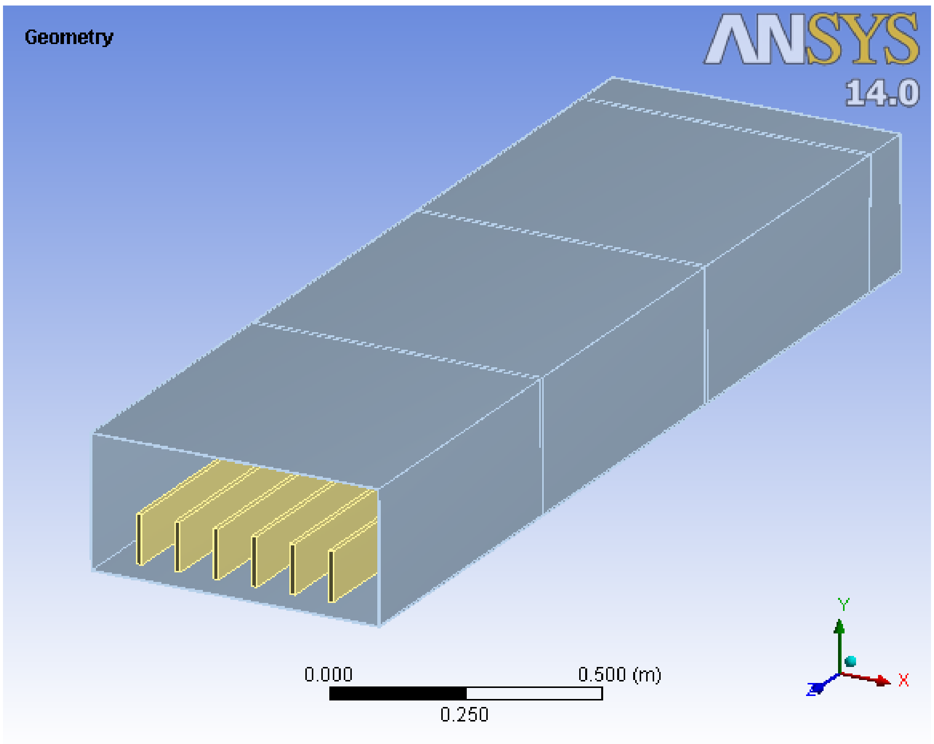

Figure 4.13: Three dimensional view of second configuration busduct system

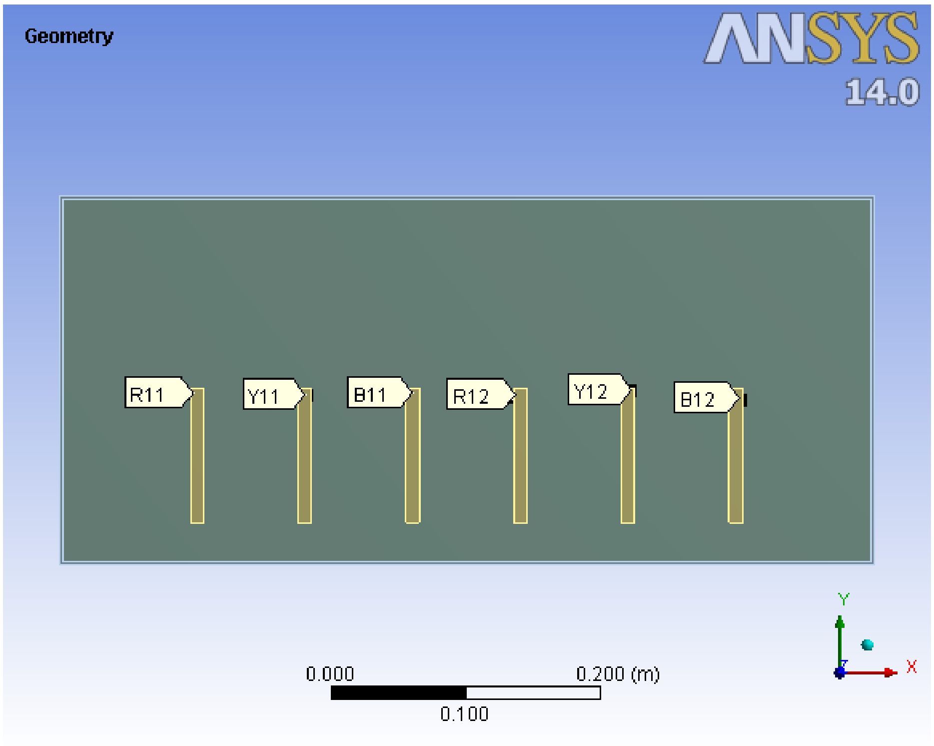

Figure 4.14: Phase position and busbar arrangement

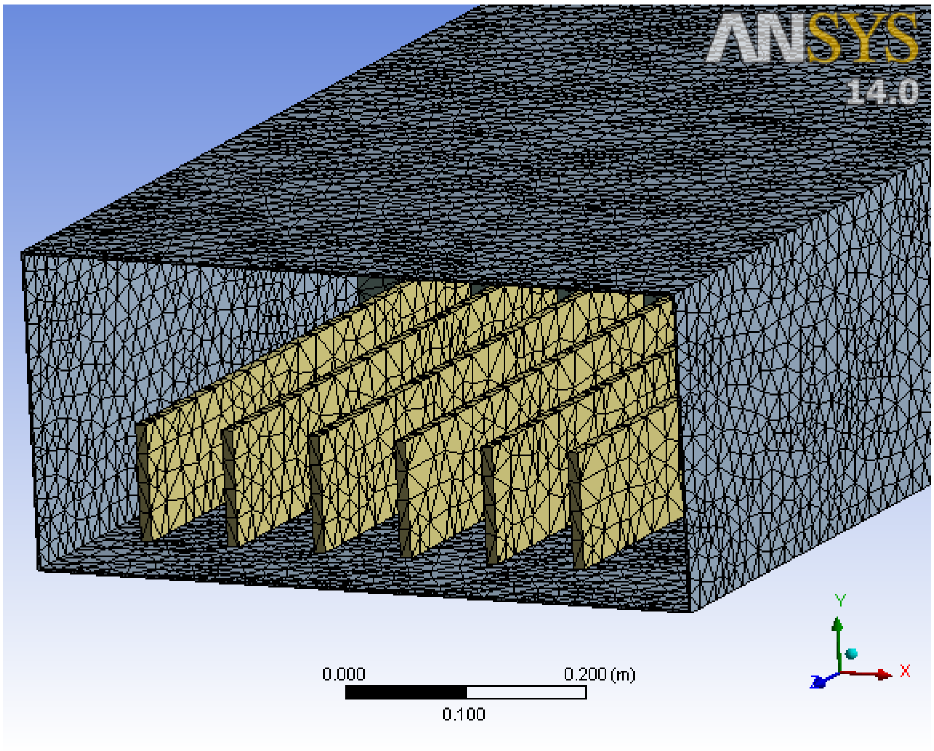

Figure 4.15: Patch conforming mesh

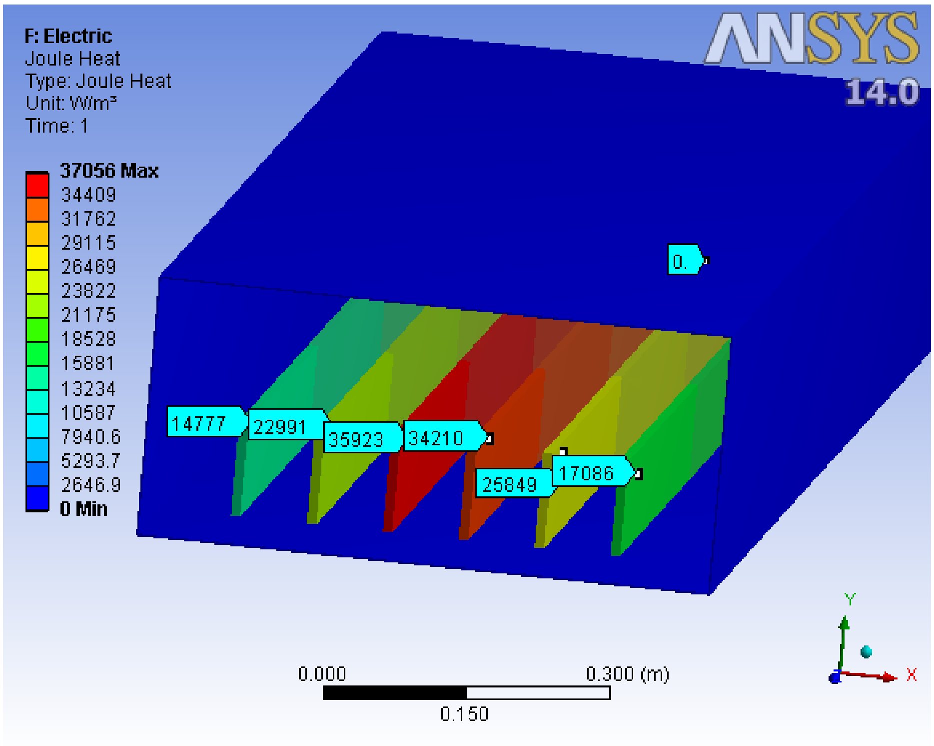

Figure 4.16: Joule Heat distribution

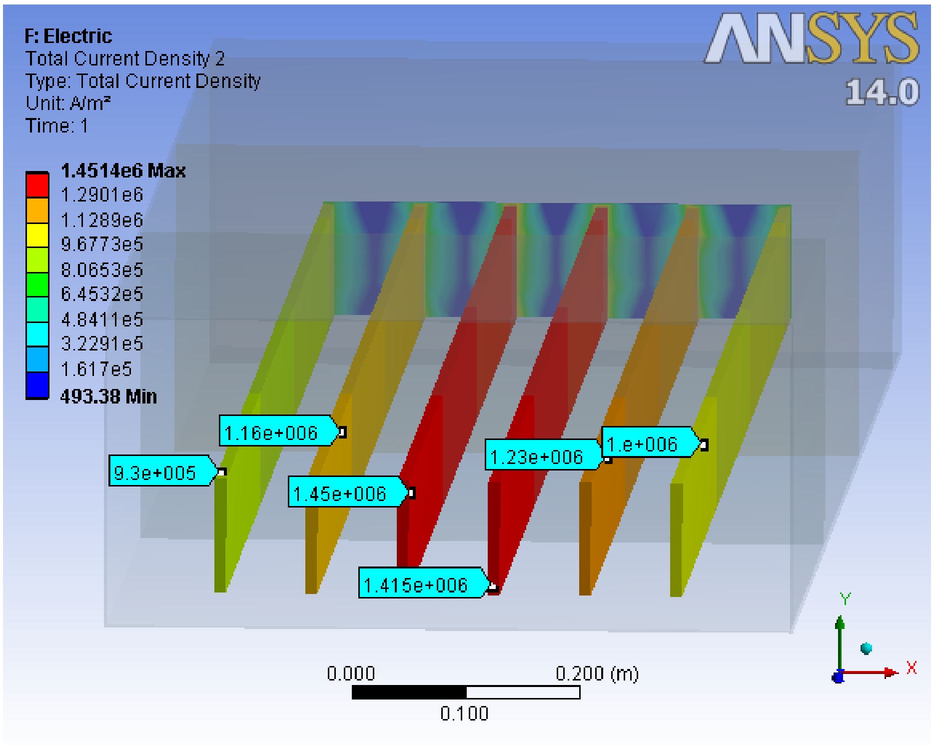

Figure 4.17: Total Current Density along with busbars

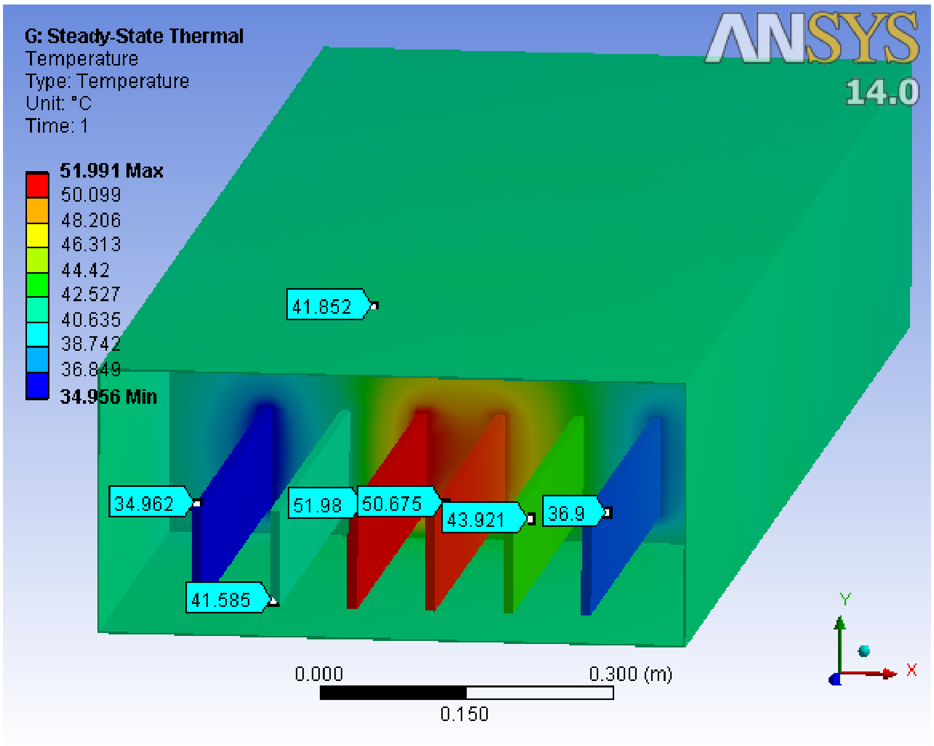

Figure 4.18: Temperature Distribution on enclosure along with busbars

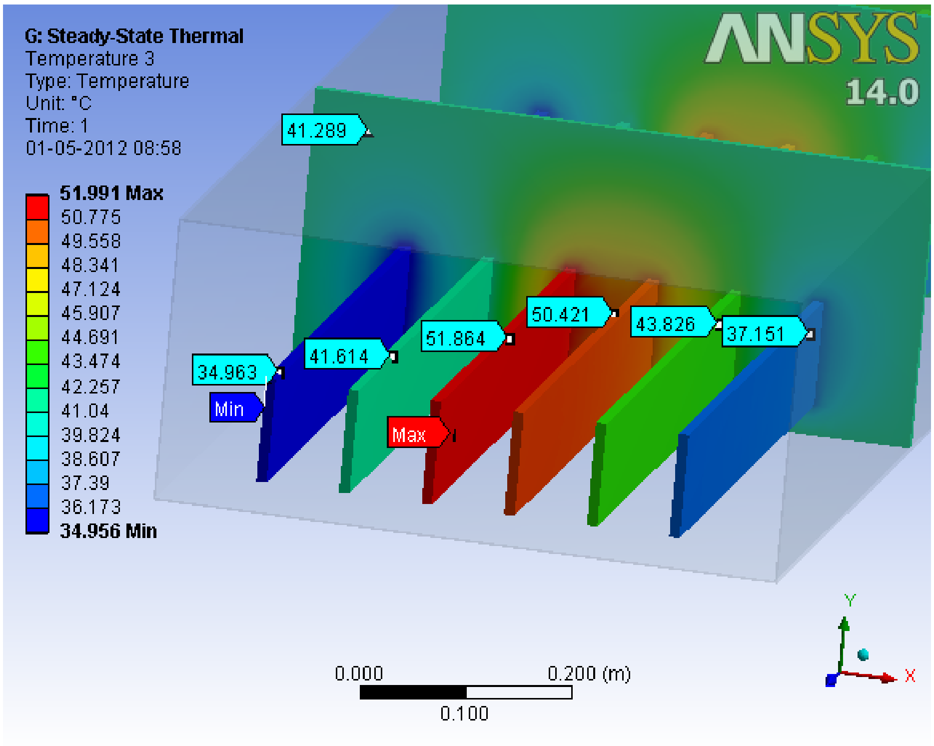

Figure 4.19: Temperature Distribution over the busbars and bakelite supports

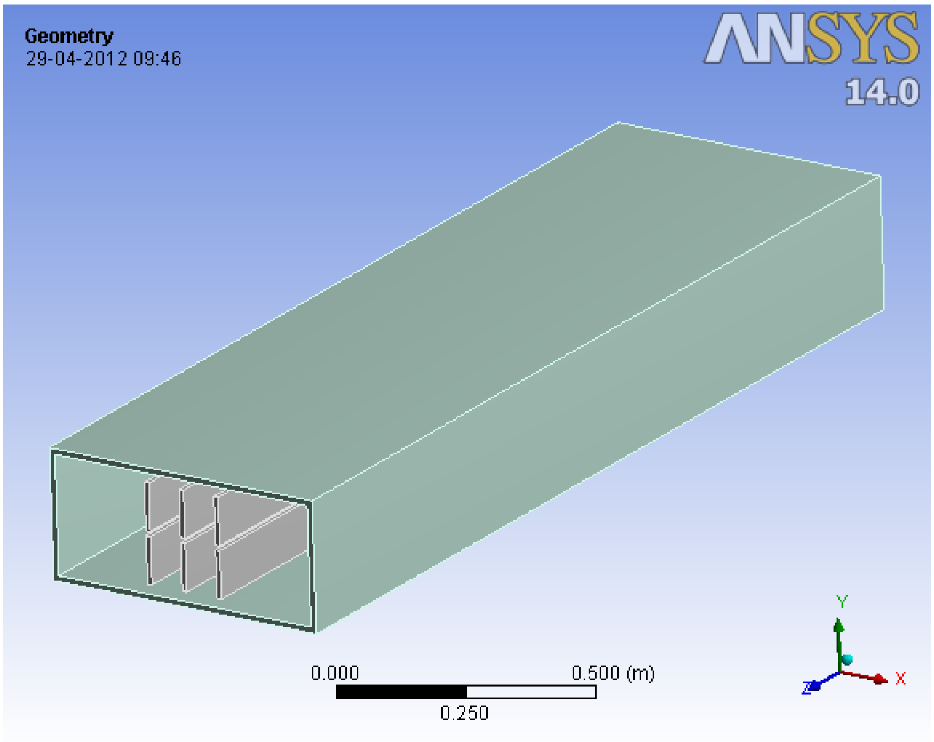

Figure 4.20: Three dimensional view of third configuration busduct system

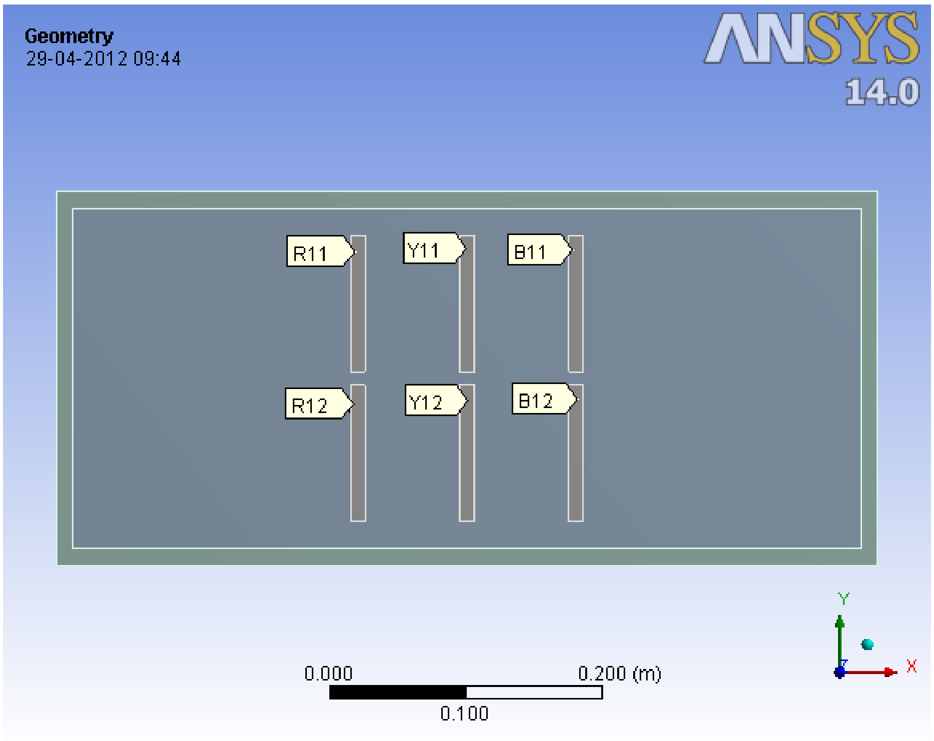

Figure 4.21: Phase position of busbars arrangement

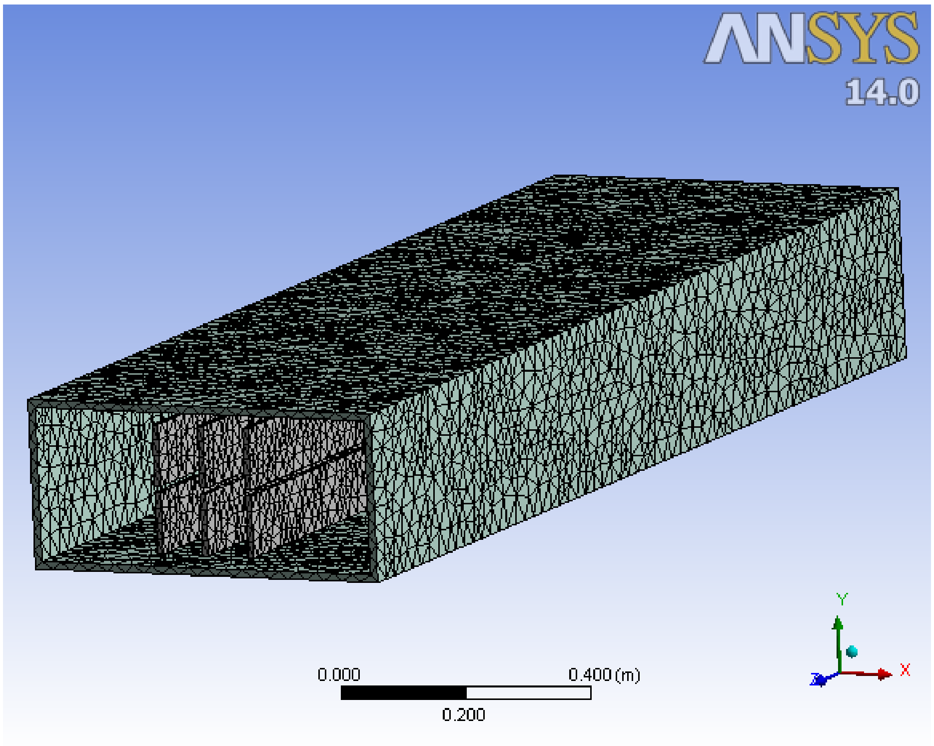

Figure 4.22: Patch Conforming meshing on Encloser

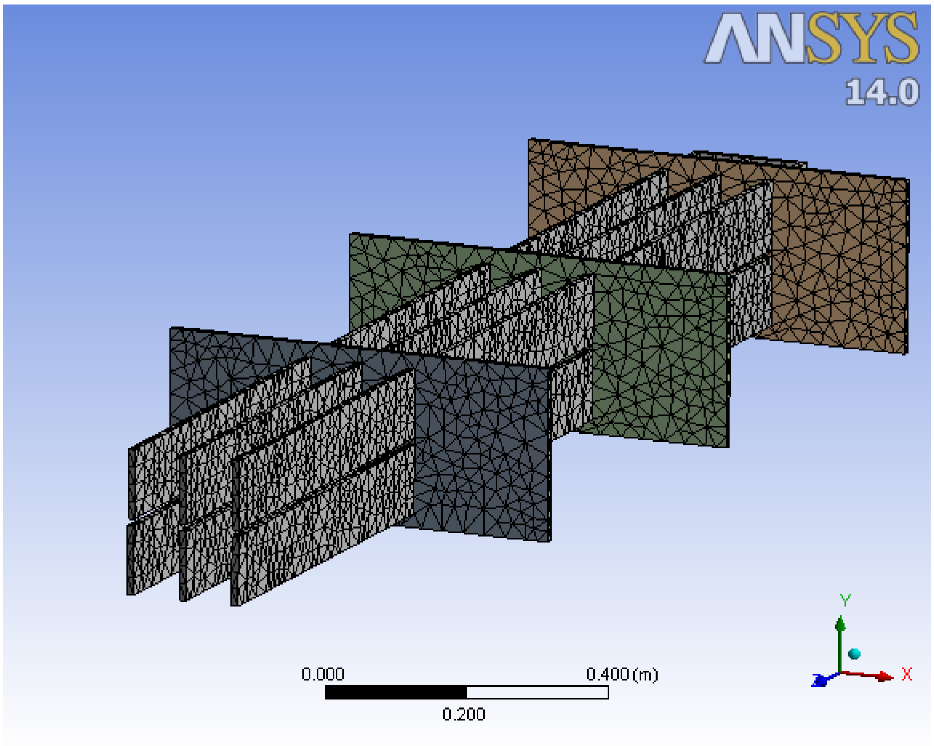

Figure 4.23: Patch conforming meshing on busbars and bakelite supports

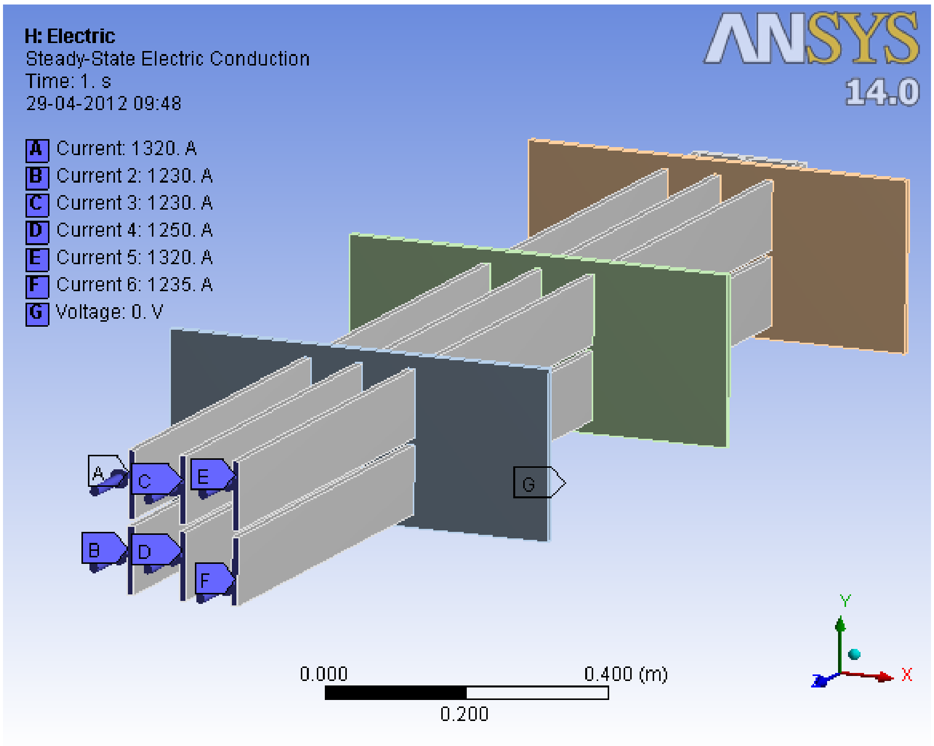

Figure 4.24: Boundary Condition for electrical analysis

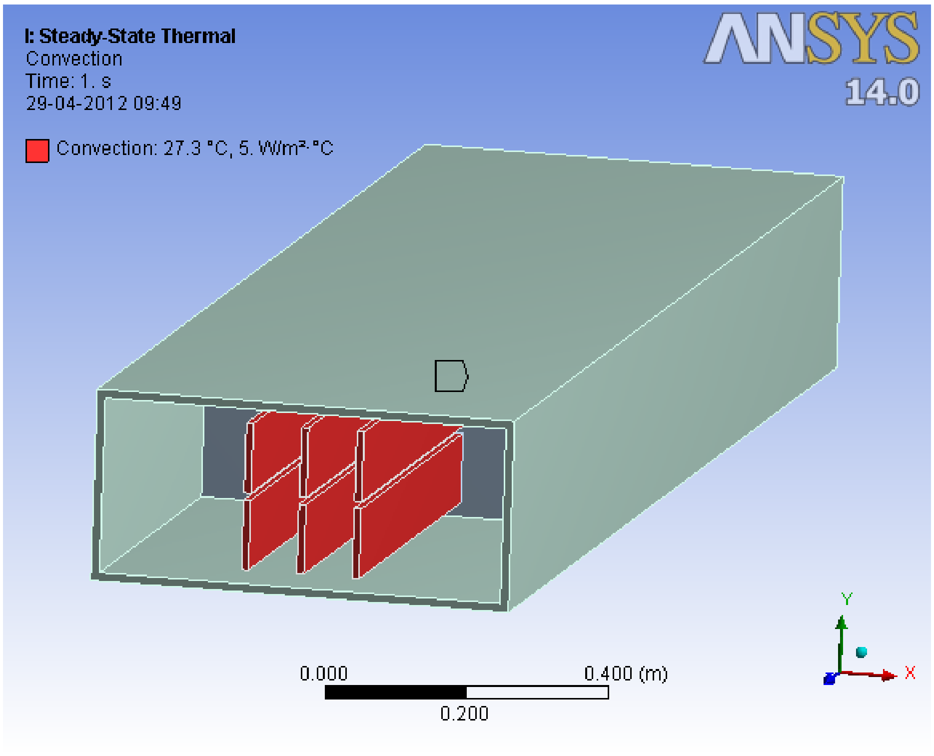

Figure 4.25: Boundary Condition for thermal analysis

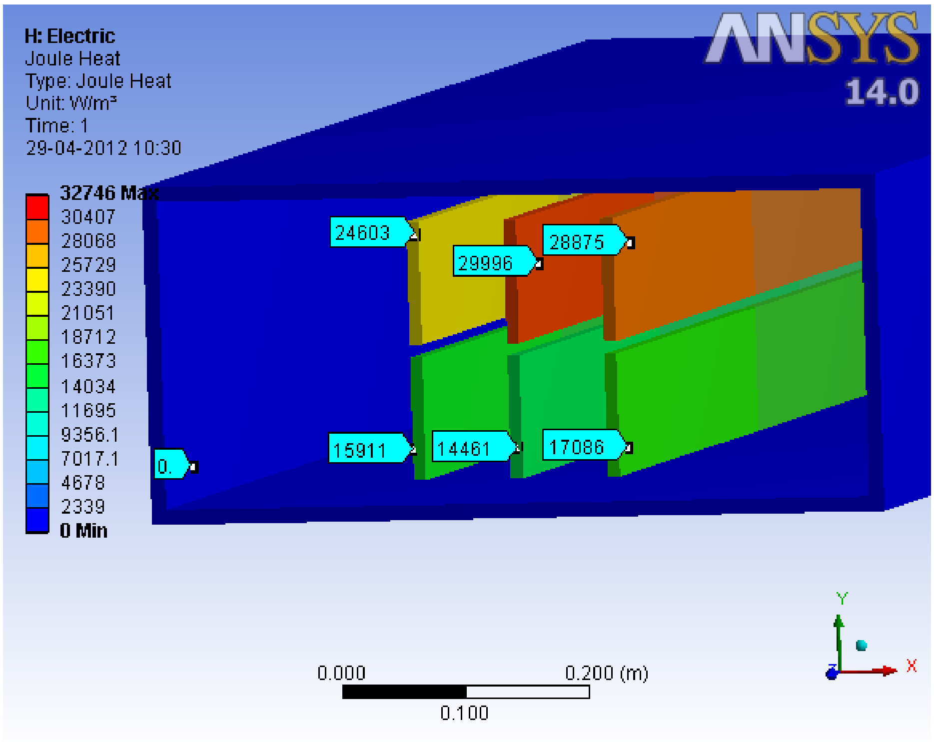

Figure 4.26: Joule Heating Distribution on enclosure along with busbars

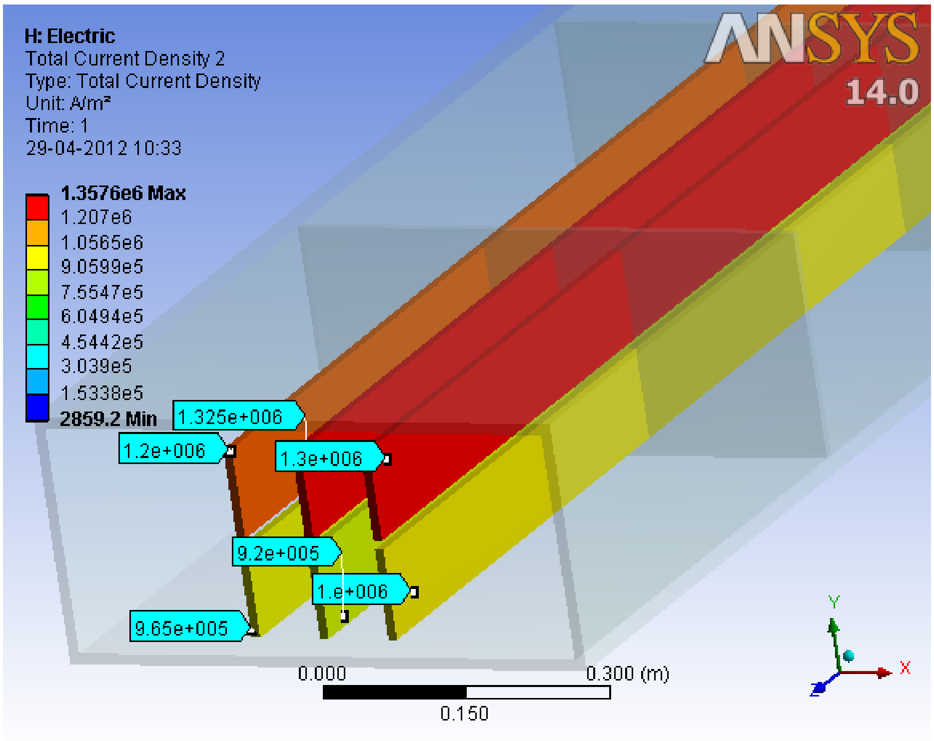

Figure 4.27: Current Density distribution over the busbars

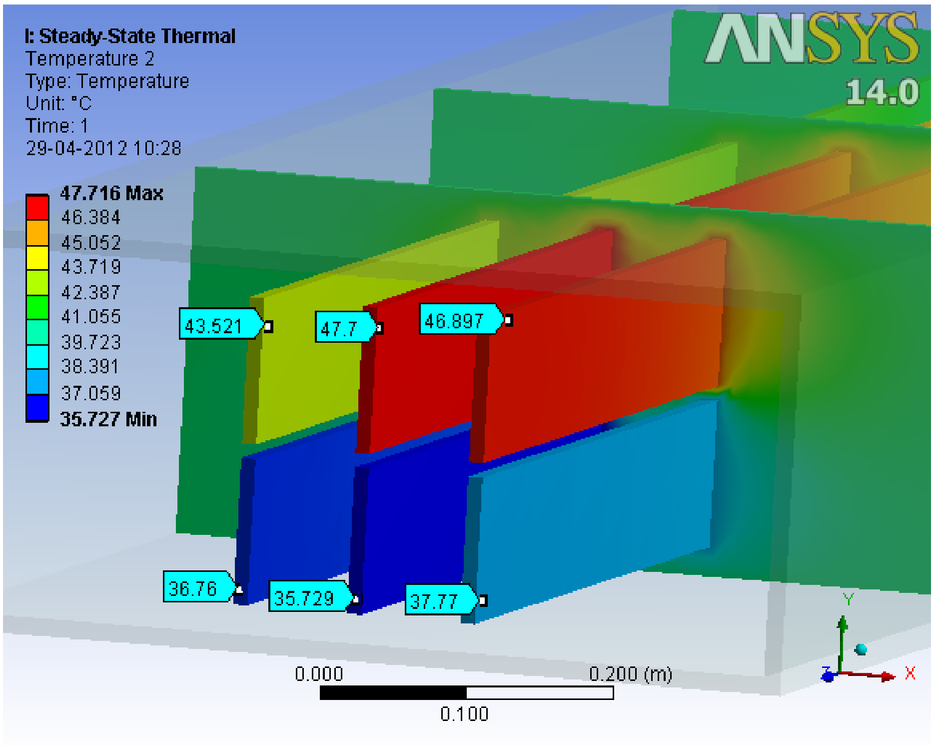

Figure 4.28: Temperature Distribution along with busbars

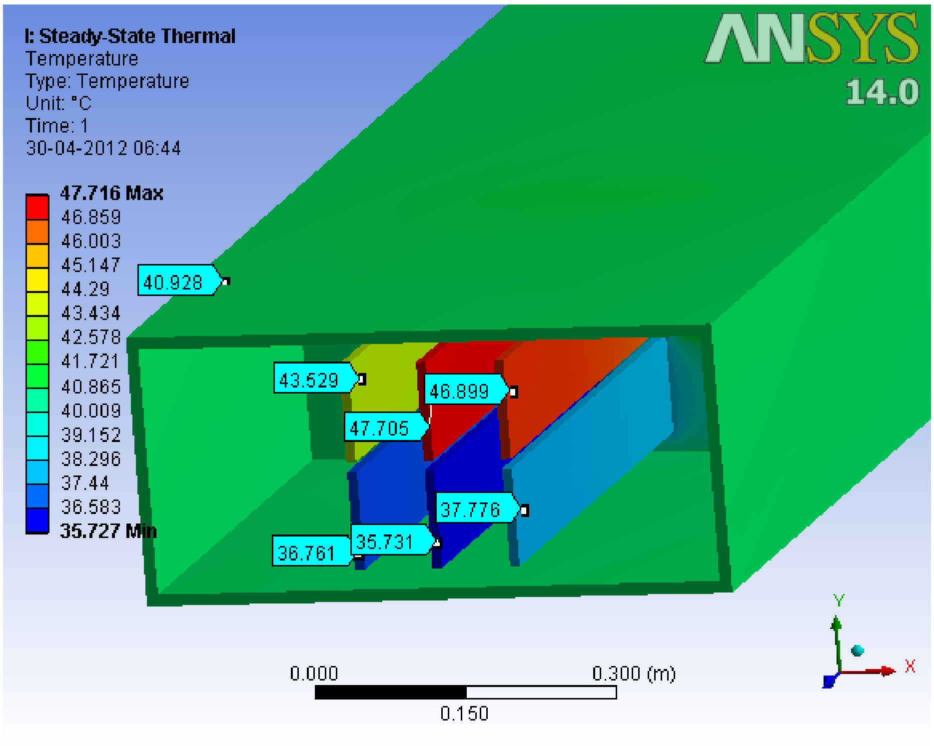

Figure 4.29: Temperature Distribution on enclosure along with busbars

Chapter 5

Experimental Test and Results Comparison

5.1 Introduction

A mathematical model represents a real physical system, albeit, on the basis of idealized assumptions, variable and parameters. Thus, such a model can be considered as having physical dimensions and can be analyzed sometimes in the laboratory or in field itself. Scaling is often required for such a models and accuracy depends on scale and simulation of the actual field condition.
In this chapter, we have done the temperature rise test for three different configuration of busduct system. This experimental test has been done with physical test data of busduct system under different ambient condition.

5.2 Temperature Rise Test

As per IEC standards 60439-2 and IEC 60439-6, the temperature rise test has been carried out for three different busbar configuration. Fig 5.1, fig 5.2 and fig 5.3 shows the two dimensional schematic diagrams for different busbar configuration respectively. In first configuration, busbars having dimensions 50mm x 10mm x 4 bus per phase arrangement and temperature rise test has been carried out with ambient temperature of 30 $^{\circ}C$.

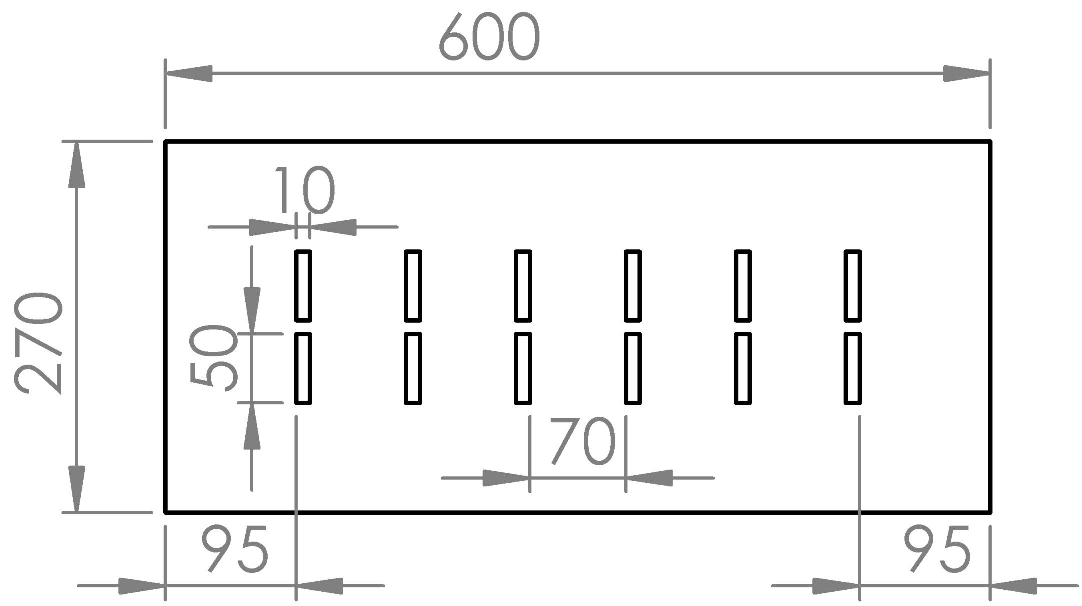

Figure 5.1: Schematic diagram for first configuration

For the test, the busduct has to be supported horizontally at approximately 1 meter from floor. The incoming terminals of the busbars have been connected to a low-voltage supply at 50 Hz frequency; the other end of conductors is short circuited. This test is to be carried out for three phase supply system, for the rated current of the system; The test current 2500 Ampere per phase has applied and adjusted to be substantially equal in all phase conductor. The branch current has been measured and recorded during test and thermocouple is arranged for the temperature measurement.

Similar procedure has followed for other configurations. For configuration 100mm x 10mm x 2 bus per phase, the temperature rise test has carried out at 27.7 $^{\circ}C$ ambient temperature. The recorded branch current and temperature rise value is mention in next section.

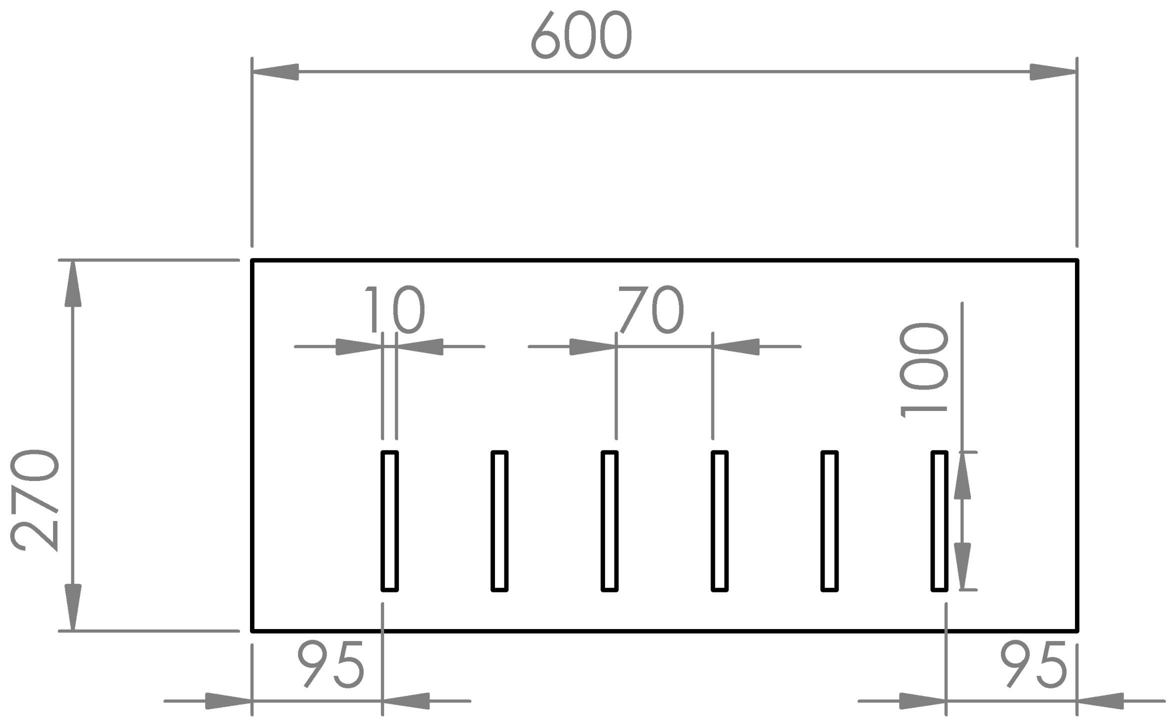

Figure 5.2: Schematic diagram for second configuration

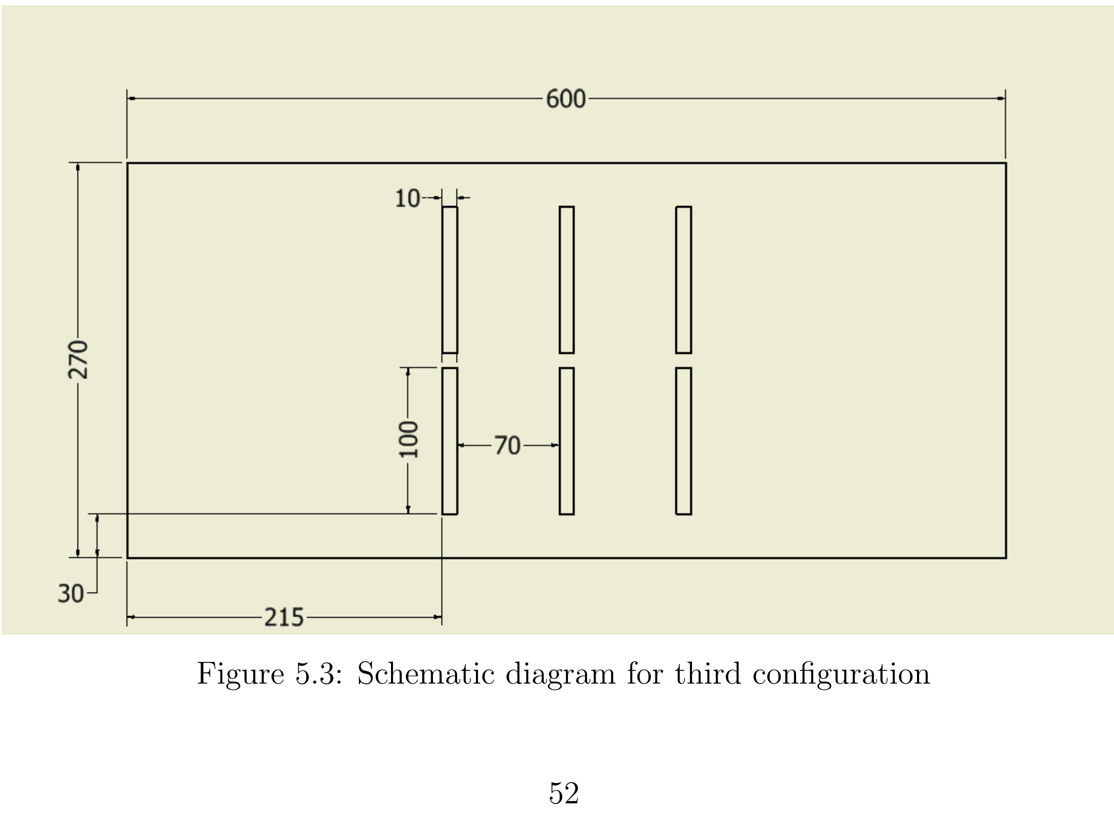

Figure 5.3: Schematic diagram for third configuration

5.3 Comparison of Experimental test Values with Simulation Results

After the carried out of temperature rise test for given busduct system with different busbar configurations, the measured branch current values, temperature rise values from experiment and simulation results of temperature for all phase busbars has shown in table 5.1 Table 5.1 indicates respective phase busbars, measured branch current and temperature obtained from experimental test and simulation. The difference between Experimental test results and simulation value has been also indicated.

Busbar phase	Branch current (Amp)	Experimental Test Temperature ($^{\circ}C$)	Simulation Value Temperature ($^{\circ}C$)	Temperature difference in ($^{\circ}C$) between Exp.value and Simulation value △T
R11	515	28.0	**28.04**	0.04
Y11	630	35.5	**34.86**	0.64
B11	785	46.1	**44.52**	1.58
R12	480	24.6	**24.23**	0.37
Y12	627	29.6	**29.94**	0.34
B12	770	35.5	**40.38**	4.88
R21	830	49.4	**48.62**	0.78
Y21	650	34.5	**34.36**	0.14
B21	550	30.8	**29.07**	1.73
R22	775	40.4	**40.53**	0.13
Y22	615	33.5	**32.10**	1.40
B22	510	26.8	**26.11**	0.69

Table 5.1: Comparison of Experimental test with Simulation value for first configuration

Similarly, Table 5.2 and table 5.3 is indicated results and differences for second and third configuration.

Busbar phase	Branch current (Amp)	Experimental Test Temperature ($^{\circ}C$)	Simulation Value Temperature ($^{\circ}C$)	Temperature difference in ($^{\circ}C$) between Exp.value and Simulation value $\triangle$T
R12	930	31.4	**34.96**	3.56
Y12	1160	40.7	**41.58**	0.88
B12	1450	51.9	**51.98**	0.08
R22	1415	51.0	**50.67**	0.33
Y22	1230	41.4	**43.92**	2.82
B22	1000	34.2	**36.90**	2.70

Table 5.2: Comparison of Experimental test with Simulation value for second configuration

Busbar phase	Branch current (Amp)	Experimental Test Temperature ($^{\circ}C$)	Simulation Value Temperature ($^{\circ}C$)	Temperature difference in ($^{\circ}C$) between Exp.value and Simulation value $\triangle$T
R11	1320	44.5	**43.52**	0.98
Y11	1230	47.5	**47.70**	0.20
B11	1320	47.0	**46.89**	0.11
R12	1230	37.3	**36.76**	0.54
Y12	1250	37.7	**35.72**	1.98
B12	1235	38.5	**37.77**	0.73

Table 5.3: Comparison of Experimental test with Simulation value for third configuration

Chapter 6

Conclusion and Future Work

6.1 Conclusion

Most practical engineering problems are complex in nature. Modeling can be done through physical means with laboratory and field experiments or through mathematical means.physical modeling in field or laboratory can be cumbersome, expensive and time consuming. Due to these difficulties, use of system approach, increase a power of digital computers and development of numerous computational methodology have made the mathematical modeling inevitable for all branches of engineering.

On basis of techniques and Methodology, Solution is obtained with help of some approximate methods such as numerical methods. Computational methods of analysis are applicable to a much wider class of mathematical formulations and hence most engineering problems can be solved. With advent of fast computers, computational models have become widely used compare to analytical and physical method.

Unfortunately, analytical solution can be obtained for small class mathematical formulation with simplified governing equations, boundary conditions and geometry. similarly, physical test method become quite expensive, time consuming and sometimes it difficult to employ.

Finite element method is one of the most flexible and versatile method for solving engineering problems. Modeling of complex geometries and irregular shapes are easily analyzed. Boundary conditions and different type of material properties can be accommodated and incorporated with analysis. Availability of large number of computer software packages and literature makes FEM as powerful numerical method to evaluate the solution.

After carried out the simulation for various busbar configuration, based on FEM software package ANSYS multiphysics, We can validate the experimental test results on software. From all three configurations, the third configuration is most **optimized configuration** which has maximum temperature rise of **47.5** $^{\circ}C$ at phase Y11. In first and second configurations, the maximum temperature rise is **49.4** $^{\circ}C$ at R21 and **51.9** $^{\circ}C$ at B12 respectively.

Test Current (Amp)	Configuration	Busbar phase	Busbar size	Maximum Temperature in $^{\circ}C$ (Experimental)	Maximum Temperature in $^{\circ}C$ (Simulation)
2500	first	R21	50mm x 10mm x 4	49.40	48.62
2500	second	B12	100mm x 10mm x 2	51.90	51.98
2500	third	Y11	100mm x 10mm x 2	**47.50**	**47.70**

Table 6.1: Comparison of maximum temperature rise based on experimental test and simulation for all three configurations

As per table 6.1, we have conclude that solution based on numerical method is advantages and results has good agreement with experimental solution. The ANSYS multiphysics software package based on numerical technique such as finite element method can used to define more optimized configuration.

6.2 Future Work

- Based on Numerical Technique such as Finite Element Method, we can evaluate all electrical as well as thermal solutions for related switchgear products with FEM based software packages.
- We can predict the electrical as well as thermal solutions based on software without performing experimental test as well as analytical solutions.
- By good agreement between experimental solution and simulation results, we can perform more couple analysis such as structural analysis to predict and optimize stresses and axial forces which are responsible for failure of structure.

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Appendix A

List of Publication

[1] Jugal Lotiya and Chanakya Bhatt, "Thermal Analysis and Simulation of Busbar joints Configuration by Finite Element Technique", in proc. 1st National Conference on Advances in Engineering and Technology (NCAET 2012), 9-10 March 2012, Kalol Institute of Technology and Research Centre, Kalol, India.