THERMAL NETWORK THEORY FOR SWITCHGEAR UNDER CONTINUOUS CURRENT

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology

In

Machine Design and Analysis

By

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Department of Mechanical Engineering

National Institute of Technology

Rourkela

2007

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Under the Guidance of

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Rourkela

2007

National Institute of Technology

Rourkela

CERTIFICATE

This is to certify the thesis entitled, “Thermal Network Theory for Switchgear under Continuous Current” submitted by Sri Krishna Swamy Cherukuri in partial fulfillment of the requirements for the award of Master of Technology in Mechanical Engineering with specialization in “Machine Design and Analysis” at the National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

Date

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ABSTRACT

All electrical equipments generate heat through I^2R loss within a specified volume resulting in temperature rise. The regulating bodies define the temperature rise limits for all equipments for safe operation. So during the design phase of any electrical equipment thermal analysis is mandatory to predict the temperature rise.

The objective is to develop an analytical tool based on thermal networking method by exploiting the similarity between thermal and electrical analogy to calculate steady state temperatures in less time along current carrying path in electrical equipments. As a later part, the tool developed is used to predict change in temperatures for change in geometry of the components in the electrical equipment.

The problem is considered as two parts. As first part, an Excel tool is developed with Visual Basic backend, based on thermal networking method to calculate steady state temperatures in electrical equipments. Here the numerical method used is Elementary Balance Method, in which every element is represented by a node and relevant energy balance equations are formulated for it. Temperatures are calculated using the Excel tool for frame 1 and 3. Test (Thermal Run) is conducted on AKD-12 switch gear (frame 1 and frame 3) under continuous current to find out temperatures. Analytical results from the tool are then validated against the test data.

As second part, dimensions of components in the switch gear are varied and variation in temperatures of components, particularly at moving contact (highest temperature point) with respect to original temperatures is observed.

Good matching is observed in temperature profile between analytical and experimental results. The maximum percentage error is 15%.By analyzing the results, it can be concluded that thermal network theory helps engineers to predict temperatures easily for changes in design reducing design cycle time and it is flexible as to expand its application to any heat generating equipment.

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1. INTRODUCTION

This chapter gives an overview of the project work reported in the thesis. First, background of the project work is outlined followed by the objective and methodology followed to achieve the objective.

1.1 BACKGROUND

All electrical equipments generate heat through I^2R loss within a specified volume resulting in temperature rise. The regulating bodies define the temperature rise limits for all equipments for safe operation. So during the design phase of any thermal equipment thermal analysis is mandatory to predict the temperature rise. Bypassing thermal analysis precludes design optimization.

Thermal analysis is done either by building a laboratory model or by simulation using simulation softwares. Generally once the basic design is completed, laboratory model is built to observe the response of the system. Later certain changes are incorporated to arrive at optimum design. Rebuilding the model for every change incorporated becomes a costly affair. So simulation work is carried out at this stage using simulation software to predict the response of the system for the changes made.

By this, though cost involved in rebuilding the lab model is cut down, time required in predicting the response of the system for new design or changes cannot be avoided. This is so because, in simulation software rebuilding the model, meshing, changing the boundary conditions and running the solution for any change in geometry of the components involves considerable time. So, one is interested to predict temperature variations in very less time using simple mathematical calculations even at the sacrifice of accuracy to certain extent.

1.2 OBJECTIVE

The objective is to develop an analytical tool based on thermal networking method by exploiting the similarity between thermal and electrical analogy to calculate steady state temperatures in less time along current carrying path in electrical equipments. As a later part, the tool developed is used to predict change in temperatures for change in geometry of the components in the electrical equipment.

Following methodology is followed to achieve the objective. The problem is considered as two parts. As first part, an Excel tool is developed with Visual Basic backend, based on thermal networking method to calculate steady state temperatures in electrical equipments. Here the numerical method used is Elementary Balance Method, in which every element is represented by a node and relevant energy balance equations are formulated for it. Analytical calculations are carried out and temperatures are calculated using the Excel tool for frame 1 and 3. Test (Thermal Run) is conducted on AKD-12 switchgear, frame 1 and frame 3 under continuous current to find out temperatures at different points along the current flow path. Analytical results from the tool are then validated against the test data. Good matching is observed in temperature profile between analytical and experimental results.

As second part, dimensions of components in the switch gear are varied and variation in temperatures of components, particularly at moving contact (highest temperature point) with respect to original temperatures is observed.

2. LITERATURE SURVEY

This chapter surveys the literature in the areas of thermal network modeling, electrical contact resistance and thermal contact resistance.

2.1THERMAL NETWORK THEORY

Peter and Hans [1] have carried out thermal simulation of a circuit Breaker to find out steady state temperatures considering all modes of heat transfer. The analysis is done based on software developed using thermal networking with a capacity of 32000 nodes. The paper explains the thermo- Electrical coupling to represent electrical carrying conductor by thermal components.

Correspondence from IEEE [2] describes a relatively simple method for manual thermal computations, particularly useful for electronic equipment where all types of heat transfer must be taken into account. The method involves construction of a simplified thermal network diagram for the equipment. The method of thermal computation described here exploits the similarity between thermal and electrical analogy, shown in table [4.1].

Hiroshi and Kazunori [3] have described the way to develop thermal network diagram for low voltage circuit breaker.

Hefner and Blackburn published a paper [9] giving thermal Component simulation for electro-thermal network simulation. It explains the structure of the electro-thermal semiconductor device models indicating the interaction with the thermal and electrical networks through the electrical and thermal terminals, respectively.

2.2 CONTACT RESISTANCE

An accurate knowledge of contact mechanics, that is, the pressure distribution, the size of contact area, and the mean separation between surface planes as functions of applied load, and the geometrical and mechanical characteristics/properties of the contacting bodies, plays an important role in predicting and analyzing thermal and electrical contact resistance and many tribological phenomena.[6]

2.2.1 Electrical Contact Resistance

The calculation of the contact resistance between two rough electrodes is a difficult task, since the contact interface comprises many spots corresponding to more or less conducting paths for the electrons [4].

In 1966, J. A. Greenwood published a paper entitled [12] in which the author derived a formula [5.2] for the constriction resistance of a set of circular spots [Fig.5.2], with each spot located at the end of a metallic electrode. The electrodes communicate via the spots with no interface film between them. In the same paper author presented a formula resulting from an approximation which holds when there is no correlation between the size of a given spot and its position.

For some ten years now, contact resistance has been computed numerically mainly by Nakamura and Minowa [13], who use the finite element method (FEM) and the boundary element method (BEM) from a different point of view, considering a system of two cubic electrodes communicating through square spots.

Finally, it should also be mentioned that a recent paper by R. S. Timsit reviews the dependence of electrical resistance on the shape and dimensions of the contact spots [14].

Maxwell's formulation for single contact spot is given by formula [5.1]. With increase in contact pressure, the electrical contact resistance decreases at the joint as shown in graph [4.1].

In the paper published by Peter and Hans [1], electrical contact resistance is given in terms of contact force, contact material type and shape of the contact, shown by formula [5.3]. Based on these formulae, empirical relations [5.4, 5.5] are developed which can be used for bolted and spring loaded contacts for different materials. Those empirical relations are used here to calculate the electrical contact resistance.

2.2.2 Thermal Contact Resistance

Heat transfer across interfaces formed by mechanical contact of nonconforming rough solids occurs in a wide range of applications, such as microelectronics cooling, spacecraft structures, satellite bolted joints, nuclear engineering, ball bearings, and heat exchangers. Because of roughness of the contacting surfaces, real contacts in the form of micro contacts occur only at the top of surface asperities, which are a small portion of the nominal contact area, normally less than a few percent. As a result of curvature or out-of flatness of the contacting bodies, a macro contact area is formed, the area where the micro contacts are distributed.

Two sets of resistances in series can be used to represent the thermal contact resistance (TCR) for a joint, the large scale or macroscopic constriction resistance RL and the small-scale or microscopic constriction resistance Rs as shown in formula [5.7].

Cooper et al. [15] studied the contact conductance of rough, conforming metals experiencing light to moderate pressure. The model presumes that the micro contacts deform plastically.

Mikic [16] developed models for the macroscopic and microscopic contact conductance that took into account non-uniform pressure distributions, but did not specify how the distributions were determined. The microscopic conductance model uses the plastic deformation model of Cooper, et al. (1969).

Thomas and Sayles [17] studied the relative effects of waviness and roughness on thermal contact conductance. They observe that the total roughness of a specimen is related to its size, defining a dimensionless waviness number.

Yovanovich [18] refined the model of Cooper, et al. (1969) for plastic deformation of microscopic contacts on conforming surfaces.

Lambert [19] and Lambert and Fletcher [20] developed a model for the thermal contact conductance of spherical rough metals that is valid in regions removed from the limiting cases of rough/flat, smooth/spherical surfaces. It is, however, a single macro contact model, and requires loading on the macrocontact as well as the surface geometry of the contact. In multiple macrocontact situations, such as those encountered in large area contacts, it is difficult to estimate number of macrocontact, much less the loading on each macrocontact.

Table 5.1 lists the dimensional and non-dimensional contact conductance correlations reviewed in this section.

Peter and Hans published a paper in which the thermal contact resistances are deduced from the electrical contact resistances. [1] The formulae used [5.8] here for thermal contact resistance calculations are based on this paper. The thermal conductivity of the contacts is increased by a factor of 2.1 to account for the thermal conductivity of the air in the voids of the contact area.

3. INTRODUCTION TO SWITCHGEAR

3.1 INTRODUCTION

Circuit protection devices are needed to protect personnel and circuits from hazardous conditions. The hazardous conditions can be caused by a direct short, excessive current or excessive heat. Circuit protection devices are always connected in series with the circuit being protected**.**

Every one is familiar with low voltage switches and rewire-able fuses. A switch is used for opening and closing an electric circuit and a fuse is used for over current protection. Every electric circuit needs a switching device (Switch) and a protective device (Fuse). The switching and protective devices have been developed in various forms depending voltage and current. Switchgear is a general term covering a wide range of equipment concerned with switching and protection.

3.2 SWITCHGEAR

The term switchgear, commonly used in association with the electric power system, or grid, refers to the combination of electrical disconnects and/or circuit breakers used to isolate electrical equipment. All equipments associated with the fault clearing process are covered by the term “Switchgear”. Switchgear is an essential part of power system and also that of any electric circuit. Between the generating station and final load point, there are several voltage levels and fault levels. Hence, in various applications, the requirements of switchgear vary depending upon the location, ratings and switching duty. Switchgear includes switches, fuses, circuit breakers, isolators, relays, control panels, lightening arresters, current transformers and various associated equipments.

3.2.1Protective Relay: The protective relays are the automatic devices, which can sense the fault and send instructions to the associated circuit breaker to open.

3.2.2Circuit Breakers: Circuit breakers are the switching and current interrupting devices. Basically a circuit breaker comprises a set of fixed and movable contacts. The contacts can be separated by means of an operating mechanism. The separation of the current carrying contacts produces an arc. The arc is extinguished by a suitable medium like dielectric oil, air, vacuum and SF_6 gas.

3.2.3 Isolators: Isolators are disconnecting switches, which can be used for disconnecting a circuit under no current condition. They are generally installed along with circuit breaker. An isolator can be opened after the circuit breaker. After opening the isolator the earthing switch can be closed to discharge the charges to the ground.

3.2.4 Transformers: The current transformers and the potential transformers are used for transforming the current and voltage to a lower value for the purpose of measurement, protection and control.

3.2.5 Lightening Arresters: Lightening arresters (surge arresters) divert the over-voltages to earth and protect the sub-station equipment from over voltages.

Some of GE Switchgear products:

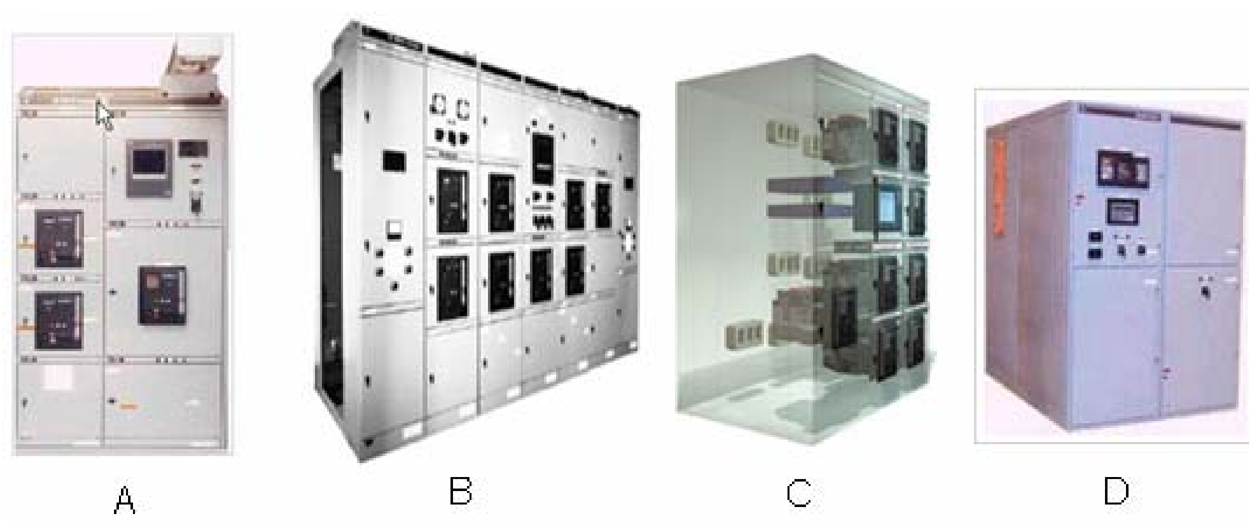


Figure 3.1 GE Switchgears

A - AKD 10 Low Voltage Metal Enclosed

B - Paralleling switch Gear

C - Entellisys Low Voltage switch Gear

D - Power/Vac® Medium Voltage Metal Clad Switch Gear

3.3 CIRCUIT BREAKER

A circuit breaker is an automatically-operated electrical switch designed to protect an electrical circuit from damage caused by overload or short circuit. It is a device to open or close an electric power circuit either during normal power system operation or during abnormal conditions. During abnormal conditions, when excessive current develops, a circuit breaker opens to protect equipment and surroundings from possible damage due to excess current. These abnormal currents are usually the result of short circuits created by lightning, accidents, deterioration of equipment, or sustained overloads. Unlike a fuse, which operates once and then has to be replaced, a circuit breaker can be reset (either manually or automatically) to resume normal operation. Circuit breakers are made in varying sizes, from small devices that protect an individual household appliance up to large switchgear designed to protect high voltage circuits feeding an entire city. Based on voltage, switch gears are classified as

3.3.1 Low voltage Circuit Breakers

Low voltage circuit breakers have voltage ratings from 250 to 600 V AC and 250 to 700 V DC. They are two types.

MCB-(Miniature Circuit Breaker Rated current is not more than 100 A.

MCCB-(Molded Case Circuit Breaker) Rated current is up to 1000 A.

Figure 3.2 MCB

Figure 3.3 PowerVac - MV Vacuum Distribution Breaker

3.3.2 Medium Voltage Breakers

Medium voltage circuit breakers are rated up to 72.5 kV

3.3.3 High-Voltage Breakers

High voltage breakers are routinely available up to 765 kV AC. They are broadly classified by the medium used to extinguish the arc as:

1. Oil-filled (dead tank and live tank)
2. Oil-filled (minimum oil volume)
3. Air blast
4. Sulfur hexafluoride

Figure 3.4 1200 A, 3-pole 115,000 V Breaker at a generating station

Figure 3.5 Front panel of a 1250 A air circuit breaker manufactured by ABB

Small circuit breakers are either installed directly in equipment, or are arranged in a breaker panel. Power circuit breakers are built into switchgear cabinets. High-voltage breakers may be free-standing outdoor equipment or a component of a gas-insulated switchgear line-up

3.4 CURRENT FLOW PATH IN SWITCHGEAR

Current flow path in switchgear involves many components of different cross sections joined with different types of joints and contacts. Generally joints involved are bolted joints and spring contacts. The components in the current flow path are test links, power connects, lower vertical busbars, run-ins, cluster fingers, cluster pad, line terminal, flexible conductors, moving conductors, load terminal, runbacks, upper vertical busbars and outgoing horizontal busbars. Figure 3.6 shows line diagram of current flow path for switchgear. Current enters the switchgear through test link which is connected to power source. Current then flows to lower vertical busbar thorough power connect. Power connect is a clamp like device used for joining horizontal test links to vertical busbars.

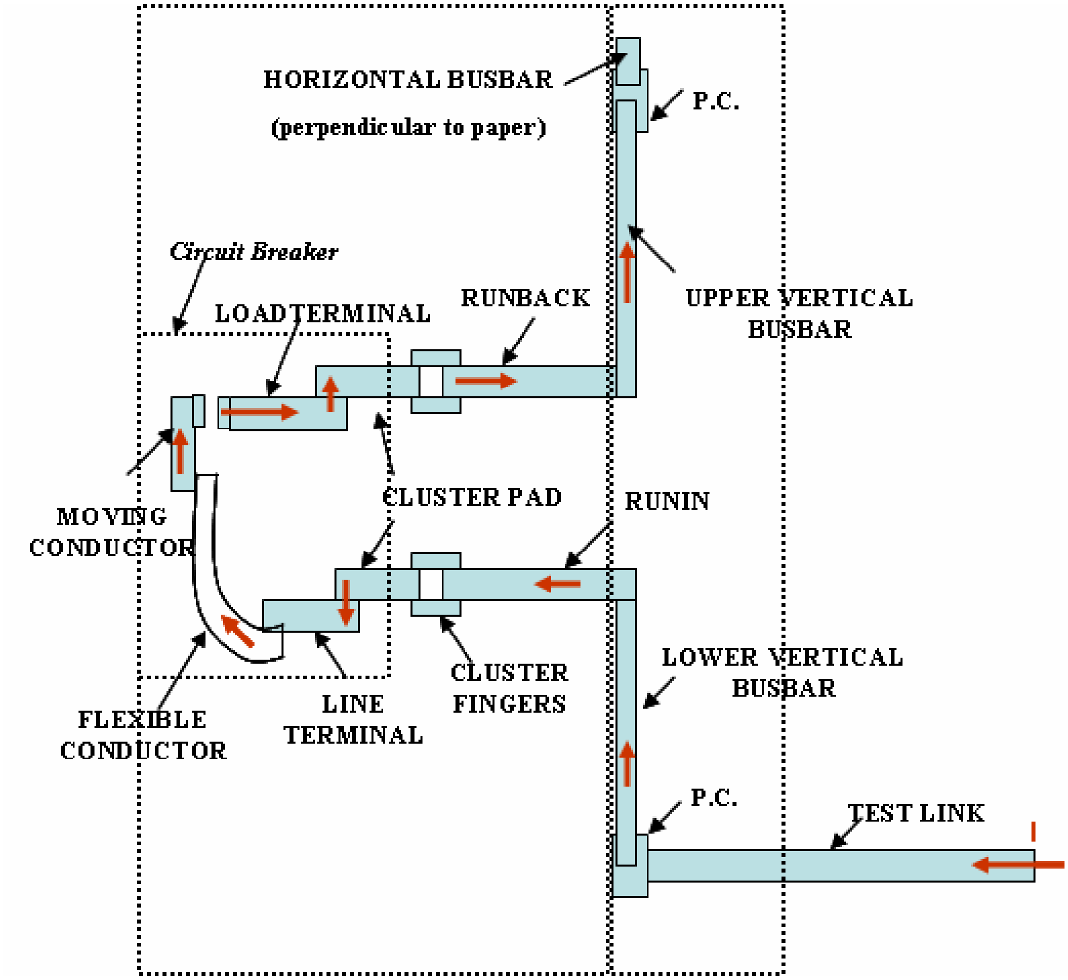


Figure3.6 Switchgear Line Diagram

A busbar in electrical power distribution refers to thick strips of copper or aluminum that conduct electricity within a switchboard, distribution board, substation or other electrical apparatus. From busbar, current flow to circuit breaker through run-in, cluster fingers and cluster pad. Run-ins are horizontal strips that connect gear with circuit breaker electrically. Cluster fingers are spring loaded thin strips connecting run-ins with cluster pad. Components in a circuit breaker are line terminal, flexible conductors, moving conductors and load terminal. Current from circuit breaker flows through runbacks to upper vertical busbars. From vertical busbars, current leaves the switch gear through power connect and horizontal busbars.

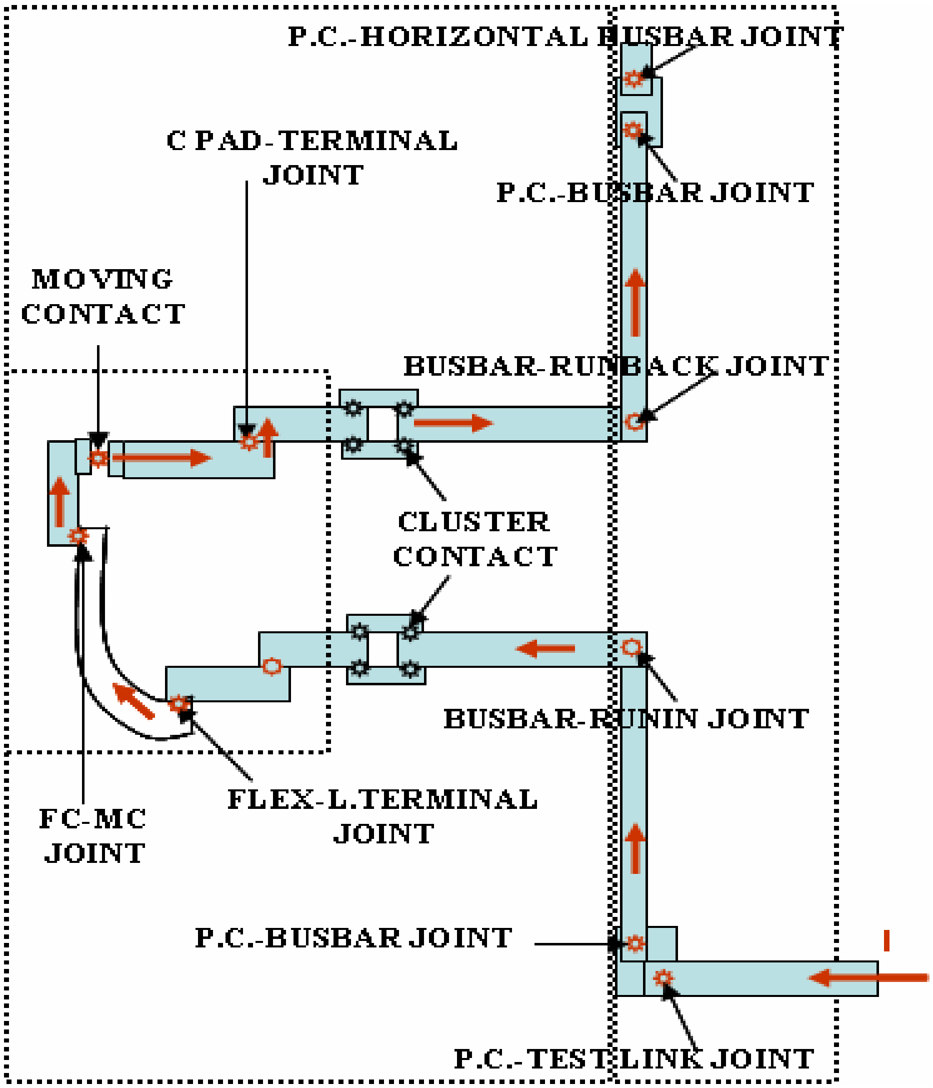


Figure3.7 Switchgear line Diagram Showing Joints

Figure 3.7 shows joints between different components in the switchgear. Joints at cluster fingers and moving contact are spring loaded contacts. All the remaining joints are bolted joints with bolts of different sizes and numbers depending upon the clamping force required at the joint. Except the test links and horizontal busbars, all the components are placed inside a compartment as shown by dotted line. Compartment with busbars is called busbar compartment and compartment with circuit breaker is called breaker compartment.

4. THERMAL NETWORK THEORY

4.1 INTRODUCTION

During the design of electrical and electronic equipments, thermal analysis of the system is very essential and disregard of a thermal analysis may lead to inadequate thermal design. Sometimes schedules and cost aspects exclude construction of thermal laboratory models which many a times lands up in severe financial penalties. In some instances such analysis is bypassed because of its complexity. This bypassing precludes design optimization. Thermal deficiencies in performance of the equipment may then result.

So conducting thermal analysis for any electrical system is inevitable either by building a laboratory model or by simulating the thermal analysis using simulation software. Generally once the basic design is completed, laboratory model is built to observe the response of the system. Later certain changes are incorporated to arrive at optimum design. Rebuilding the model for every change incorporated becomes a costly affair. So simulation work is carried out at this stage using simulation software to predict the response of the system for the changes made.

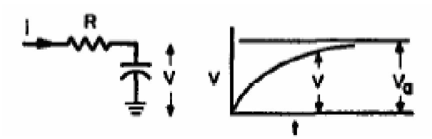
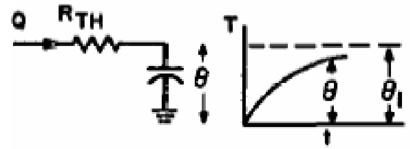
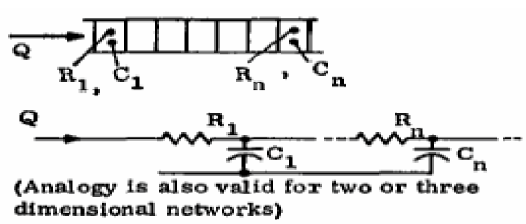
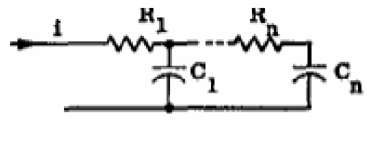
Thermal simulation can be carried out using many types of software like ANSYS, CFD, FLUX etc and results can be predicted very precisely. By this, though cost involved in rebuilding the lab model is cut down, time required in predicting the response of the system for new design or changes cannot be avoided. This is so because, in simulation software rebuilding the model, meshing, changing the boundary conditions and running the solution for any change in geometry of the components involves considerable time. So one is interested to have an analytical tool which can predict the results in lesser time even by compromising with the accuracy of results up to some extent. This gave birth to a relatively simple method for manual thermal computations, particularly useful for electronic and electrical equipment where all types of heat transfer must be taken into account. The method involves construction of a simplified thermal network diagram for the equipment, developing energy equation at each node and solving for temperature rise. When good judgment is used, predicted temperature values approach actual ones.

4.2 ELECTRICAL AND THERMAL ANALOGY

The method of thermal computation used here exploits the similarity between thermal and electrical networks as shown in Table 4.1. Heat flow is represented in the electrical analog scheme by current flow, temperature potential is represented by voltage potential and a thermal resistor by an electrical resistor. For transient heat flow, the analogy also applies in that heat stored and absorbed in a mass may be represented by an electrical current stored and absorbed in a capacitor.

Table 4.1 Electrical and Thermal Analogy

ELECTRICAL	THERMAL
Current, $I = dq/dt$ [Amps]	Heat flow, q [Joules/sec]
Voltage, V [Volts]	Temperature difference, T [°C]
Resistance, $R = \rho L/A$ [Ohms] Ohm's Law: $I = V/R$	Heat transfer resistance, R $R_{convection} = 1/(h A)$, $R_{conduction} = KA/L$ $q = T / R$
Capacitance, $C = \varepsilon A/d$ [Farads] $I = C\, dV/dt$	Thermal heat capacity, $m\, c_p$ $q = m\, c_p\, dT/dt$
Time constant, $T = R.\ C$	Time constant, $T_{th} = R_{th}\ .\ W.C_P$
Ohm's law for current flow $I = \frac{1}{R}(V_1 - V_2)$	One dimensional steady flow equation $\dot{Q} = \frac{kA}{\Delta x}(T_1 - T_2)$
$P = I\ V$ [Watts]	$P = T\ q$ [Watts °C]
Kirchhoff's Current Law $\sum I = 0$	Energy equation $\sum q = 0$
Charge, $q = \int I\ dt$ [Coulombs]	Heat, $Q = \int q\ dt$ [Joules]
Kirchhoff's Voltage Law $\sum V = 0$	$\sum T = 0$

Current flow through resistor, stored in capacitor  	Heat flow to ambient ,stored in mass of material of specific heat c_p 
One dimensional current flow trough RC network  	One dimensional transient heat flow through bar 

4.3 THERMAL NETWORK THEORY

The finite difference method provides the basis for converting a distributed parameter description of a system into a lumped parameter model of that system. We can expand the concept of a finite node to include a larger macroscopic control volume (which physically may be very large or small). In connecting individual control volumes, it is often useful to use an electrical analogy to describe the system. In thermal systems, this electrical analogy gives rise to the so-called thermal network model.

A thermal network is a representation (model) of the thermal characteristics of any system modeled by considering points (nodes) at discrete parts of the system that are linked by conductors through which heat may flow. This type of thermal network is often described as a lumped parameter model because the thermal properties, such as the heat capacity, of a part of the system are “lumped” together on the node representing that part.

The method developed here is called the Equivalent Thermal Network and takes advantage of the theory of analogy between electrical and thermal elements. In steady state temperature rise computations, current generators are used to represent heat generators, and electrical resistances to represent the internal thermal conduction resistances. In transient heat flow condition, capacitor is connected in parallel to represent the heat stored in the body along with heat generator and thermal resistance. Here the mathematical model is based on a numerical method called Elementary Balance Method, in which every element is represented by a node and relevant energy balance equations are formulated for it.

4.4 THE LUMPED-PARAMETER METHOD FOR STEADY STATE SOLUTION

The lumped-parameter method involves dividing the object being analyzed into a network of discrete nodes connected by thermal conductors. Each node is considered to be isothermal i.e. has a single temperature associated with it.

To determine the steady state a heat balance is applied to each node,

$$\sum Q = 0 \tag{4.1}$$

Where Q represents heat input, and the removal of heat is regarded as a negative Q. The symbol $\sum$ signifies a summation. In words, this can be stated:

At any node, HEAT IN = HEAT OUT

Equation 4.1 is applied to each node in the model to obtain a system of simultaneous equations from which all nodal temperatures are calculated.

4.5 THE LUMPED-PARAMETER METHOD FOR TRANSIENT SOLUTION

For evolution of temperatures in a model during the transient stage (not just the final steady-state values) then the node equation acquires a time-derivative on the right-hand side.

The energy equation is written as

$$\sum Q = m.c\frac{dT}{dt} \tag{4.2}$$

Where, m is the mass of the node and *C* the specific heat capacity.

The derivative is approximated by finite differences (dT/dt).

Applying the above equation to all nodes, gives a system of algebraic equations that are solved for temperature *T* at time t+dt. The solution is done by iterative method.

As the highest temperatures occur after the transient phase is over and the steady state (thermal equilibrium) has been reached, we are interested to calculate the steady state temperatures and so the entire work is concentrated on one dimensional steady state solution by lumped parameter method. Most of the thermal calculations for electrical equipments are limited to one dimensional only.

4.6 BUILDING THERMAL NETWORK

Building thermal network diagram for electrical equipment involves visualizing it as thermal network with thermal resistances, heat generators and thermal capacitors. As the work is limited to steady state, thermal capacitors are absent. First the entire structure is descritized into number of nodes, each node representing a component with certain mass i.e. a lumped mass. The nodes are taken as three types- diffusion nodes, boundary nodes and arithmetic nodes. Each node is connected to the other by a conductor which represents internal conduction resistance or convection resistance or radiation resistance. Conductors are considered as two types—linear conductor and radiation conductors. Due to the current flow in a element (node), there is some internal heat generation due to I^2R loss and that amount of heat is added as heat input at the corresponding node. With this the equipment is represented as a network with different types of nodes with heat generation and connected by different types of conductors.

4.7 NODES

At nodes energy is conserved. Each node has a single characteristic temperature ‘T’. Nodes may represent the temperature of a finite volume of material. There are three types of nodes, classified by their capacitance or ability to transiently store or release thermal energy.

4.7.1 Diffusion Nodes: Diffusion nodes have a finite capacitance ‘C’, usually equal to the product of mass and specific heat (mCp or ρVCp). Diffusion nodes may represent a finite volume and mass. These nodes are used in transient analysis.

4.7.2 Arithmetic Nodes: rithmetic nodes have zero capacitance. Energy flowing into an arithmetic node must balance the energy flowing out at all times. These nodes are used in steady state analysis as no heat is accumulated in the body once the system comes to thermal equilibrium and all the heat in is equal to heat out. Heat source is added to these nodes.

4.7.3 Boundary Nodes: Boundary nodes have an infinite capacitance, and hence usually represent sources or sinks, large masses, or ideally controlled temperature zones. Air is represented using these nodes.

4.8 CONDUCTORS

Conductors describe the means by which heat flows from one node to another. Each conductor has a single characteristic conductance "G" (inverse of resistance). Conductors represent energy paths via solid conduction, contact conduction, convection, advection, radiation, etc. There are two types of conductors.

4.8.1 Linear Conductors: Linear conductors transport heat in direct proportion to the difference in nodal temperatures

$$Q_{1-2} = G(T_1 - T_2) \tag{4.3}$$

Q_{1-2} is the heat flow from node 1 to node 2 through a conductor of conductance G

T_1 is the temperature of node 1

T_2 is the temperature of node 2

Usually, linear conductors represent solid conduction with 'G', calculated as the product of the material conductivity and inter nodal cross-sectional area, divided by the distance between node centers.

$$G = \frac{KA}{L} \tag{4.4}$$

Linear conductors may also represent convection conductance with 'G', calculated as the product of convective heat transfer coefficient 'h' and surface area 'a'. Here we represent convective conductance by H to avoid confusion.

$$H = h*a \tag{4.5}$$

4.8.2 Radiation Conductors: Radiation conductors transport heat according to the difference in the fourth power of absolute temperature.

$$Q_{1-2} = G(T_1^4 - T_2^4) \tag{4.6}$$

They are used almost exclusively for radiation heat transfer, with

$$G = \sigma\varepsilon_1 F_{1-2} A_1 \tag{4.7}$$

σ is the Stefan-Bolt Mann constant

ε_1 is the emissivity of node 1

A_1 is the area of node 1 and

F_{1-2} is the form factor from node 1 to node 2

4.9 CRITERIA FOR SELECTING NODES

Generally any equipment contains many components connected by joints. The entire equipment can be divided into number of nodes, with a new node wherever

1. There is change in cross section or shape of the component.
2. Joint occurs. New node is considered to represent the joint between the two elements.
3. Length of the component is large. The same component is considered as more than one node and the number of nodes to be considered depends on the accuracy required. More nodes are considered for better temperature distribution. But one has to strike a balance between the increased complexity of the network and the required accuracy.
4. Imaginary or dummy nodes are introduced wherever branching or joining of resistances occurs to generalize the node equations. No thermal properties are considered for dummy nodes.

4.10 NODE EQUATIONS

As the general phenomenon, when current flows through a conductor, heat is generated in the conductor due to I^2R loss and temperature of the conductor rises above the ambient air temperature. Heat is transferred from one end of the conductor to the other by thermal conduction and at the same time heat is lost to atmospheric air by convection bringing the system to thermal stability after certain time period. (Neglecting radiation) The same is explained schematically as follows. Consider a stepped bar with rectangular cross section as shown in fig 4.1(1). Current "I" flows form the left hand side and the bar is placed in ambient air. The bar is descritized into parts for change in cross section giving 3 parts. Each part is lumped and considered as a small node. Node represents the part in mass and thermal characteristics. The internal thermal conduction resistance of a part is represented by a resistance symbol (R_c).

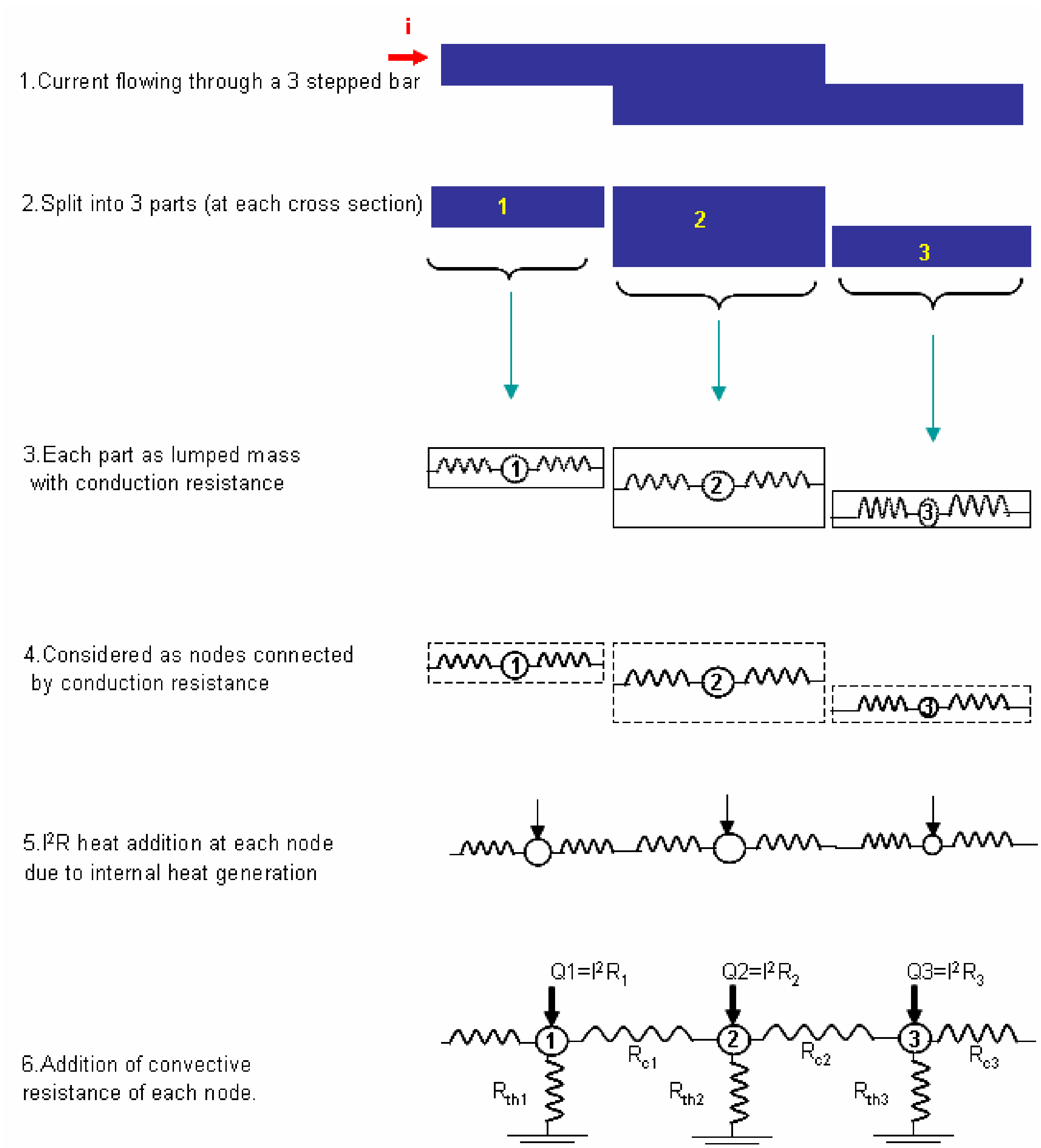


Figure 4.1 Network Diagram

Resistance (R_{c1}) represents the thermal conduction resistance between node1 and node 2. It is equal to sum of fifty percent of conduction resistance of part one and fifty percent of conduction resistance of part two. Assembling the nodes, thermal resistances and heat generators, thermal network diagram is developed as shown in figure 4.1(6). There are 3 nodes-- node1, node2 and node3 connected by thermal conduction resistances R_{c1}, Rc_2, R_{c3}. Each node is connected to the ambient air by convection resistance R_{th}—convection resistances Rth1, Rth2, R_{th3}. The heat generated (Q) by I^2R loss in each part is represented by Q_1, Q_2 and Q_3 and added as heat inputs at corresponding nodes

The next step is to develop energy balance equation at each node. The elementary energy balance equation (steady state) is given as

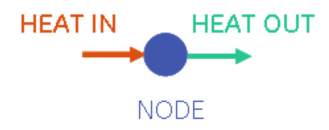


Figure 4.2 Energy Balance at a Node

I.e. the heat input to a node by different modes is equal to heat lost from the node by different modes. It can be written as

Heat added by I^2R (Q) + Heat added by conduction from the previous node	=	Heat lost by convection to ambient air + Heat lost by conduction to next node

For a node I, the nodal equation can be written mathematically as:

$$Q_i + \frac{(T_{i-1} - T_i)}{R_{C(i-1)}} = \frac{(T_i - T_{i+1})}{R_{Ci}} + \frac{(T_i - T_{ambient})}{R_{th(i)}} \tag{4.8}$$

4.10.1 Internal Heat Generation

Internal heat generated at node i, $Qi = I^2R_i$

I = Current flowing through the node i

R_i = Electrical resistance of node i (part i)

Electrical resistance, $$R_i = \frac{\rho L_i}{A_i} \tag{4.9}$$

ρ = Electrical resistivity of the material

L_i = Length of the conductor

A_i = Cross sectional area of the conductor

4.10.2 Heat Input from Previous Node by Conduction

Heat flow from node (i-1) to node i by conduction = $\dfrac{(T_{(i-1)} - T_i)}{R_{C(i-1)}}$ (4.10)

T_i = Temperature of node i

$T_{(i-1)}$ = Temperature of node (i-1)

$R_{c(i-1)}$= conduction resistance between node (i-1) and node i

$$R_{C(i-1)} = 0.5\left[\frac{L_{(i-1)}}{KA_{(i-1)}}\right] + 0.5\left[\frac{L_{(i)}}{KA_{(i)}}\right] \quad (4.11)$$

$L_{(i)}$ = Length of part (i) [node i]

$L_{(i-1)}$ = Length of part (i-1) [node (i-1)]

K =Thermal conductivity of the material

$A_{(i)}$ = Cross sectional area of part (i) [node i]

$A_{(i-1)}$ = Cross sectional area of part (i-1) [node (i-1)]

Length is considered along the current flow direction.

Cross sectional area is considered perpendicular to current flow.

4.10.3 Heat Output to Next Node by Conduction

Heat flow from node i to node (i+1) by conduction = $\dfrac{(T_i - T_{i+1})}{R_{Ci}}$ (4.12)

T_i = Temperature of node i

T_{i+1} = Temperature of node i+1

R_{ci} = Conduction resistance between node i and node i+1

$$R_{C(i)} = 0.5\left[\frac{L_{(i-1)}}{KA_{(i-1)}}\right] + 0.5\left[\frac{L_{(i)}}{KA_{(i)}}\right] \quad (4.13)$$

L_i= Length of part i [node i]

$L_{(i+1)}$= Length of part(i+1) [node (i+1)]

K= Thermal conductivity of the material

A_i = Cross sectional area of part i (node i)

$A_{(i+1)}$ = Cross sectional area of part (i+1) [node (i+1)]

4.10.4 Heat Output to Air by Convection

$$\text{Heat flow from node i to air by convection} = \frac{(T_i - T_{ambient})}{R_{th(i)}} \tag{4.14}$$

T_i = Temperature of node i

$T_{ambient}$ = Temperature of atmospheric air.

$R_{th(i)}$ = Thermal convection resistance between node i and air.

$$R_{th(i)} = \frac{1}{h_i a_i} \tag{4.15}$$

h_i = Heat transfer co-efficient of part i (node i)

a_i = Surface area of part i (node i)

Considering node 2, heat input is by I^2R_2 heat generation and from node1 by conduction through R_{c1}.Heat is lost by conduction thorough R_{c2} to node3 and by convection through R_{th2} to ambient air. Energy balance equation for node 2 is as follows.

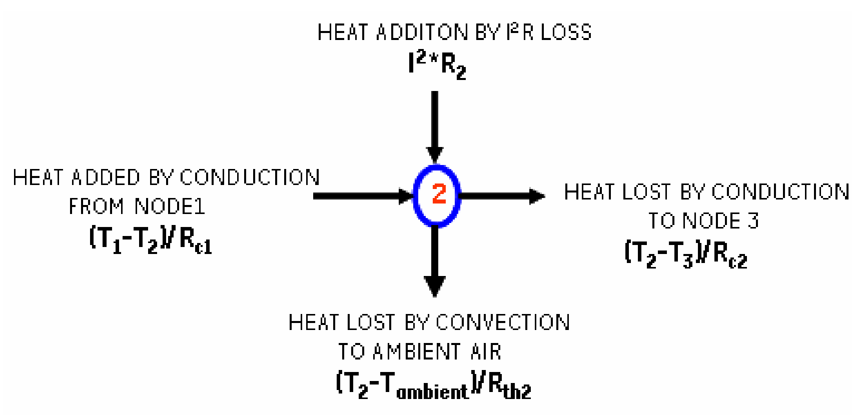


Figure 4.3 Energy balance at Node 2

The node equation can be written as

$$I^2R_2 + \frac{(T_1 - T_2)}{R_{C1}} = \frac{(T_2 - T_3)}{R_{C2}} + \frac{(T_2 - T_{ambient})}{R_{th2}} \tag{4.16}$$

Internal heat generated at node2, $Q_2 = I^2R_2$

Electrical resistance, $R_2 = \frac{\rho L_2}{A_2}$ (4.17)

Heat flow from node1 to node2 by conduction = $\frac{(T_1 - T_2)}{R_{C1}}$ (4.18)

R_{c1}= Conduction resistance between node1 and node2

$$R_{C1} = 0.5\left[\frac{L_1}{KA_1}\right] + 0.5\left[\frac{L_2}{KA_2}\right] \quad (4.19)$$

Heat flow from node2 to node3 by conduction = $\frac{(T_2 - T_3)}{R_{C2}}$ (4.20)

R_{c2} = Conduction resistance between node 2 and node 3

$$R_{C2} = 0.5\left[\frac{L_2}{KA_2}\right] + 0.5\left[\frac{L_3}{KA_3}\right] \quad (4.21)$$

Heat flow from node 2 to air by convection= $\frac{(T_2 - T_{ambient})}{R_{th2}}$ (4.22)

R_{th2} = Thermal convection resistance between node2 and air.

Convection resistance, $R_{th2} = \frac{1}{h_2 a_2}$ (4.23)

4.11 NODE EQUATION AT JOINT

Nodal equation changes slightly for joint node.At a joint between conductors, two resistances come into picture, electrical contact resistance and thermal contact resistance. Electrical contact resistance is responsible for additional heat generation at the joint due to increased electrical resistance at the joint and thermal contact resistance is responsible for restriction to the heat flow between the two conductors of the joint. Consider two stepped bars connected by a joint as shown in figure 4.4. Joint is represented by node 4. Half the thermal contact resistance is taken on either side of the joint node and heat (Q_c) generated at joint is added at the node. At joint node, heat lost by convection is not considered as the inner surface of joint is not exposed to air and the outer surface area of the joint is considered

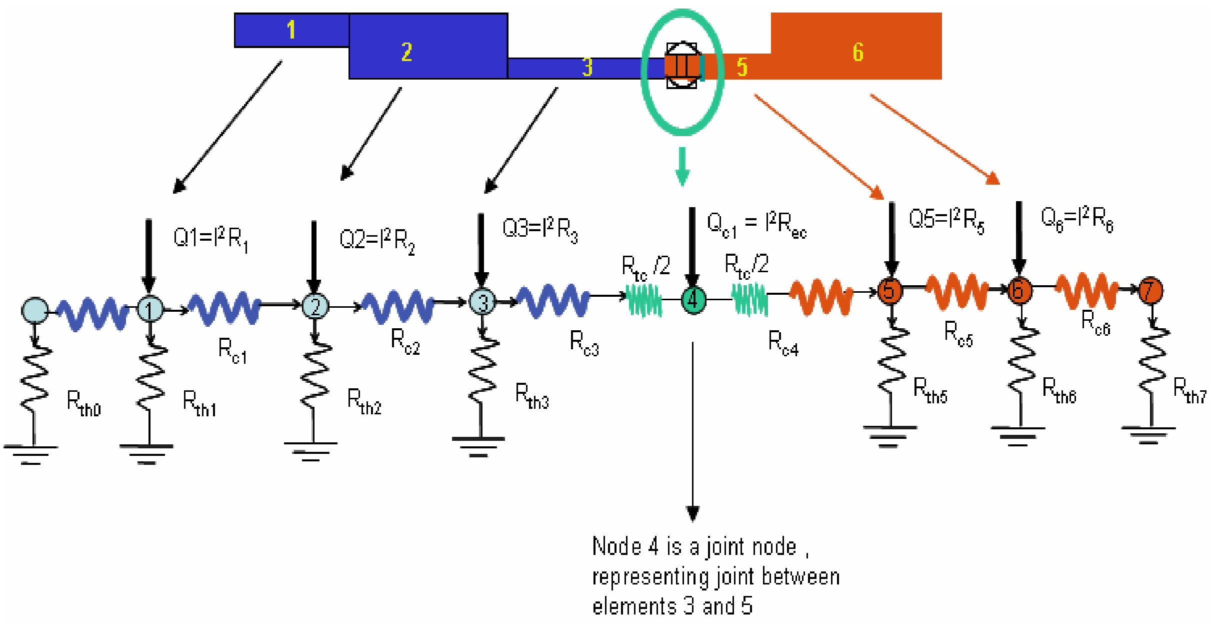


Figure 4.4 Network Diagram at Joint

in node 3 and node 4 while calculating heat lost by convection from those nodes. The node equation for joint is as follows:

$$Q_{c1} + \frac{(T_3 - T_4)}{R_{c3}} = \frac{(T_4 - T_5)}{R_{c4}} \qquad (4.24)$$

T_3 = temperature of node 3

T_4 = Temperature at joint node (node 4)

T_5 = Temperature of node 5

Q_{c1}= Heat generated at joint = I^2R_{ec}

I = current flowing through the joint

R_{ec} = Electrical contact resistance [Dealt in chapter 5]

R_{tc} = Thermal contact resistance of the joint [Dealt in chapter 5]

R_{c3} = Conduction resistance between nodes 3 and 4.

$$R_{C3} = 0.5\left[\frac{L_3}{KA_3}\right] + 0.5R_{tc} \qquad (4.25)$$

R_{c4} = Conduction resistance between nodes 4 and 5.

$$R_{C4} = 0.5R_{tc} + 0.5\left[\frac{L_4}{KA_4}\right] \qquad (4.26)$$

It can be observed that at starting and ending nodes i.e. at the first element and last elements of the entire structure considered, only half the thermal conduction resistance is considered by the above node equations. To consider remaining half also into account, nodes are assumed on the start and end faces. These are termed as half nodes. Internal heat generation is zero at these nodes and heat flowing in by conduction is dissipated by convection to air. Half nodes can also be neglected provided more number of nodes are considered for the first and last components.

For making the job of writing nodal equations easy and fast, instead of considering thermal resistance in the denominator, its reciprocal i.e. thermal conductance is considered in the numerator. The reciprocal of conduction resistance i.e. conduction conductance is denoted by G

Thermal conduction resistance, $R_C = \frac{L}{KA}$ (4.27)

Conduction conductance, $G = \frac{1}{R_c} = \frac{KA}{L}$ (4.28)

Similarly, convection conductance, $H = \frac{1}{R_{th}} = ha$ (4.29)

For joint, joint conduction conductance, $J = \frac{1}{R_{tc}} = \frac{\overline{K} * \overline{\lambda} * 2.1}{R_{ec}}$ (4.30)

The nodal equations are as follows:

Node 1 $Q_1 = G_1(T_1 - T_2) + H_1(T_1 - T_{air})$ (4.31)

Node 2 $Q_2 + G_1(T_1 - T_2) = G_2(T_2 - T_3) + H_2(T_2 - T_{air})$ (4.32)

Node 3 $Q_3 + G_2(T_2 - T_3) = G_3(T_3 - T_4) + H_3(T_3 - T_{air})$ (4.33)

Node 4 $Q_{c1} + G_3(T_3 - T_4) = G_4(T_4 - T_5)$ (Joint) (4.34)

Node 5 $Q_5 + G_4(T_4 - T_5) = G_5(T_5 - T_6) + H_5(T_5 - T_{air})$ (4.35)

Node 6 $Q_6 + G_5(T_5 - T_6) = G_6(T_6 - T_7) + H_6(T_6 - T_{air})$ (4.36)

Node 7 $G_6(T_6 - T_7) = H_7(T_7 - T_{air})$ (4.37)

By simplifying the equations, the equations can be written with temperature coefficients on one side and heat terms on the other side.

Node 1 $Q_1 + H_1 T_{air} = (G_1 + H_1)T_1 - G_1 T_2$ (4.38)

Node 2 $Q_2 + H_2 T_{air} = -G_1 T_1 + (G_1 + G_2 + H_2)T_2 - G_2 T_3$ (4.39)

Node 3 $Q_3 + H_3 T_{air} = -G_2 T_2 + (G_2 + G_3 + H_3)T_3 - G_3 T_4$ (4.40)

Node 4 $Q_{cl} = -G_3 T_3 + (G_3 + G_4)T_4 - G_4 T_5$ (4.41)

Node 5 $Q_5 + H_5 T_{air} = -G_4 T_4 - (G_4 + G_5 + H_5)T_5 - G_5 T_6$ (4.42)

Node6 $Q_6 + H_6 T_{air} = -G_5 T_5 + (G_5 + G_6 + H_6)T_6 - G_6 T_7$ (4.43)

Node 7 $H_7 T_{air} = -G_6 T_6 + (G_6 + H_7)T_7$ (4.44)

The above nodal equations can be written in matrix form as follows

$$\begin{bmatrix} Q_1 + H_1 T_{air} \\ Q_2 + H_2 T_{air} \\ Q_3 + H_3 T_{air} \\ Q_{cl} \\ Q_5 + H_5 T_{air} \\ Q_6 + H_6 T_{air} \\ H_7 T_{air} \end{bmatrix} = \begin{bmatrix} G_1 + H_1 & -G_2 & 0 & 0 & 0 & 0 & 0 \\ -G_1 & G_1 + G_2 + H_2 & -G_2 & 0 & 0 & 0 & 0 \\ 0 & -G_2 & G_2 + G_3 + H_3 & -G_3 & 0 & 0 & 0 \\ 0 & 0 & -G_3 & G_3 + G_4 & -G_4 & 0 & 0 \\ 0 & 0 & 0 & -G_4 & G_4 + G_5 + H_5 & -G_5 & 0 \\ 0 & 0 & 0 & 0 & -G_5 & G_5 + G_6 + H_6 & -G_6 \\ 0 & 0 & 0 & 0 & 0 & -G_6 & G_6 + H_7 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \\ T_7 \end{bmatrix}$$

Multiplying the inverse of conductance matrix with power matrix, temperatures at different nodes can be found out.

$$\begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \\ T_7 \end{bmatrix} = \begin{bmatrix} G_1 + H_1 & -G_2 & 0 & 0 & 0 & 0 & 0 \\ -G_1 & G_1 + G_2 + H_2 & -G_2 & 0 & 0 & 0 & 0 \\ 0 & -G_2 & G_2 + G_3 + H_3 & -G_3 & 0 & 0 & 0 \\ 0 & 0 & -G_3 & G_3 + G_4 & -G_4 & 0 & 0 \\ 0 & 0 & 0 & -G_4 & G_4 + G_5 + H_5 & -G_5 & 0 \\ 0 & 0 & 0 & 0 & -G_5 & G_5 + G_6 + H_6 & -G_6 \\ 0 & 0 & 0 & 0 & 0 & -G_6 & G_6 + H_7 \end{bmatrix}^{-1} * \begin{bmatrix} Q_1 + H_1 T_{air} \\ Q_2 + H_2 T_{air} \\ Q_3 + H_3 T_{air} \\ Q_{cl} \\ Q_5 + H_5 T_{air} \\ Q_6 + H_6 T_{air} \\ H_7 T_{air} \end{bmatrix}$$

4.12 CONVECTION

Heat energy transferred between a surface and a moving fluid at different temperatures is known as convection. Convection can be either natural or force depending on the fluid flow velocity.

Natural convection is caused by buoyancy forces due to density differences caused by temperature variations in the fluid. By heating, the density change in the boundary layer will cause the fluid to rise and be replaced by cooler fluid which also will heat and rise. This continuous phenomena is called free or natural convection

Heat transfer by convection is given by $$Q = h * a * \Delta T \qquad (4.45)$$

Where Q= Heat transfer by convection

h =Convective Heat transfer co-efficient

a = Surface area of the body

ΔT = Temperature difference between plate and fluid flowing

4.12.1 Convective Heat Transfer coefficient

The convective heat transfer coefficient, 'h' relates the amount of heat transferred between a moving bulk fluid (liquid or gas) and a bounding surface. It is sometimes referred to as a film coefficient representing thermal resistance of a relatively stagnant layer of fluid between a heat transfer surface and the fluid medium. The important physical properties of the fluid which affect the convection coefficient are thermal conductivity, viscosity, density (proportional to pressure) and specific heat of the fluid. Other parameters that affect the coefficient are the fluid velocity, geometry of the bounding surface and pressure (to which fluid density is directly proportional).

In the project carried out, the flow is natural and the components are simplified to vertical plates and horizontal plates. So the attention is confined to calculation of "h" values for isothermal vertical and horizontal plate with natural convection. Two 'h' tables are developed in the analytical tool to calculate 'h' value based on the following formulae.

4.12.1 (a) 'h' Correlations For Vertical Plate In Natural Convection

t_{plate} = Temperate of the plate ^{0}C

t_{air} = Temperature of the fluid ^{0}C

Film Temperature……………..... $t_f = (t_{plate} + t_{air})/2$ (4.46)

Absolute Film Temperature…...... $T_f = t_f + 273$ (K) (4.47)

Prandtl Number………………… $p_r = \frac{\mu . C_p}{K}$ (4.48)

Where

Absolute Viscosity……..... $\mu = \frac{0.000001492 * T_f^{1.5}}{109.1 + T_f}$ Kg/m.s (4.49)

Specific Heat ……………. (4.50)

$$C_p = 1030.5 - 0.19975 * T_f + 0.00039734 * T_f^2 + 0.000000083504 * T_f^3 \quad \text{KJ/Kg.}^0\text{C}$$

Thermal conductivity……. $K = \frac{0.002334 * T_f^{1.5}}{164.54 * T_f} * 100$ W/m.^{0}C (4.51)

Grashof Number………………… $G_r = \frac{g.\beta.\Delta T.L^3}{\upsilon^2}$ (4.52)

Where

Beta……………………….. $\beta = \frac{1}{T_f}$ 1/^{0}K (4.53)

Gravitational Constant……..g = 9.81 m/s^2

Kinematic Viscosity………$\upsilon = \frac{\mu}{\rho}$ m^2/s (4.54)

Density…………………….. $\rho = \frac{351.99}{T_f} + \frac{344.84}{T_f^2}$ g/m^3 (4.55)

Length…………………… .L = Height of the plate in m

Rayleigh Number…………..$R_a = p_r * G_r$ (4.56)

Nussalt Number………….. $Nu = 0.825 + \frac{0.387R_a^{1/6}}{\left[1+(0.492/Pr)^{9/16}\right]^{8/27}}$

For $10^{-1} < R_{aL} < 10^{12}$ (4.57)

Convective Heat Transfer Coefficient… $h = \frac{Nu * K}{L}$ $W/m^2.K$ (4.58)

4.12.1 (b) 'h' Correlations For Horizontal Plate In Natural Convection

The heat transfer coefficient from horizontal plate depends on whether the plate is cooler or warmer then the ambient fluid and also on whether the plate is facing upward or downward. Correlations used for horizontal plate are:

$$\text{Characterstic Lenght, } L = \frac{\text{surface area of the Plate}}{\text{Perimeter of the Plate}}$$

Upper surface heated or lower surface cooled

$$N_{uL} = 0.54 * R_{aL}^{1/4} \text{ for } 2.6*10^4 < R_{aL} < 10^7 \quad (4.59)$$

$$N_{uL} = 0.15 * R_{aL}^{1/3} \text{ for } 10^7 < R_{aL} < 3*10^{10} \quad (4.60)$$

Lower surface heated or upper Surface cooled

$$N_{uL} = 0.27 * R_{aL}^{1/4} \text{ for } 3*10^5 < R_{aL} < 3*10^{10} \quad (4.61)$$

Convective Heat Transfer Coefficient… $h = \frac{Nu * K}{L}$ w/m^2K (4.62)

4.13 EFFECT OF RADIATION

Radiation effect is not considered in the temperature rise calculations. In switch gear, as per standards the maximum allowed temperature rise up to run-in region is 65^0C and 85^0C inside the circuit breaker. At a temperature rise of 65^0C, the effect of radiation can be neglected compared to the complexity it creates in the network calculations by considering it. In circuit breaker, thought the temperature rise is 85^0C, the size of the components are small and the temperature difference between the components and the surrounding air or casing is very less as the components are almost enclosed completely. So the effect of radiation is neglected avoiding the complexity in network calculations.

5. JOINT RESISTANCE

5.1 INTRODUCTION

It is necessary that a conductor joint shall be mechanically strong and electrically have a relatively low resistance which must remain substantially constant throughout the life of the joint. Efficient joints in copper conductors can be made by bolting, clamping, riveting, soldering or welding, the first two being used extensively. The various types of electrical contacts are stationary contacts, switching contacts, sliding contacts, point contacts, line contacts and plain contacts.

At a joint between conductors, two resistances come into picture.

1. Electrical contact resistance and
2. Thermal contact resistance.

An accurate knowledge of contact mechanics, that is, the pressure distribution, the size of contact area, and the mean separation between surface planes as functions of applied load, and the geometrical and mechanical characteristics/properties of the contacting bodies, plays an important role in predicting and analyzing thermal and electrical contact resistance and many tribological phenomena. Electrical contact resistance is responsible for additional heat generation at the joint due to increased electrical resistance at the joint and thermal contact resistance is responsible for restriction to the heat flow between the two conductors of the joint.

5.2 ELECTRICAL CONTACT RESISTANCE

The contact surfaces of two contiguous current carrying conductors offer a comparatively high electrical resistance to current, known as the contact surface resistance or simply the contact resistance of the junction.

Electrical contact resistance plays a prominent role in temperature rise as excess heat is generated at the contact points due to increased resistance at the contact portion. Electrical contact resistance depends on many factors like surface roughness of contact material, crushing resistance of the contact material, shape of the contact faces and force acting on the contact area. Force acting at the joint greatly affects the resistance. As shown in figure 5.1(a), when no force is applied the two surfaces are in contact at sharp asperities creating very less contact area. When a force F is applied, the sharp asperities deform plastically and the contact area increases as shown in figure 5.1(b) and (c). With increase in contact pressure, resistance drastically decreases and becomes constant up to certain pressure, beyond which contact pressure has almost no effect on resistance. Figure 5.1 shows the effect of joint load on contact resistance during loading and unloading.

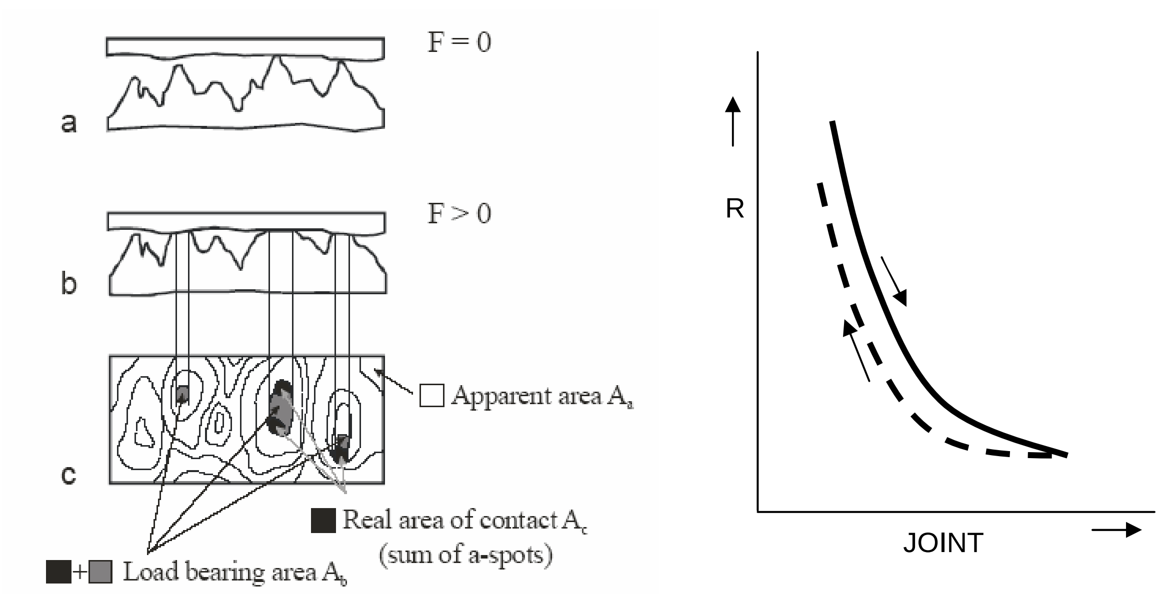


Figure 5.1 Effect of contact pressure on contact resistance

5.3 CALCULATION OF ELECTRICAL CONTACT RESISTANCE

5.3.1. Maxwell's Formula

When two large conductors make perfect electrical contact over a small circular area of radius *a*, there will be a constriction resistance to electrical flow between them is given

$$R = \frac{\rho}{2a} \tag{5.1}$$

Where ρ is the electrical resistivity. This equation is widely used in the design and study of electrical contacts.

5.3.2 Greenwood's Formula

However, if the contacting bodies have rough surfaces, contact will rarely be restricted to a single area. Instead, there will be contact at a multitude of microscopic ''actual'' contacts clustered within a macroscopic ''nominal'' or ''apparent'' contact area. Greenwood has analyzed such clusters, treating a number of distributions of size and spacing and formulated the following formula

$$R = \frac{\rho}{2\sum a_i} + \frac{\rho}{\Pi}\left(\sum_{i \neq j}\sum \frac{a_i a_j}{d_{ij}}\right) \Bigg/ \left(\sum a_i\right)^2 \tag{5.2}$$

in ρ which is the resistivity, a_i the radius of the spot i , aj the radius of the spot j d_{ij} the distance between the centers of the spots i and j,

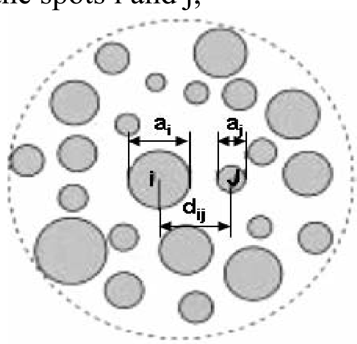


Figure 5.2 Set of Circular Contact Spots Showing the Symbol Notation.

Equation 5.2 provides a good approximation to the electrical contact resistance for a deterministic distribution of contact spots of known size and location, but information about the distribution of asperities is most likely to be statistical in nature, since surface roughness is essentially a random process. Furthermore, surface roughness descriptions are typically multiscale in nature, and on a sufficiently fine scale the number of discrete contact spots is likely to be too large to permit an efficient deterministic calculation.

5.3.3. Empirical Relations

The contact resistance may be found from the following relationship which is obtained experimentally

$$R \approx \frac{C\rho}{F^m} \tag{5.3}$$

Where $C\rho$ = factor dependent on the material and shape of the contact members and by the finish and condition of the contact faces.

F = Force pressing the contact members together.

m= exponent dependent on the number of points at contact, with following values

m = 0.5 for single point contacts

= 0.7 to 1 for multi-point contacts

= 0.7 to 0.8 for line contacts

= 1 for plane contacts

Based on this, the following equations are developed empirically, which are generally used to calculate the electrical contact resistance quickly.

For new contacts, Electrical Contact Resistance is given by

$$R_{ec} = \frac{(\rho_1 + \rho_2)}{\sqrt{2 * \Pi}} * \sqrt{\frac{\min(\sigma_1, \sigma_2)}{F^m}} * 1000 \ldots\ldots\ldots \mu\Omega \qquad (5.4)$$

After some switchings, Electrical contact resistance is given by

$$R_{ec} = \frac{(\rho_1 + \rho_2)}{\sqrt{2 * \Pi}} * \sqrt{\frac{\max(\sigma_1, \sigma_2)}{F^m}} * 1000 \ldots\ldots\ldots \mu\Omega \qquad (5.5)$$

ρ_1, ρ_2 are electrical resistivities of the two materials in contact at the joint in ohm-mm^2/m

σ_1, σ_2 are crushing strength of the two materials in contact at the joint in kg/mm^2

F is the contact force applied at the joint in Kg

m is a constant representing number of points at contact. I.e. the type of contact.

Generally m is taken 1 for new contacts and 0.7 after some switchings for plane contact

For a bolt tightened with a torque wrench the torque required to provide an initial bolt tension may be approximated by the formula.

$$T = F * K * d \qquad (5.6)$$

d = nominal diameter of bolt (m)

F = Preload applied (N)

K = Factor based on thread condition, usage

Typical K factors are tabulated as follows. Generally tightening torque corresponding to a bolt size is taken form standard tables available in design data books.

Table5.1 K factor values

Steel Thread Condition	K
As received, stainless on mild or alloy	0.30
As received, mild or alloy on same	0.20
Cadmium plated	0.16
Molybdenum-disulphide grease	0.14
PTFE lubrication	0.12

5.4 THERMAL CONTACT CONDUCTANCE

Thermal contact conductance plays an instrumental role for temperature drop across the joint. It constricts the flow of heat across the joint contact surfaces because of reduced contact area at the joint as shown in figure 5.3. The amount of actual contact area is also dependent on the physical properties of the contacting materials. If one of the materials is softer than the other, then the asperities of the harder material are likely to penetrate the surface of the softer material and increase the contact area.

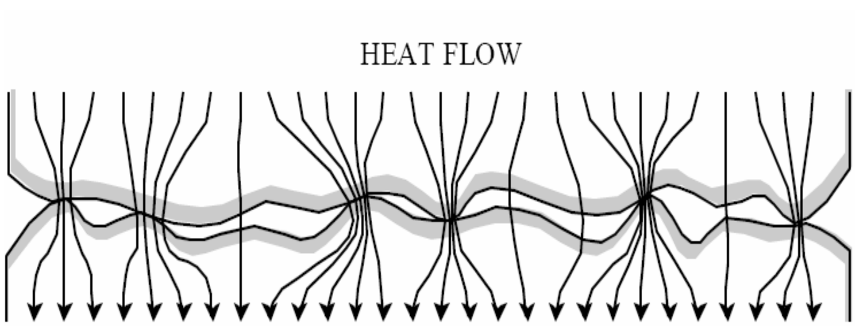


Figure 5.3 – Constriction of Heat Flow through an Interface formed by Two Materials.

At higher pressures, one would expect that the penetration of these asperities would increase. In the case of materials of nearly the same hardness, the asperities would deform, and one might expect that the amount of deformation would increase with pressure. Interfaces with a higher mean thermal conductivity would be expected to have a lower resistance to heat transfer than those interfaces that have lower mean thermal conductivities.

This limited contact area constricts the flow of heat to a few channels at the interface between the materials, making the temperature distribution in the vicinity of the interface complex and three-dimensional. An approximation to this complex temperature distribution is to assume a temperature discontinuity at the interface, with the associated temperature drop determined by the temperature distribution on either side of the interface (Figure 5.4).

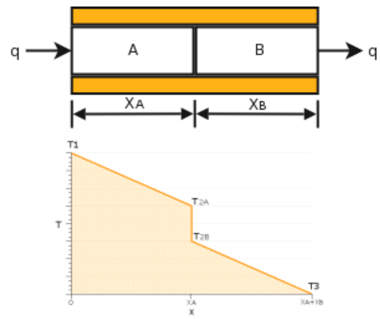


Figure 5.4 Temperature drop on either side of interface

Thermal energy can be transferred between contacting bodies by three different modes:
1) conduction, through the microcontacts, 2) conduction, through the interstitial fluid in the gap between the solids, and 3) thermal radiation across the gap if the interstitial substance is transparent to radiation as shown in figure 5.5. Heat transfer across the interface by radiation remains small as long as the body temperatures are not too high, that is, less than 700 K, and in most typical applications it can be neglected.

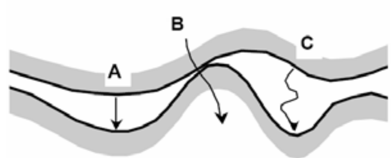


Figure 5.5 Heat transfer paths at an interface: A) conduction through interstitial material, B) conduction at contact spot, C) radiation across interstitial space

As illustrated in Figure 5.6, heat flow is constrained to pass through the macrocontact and, then, in turn through the microcontacts. This phenomenon leads to a relatively high-temperature drop across the interface. Two sets of resistances in series can be used to represent the thermal contact resistance (TCR) for a joint: the large-scale or macroscopic constriction resistance R_L and the small-scale or microscopic constriction resistance Rs

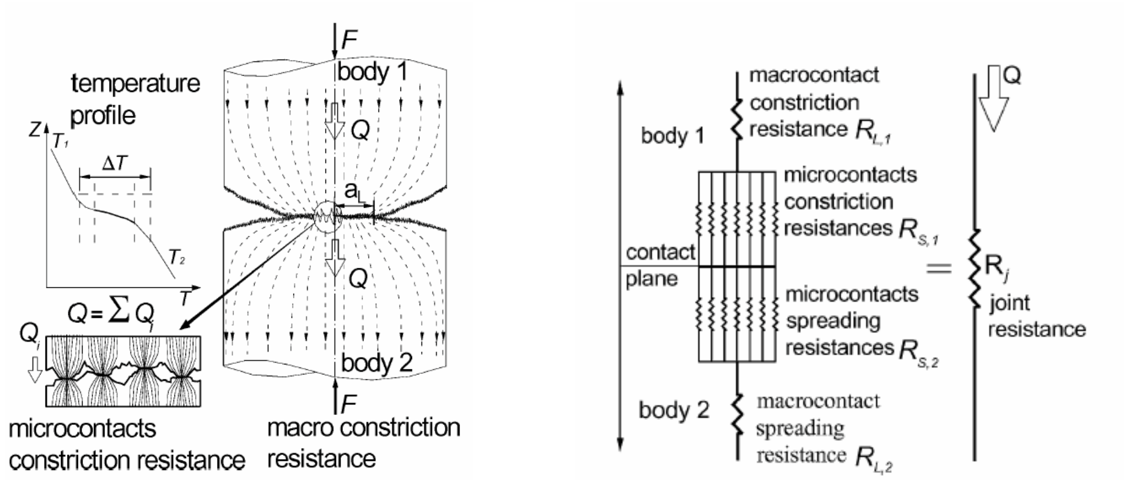


Figure 5.6 Thermal Resistance Network for nonconforming Rough Contacts

$$R_j = R_s + R_L \tag{5.7}$$

Many theoretical models for determining TCR have been developed for two limiting cases: 1) conforming rough, here contacting surfaces are assumed to be perfectly flat and 2) elasto constriction, where the effect of roughness is neglected, that is, contact of two smooth spherical surfaces. These two limiting cases are simplified cases of real contacts because engineering surfaces have both out of- flatness and roughness simultaneously. Few analytical models for contact of two nonconforming rough surfaces exist in the literature.

Table 5.1 – Thermal Contact Conductance Models

correlation	Condition
Ross and Stoute $h_c = \dfrac{k_c.p_c}{0.05H\sqrt{\dfrac{\sigma_1^2+\sigma_2^2}{2}}}$	Modified flat contact model, some dependence on thermo-mechanical properties
Shlykov and Gamin $h_c = 4.2*10^4 \dfrac{K_C P_C}{d_0(345MPa)} + \dfrac{K_{go}}{\sigma_1+\sigma_2}$	Modified flat contact model, some dependence on thermo-mechanical properties
Cooper et,al $\dfrac{h_c\sigma}{Km} = 1.45\left[\dfrac{P}{H_v}\right]^{0.98}$	Nominally flat, rough surfaces.

Yovanovich	Modification of Cooper,et al, rough surface
$\frac{h_c\sigma}{Km} = 1.25\frac{K_S m}{\sigma}\left[\frac{P}{H_v}\right]^{0.95} + \frac{K_{go}}{Y + \alpha_a \beta \wedge}$	$\beta = \left[2\frac{C_p / C_v}{C_p / C_v + 1}\right]\frac{1}{Pr}$

5.5 RELATION BASED ON THERMO-ELECTROMECHANICAL PROPERTIES

The above relations are developed in terms of thermo- mechanical properties. I.e. in terms of mechanical properties like force at the joint area, surface roughness, hardness of the contacting elements and thermal property like thermal conductivity. Empirical relation in terms of thermo-electromechanical properties as electrical contact resistance is known is given by

$$R_{tc} = \frac{R_{ec}}{\overline{K} * \overline{\lambda}} \tag{5.8}$$

Generally air is entrapped between two asperities. To take care of conduction of heat through the air gap in the voids, the thermal conductivity of the contacts has to be increased by a factor of 2.1. So the thermal contact resistance is given by

$$R_{tc} = \frac{R_{ec}}{\overline{K} * \overline{\lambda} * 2.1} \tag{5.9}$$

R_{ec}= Electrical contact resistance in micro-ohms

$\overline{K}$ is the average thermal conductivity of two different material in contact

$\overline{\lambda}$ is the average electrical resistivity of the two different material in contact

6. PROBLEM SOLVING PROCESS

6.1 PROBLEM DEFINITION

The problem has two parts. First part is to calculate steady state temperatures in AKD-12 switch gear (frame 1and 3) by developing an analytical tool. Second part is to predict the temperature variation in the switch gear for change in geometry of components.

As first part, an Excel tool is developed with Visual Basic backend, based on thermal networking method to calculate steady state temperatures in electrical equipments. Analytical calculations are carried out and temperatures are calculated using the Excel tool for frame 1and 3. Test is conducted on AKD-12 switch gear –frame 1 and frame 3 under continuous current to find out temperatures at different points along the current flow path. Analytical results from the tool are then validated against the test data.

As second part, geometry of components in both the frames are varied and variation in temperature at moving contact (highest temperature point) with respect to original temperatures is observed.

Frame1 defines a switch gear through which 2000Amps current flows and 2000Amps circuit beaker is used. Frame 3 defines a switch gear through which 5000 Amps current flows and the breaker assembled is 5000Amps rated air circuit breaker.

6.2 STEPS IN SOLVING THE PROBLEM

Steps followed to calculate temperatures analytically are listed below

1. Initially an electrical network diagram is developed for the switch gear considering all the current flow paths and joints.
2. Electrical body resistance of each component and the corresponding joint resistance are calculated.
3. The total calculated electrical resistance of the switch gear is compared with the tested electrical resistance. Similarity of the two values replicates correctness of the electrical network diagram.

4. Thermal network diagram is developed from the electrical network diagram.
5. Once the thermal network diagram is prepared, all the input parameters required for "input and joints" sheets of the analytical tool are calculated.
6. Initial 'h' values are calculated based on natural convection correlations for vertical and horizontal plate with constant wall temperature.
7. Following the sequence of steps in working with the analytical tool, steady state temperatures at different point are obtained.
8. Further iterations are run with 'h' values corresponding to the temperatures obtained from the first run to obtain accurate temperatures.

6.2.1 Electrical Network Diagram

As a first step, electrical network diagram is prepared. Fig 6.1 shows electrical network diagram for AKD-12 frame 1 switch gear (For one phase). Components of the switch gear are represented by their electrical body resistances and joints are represented by electrical contact resistances. Resistances are arranged in series and parallel to replicate the way current faces restriction to flow in the switch gear. Figure 6.2 represents electrical network diagram for frame 3 (for single phase). Figure 6.3 shows electrical network diagram for frame3 with three phases.

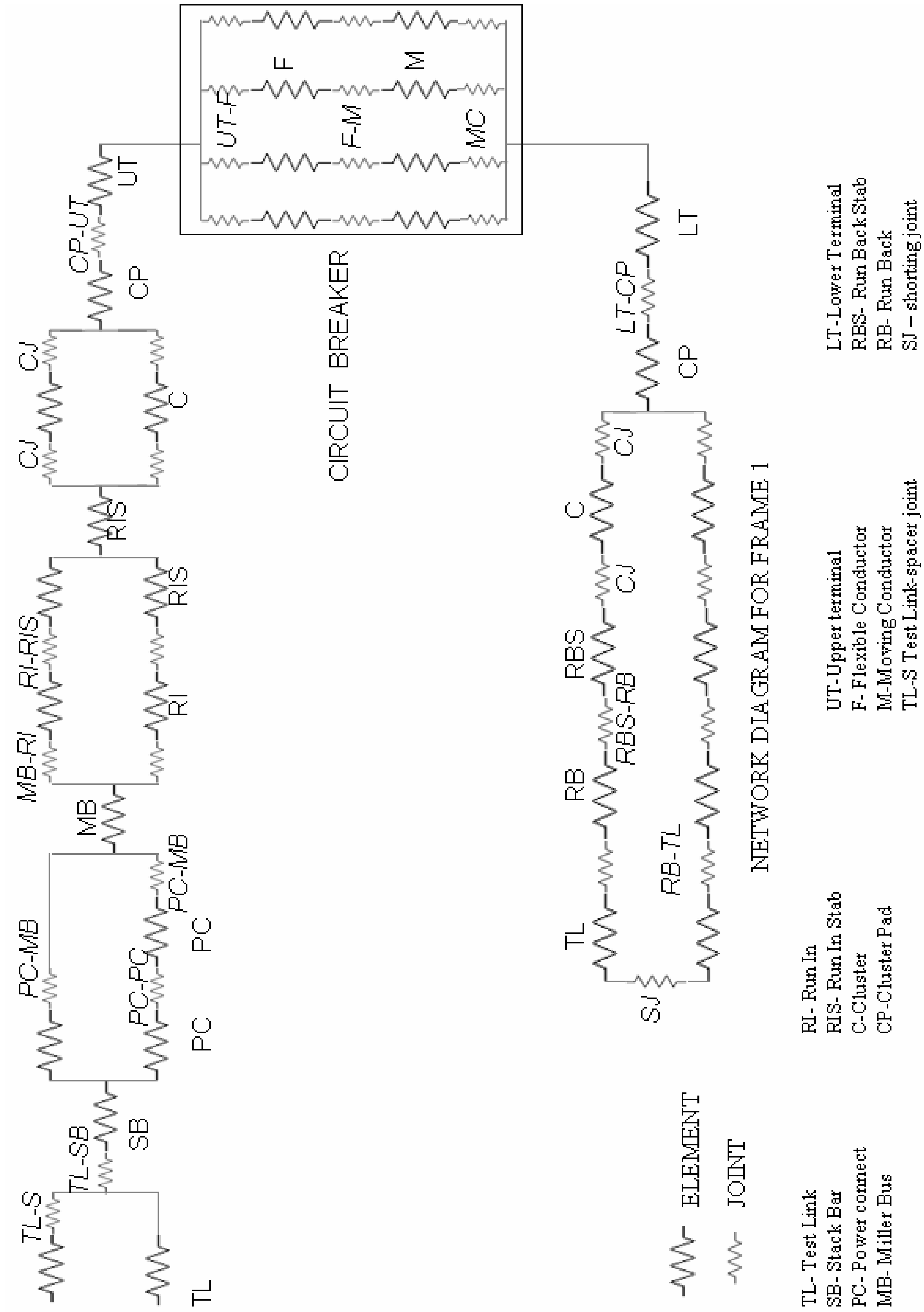

TL
TL-S
TL-SB
SB
PC
PC-MB
PC-PC
PC
PC-MB
MB
MB-RI
RI-RIS
RI
RIS
RIS
CJ
CJ
C
CP
CP-UT
UT
UT-F
F
F-M
M
MC
CIRCUIT BREAKER
LT
LT-CP
CP
CJ
C
CJ
RBS
RBS-RB
RB
RB-TL
TL
SJ
NETWORK DIAGRAM FOR FRAME 1
ELEMENT
JOINT
TL- Test Link
SB- Stack Bar
PC- Power connect
MB- Miller Bus
RI- Run In
RIS- Run In Stab
C-Cluster
CP-Cluster Pad
UT-Upper terminal
F- Flexible Conductor
M-Moving Conductor
TL-S Test Link-spacer joint
LT-Lower Terminal
RBS- Run Back Stab
RB- Run Back
SJ – shorting joint

Figure 6.1

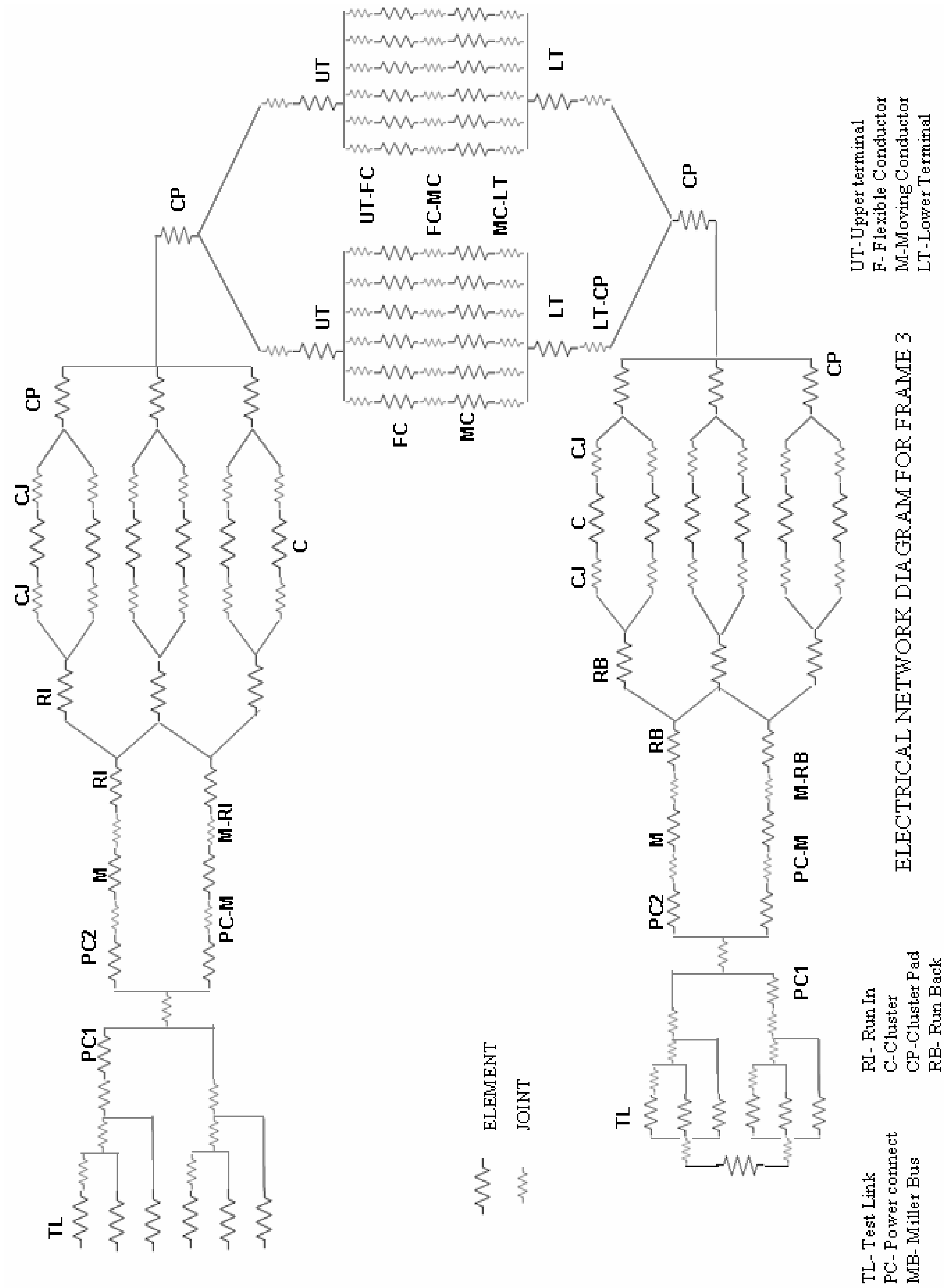
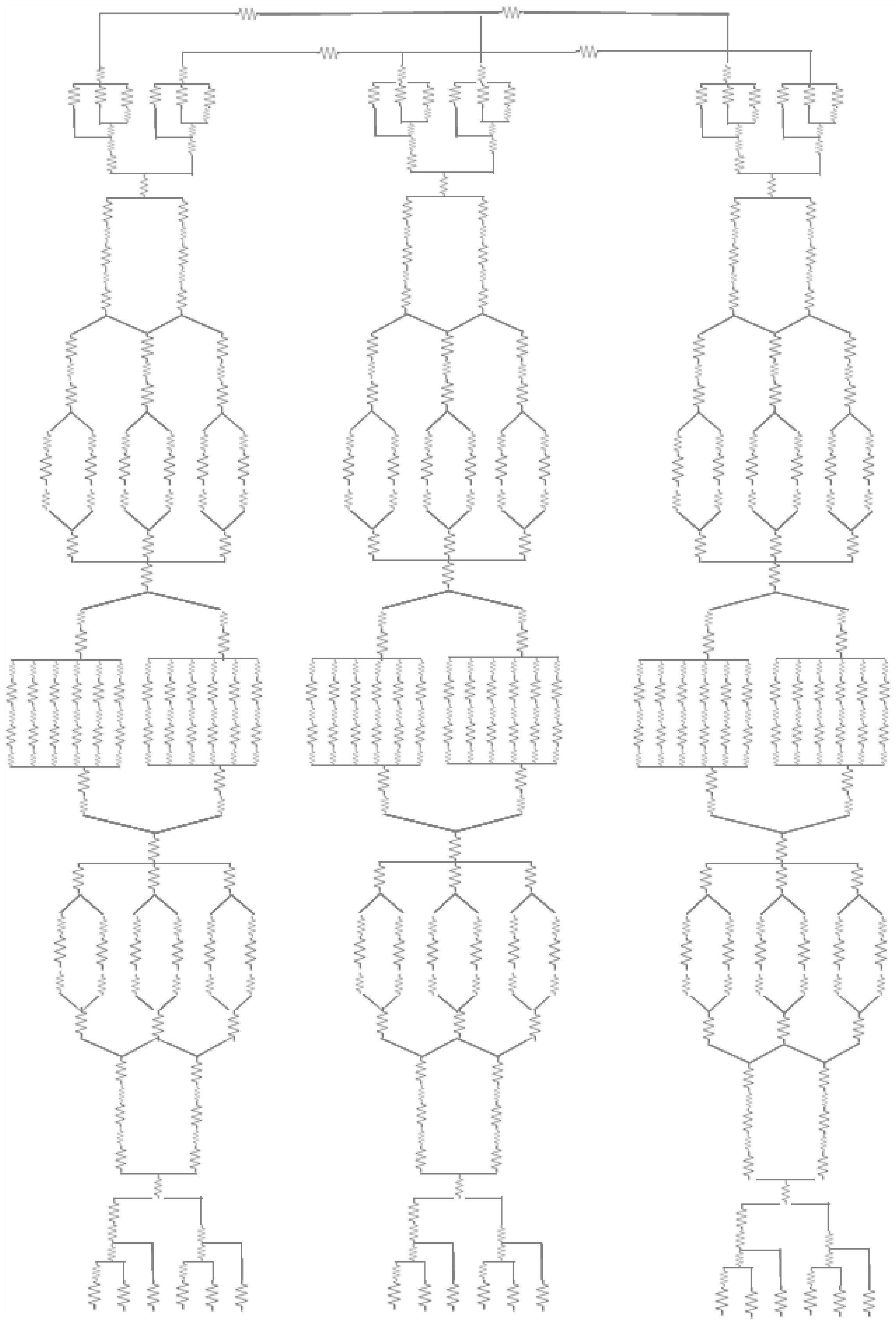

ELECTRICAL NETWORK DIAGRAM FOR FRAME 3
TL
PC1
PC2
PC-M
M
M-RI
RI
CJ
C
CP
UT
LT
LT-CP
UT-FC
FC-MC
MC-LT
FC
MC
RB
M-RB
ELEMENT
JOINT
TL- Test Link
PC- Power connect
MB- Miller Bus
RI- Run In
C-Cluster
CP-Cluster Pad
RB- Run Back
UT-Upper terminal
F- Flexible Conductor
M-Moving Conductor
LT-Lower Terminal

Figure 6.2



ELECTRICAL NETOWORK DIAGRAM FOR FRAME 3 FOR 3 PHASES

Figure 6.3

6.2.2 Electrical Resistance Calculation

In this step, electrical resistance of the electrical network diagram is calculated which involves calculation of body resistances of components and contact resistance of joints. From the geometry of the components, body resistance (DC electrical resistance) is calculated using the formula $$R = \frac{\rho L}{A} \tag{6.1}$$

Joint resistance of bolted joint is calculated knowing the bolting torque or force and number of bolts using the contact resistance tool. Resistance at contacts held by spring loading is calculated based on spring force acting at the contact. (*Details in chapter 5)* Following shows resistance calculation for AKD 12 frame 1 Global Air Circuit Breaker portion

Force applied at each cluster finger contact tip = 55 N. From the Excel Contact resistance calculation tool, contact resistance is 35.3 micro-ohms for 55 N. There are 18 such contact point i.e. 18 resistances connected in parallel. So equivalent cluster contact resistance

$$= \frac{35.3}{18} = 1.96\mu - \Omega$$

1. Equivalent Resistance of cluster assembly (both sides) = 2.1 micro –ohms
2. Body resistance of cluster pad = 0.72 micro –ohms
3. Joint resistance between cluster pad and load terminal = 0.65 micro-ohms
4. Load terminal body resistance =1.53 micro –ohms
5. Resistance of flexible conductor, moving conductor, moving contact and their joint (Considering 300 N spring force at each moving contact) =12.9micro-ohms
6. Line terminal body resistance =1.24 micro-ohms
7. Joint resistance at line terminal and cluster pad =0.65 micro-ohms
8. Body resistance of cluster pad =0.72 micro –ohms
9. Equivalent Resistance of cluster assembly =2.1 micro –ohms

Total Breaker resistance calculated by excel tool= 22.6micro –ohms

6.2.3 Comparison with Measured Value

In this step, electrical resistance from analytical calculations is compared with the resistance value from test data to validate the correctness of the electrical network diagram.

Breaker resistance calculated by excel tool= 22.6micro –ohms

Resistance from Test =19 micro –ohms

While calculating body resistance of flexible conductor, it is considered as solid conductor though it is made of laminates pressed together. This may be the major cause for 3.6 micro-ohms difference between the analytical and test value. In the same way, electrical resistance is calculated for the entire switch gear and compared with test data. Comparing electrical resistances is very important, as similarity of both the results indicates the correctness of the electrical network diagram and based on this diagram all the remaining work is carried out.

6.2.4 Thermal Network Diagram

The next step is to draw thermal network diagram based on electrical network diagram. It is drawn considering conduction, convection resistances, thermal contact resistances at joints and heat generators. Figure6.4 shows thermal network diagram for Frame 1(for one phase only). It has 143 nodes, out of which 5 nodes represent air in the compartment of switch gear. Figure 6.5 shows thermal network diagram for frame 3. Each node is connected to the other with a thermal conductor maintaining continuity through out the network. Frame 3 has 658 nodes with 208 nodes for each phase. Black node represents a component; red node represents a joint, blue node represents air. Green conductor represents conduction resistance, blue conductor represents convection resistance and red conductor represents half the thermal contact resistance. Heat generated by I^2R loss in the component is represented by black arrow, heat generation at joint by red arrow. Single component is represented as more than one node depending on the length of the component. A node is considered at each joint and a new node is considered wherever cross section changes.

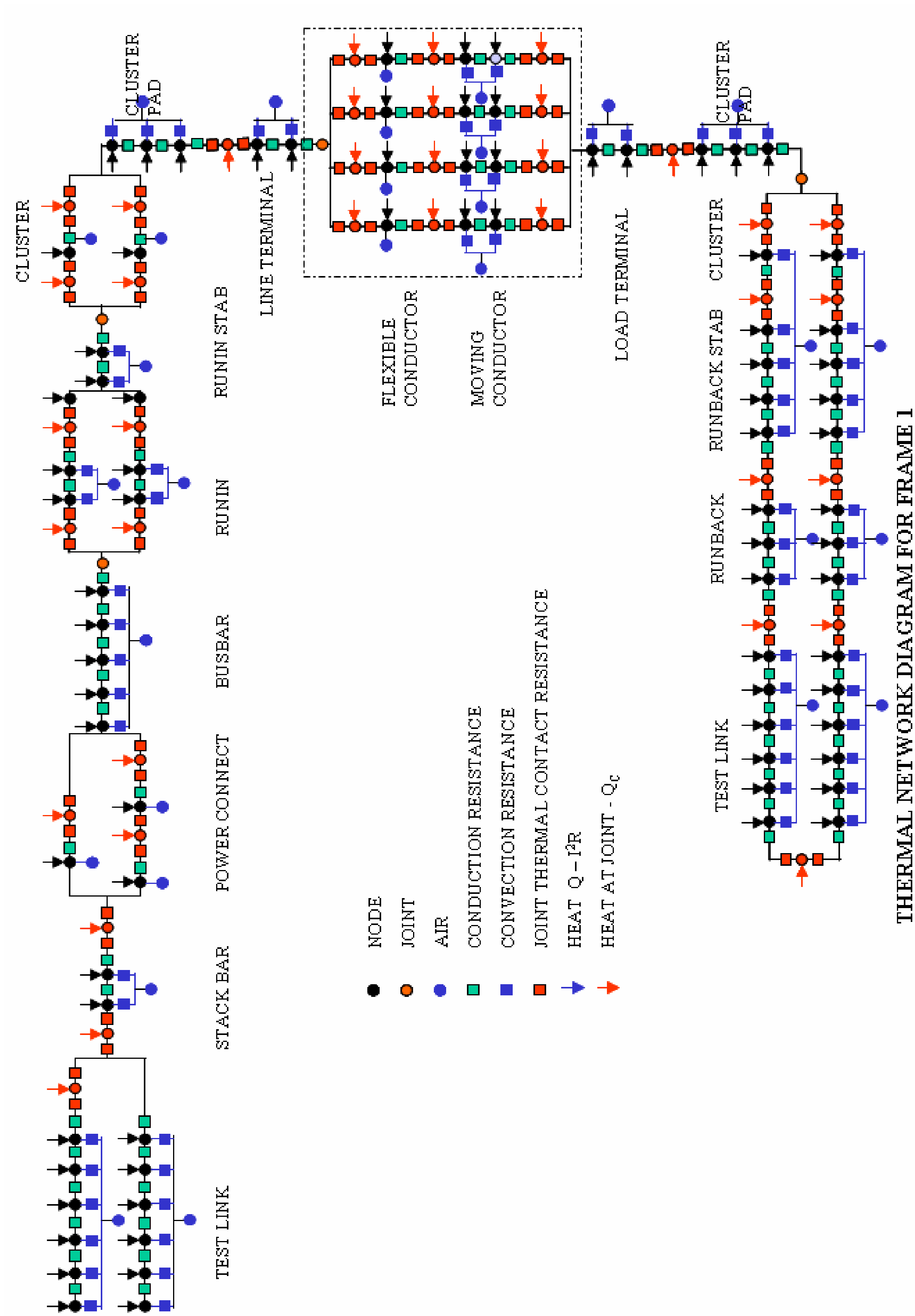
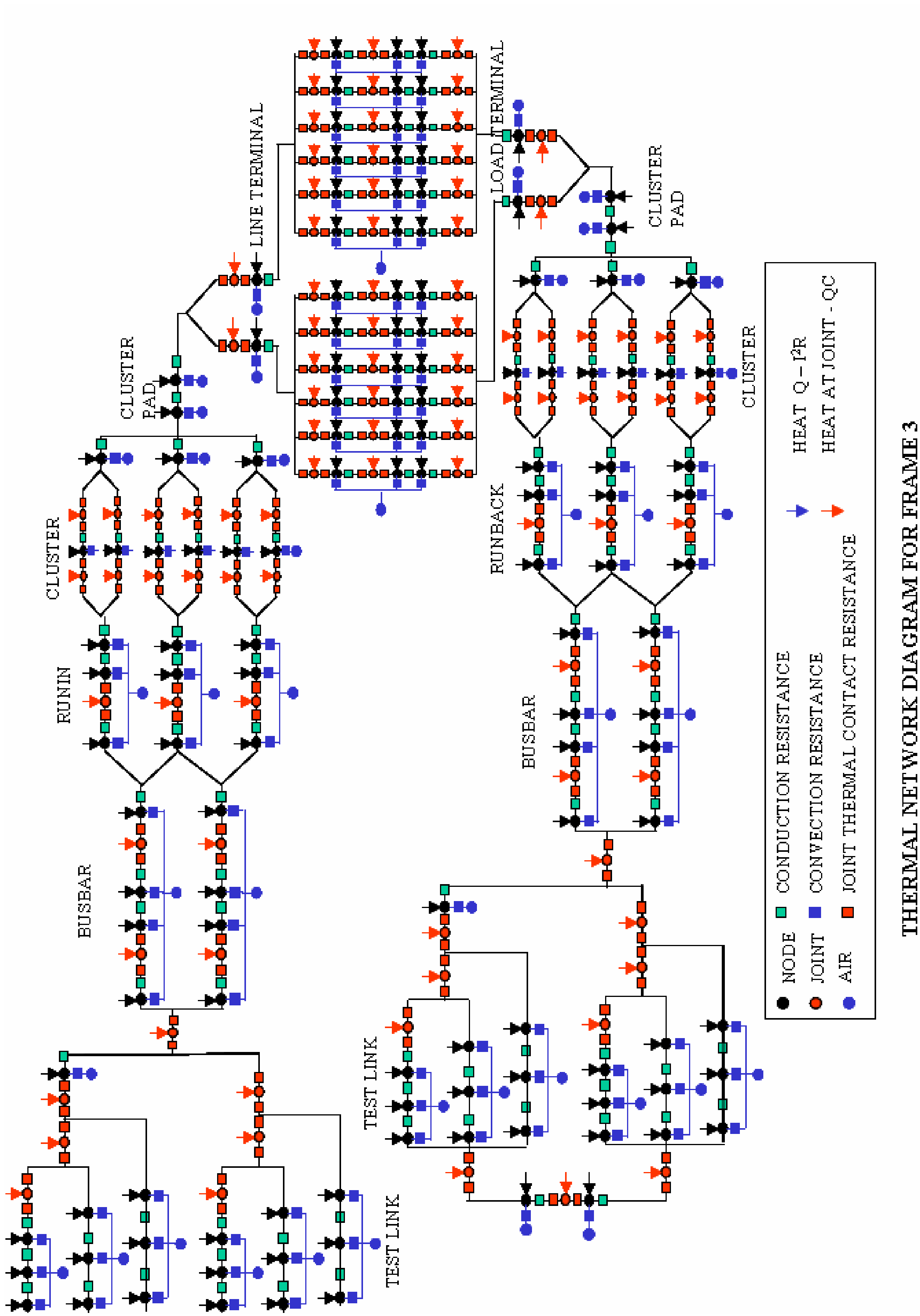

CLUSTER
CLUSTER PAD
RUNIN STAB
LINE TERMINAL
FLEXIBLE CONDUCTOR
MOVING CONDUCTOR
LOAD TERMINAL
CLUSTER
CLUSTER PAD
TEST LINK
STACK BAR
POWER CONNECT
BUSBAR
RUNIN
RUNBACK STAB
RUNBACK
TEST LINK
NODE
JOINT
AIR
CONDUCTION RESISTANCE
CONVECTION RESISTANCE
JOINT THERMAL CONTACT RESISTANCE
HEAT Q – I²R
HEAT AT JOINT - Qc
THERMAL NETWORK DIAGRAM FOR FRAME 1

Figure6.4



TEST LINK
BUSBAR
RUNIN
CLUSTER
CLUSTER
PAD
LINE TERMINAL
LOAD TERMINAL
CLUSTER
PAD
RUNBACK
CLUSTER
BUSBAR
TEST LINK
NODE
JOINT
AIR
CONDUCTION RESISTANCE
CONVECTION RESISTANCE
JOINT THERMAL CONTACT RESISTANCE
HEAT Q – I²R
HEAT AT JOINT - QC
THERMAL NETWORK DIAGRAM FOR FRAME 3

Figure 6.5

6.2.4(a) Node Equations

Now equations are developed at every node seen in the thermal network diagram. Node equations for cluster pad portion are written as follows. Thermal network diagram shows contact between cluster finger and cluster pad, cluster pad, joint between cluster pad and line terminal and line terminal. Nodes 0, 1 represent cluster fingers. Nodes 2, 3 represent cluster finger contact. The network diagram is as shown in figure 5.6. Cluster pad has 3 different cross-sections, so 3 nodes are considered (Nodes 4, 5, 6). Line terminal is divided into two parts, so two nodes are considered (Nodes 8, 9).

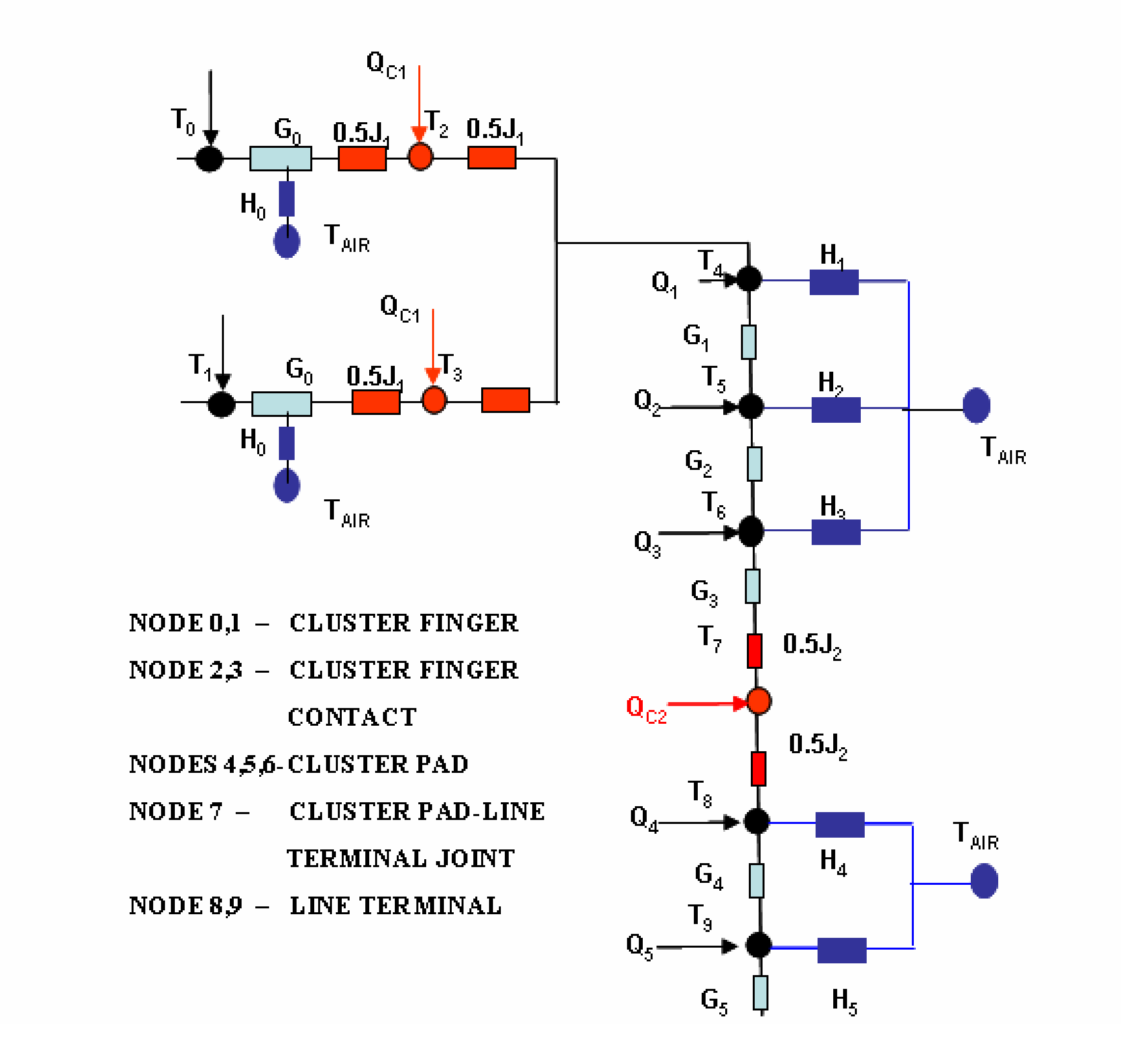


Figure 6.6Thermal Network Diagram for cluster pad region

Where

G_0 = Conduction conductance in cluster finger

G_1= Conduction conductance in cluster pad 1

G_2 = Conduction conductance in cluster pad 2

G_3 = Conduction conductance in cluster pad 3

G_4 = Conduction Conductance in line terminal first part

G_5 = Conduction conductance in line terminal second part

H_0 = Convection conductance for cluster finger

H_1 = convection conductance for cluster pad 1

H_2 = convection conductance for cluster pad 2

H_3 = convection conductance for cluster pad 3

H_4 = convection conductance for cluster pad 4

H_5 = convection conductance for cluster pad 5

Q_1, Q_2, Q_3 = Heat generated in cluster pad 1, 2, 3.

Q_4, Q_5 = Heat generated in line terminal parts 1, 2

Q_{c1} = Heat generated at cluster finger contact

Q_{c2} = Heat generated at cluster pad-line terminal joint

T_0, T_1 = Temperature of cluster finger (either sides)

T_2, T_3 = temperature at cluster finger contact (either side)

T_4, T_5, T_6 = temperature of cluster pad 1, 2, 3 respectively.

T_7, T_8 = Temperature of line terminal parts 1, 2 respectively.

$0.5J_1$= Half thermal contact conductance between cluster finger and cluster pad

$0.5J_2$ = Half thermal contact conductance between cluster pad and line terminal

The node equations are as follows:

At node 2, $Q_{c1} + (G_0 + 0.5J_1)(T_0 - T_2) = 0.5J_1(T_2 - T_4)$ (6.2)

At node 3, $Q_{c1} + (G_0 + 0.5J_1)(T_1 - T_3) = 0.5J_1(T_3 - T_4)$ (6.3)

At node 4, $Q_1 + 0.5J_1(T_2 - T_4) + 0.5J_1(T_3 - T_4) = G_1(T_4 - T_5) + H_1(T_4 - T_{AIR})$ (6.4)

At node 5, $Q_2 + G_1(T_4 - T_5) = G_2(T_5 - T_6) + H_2(T_5 - T_{AIR})$ (6.5)

At node 6, $Q_3 + G_2(T_5 - T_6) = (G_3 + 0.5J_2)(T_6 - T_7) + H_3(T_6 - T_{AIR})$ (6.6)

At node 7, $Q_{c2} + (G_3 + 0.5J_2)(T_6 - T_7) = 0.5J_2(T_7 - T_8)$ (6.7)

At node 8, $Q_4 + 0.5J_2(T_7 - T_8) = (G_4)(T_8 - T_9) + H_4(T_8 - T_{AIR})$ (6.8)

6.2.5 Calculation of Input Parameters

In this step, all the input parameters required for the calculation of conduction, conductance, convection conductance, I^2R heat generated in the components and joints, convective heat transfer coefficient, electrical and thermal contact resistances are calculated. Input parameters required are current, electrical resistivity, thermal conductivity, geometry of the components, joint forces etc. (Described in detail at section 6.3.1)

6.2.6 Convective Heat Transfer Coefficient Calculation

Convective heat transfer co-efficient (h) values are calculated based on correlations for isothermal vertical plate and horizontal plate with natural convection. Initial film temperature is calculated based on approximate temperature the component would reach. By standards, temperature rise should not exceed 85^0C for any component in the switch gear. Maximum temperature in gear region is limited to 65^0C. Correlations used in calculating 'h' are given at section 4.12.1(a), (b).

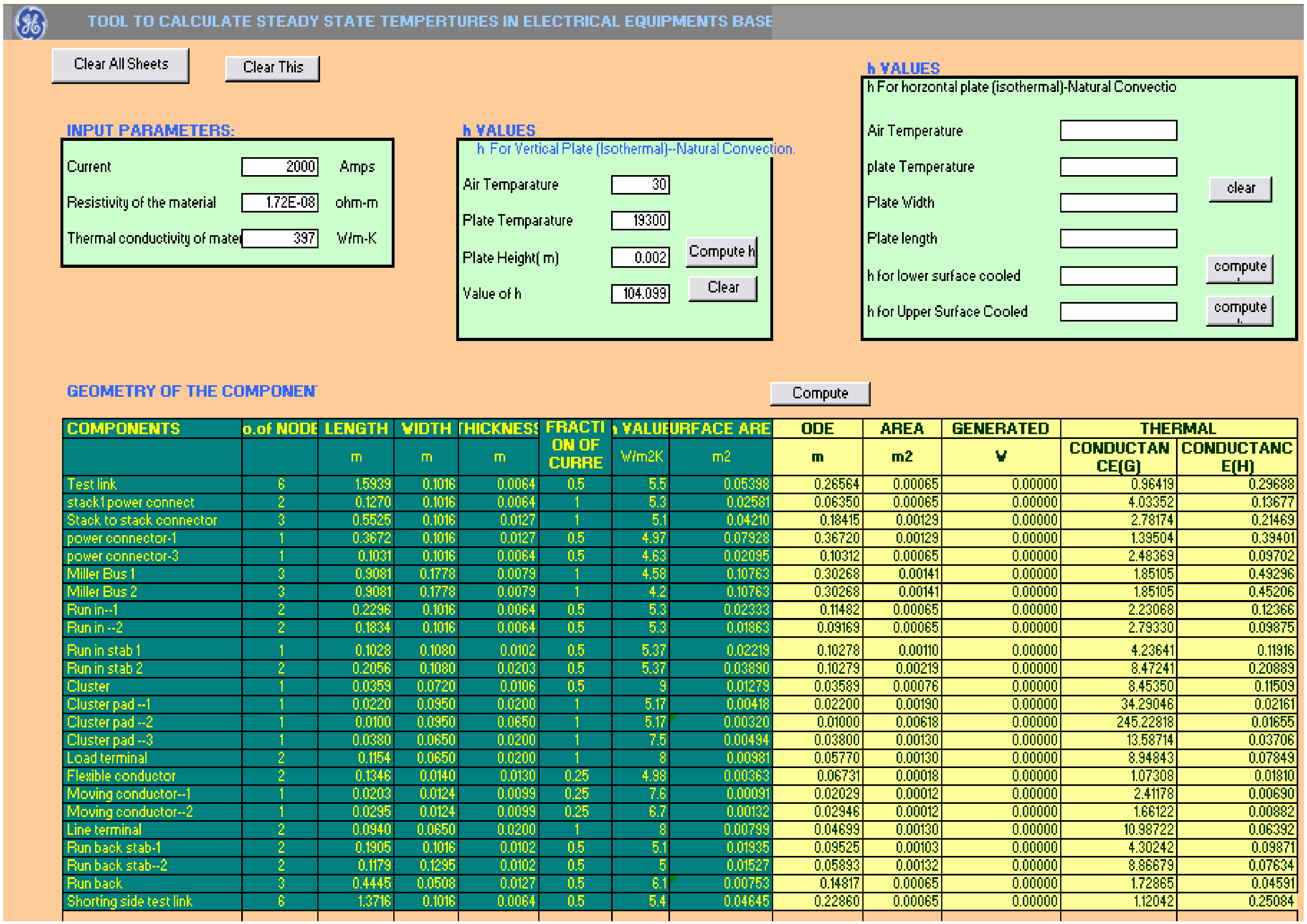
6.3 ANALYTICAL TOOL TO CALCULATE TEMPERATURES

An analytical tool is developed with Excel interface and Visual basic back up to calculate steady state temperatures. The solver method followed is Gauss elimination method. Nodal equations are developed at each node and the linear equations are solved by multiplying the inverse of temperature co-efficient matrix with heat column matrix to obtain the temperatures. The tool is considered as five worksheets, out of which 2 are input sheets. They are:

1. Input Sheet
2. Joints sheet
3. Nodes Sheet
4. Network Sheet
5. Output Sheet

6.3.1 Input Sheet

Snap shot of input sheet is shown in figure 6.7. Input sheet contains four tables—input parameters table, ‘h’ table for vertical plate, ‘h’ table for horizontal plate and geometry of the components table. Input for input parameters table are –current, electrical resistivity and thermal conductivity. Inputs for ‘h’ tables are air temperature, plate temperature and plate width, height. Selection of ‘h’ table depends on position of plate considered whether placed vertically or horizontally (whether cooling is on top surface or lower surface). Input for geometry of components table are component length, width , thickness, number of nodes, h value calculated from h table and surface area. Surface area is given as input to allow the user to enter the value depending on the actual area subjected to air flow. Input columns are represented by green color and values calculated by yellow color. Upon clicking compute button, length per node, cross sectional area, heat generated, conduction and convection conductances are calculated. Upon clicking “clear this sheet” button all the vales entered the sheet are cleared. Upon clicking “clear all sheets button”, entire data in all sheets is deleted and this is used when starting a new problem.



COMPONENTS	o.of NODE	LENGTH	VIDTH	THICKNESS	FRACTION OF CURRE	h VALUE	SURFACE ARE	ODE	AREA	GENERATED	THERMAL CONDUCTANCE(G)	CONDUCTANCE(H)
		m	m	m		W/m2K	m2	m	m2	W		
Test link	6	1.5939	0.1016	0.0064	0.5	5.5	0.05398	0.26564	0.00065	0.00000	0.96419	0.29688
stack1 power connect	2	0.1270	0.1016	0.0064	1	5.3	0.02581	0.06350	0.00065	0.00000	4.03352	0.13677
Stack to stack connector	3	0.5525	0.1016	0.0127	1	5.1	0.04210	0.18415	0.00129	0.00000	2.78174	0.21469
power connector-1	1	0.3672	0.1016	0.0127	0.5	4.97	0.07928	0.36720	0.00129	0.00000	1.39504	0.39401
power connector-3	1	0.1031	0.1016	0.0064	0.5	4.63	0.02095	0.10312	0.00065	0.00000	2.48369	0.09702
Miller Bus 1	3	0.9081	0.1778	0.0079	1	4.58	0.10763	0.30268	0.00141	0.00000	1.85105	0.49296
Miller Bus 2	3	0.9081	0.1778	0.0079	1	4.2	0.10763	0.30268	0.00141	0.00000	1.85105	0.45206
Run in--1	2	0.2296	0.1016	0.0064	0.5	5.3	0.02333	0.11482	0.00065	0.00000	2.23068	0.12366
Run in --2	2	0.1834	0.1016	0.0064	0.5	5.3	0.01863	0.09169	0.00065	0.00000	2.79330	0.09875
Run in stab 1	1	0.1028	0.1080	0.0102	0.5	5.37	0.02219	0.10278	0.00110	0.00000	4.23641	0.11916
Run in stab 2	2	0.2056	0.1080	0.0203	0.5	5.37	0.03890	0.10279	0.00219	0.00000	8.47241	0.20889
Cluster	1	0.0359	0.0720	0.0106	0.5	9	0.01279	0.03589	0.00076	0.00000	8.45350	0.11509
Cluster pad --1	1	0.0220	0.0950	0.0200	1	5.17	0.00418	0.02200	0.00190	0.00000	34.29046	0.02161
Cluster pad --2	1	0.0100	0.0950	0.0650	1	5.17	0.00320	0.01000	0.00618	0.00000	245.22818	0.01655
Cluster pad --3	1	0.0380	0.0650	0.0200	1	7.5	0.00494	0.03800	0.00130	0.00000	13.58714	0.03706
Load terminal	2	0.1154	0.0650	0.0200	1	8	0.00981	0.05770	0.00130	0.00000	8.94843	0.07849
Flexible conductor	2	0.1346	0.0140	0.0130	0.25	4.98	0.00363	0.06731	0.00018	0.00000	1.07308	0.01810
Moving conductor--1	1	0.0203	0.0124	0.0099	0.25	7.6	0.00091	0.02029	0.00012	0.00000	2.41178	0.00690
Moving conductor--2	1	0.0295	0.0124	0.0099	0.25	6.7	0.00132	0.02946	0.00012	0.00000	1.66122	0.00882
Line terminal	2	0.0940	0.0650	0.0200	1	8	0.00799	0.04699	0.00130	0.00000	10.98722	0.06392
Run back stab-1	2	0.1905	0.1016	0.0102	0.5	5.1	0.01935	0.09525	0.00103	0.00000	4.30242	0.09871
Run back stab--2	2	0.1179	0.1295	0.0102	0.5	5	0.01527	0.05893	0.00132	0.00000	8.86679	0.07634
Run back	3	0.4445	0.0508	0.0127	0.5	6.1	0.00753	0.14817	0.00065	0.00000	1.72865	0.04591
Shorting side test link	6	1.3716	0.1016	0.0064	0.5	5.4	0.04645	0.22860	0.00065	0.00000	1.12042	0.25084

Figure 6.7 Input Sheet

6.3.2 Joints Sheet

In this sheet all the joint related parameters are calculated. One input table and two operation buttons are seen in this sheet. Snapshot of joints sheet is shown in figure (6.9) Clear button is to clear all the data in the sheet and upon clicking input form button, an input form opens as shown in figure (6.8). The input parameter for a joint are entered here. Inputs are joint name, type of joint (ex... Bolted, spring etc), contact materials at the joint, force applied by the clamping element and fraction of total current flowing through the joint. The calculated values are current, electrical contact resistance, thermal contact conductance and heat generated at the joint. Except joint name and joint type, all the remaining inputs are compulsory.

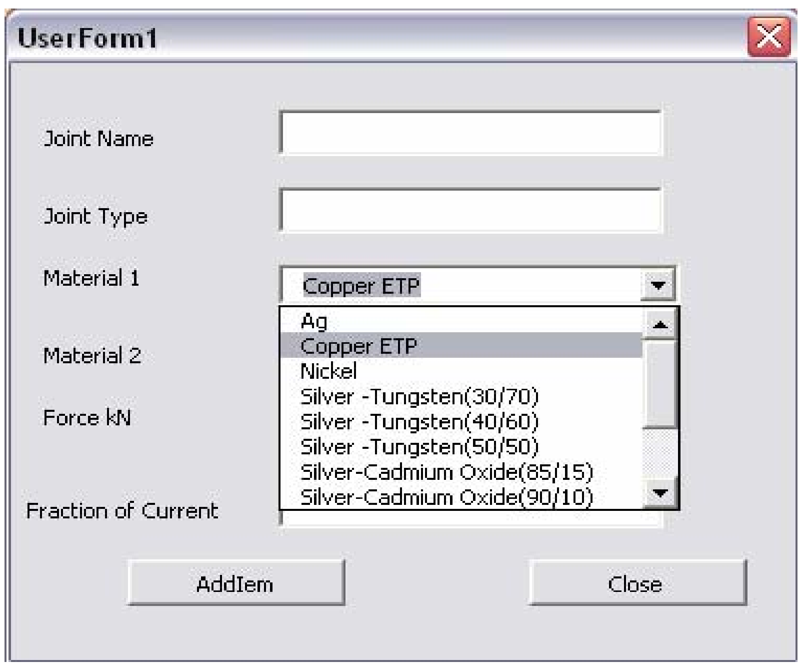
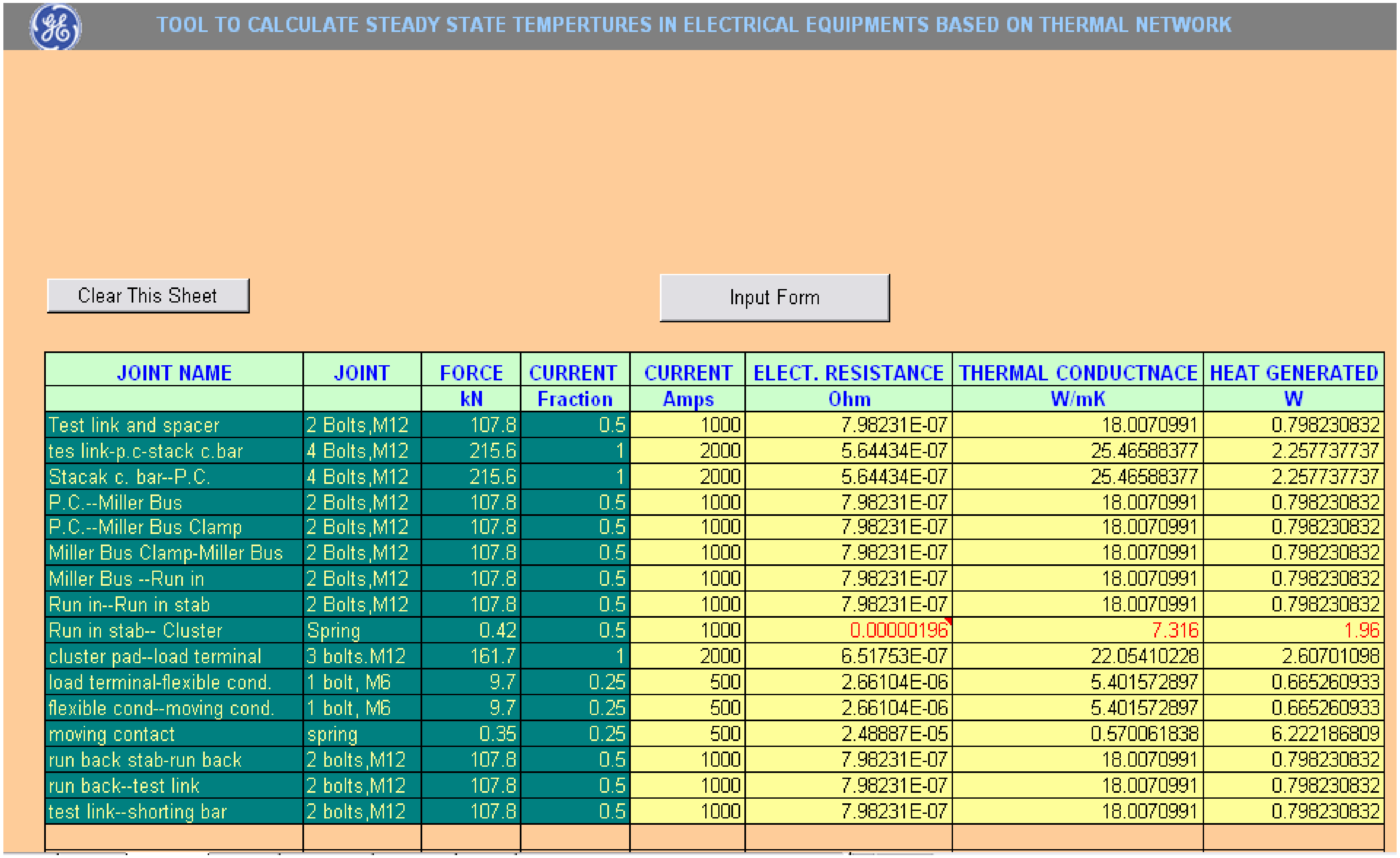


Figure 6.8 Input Form for Joints



JOINT NAME	JOINT	FORCE	CURRENT	CURRENT	ELECT. RESISTANCE	THERMAL CONDUCTNACE	HEAT GENERATED
		kN	Fraction	Amps	Ohm	W/mK	W
Test link and spacer	2 Bolts,M12	107.8	0.5	1000	7.98231E-07	18.0070991	0.798230832
tes link-p.c-stack c.bar	4 Bolts,M12	215.6	1	2000	5.64434E-07	25.46588377	2.257737737
Stacak c. bar--P.C.	4 Bolts,M12	215.6	1	2000	5.64434E-07	25.46588377	2.257737737
P.C.--Miller Bus	2 Bolts,M12	107.8	0.5	1000	7.98231E-07	18.0070991	0.798230832
P.C.--Miller Bus Clamp	2 Bolts,M12	107.8	0.5	1000	7.98231E-07	18.0070991	0.798230832
Miller Bus Clamp-Miller Bus	2 Bolts,M12	107.8	0.5	1000	7.98231E-07	18.0070991	0.798230832
Miller Bus --Run in	2 Bolts,M12	107.8	0.5	1000	7.98231E-07	18.0070991	0.798230832
Run in--Run in stab	2 Bolts,M12	107.8	0.5	1000	7.98231E-07	18.0070991	0.798230832
Run in stab-- Cluster	Spring	0.42	0.5	1000	0.00000196	7.316	1.96
cluster pad--load terminal	3 bolts.M12	161.7	1	2000	6.51753E-07	22.05410228	2.60701098
load terminal-flexible cond.	1 bolt, M6	9.7	0.25	500	2.66104E-06	5.401572897	0.665260933
flexible cond--moving cond.	1 bolt, M6	9.7	0.25	500	2.66104E-06	5.401572897	0.665260933
moving contact	spring	0.35	0.25	500	2.48887E-05	0.570061838	6.222186809
run back stab-run back	2 bolts,M12	107.8	0.5	1000	7.98231E-07	18.0070991	0.798230832
run back--test link	2 bolts,M12	107.8	0.5	1000	7.98231E-07	18.0070991	0.798230832
test link--shorting bar	2 bolts,M12	107.8	0.5	1000	7.98231E-07	18.0070991	0.798230832

Figure 6.9 Joints Sheet

6.3.3 Nodes Sheet

In nodes sheet, all the nodes are entered in a sequence as per the numbering given in the thermal network diagram. Snap shot of nodes sheet is shown in figure (6.11). In the sheet seen is a nodes table, clear sheet button and add nodes button. Upon clicking add nodes button, an input form drops down as shown in figure (6.10). It contains many options like component, joint, air and dummy node. Only one can be chosen at a time. Upon choosing an option, corresponding input form is activated. By choosing components radio button, particular component can be selected form the drop down menu and click add component button to add to the nodes sheet. Similarly joint nodes, air nodes and dummy nodes can be added to the nodes sheet. Dummy nodes are imaginary nodes used at branching and joining of resistances. It does have zero values for the thermal properties. Generally air nodes are entered at the end and air temperature input option is compulsory.

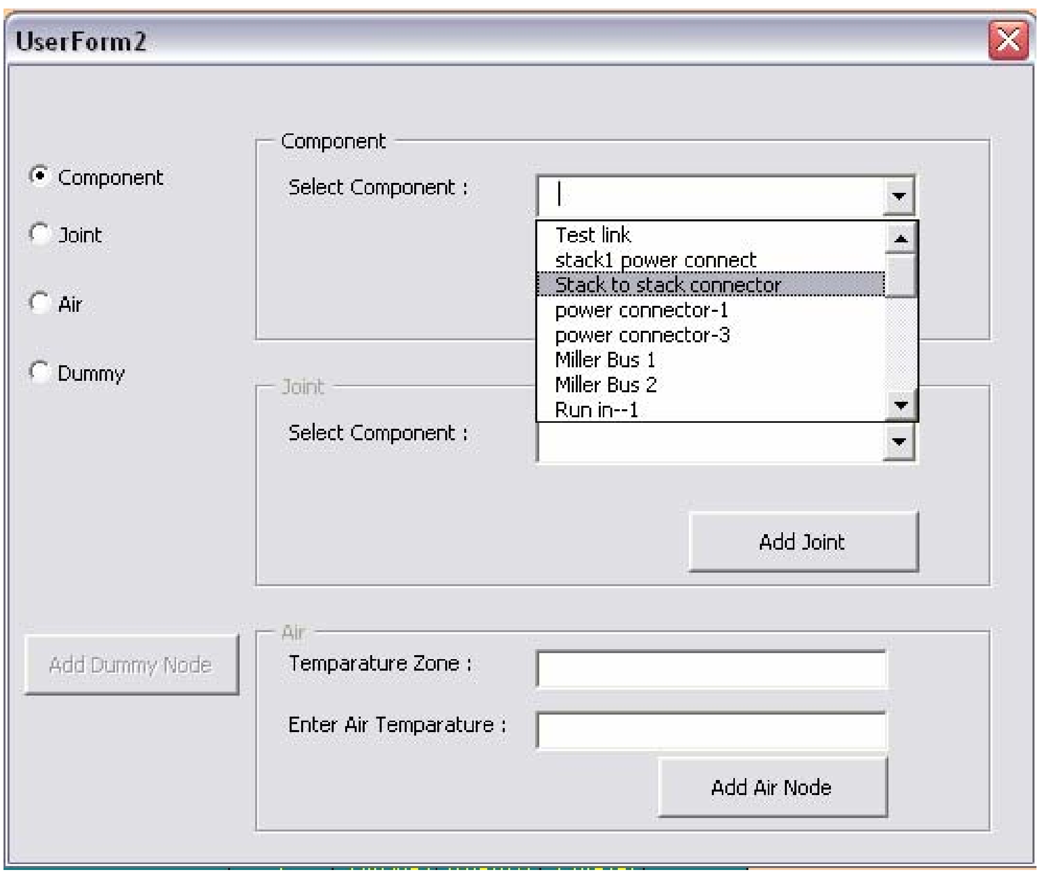
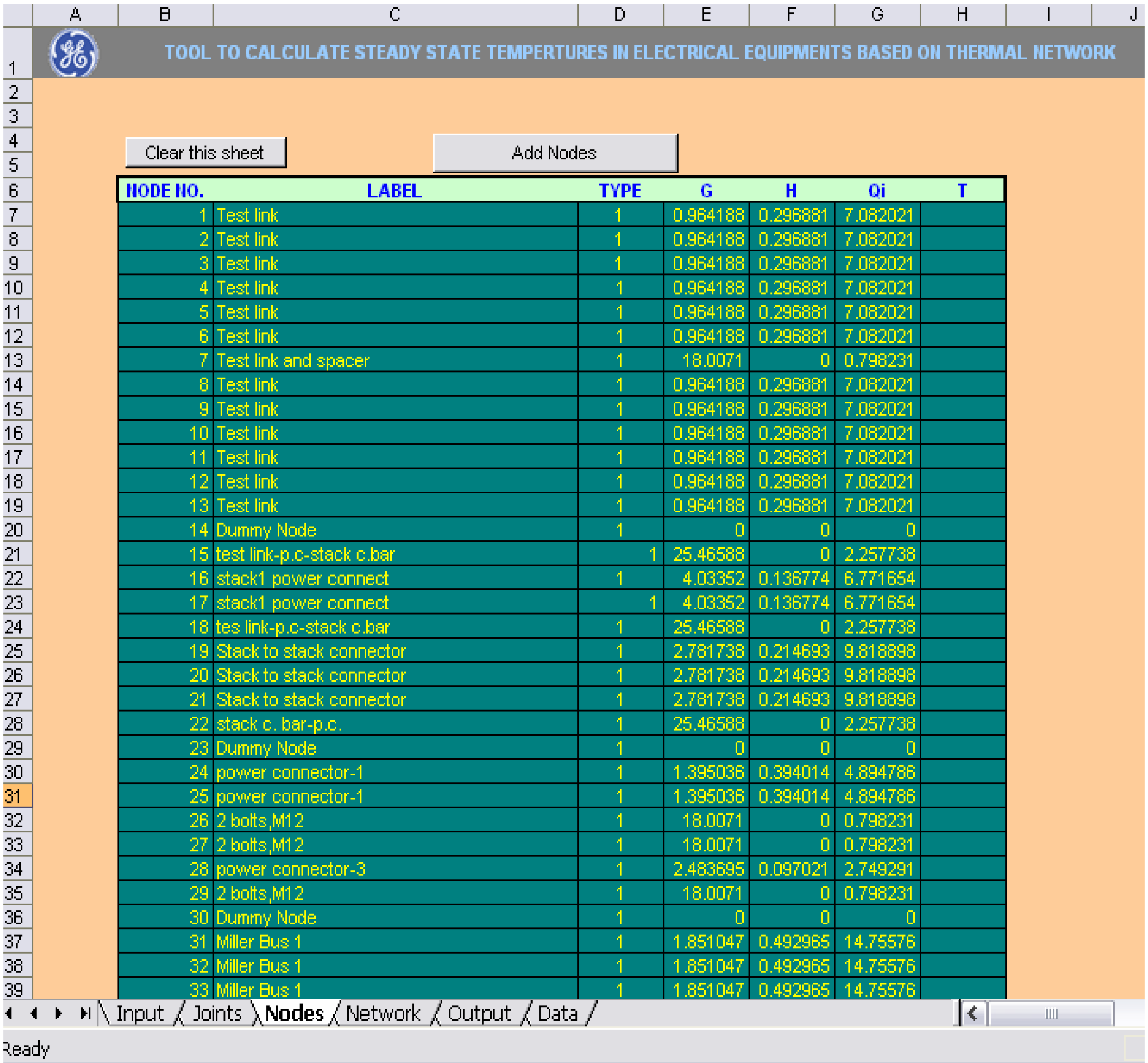


Figure 6.10 Input Form for Nodes



NODE NO.	LABEL	TYPE	G	H	Qi	T
1	Test link	1	0.964188	0.296881	7.082021	
2	Test link	1	0.964188	0.296881	7.082021	
3	Test link	1	0.964188	0.296881	7.082021	
4	Test link	1	0.964188	0.296881	7.082021	
5	Test link	1	0.964188	0.296881	7.082021	
6	Test link	1	0.964188	0.296881	7.082021	
7	Test link and spacer	1	18.0071	0	0.798231	
8	Test link	1	0.964188	0.296881	7.082021	
9	Test link	1	0.964188	0.296881	7.082021	
10	Test link	1	0.964188	0.296881	7.082021	
11	Test link	1	0.964188	0.296881	7.082021	
12	Test link	1	0.964188	0.296881	7.082021	
13	Test link	1	0.964188	0.296881	7.082021	
14	Dummy Node	1	0	0	0	
15	test link-p.c-stack c.bar	1	25.46588	0	2.257738	
16	stack1 power connect	1	4.03352	0.136774	6.771654	
17	stack1 power connect	1	4.03352	0.136774	6.771654	
18	tes link-p.c-stack c.bar	1	25.46588	0	2.257738	
19	Stack to stack connector	1	2.781738	0.214693	9.818898	
20	Stack to stack connector	1	2.781738	0.214693	9.818898	
21	Stack to stack connector	1	2.781738	0.214693	9.818898	
22	stack c. bar-p.c.	1	25.46588	0	2.257738	
23	Dummy Node	1	0	0	0	
24	power connector-1	1	1.395036	0.394014	4.894786	
25	power connector-1	1	1.395036	0.394014	4.894786	
26	2 bolts,M12	1	18.0071	0	0.798231	
27	2 bolts,M12	1	18.0071	0	0.798231	
28	power connector-3	1	2.483695	0.097021	2.749291	
29	2 bolts,M12	1	18.0071	0	0.798231	
30	Dummy Node	1	0	0	0	
31	Miller Bus 1	1	1.851047	0.492965	14.75576	
32	Miller Bus 1	1	1.851047	0.492965	14.75576	
33	Miller Bus 1	1	1.851047	0.492965	14.75576	

Figure 6.11 Nodes Sheet

The user must observe that upon changing any values in the previous two sheets, values are not updated in this sheet. The user has to manually update this sheet by deleting corresponding rows or by clearing the sheet and adding nodes again by clicking the add nodes button. No row can be left unfilled between two filled rows. Row with no elements is considered as end of the nodes table.

6.34 Network Sheet

The inputs to network sheet are start and end nodes. Network sheet is as shown in figure (6.12). Node numbers are entered in the start node and end node columns in the sequence nodes are connected in the network diagram maintaining continuity form first to last node. Node connections representing conduction conductance are entered first and then node connections representing convection conductance are entered. By clicking clear sheet button data in the sheet is cleared and upon clicking compute button steady state temperatures are calculated and displayed in output sheet.

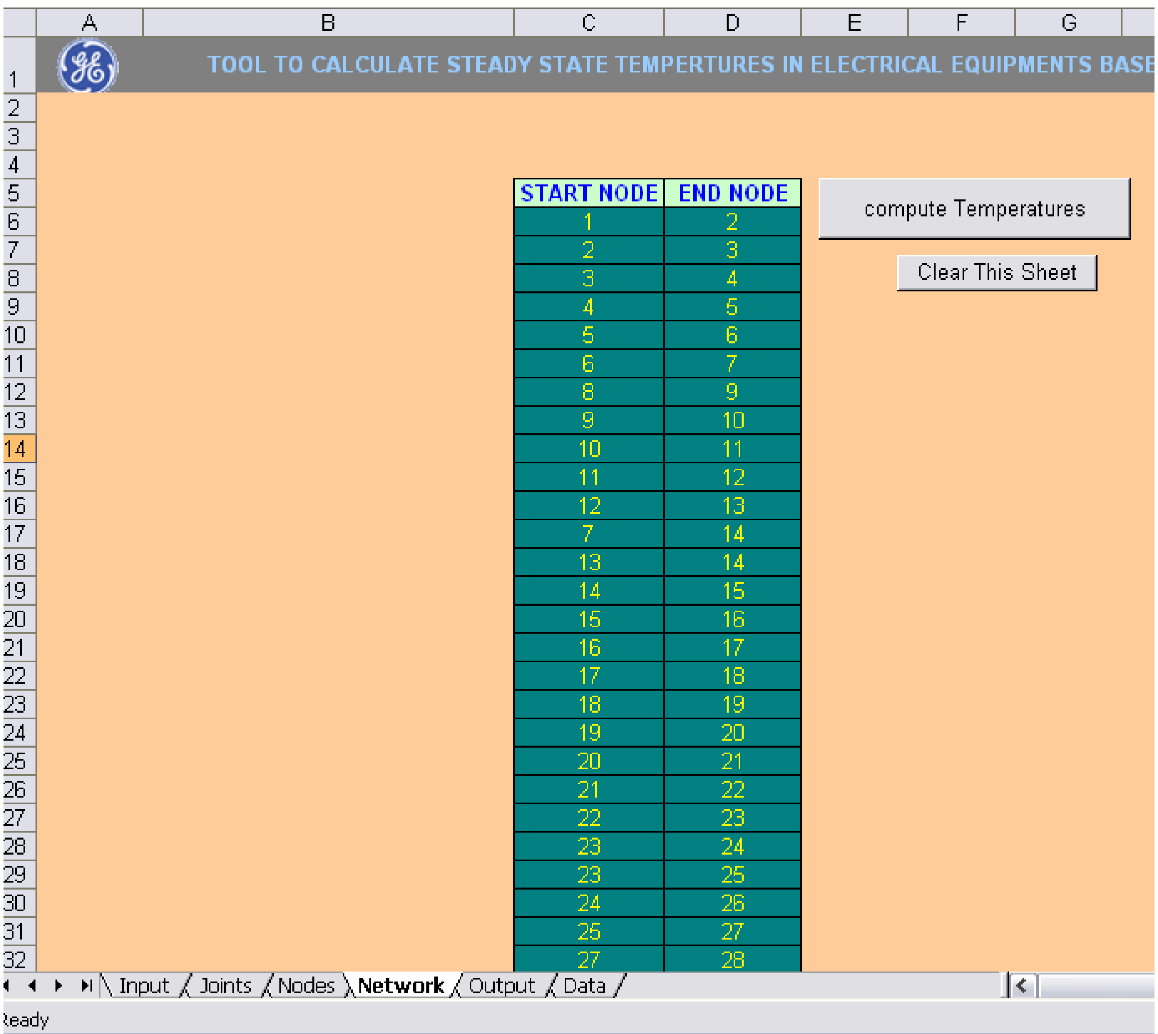


Figure 6.12 Network Sheet

6.3.5 Output Sheet

In this sheet steady state temperatures are displayed. Figure 6.13 shows the output sheet. Parameters seen are component name, node number and steady state temperature. Once first temperature set is obtained, using these temperatures, ‘h’ values are recalculated and substituted in the “input sheet” ‘h’ column and temperatures are computed again to obtain accurate results. This process can be repeated until difference in temperature between two consecutive iteration is negligible.

TOOL TO CALCULATE STEADY STATE TEMPERTURES

LABEL	NODE	TEMPERATURE
Test link	1	52.00
Test link	2	52.35
Test link	3	53.16
Test link	4	54.69
Test link	5	57.39
Test link	6	62.10
Test link and spacer	7	62.84
Test link	8	51.46
Test link	9	51.64
Test link	10	52.07
Test link	11	52.87
Test link	12	54.29
Test link	13	56.77
Dummy Node	14	63.53
test link-p.c-stack c.bar	15	64.27
stack1 power connect	16	64.76
stack1 power connect	17	66.04
tes link-p.c-stack c.bar	18	66.27
Stack to stack connector	19	66.34
Stack to stack connector	20	66.00
Stack to stack connector	21	64.92
stack c. bar-p.c.	22	64.54
Dummy Node	23	63.94
power connector-1	24	58.58
power connector-1	25	58.39
2 bolts,M12	26	58.85
2 bolts,M12	27	58.64

Input / Joints / Nodes / Network / Output / Data

Ready

Figure 6.13 Output Sheet

7. RESULTS

7.1 FRAME 3

By thermal networking, total numbers of nodes considered are 656 with 208 nodes for each phase. Thermal run is carried out and steady state temperatures are recorded after 12 hours.122 thermocouples are used to measure temperature of components and air at different points inside the switch gear. Following graph (Figure 7.1) shows the temperature profile for the current carrying path in the frame 3. Temperature increases gradually from test link side, reaches the maximum value at moving contact and then decreases gradually towards shorting side.

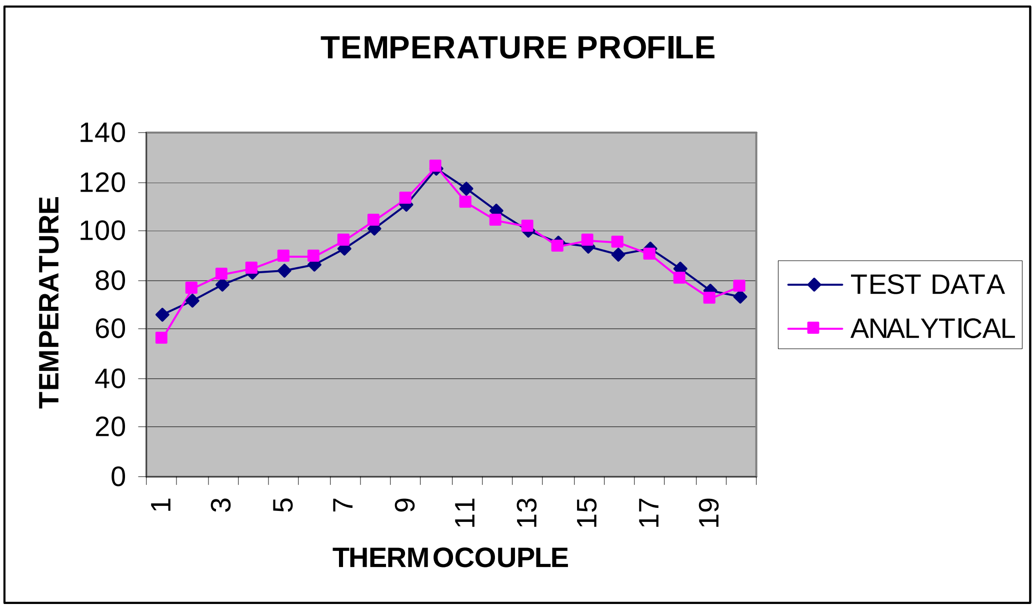


Figure 7.1 Frame 3 Temperature profile

Table 7.1 shows the highest temperatures measured on all three phases and temperatures calculated at different points. The highest temperature is recorded at moving contact tip. At that point, the difference between measured and calculated value is 1^0 C. It is observed that error is not the same at every point. A main reason for this is different cross sections at different points and here the calculations are based on one dimensional heat flow.

Table 7.1 Temperatures at Different Points in Frame3

COMPONENT	NODE NO.	THERMO- -COUPLE	TEST DATA	ANALYTICAL	DIFFERENCE	%ERROR
INCOMING BUS	T3	T100	66	56	-10	15
INCOMING BUS CONNECTION	T4	T40	72	77	5	7
LOWER POWER CONNECT	T27	T41	78	82	4	5
LOWER RISER BUS	T31	T42	83	85	2	2
RISER/RUN IN CONNECTION	T35	T43	84	89	5	6
LOWER RUN IN NOTCH	T42	T44	86	90	4	4
LOWER RUN IN BEHIND CASSETE	T45	T47	93	96	3	4
LOWER RUN IN AT FINGER CONNECTION	T48	T50	101	104	3	3
BREAKER BEHIND LOWER FINBERS	T71	T53	111	113	2	2
BREAKER MOVABLE CONTACT	T126	T54	125	126	1	1
BREAKER BEHIND UPPER FINGERS	T155	T55	117	112	-5	4
UPPER RUN IN AT FINGER CONNECTION	T177	T56	108	104	-4	3
UPPER RUN IN BEHIND CASSETE	T180	T59	100	102	2	2
UPPER RUN IN NOTCH	T183	T62	95	94	-1	1
RISER/RUN BACK CONNECTION	T191	T65	94	96	2	2
UPPER RISER BUS	T193	T67	90	95	5	6
UPPER POWER CONNCET SIDE	T199	T68	93	90	-3	3
OUTGOING BUS CONNECTION	T204	T69	85	81	-4	5
OUTING GOING BUS	T209	T103	76	72	-4	5
SHORTING BAR	TT234	T106	73	78	5	6

Highest deviation is 15^o. It is observed that at first node i.e. incoming bus, temperature from analytical calculation is well below the test temperature. This is because the network diagram is started from that point without considering the heat addition or subtraction on the system prior to the starting node. The maximum percentage error is 15% and minimum percentage error is 1%. The percentage error at highest temperature node, i.e. moving contact is 1%.

7.1.1 Reasons for Temperature Deviation

1. Calculations are limited to one dimensional heat flow.
2. Complex shapes are simplified as horizontal and vertical rectangular blocks for conduction and convection calculations
3. Radiation is neglected
4. Current flow path considered for internal heat generation may not be the same due to electrical resistance imbalances and shapes like sharp bends.

5. Error in contact resistance calculation tool accounts for error in electrical and thermal contact resistances at the joints.
6. Proximity effect excluded because calculating corresponding 'h' values using analytical formulae is impossible.
7. Heat flow through arcing contact is neglected
8. 'h' value calculations are based on simplifying the complex shapes to vertical plates and horizontal plates with natural convection.
9. Clusters are grouped and considered as a single block of equivalent cross section and electrical resistance.
10. Flexible conductor is considered as a solid piece. But it is made of many laminates pressed together.

7.1.2 Regions of Maximum Deviation

Certain region are observed where temperature deviation is more, like test links, power connect joints, cluster and shorting bar. Reasons for temperature deviation are:

1. Test links- Network starts from that point and heat added to or lost from the system prior to that node is not considered.
2. Power connect joints- Current is considered to flow equally in both legs of power connect 1 and 2. But current flow is not as considered due to imbalance in electrical resistance.
3. Cluster – individual clusters fingers are grouped and considered as a single block. Due to this internal heat generated increases because heat generated depends on cross sectional area and square of current.
4. Shorting side – Current flow is not as considered. Shorting side has star connection, so current is zero at common point and current flow path is controlled by resistance imbalance.

7.1.3 RESULTS COMPARISION

7.1.3(a) Phase A

Analytical results are compared with test data of phase A, phase B and phase C. Temperature rise is different on different phases, with maximum temperature rise on central phase (phase B). Table 7.2 shows temperature at different point of phase 'A' by analytical, CFD and experiment. (CFD results are from Analysis Team). Graph 7.2 shows temperature profile for phase A. Analytical, CFD results and experimental values are compared in the graph. Analytical results are on higher side and CFD results are on lower side compared to test results. At same points on similar components temperature difference is observed in test data due to proximity effect, as observed at thermocouples 14, 15, 16. But analytical values show the same temperature for all those three points as proximity effect is not considered. Figure 7.3 shown temperature profile of phase A without considering proximity effect.

Table 7.2 Temperatures on Phase A

PHASE A	T.C.	ANALYTICAL	TEST DATA	CFD
COMPONENT				
Incoming bus connection	10	77	69	67
Lower PC side	11	78	75	66
Middle of lower riser bus	12	86	79	66
Riser/run in connection	13	89	80	66
Lower run in notch-left	14	90	79	68
Lower run in notch-center	15	90	83	68
Lower run in notch-right	16	90	87	68
Lower run in behind cassete- left	17	96	83	81
Lower run in behind cassete- center	18	96	86	82
Lower run in behind cassete- right	19	96	93	81
Lower run in at finger connection- left	20	104	92	101
Lower run in at finger connection- center	21	104	95	101
Lower run in at finger connection- right	22	104	101	101
Breaker behind lower fingers	23	113	108	103
Breaker movable contacts	24	126	125	115
Breaker behind upper fingers	25	112	113	113
Upper run in at finger connection- left	26	104	106	110
Upper run in at finger connection- center	27	104	101	111
Upper run in at finger connection- right	28	104	97	111
Upper run in behind cassete- left	29	102	84	89
Upper run in behind cassete- center	30	102	93	91
Upper run in behind cassete- right	31	102	96	90
Upper run in notch-left	32	94	82	77
Upper run in notch-center	33	94	86	78
Upper run in notch-right	34	94	92	77
Riser/run in connection- left	35	96	76	72
Riser/run in connection- right	36	96	90	72
Middle of upper riser bus	37	94	89	72
Upper PC side	38	90	88	78
Outgoing bus connection	39	81	81	80

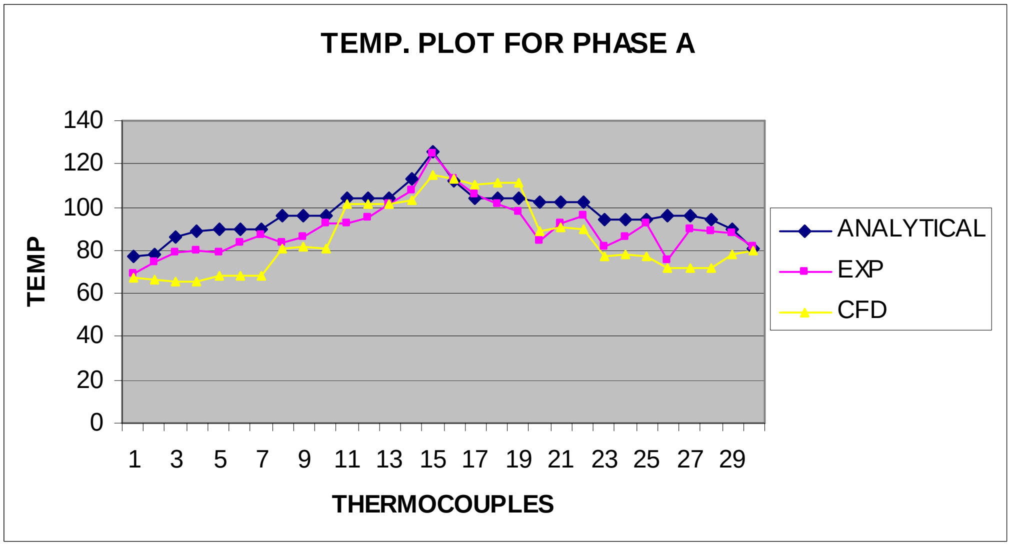


Figure 7.2 Temperatures Comparison for Phase A

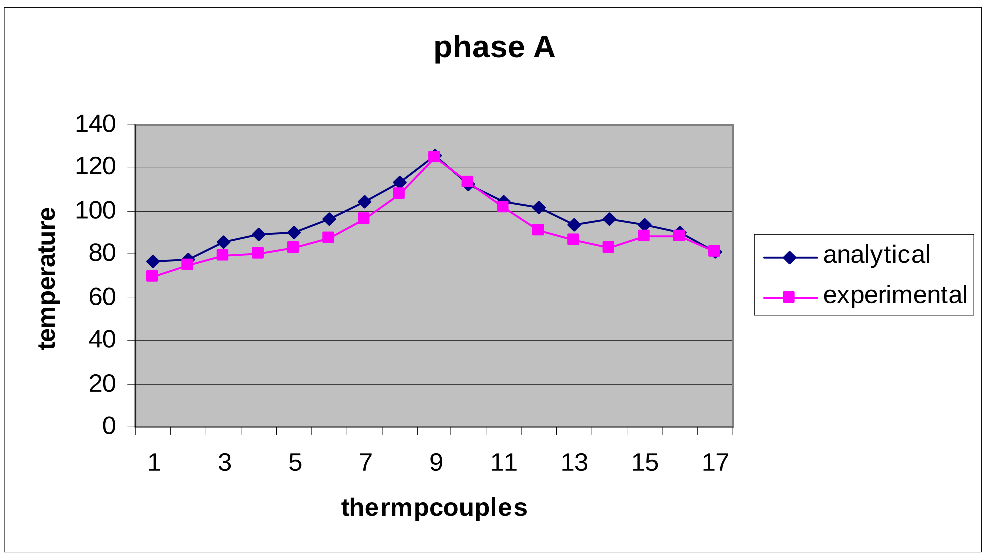


Figure 7.3 Temperatures Comparison without Proximity Effect

7.1.3(b) Phase B

Out of all three phases, maximum temperature is observed on this phase. Graph 7.4 shows temperature profile for phase B corresponding to similar point on phase A. The analytical values match better with test data as the proximity effect is less in the central phase. Graph 7.5 shows temperature profile without considering proximity effect.

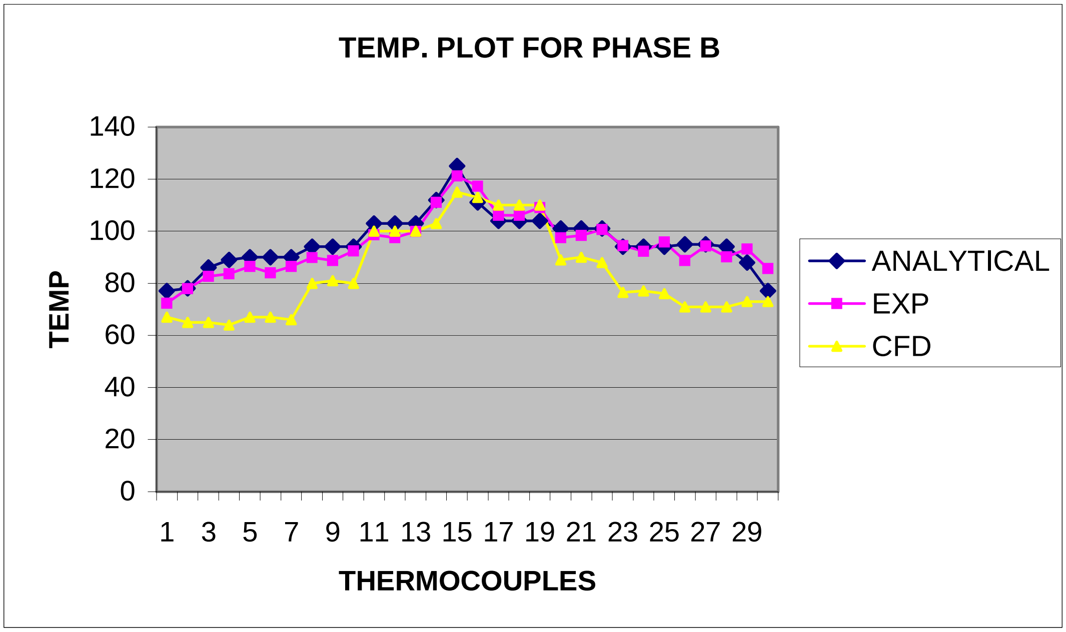


Figure 7.4 Temperatures comparison for phase B

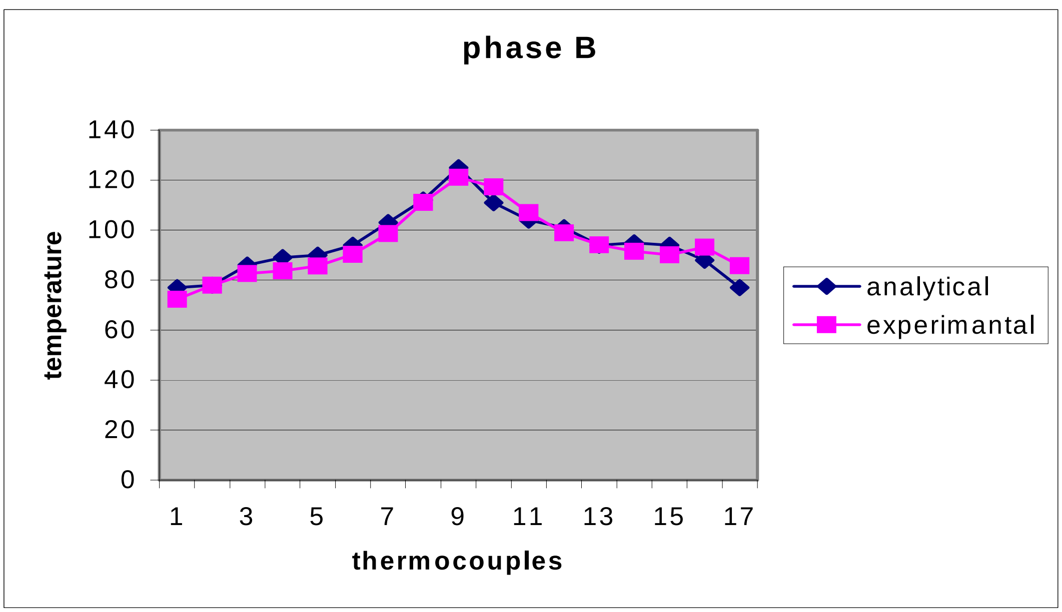


Figure 7.5 Temperatures comparison without Proximity Effect

7.1.3(c) Phase C

Graph 7.6shows temperature profile for phase C .Here deviation is observed to be more. Graph 7.7 shows temperature profile for phase C without considering proximity effect.

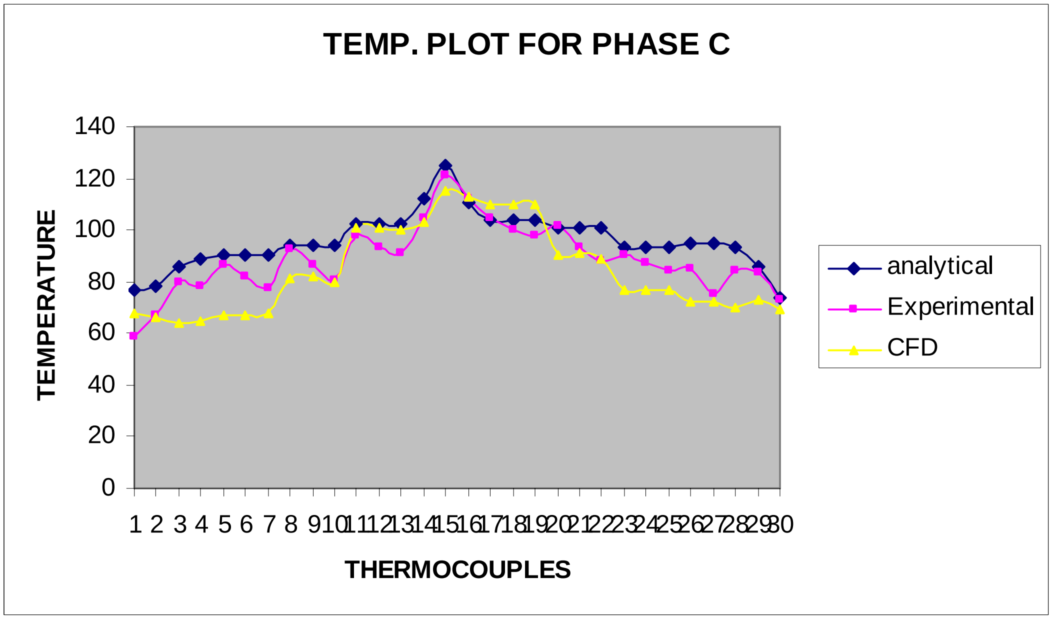


Figure 7.6 Temperatures comparison for phase C

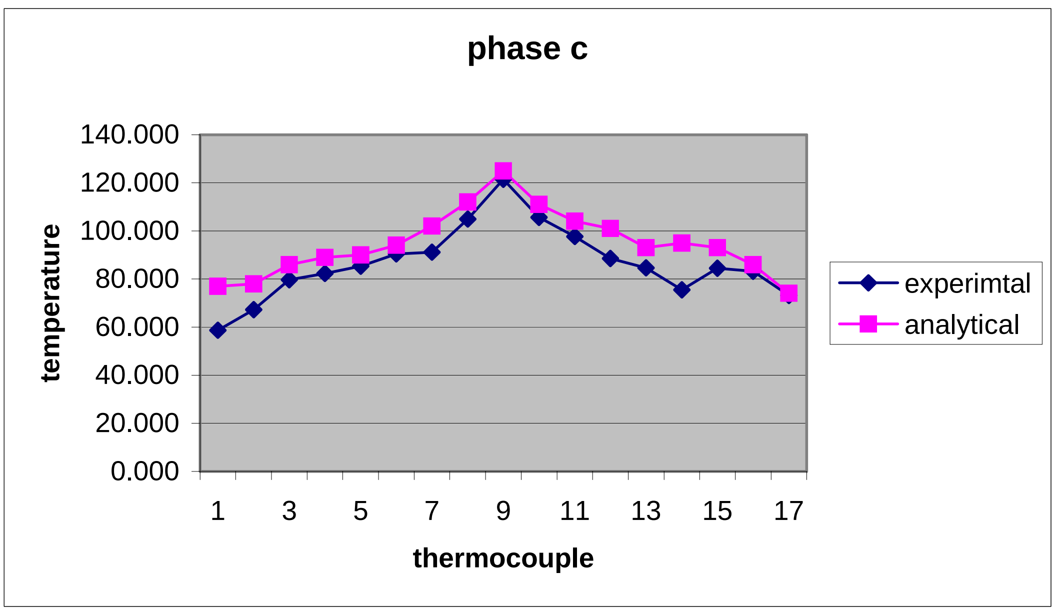


Figure 7.7 Temperatures comparison without Proximity Effect

7.1.4 TEMPERATURE PREDICTION

By changing different parameters, the change in temperatures and temperature profile are observed. This gives an insight into how different input parameters affect the temperatures of different components.

7.1.4(a) Change in Run-In Geometry

Dimensions of run-in and run-back are changed to predict the temperature change at highest temperature, .i.e. moving contact. Table 7.3 shows the actual values and changed geometry of run-ins. It is observed that with new geometry, temperature at moving contact decreases by 10^0C.

Table 7.3 Run-In Geometry

CASE-1	ACTUAL VALUES (m)		
COMPONENT	WIDTH	THICKNESS	LENGTH
Run in--part—1(One Strip)	0.1524	0.00635	0.234
part--2	0.1778	0.00635	0.1092
part--3	0.1524	0.00635	0.209
part--4	0.1016	0.00635	0.159
Part--5	0.0944	0.00635	0.05

CASE-1	CHANGED VALUES (m)		
COMPONENT	WIDTH	THICKNESS	LENGTH
Run in--part—1(One Strip)	0.1016	0.02921	0.1206
part--2	0.127	0.01905	0.2159
part--3	0.127	0.01905	0.2159
part--4	0.1016	0.01905	0.104775
Part--5	0.1016	0.01905	0.104775

Table 7.4 Analytical Temperatures with and without Change in Run-In Dimensions

COMPONENT NAME	ANALY.TEMP.		
	BEFORE	AFTER	DIFF.
INCOMING BUS	56	56	0
INCOMING BUS CONNECTION	77	77	0
LOWER POWER CONNECT SIDE	78	78	0
LOWER POWER CONNECT	82	81	1
LOWER RISER BUS	83	82	1

COMPONENT NAME	BEFORE	AFTER	DIFF.
RISER/RUN IN CONNECTION	89	87	3
LOWER RUN IN NOTCH	90	87	2
LOWER RUN IN BEHIND CASSETE	96	90	6
LOWER RUN IN AT FINGER CONNECTION	104	92	12
BREAKER BEHIND LOWER FINBERS	113	102	11
BREAKER MOVABLE CONTACT	126	116	10
BREAKER BEHIND UPPER FINGERS	112	102	10
UPPER RUN IN AT FINGER CONNECTION	104	94	10
UPPER RUN IN BEHIND CASSETE	102	92	10
UPPER RUN IN NOTCH	94	90	4
RISER/RUN BACK CONNECTION	96	92	4
UPPER RISER BUS	96	92	4
UPPER POWER CONNCET SIDE	90	89	1
OUTGOING BUS CONNECTION	81	80	1
OUTING GOING BUS	72	72	0
SHORTING BAR	78	78	0

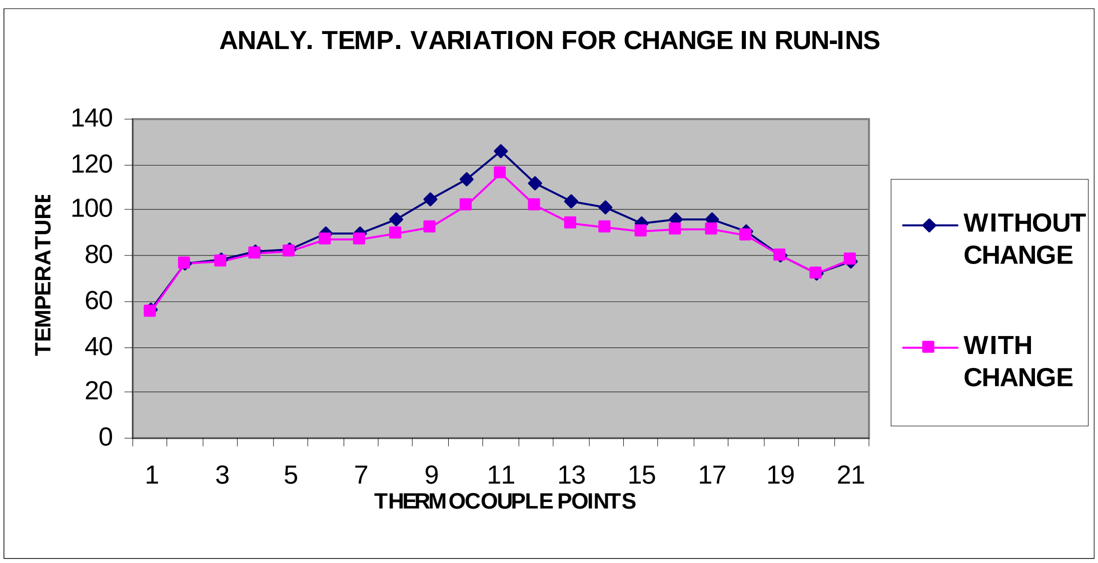


Figure 7.8 Temperature Profile with Change in Run-in Geometry

7.1.4(b) Change in Heat Sink Surface Area

Heat sinks are provided on run-ins to dissipate heat by convection, there by decreasing the temperature rise. Here the equivalent surface areas of the heat sinks are doubled to checkout the effect on temperatures of components. 5^0C decrease in temperature is observed at moving contacts. Maximum temperature decrease is 7^0C.

Table 7.5 Analytical Temperatures Comparison by Doubling the Heat Sink Surface Area

COMPONENT NAME	ANALY.TEMP.		
	BEFORE	AFTER	DIFF.
INCOMING BUS	56	56	0
INCOMING BUS CONNECTION	77	76	1
LOWER POWER CONNECT SIDE	78	78	1
LOWER POWER CONNECT	82	81	1
LOWER RISER BUS	83	81	2
RISER/RUN IN CONNECTION	89	84	5
LOWER RUN IN NOTCH	90	83	6
LOWER RUN IN BEHIND CASSETE	96	91	6
LOWER RUN IN AT FINGER CONNECTION	104	100	5
BREAKER BEHIND LOWER FINBERS	113	109	4
BREAKER MOVABLE CONTACT	126	122	5
BREAKER BEHIND UPPER FINGERS	112	106	6
UPPER RUN IN AT FINGER CONNECTION	104	98	6
UPPER RUN IN BEHIND CASSETE	102	95	6
UPPER RUN IN NOTCH	94	87	7
RISER/RUN BACK CONNECTION	96	92	4
UPPER RISER BUS	96	92	4
UPPER POWER CONNCET SIDE	90	89	1
OUTGOING BUS CONNECTION	81	80	1
OUTING GOING BUS	72	72	0
SHORTING BAR	78	78	0

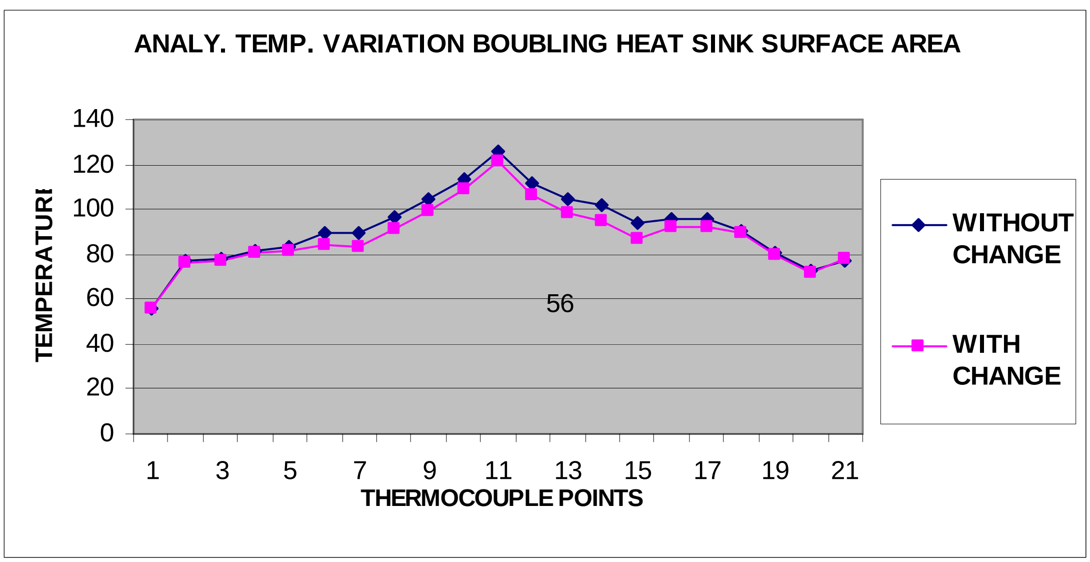


Figure7.9 Temperature Variation by Doubling Surface Area

7.1.4(c) Increasing Cluster Contact Force

Contact force at each cluster contact is increased from 26.5 KN to 50 KN. By doing so, 3^0C decrease in temperature is observed at moving contacts.

Table7.6 Analytical Temperatures Comparison by Increasing Contact Force at clusters

COMPONENT NAME	ANALY.TEMP.		
	BEFORE	AFTER	DIFF.
INCOMING BUS	56	56	0
INCOMING BUS CONNECTION	77	77	0
LOWER POWER CONNECT SIDE	78	78	0
LOWER POWER CONNECT	82	82	0
LOWER RISER BUS	83	83	0
RISER/RUN IN CONNECTION	89	89	0
LOWER RUN IN NOTCH	90	89	1
LOWER RUN IN BEHIND CASSETE	96	95	1
LOWER RUN IN AT FINGER CONNECTION	104	103	1
BREAKER BEHIND LOWER FINBERS	113	111	3
BREAKER MOVABLE CONTACT	126	124	3
BREAKER BEHIND UPPER FINGERS	112	109	3
UPPER RUN IN AT FINGER CONNECTION	104	103	1
UPPER RUN IN BEHIND CASSETE	102	100	1
UPPER RUN IN NOTCH	94	93	1
RISER/RUN BACK CONNECTION	96	96	0
UPPER RISER BUS	96	96	0
UPPER POWER CONNCET SIDE	90	90	0
OUTGOING BUS CONNECTION	81	80	0
OUTING GOING BUS	72	72	0
SHORTING BAR	78	78	0

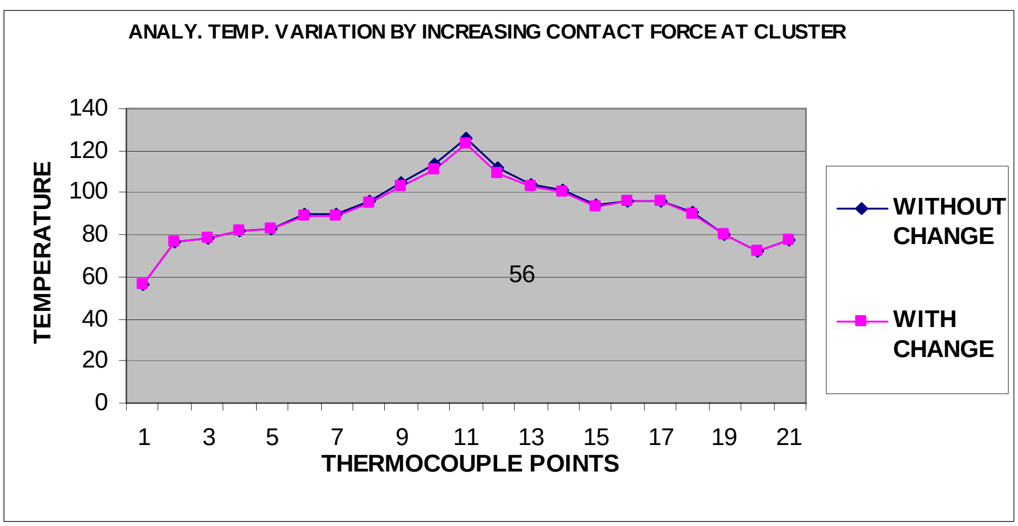


Figure 7.10 Temperature variation for change in cluster contact force

7.2 FRAME 1

By thermal networking method, current flowing path in frame 1 is considered as 138 nodes. 5 nodes are considered for air. Steady state temperatures are calculated analytically using the analytical tool. Thermal run is carried out and steady state temperatures are recorded after 12 hours. Analytical and experimental values at different points are tabulated as shown in table 7.7.

Table 7.7 Temperatures for Frame1

	TEST TEMPERATURE		ANALYTICAL	DIFF.	% ERROR
LABEL	**RISE**	**TOTAL**	**TOTAL**		
Test link	37	64	62.10	-1.9	2.97
Stack to stack bar joint	30	57	64.54	7.5	13.22
Power connect	26	53	58.58	5.6	10.53
Miller bus-middle	40	67	72.00	5.0	7.47
miller bus- End	56	83	82.60	-0.4	0.48
Run-in stab	57	84	86.83	2.8	3.37
Lower terminal(line)	78	105	109.87	4.9	4.64
Moving contact	94	121	129.06	8.1	6.66
Top terminal (load)	74	101	106.85	5.9	5.80
Runback Stab	62	89	91.71	2.7	3.04
Runback stab-test link joint	54	81	81.51	0.5	0.63
Shorting side test link	42	69	64.87	-4.1	5.99

Maximum temperature deviation is 8.1^0 and minimum 0.4^0C. The maximum percentage error is 13.2% and minimum percentage error is 0.48%. At moving contact, i.e. the maximum temperature node, temperature deviation is 8.1^0C giving 6.7 % error. Graph 7.11 shows the temperature profile of frame1. Analytical temperatures at start node and end node are lower than the experimental values while at all other nodes analytical values are more than experimental values. This is because the network diagram is started from particular point and effect of heat addition or loss on the system prior to that node is not considered. The temperatures calculated analytically are for single phase only but in actual testing condition, all three phases are considered and so the node at the shorting side node, i.e. the end node differs.

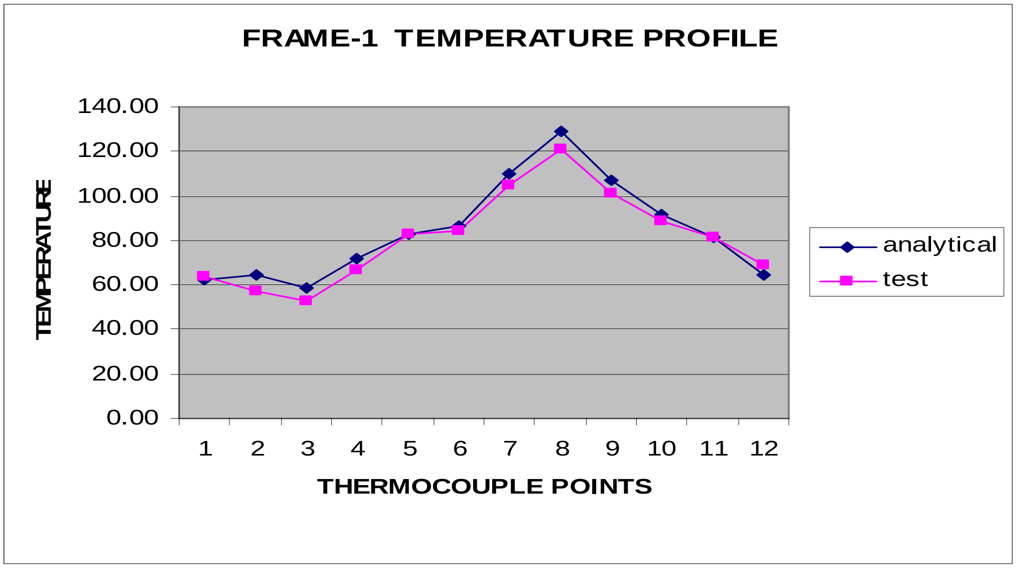


Figure 7.11 Frame -1 Temperature Profile

8. CONCLUSION AND FURTHER WORK

The aim of this work is to develop an analytical tool to calculate steady state temperatures in electrical equipments and predict the temperature variation with change in geometry of the components in the equipment, particularly with switch gear. This chapter summarizes the contribution, conclusion of the work and proposes ideas for further work.

8.1 CONTRIBUTION

An analytical tool is developed to calculate contact resistances at joints in current carrying paths. This tool is suitable to calculate electrical and thermal contact resistances at bolted joints and spring loaded contacts with different types of contact materials at contact tips.

An analytical tool is developed to calculate convective heat transfer co-efficient in natural convection. This tool is useful to calculate ‘h’ values for isothermal vertical and horizontal plates in natural convection.

An analytical tool is developed to calculate steady state temperatures in current carrying paths. This tool is useful to calculate steady state temperatures in electrical equipment and it is validated with AKD-12 –Frame 1 and Frame3 thermal run data. Above mentioned two tools are used in this tool.

Temperature prediction work is carried out by changing input parameters in the switch gears to observe its effect on temperatures of different components.

8.2 CONCLUSION

Comparing the results from analytical tool and experimental data, it can be concluded that the analytical tool can be used to calculate steady state temperatures and to have an idea of temperature profile along the current carrying path in electrical equipment.

Comparing the test data and analytical results, good matching is observed in the temperature profiles. Deviation is much at few points like starting nodes and ending nodes.

The maximum percentage error in frame 1 is 13%. The percentage error at point of interest i.e. at moving contact is 6.7%. The maximum percentage error for frame 3 is 15% and at moving contact, it is 1 %. For change in run-in geometry, 10^0C temperature decrease is observed. Change in cluster contact force doesn't have much effect on temperatures.

By analyzing the results, it can be concluded that thermal network theory helps engineers to predict temperatures easily for changes in design reducing design cycle time and it is flexible as to expand its application to any heat generating equipment.

8.3 FURTHER WORK

The following are the suggestions for further investigation

- In the current project work, initial 'h' values are calculated based on some reliable data giving the temperatures the components would reach. Using those 'h' values, temperatures are found out using the analytical tool. Based on these temperatures, 'h' values are calculated and temperatures are found out again. This is carried out manually till the difference between temperatures from two successive iterations is small. So logic has to be included in the tool to do the iteration work by itself.

- In the work done , for calculating temperatures of components placed in a closed compartment like switch gears, temperature of air inside the compartment is taken as input as components are placed at different distances form the compartment walls. Further work has to be done to avoid considering temperature of air in the compartment as input parameter.

- Error is not same at every point, so applying correction factor has become tricky. Further work has to be carried out to identify the pockets and apply correction factor accordingly.

- In the present work, radiation effect is neglected as the maximum temperature rise is 85^0C and to avoid the complexity in building network. Further investigation may be done to include radiation in the thermal network to take care of problems involving higher temperatures.

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APPENDIX-A

VISUAL BASIC CODE USED IN THE PROJECT

1. CODE FOR INPUT SHEET –GEOMETRY OF COMPONENTS TABLE

```
Sub TNetworkInput()
   If Worksheets("input").Range("D8") = "" Or Worksheets("input").Range("D10") = ""
        Or Worksheets("input").Range("D12") = "" Then
        MsgBox ("plz. Enter All The Values in INPUT PARAMETERS Table")
       End If
        X = 1
        LengthPerNode
        i = 26
While (Worksheets("input").Cells(i, 6)) <> ""
       If (Worksheets("input").Cells(i, 9)) = "" Then
        MsgBox ("Enter h Values at line" & i & "& Press Compute to Continue.....")
        Exit Sub
      End If
      i = i + 1
Wend
        CSArea
        HeatGenerated
        ConductionConductance
        ConvectionConductance
End Sub

Sub LengthPerNode()
        i = 26
      While (Worksheets("input").Cells(i, 5)) <> ""
        Worksheets("input").Cells(i, 11) = (Worksheets("input").Cells(i, 5)) / (Worksheets("input").Cells(i, 4))
        i = i + 1
     Wend
End Sub

Sub CSArea()
        i = 26
      While (Worksheets("input").Cells(i, 6)) <> ""
        Worksheets("input").Cells(i, 12) = (Worksheets("input").Cells(i, 6)) *  (Worksheets("input").Cells(i,
        7))
        i = i + 1
      Wend
End Sub

Sub HeatGenerated()
        i = 26
```

```
    While (Worksheets("input").Cells(i, 6)) <> ""
        Worksheets("input").Cells(i, 13) = ((Worksheets("input").Cells(i, 8)) * (Worksheets("input").Cells(8,
        4))) ^ 2 * (Worksheets("input").Cells(10, 4)) * (Worksheets("input").Cells(i, 11)) /
        (Worksheets("input").Cells(i, 12))
        i = i + 1
    Wend
End Sub

Sub ConductionConductance()
        i = 26
    While (Worksheets("input").Cells(i, 6)) <> ""
        Worksheets("input").Cells(i, 14) = (Worksheets("input").Cells(12, 4)) * (Worksheets("input").Cells(i,
        12)) / (Worksheets("input").Cells(i, 11))
        i = i + 1
   Wend
End Sub

Sub ConvectionConductance()
        i = 26
   While (Worksheets("input").Cells(i, 6)) <> ""
        Worksheets("input").Cells(i, 15) = (Worksheets("input").Cells(i, 9)) * (Worksheets("input").Cells(i,
        10))
        i = i + 1
    Wend
End Sub
```

2. CODE FOR ‘h’ VALUE FOR VERTICAL PLATE (NATURAL CONVECTION)

```
Sub Computeh()
         If Worksheets("input").Range("i9") = "" Or Worksheets("input").Range("i11") = ""
        Or Worksheets("input").Range("i13") = "" Then
        MsgBox ("Plz. Enter the Input Parameters")
        Exit Sub
         End If
         If Worksheets("input").Range("i9") - Worksheets("input").Range("i11") > 0 Then
        MsgBox ("Check temparatures: ----- Air Temp. exceeds Body Temp.")
        Exit Sub
         End If
        t = (Worksheets("input").Range("i9") + Worksheets("input").Range("i11")) / 2
        tf = t + 273
        beta = 1 / tf
        g = 9.81
        cp = 1030.5 - 0.19975 * tf + 0.00039734 * tf ^ 2 + 0.000000083504 * tf ^ 3
        rho = 351.99 / tf + 344.84 / tf ^ 2
        mu = 0.000001492 * tf ^ 1.5 / (109.1 + tf)
        k = 0.002334 * tf ^ 1.5 / (164.54 * tf) * 100
        v = mu / rho
```

```
        pr = mu * cp / k
        gr = g * beta * (Worksheets("input").Range("i11") - Worksheets("input").Range("i9")) *
        Worksheets("input").Range("i13") ^ 3 / v ^ 2
        ra = pr * gr
        num = 0.387 * ra ^ (1 / 6)
        den = (1 + (0.492 / pr) ^ (9 / 16)) ^ (8 / 27)
        nu = (0.825 + num / den) ^ 2
        h = nu * k / Worksheets("input").Range("i13")
        Worksheets("input").Range("i15") = h
End Sub
Sub Clearh()
        Worksheets("input").Range("i9:i15") = ""
End Sub
```

3. CODE FOR CREATING TEMPERATURE CO-EFFICIENT MATRIX

```
Sub ComputeResult()
    If Worksheets("network").Range("c6") = "" Or Worksheets("network").Range("c6") =
        "" Then
        MsgBox ("Enter Start Nodes and End Nodes")
        Exit Sub
       End If
        Dim Matrix() As Double
        Dim iMatrix() As Double
        Dim power() As Double
        Dim Con As Double
        Dim SNode As Integer
        Dim ENode As Integer
        Dim Temp() As Double
        i = 0
        j = 0
     While (Worksheets("nodes").Cells(i + 7, 2)) <> ""
                i = i + 1
          If Worksheets("nodes").Cells(i + 7, 4) = 2 Then
                  j = j + 1
          End If
   Wend
        'On Error GoTo errhandler
        Nodes = i - j
        ReDim Matrix(Nodes - 1, Nodes - 1)
        ReDim power(Nodes - 1)
        ReDim iMatrix(Nodes - 1, Nodes - 1)
        ReDim Temp(Nodes - 1)
   For i = 0 To Nodes - 1
        power(i) = Worksheets("nodes").Cells(i + 7, 7)
   Next
          Con = 6
```

```
    While (Worksheets("network").Cells(Con, 3) <> "")
        SNode = Worksheets("network").Cells(Con, 3) - 1
        ENode = Worksheets("network").Cells(Con, 4) - 1
           If Worksheets("nodes").Cells(ENode + 7, 4) = 1 Then
        Matrix(SNode, ENode) = -1 * (Worksheets("nodes").Cells(SNode + 7, 5) +
        Worksheets("nodes").Cells(ENode + 7, 5)) / 2
        'Worksheets("iMatrix").Cells(SNode + 1, ENode + 1) = Matrix(SNode, ENode)
        Matrix(ENode, SNode) = -1 * (Worksheets("nodes").Cells(SNode + 7, 5) +
        Worksheets("nodes").Cells(ENode + 7, 5)) / 2
        'Worksheets("iMatrix").Cells(ENode + 1, SNode + 1) = Matrix(ENode, SNode)
             Else
        Matrix(SNode, SNode) = -1 * Worksheets("nodes").Cells(SNode + 7, 6)
        'Worksheets("iMatrix").Cells(SNode + 1, SNode + 1) = Matrix(SNode, SNode)
        power(SNode) = power(SNode) + Worksheets("nodes").Cells(SNode + 7, 6) *
        Worksheets("nodes").Cells(ENode + 7, 8)
          End If
              Con = Con + 1
    Wend

    For i = 0 To Nodes - 1
        Sum = 0
        For j = 0 To Nodes - 1
                 Sum = Sum + Matrix(i, j)
        Next
        Matrix(i, i) = -Sum
        'Worksheets("iMatrix").Cells(i + 1, i + 1) = -Sum
    Next
        Calculate_Inverse Matrix, iMatrix, Nodes

    For i = 0 To Nodes - 1
        Sum = 0
        For j = 0 To Nodes - 1
               Sum = Sum + iMatrix(i, j) * power(j)
        Next
        Temp(i) = Sum
        Worksheets("output").Cells(i + 6, 2) = Worksheets("nodes").Cells(i + 7, 3)
        Worksheets("output").Cells(i + 6, 3) = i + 1
        Worksheets("output").Cells(i + 6, 4) = Sum
    Next
        'errhandler:
        'MsgBox ("An Error Occured During The Calculation Process.May be Insufficent Data or
        Worng Data ..Plz Check Out The Node Numbering.")
End Sub
```

4. CODE FOR MATRIX INVERSE

```
Public Sub Calculate_Inverse(ByRef Matrix_A() As Double, ByRef ResultMatrix() As Double,
System_DIM)
'Uses Gauss elimination method in order to calculate the inverse matrix [A]-1
'Method: Puts matrix [A] at the left and the singular matrix [I] at the right:
'[ a11 a12 a13 | 1 0 0 ]
'[ a21 a22 a23 | 0 1 0 ]
'[ a31 a32 a33 | 0 0 1 ]
'Then using line operations, we try to build the singular matrix [I] at the left.
'After we have finished, the inverse matrix [A]-1 (bij) will be at the right:
'[ 1 0 0 | b11 b12 b13 ]
'[ 0 1 0 | b21 b22 b23 ]
'[ 0 0 1 | b31 b32 b33 ]

On Error GoTo errhandler 'In case the inverse cannot be found (Determinant = 0)
Dim Operations_Matrix() As Double
ReDim Operations_Matrix(System_DIM, System_DIM * 2)

Solution_Problem = False

'Assign values from matrix [A] at the left
For N = 0 To System_DIM - 1
      For m = 0 To System_DIM - 1
                  Operations_Matrix(m, N) = Matrix_A(m, N)
      Next
Next

'Assign values from singular matrix [I] at the right
For N = 0 To System_DIM - 1
      For m = 0 To System_DIM - 1
            If N = m Then
                  Operations_Matrix(m, N + System_DIM) = 1
            Else
                  Operations_Matrix(m, N + System_DIM) = 0
            End If
      Next
Next
MAX_DIM = System_DIM - 1
'Build the Singular matrix [I] at the left
For k = 0 To System_DIM - 1
     'Bring a non-zero element first by changes lines if necessary
     If Operations_Matrix(k, k) = 0 Then
          For N = k To System_DIM - 1
             If Operations_Matrix(N, k) <> 0 Then line_1 = N: Exit For 'Finds line_1 with non-
          zero element
          Next N
```

```
                'Change line k with line_1
        For m = k To System_DIM * 2 - 1
            temporary_1 = Operations_Matrix(k, m)
            Operations_Matrix(k, m) = Operations_Matrix(line_1, m)
            Operations_Matrix(line_1, m) = temporary_1
        Next m
    End If
            elem1 = Operations_Matrix(k, k)
    For N = k To 2 * System_DIM - 1
            Operations_Matrix(k, N) = Operations_Matrix(k, N) / elem1
    Next N

    'For other lines, make a zero element by using:
    'Ai1=Aij-A11*(Aij/A11)
    'and change all the line using the same formula for other elements
    For N = 0 To System_DIM - 1
          If N = k And N = MAX_DIM Then Exit For 'Finished
          If N = k And N < MAX_DIM Then N = N + 1 'Do not change that element (already
        equals to 1), go for next one
        If Operations_Matrix(N, k) <> 0 Then 'if it is zero, stays as it is multiplier_1 =
        Operations_Matrix(N, k) / Operations_Matrix(k, k)
        For m = k To 2 * System_DIM - 1
                Operations_Matrix(N, m) = Operations_Matrix(N, m) - Operations_Matrix(k, m)
        * multiplier_1
            Next m
        End If
    Next N
Next k

'Assign the right part to the Inverse_Matrix
For N = 0 To System_DIM - 1
     For k = 0 To System_DIM - 1
          ResultMatrix(N, k) = Operations_Matrix(N, System_DIM + k)
     Next k
Next N
Exit Sub
errhandler:
Message$ = "An error occured during the calculation process. Determinant of Matrix [A] is probably
equal to zero."
response = MsgBox(Message$, vbCritical)
Solution_Problem = True

End Sub
```

5. CODE FOR 'h' IN HORIZONTAL PLATES

```
Sub Computehlower()
        If Worksheets("input").Range("n6") = "" Or Worksheets("input").Range("n8") = "" Or
          Worksheets("input").Range("n10") = "" Or Worksheets("input").Range("n12") = "" Then
          MsgBox ("Plz. Enter the Input Parameters")
                 Exit Sub
        End If
        If Worksheets("input").Range("n6") - Worksheets("input").Range("n8") > 0 Then
         MsgBox ("Plz Check temparatures: ----- Air Temp. Exceeds Body Temp.")
         Exit Sub
        End If
        Call xxx(ra, k, l)
        If ra < 10 ^ 7 Then
         nu = 0.54 * ra ^ 0.25
         Else
        If ra >= 10 ^ 7 And ra < 3 * 10 ^ 10 Then
         nu = 0.15 * ra ^ 0.333
         Else
         MsgBox ("Rayleigh Number is Greater Than 3*10^10 ..check out Input Parameters.")
        End If
        End If
         hlower = nu * k / l
         Worksheets("input").Range("n14") = hlower
End Sub
Sub Computehupper()
        If Worksheets("input").Range("n6") = "" Or Worksheets("input").Range("n8") = "" Or
         Worksheets("input").Range("n10") = "" Or Worksheets("input").Range("n12") = "" Then
         MsgBox ("Plz. Enter the Input Parameters")
         Exit Sub
        End If
        If Worksheets("input").Range("n6") - Worksheets("input").Range("n8") > 0 Then
         MsgBox ("Plz Check temparatures: ----- Air Temp. Exceeds Body Temp.")
         Exit Sub
        End If
         Call xxx(ra, k, l)
        If ra < 3 * 10 ^ 10 Then
        nu = 0.27 * ra ^ 0.25
         Else
                  MsgBox ("Rayleigh Number is Greater Than 3*10^10..Plz. Check Out
         Input Parameters.")
        End If
         hupper = nu * k / l
         Worksheets("input").Range("n16") = hupper
End Sub

Sub Clearhhorizontal()
```

```
        Worksheets("input").Range("n6:n16") = ""
End Sub

Public Function xxx(ra, k, l)
        l = Worksheets("input").Range("n10") * Worksheets("input").Range("n12") / 2 *
        (Worksheets("input").Range("n10") + Worksheets("input").Range("n12"))
        t = (Worksheets("input").Range("n6") + Worksheets("input").Range("n8")) / 2
        tf = t + 273
        beta = 1 / tf
        g = 9.81
        cp = 1030.5 - 0.19975 * tf + 0.00039734 * tf ^ 2 + 0.000000083504 * tf ^ 3
        rho = 351.99 / tf + 344.84 / tf ^ 2
        mu = 0.000001492 * tf ^ 1.5 / (109.1 + tf)
        k = 0.002334 * tf ^ 1.5 / (164.54 * tf) * 100
        v = mu / rho
        pr = mu * cp / k
        gr = g * beta * (Worksheets("input").Range("n8") - Worksheets("input").Range("n6")) * l ^ 3 /
        v ^ 2
        ra = pr * gr
End Function
```

6. CODE FOR CLEARING SHEETS

```
Sub clearinputsheet()
        Worksheets("input").Range("d8:d12") = ""
        Worksheets("input").Range("i9:i15") = ""
        Worksheets("input").Range("n6:n16") = ""
        Worksheets("input").Range("c26:o117") = ""
End Sub
Sub clearjointssheet()
        Worksheets("joints").Range("c16:j40") = ""
End Sub
Sub clearnodessheet()
        Worksheets("nodes").Range("b7:h1000") = ""
End Sub
Sub clearnetworksheet()
        Worksheets("network").Range("c6:d600") = ""
End Sub
Sub clearallsheets()
        YesNo = MsgBox("This will Delete Data in all The Sheets .. Do you want to Continue?",
        vbYesNo + vbCritical, "Caution")
        Select Case YesNo
        Case vbNo
Exit Sub
Case vbYes
        Call clearinputsheet
        Call clearjointssheet
```

```
        Call clearnodessheet
        Call clearnetworksheet
        Worksheets("output").Range("b6:d600") = ""
End Select
End Sub
```

7. CODE FOR USER FORM IN JOINTS INPUT SHEET

```
Private Sub CmdAddRow_Click()
       If cmbMaterial1.Text = "" Then
        MsgBox ("Select Material 1")
        Exit Sub
       ElseIf cmbMaterial2.Text = "" Then
        MsgBox ("Select Material 2")
        Exit Sub
       ElseIf TxtForce = "" Then
        MsgBox ("Enter The Contact Force")
        Exit Sub
      ElseIf TxtFCurrent = "" Then
        MsgBox ("Enter The Fraction of Total Current")
        Exit Sub
    End If

        Dim i
        Dim j
        Dim Row1
        Dim Q
        Dim Cth
        Dim F
        Dim S
        Dim s1
        Dim s2
        Dim k
        Dim X
        Dim Counter

        i = cmbMaterial1.ListIndex + 8
        j = cmbMaterial2.ListIndex + 8
        s1 = Worksheets("Data").Cells(i, 4)
        s2 = Worksheets("Data").Cells(j, 4)
        Row1 = (Worksheets("Data").Cells(i, 5) + Worksheets("Data").Cells(j, 5))
        k = (Worksheets("data").Cells(i, 7) + Worksheets("data").Cells(j, 7)) / 2
        F = TxtForce / 9.81 * 1000
      If s1 < s2 Then
        S = s1
      Else
        S = s2
```

```
      End If
        X = (Row1 / 2.506628275) * (S / F) ^ 0.5 * 1000 * 10 ^ -6
        Row1 = Row1 / 2
        i = TxtFCurrent * Worksheets("Input").Cells(8, 4)
        Q = i ^ 2 * X
        Cth = 2.1 * Row1 * k / X * 10 ^ -6
                Counter = 16
      While (Worksheets("Joints").Cells(Counter, 5)) <> ""
        Counter = Counter + 1
      Wend

        Worksheets("Joints").Cells(Counter, 4).Interior.Color = 8421376
        Worksheets("Joints").Cells(Counter, 5).Interior.Color = 8421376
        Worksheets("Joints").Cells(Counter, 6).Interior.Color = 8421376
        Worksheets("Joints").Cells(Counter, 7).Interior.Color = 10092500
        Worksheets("Joints").Cells(Counter, 8).Interior.Color = 10092543
        Worksheets("Joints").Cells(Counter, 9).Interior.Color = 10092543
        Worksheets("Joints").Cells(Counter, 10).Interior.Color = 10092543
        Worksheets("Joints").Cells(Counter, 3).Interior.Color = 8421376
        'Worksheets("Joints").Cells(Counter, 3).Border = xlAll
        Worksheets("Joints").Cells(Counter, 3).Font.Color = 10092543
        Worksheets("Joints").Cells(Counter, 4).Font.Color = 10092543
        Worksheets("Joints").Cells(Counter, 5).Font.Color = 10092543
        Worksheets("Joints").Cells(Counter, 6).Font.Color = 10092543
        Worksheets("Joints").Cells(Counter, 3) = TxtJName
        Worksheets("Joints").Cells(Counter, 4) = TxtJType
        Worksheets("Joints").Cells(Counter, 5) = F * 9.81 / 1000
        Worksheets("Joints").Cells(Counter, 6) = Val(TxtFCurrent)
        Worksheets("Joints").Cells(Counter, 7) = i
        Worksheets("Joints").Cells(Counter, 8) = X
        Worksheets("Joints").Cells(Counter, 9) = Cth
        Worksheets("Joints").Cells(Counter, 10) = Q
End Sub
Private Sub CommandButton1_Click()
        Unload Me
End Sub
Private Sub UserForm_Initialize()
        i = 8
      While (Worksheets("Data").Cells(i, 3)) <> ""
        cmbMaterial1.AddItem Worksheets("Data").Cells(i, 3)
        cmbMaterial2.AddItem Worksheets("Data").Cells(i, 3)
        i = i + 1
      Wend
End Sub
```

8. CODE FOR USER FORM IN NODES SHEET

```
Private Sub CmdAir_Click()
        If LTrim(RTrim(Me.TxtAirTEmp)) = "" Then
    MsgBox "Enter Air Temparature"
      ElseIf LTrim(RTrim(Me.TxtTempZone)) = "" Then
    MsgBox "Enter Air zone"
      Else
    i = 7
     While (Worksheets("nodes").Cells(i, 2)) <> ""
    i = i + 1
     Wend

    Worksheets("nodes").Cells(i, 2) = i - 6
    Worksheets("nodes").Cells(i, 3) = Me.TxtTempZone
    Worksheets("nodes").Cells(i, 4) = 2
    Worksheets("nodes").Cells(i, 8) = Me.TxtAirTEmp
    Worksheets("nodes").Cells(i, 7).Select
     End If
End Sub
Private Sub cmdComponent_Click()
    Dim i
    Dim j
    Dim k
    Dim z
    j = 26 + CmbComponent.ListIndex
    i = 7
   While (Worksheets("nodes").Cells(i, 2)) <> ""
    i = i + 1
   Wend
    z = Worksheets("input").Cells(j, 4)
     For k = 1 To z
    Worksheets("nodes").Cells(i, 2) = i - 6
    Worksheets("nodes").Cells(i, 3) = Worksheets("input").Cells(j, 3)
    Worksheets("nodes").Cells(i, 4) = 1
    Worksheets("nodes").Cells(i, 6) = Worksheets("input").Cells(j, 15)
    Worksheets("nodes").Cells(i, 5) = Worksheets("input").Cells(j, 14)
    Worksheets("nodes").Cells(i, 7) = Worksheets("input").Cells(j, 13)
    Worksheets("nodes").Cells(i, 7).Select
    i = i + 1
   Next

End Sub

Private Sub CmdDummy_Click()
    Dim i
    Dim j
```

```
            Dim k
            Dim z
            i = 7
           While (Worksheets("nodes").Cells(i, 2)) <> ""
            i = i + 1
           Wend
            Worksheets("nodes").Cells(i, 2) = i - 6
            Worksheets("nodes").Cells(i, 3) = "Dummy Node"
            Worksheets("nodes").Cells(i, 4) = 1
            Worksheets("nodes").Cells(i, 6) = 0
            Worksheets("nodes").Cells(i, 5) = 0
            Worksheets("nodes").Cells(i, 7) = 0
            Worksheets("nodes").Cells(i, 7).Select
End Sub
Private Sub CmdJoint_Click()
            Dim i
            Dim j
            Dim k
            Dim z
            j = 16 + cmbjoint.ListIndex
            i = 7
         While (Worksheets("nodes").Cells(i, 2)) <> ""
            i = i + 1
         Wend
            Worksheets("nodes").Cells(i, 2) = i - 6
            Worksheets("nodes").Cells(i, 3) = Worksheets("Joints").Cells(j, 3)
            Worksheets("nodes").Cells(i, 4) = 1
            Worksheets("nodes").Cells(i, 6) = 0
            Worksheets("nodes").Cells(i, 5) = Worksheets("Joints").Cells(j, 9)
            Worksheets("nodes").Cells(i, 7) = Worksheets("joints").Cells(j, 10)
            Worksheets("nodes").Cells(i, 7).Select
End Sub

Private Sub OptionButton1_Click()
            FrComp.Enabled = True
            Frame1.Enabled = False
            CmdDummy.Enabled = False
            FrAir.Enabled = False

End Sub

Private Sub OptionButton2_Click()
            FrComp.Enabled = False
            Frame1.Enabled = True
            CmdDummy.Enabled = False
            FrAir.Enabled = False
End Sub
```

```
Private Sub OptionButton3_Click()
        FrComp.Enabled = False
        Frame1.Enabled = False
        CmdDummy.Enabled = True
        FrAir.Enabled = False
End Sub

Private Sub OptionButton4_Click()
        FrComp.Enabled = False
        Frame1.Enabled = False
        CmdDummy.Enabled = False
        FrAir.Enabled = True
End Sub

Private Sub UserForm_Initialize()
        i = 26
       While (Worksheets("input").Cells(i, 3)) <> ""
        CmbComponent.AddItem Worksheets("input").Cells(i, 3)
        i = i + 1
       Wend
        i = 16
       While (Worksheets("joints").Cells(i, 3)) <> ""
        cmbjoint.AddItem Worksheets("joints").Cells(i, 3)
        i = i + 1
      Wend

End Sub
```