University of Southern Queensland

Faculty of Health, Engineering & Sciences

Operating Temperature of Current Carrying Copper Busbar Conductors

A dissertation submitted by

Roland Barrett

in fulfilment of the requirements of

Courses ENG4111 and 4112 Research Project

towards the degree of

Bachelor of Engineering (Electrical and Electronic)

Submitted: October, 2013

Abstract

Copper busbar conductors are an integral part of any high current switchboard. A suitable switchboard design must be capable of withstanding the mechanical, electrical and thermal stresses which are likely to be encountered in normal service. The aim of the project is to simulate and model, in Matlab, the operating temperature of various current carrying copper busbar conductor arrangements in a specific bus zone and to assist with design selection to Australian Standards.

The project objectives, detailed in the dissertation, list several milestones to achieve the project aim. The objectives can be summarised into three categories:

1. Research
2. Matlab Script Development
3. Testing

Although three distinct categories, a continuous cycle of all three was implemented throughout the project to generate acceptable results.

The developed Matlab Script is able to produce plots that contain operating temperature curves for a given current and ambient temperature. This provides another method for switchboard manufactures to determine busbar current carrying capacities within the specific enclosure. The accuracy of the curves are within ±8% when compared with the AS 3000:1991 method, which is also an approximation, and within 1% error when compared with the real test results (Type Tested) for the specified enclosure at a single point.

Limitation of Use

The Council of the University of Southern Queensland, its Faculty of Health, Engineering & Sciences, and the staff of the University of Southern Queensland, do not accept any responsibility for the truth, accuracy or completeness of material contained within or associated with this dissertation.

Persons using all or any part of this material do so at their own risk, and not at the risk of the Council of the University of Southern Queensland, its Faculty of Health, Engineering & Sciences or the staff of the University of Southern Queensland.

This dissertation reports and educational exercise and has no purpose or validity beyond this exercise. The sole purpose of the course pair entitled "Research Project" is to contribute to the overall education within the student's chosen degree program. This document, the associated hardware, software, drawings, and other material set out in the associated appendices should not be used for any other purpose: if they are so used, it is entirely at the risk of the user.

Certification

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Roland Barrett

Student Number: 0050070099

Date: 21 / 10 / 2013

Acknowledgements

I would like to express my appreciation to my project supervisor Dr Tony Ahfock, whose contribution in suggestions and advice helped me in executing this project.

Furthermore I would also like to acknowledge J. & P. Richardson Industries Pty Ltd, who gave the permission to use their standard busbar zone design and Type Test reports for verification of my results.

Table of Contents

List of Figures

List of Tables

Glossary of Terms

Assembly is a combination of one or more low voltage switching devices assembled by a manufacturer (e.g. a switchboard).

Australian Standard (AS) is a published document setting out specifications and procedures.

Busbar is a low impedance conductor to which several electric circuits can be separately connected.

Current Carrying Capacity (CCC) is the maximum rated current a conductor can carry during normal operating conditions.

High current is defined where the rated current is equal to or exceeds 800 Amps.

Low voltage is defined where the rated voltage does not exceed 1000 V a.c. at frequencies not exceeding 1000 Hz, or 1500 V d.c.

New Zealand Standard (NZS) is a published document setting out specifications and procedures.

Partially Type Tested low voltage switchgear and control gear Assembly (PTTA) is a low voltage switchgear and controlgear Assembly, containing both Type Tested and non-Type Tested arrangements, provided that the latter are derived (e.g. by calculation) from Type Tested arrangements which have complied with the relevant tests.

1 Introduction

1.1 Outline of the Project

The need to determine the operating temperature of current carrying copper busbar conductors was identified by a commercial switchboard manufacture contracting company using superseded Australian Standards for their busbar conductor selection in high current switchboards. The purpose and scope of this project is detailed in Section 1.4, Project Objectives.

1.2 Introduction

Copper busbar conductors are an integral part of any high current switchboard. AS/NZS3008.1.1:2009 provides a method for electrical cable selection for various common installations, however busbar selection is not provided with the same level of detailed guidance. A suitable switchboard design must be capable of withstanding the mechanical, electrical and thermal stresses which are likely to be encountered in normal service. The Australian Standards provide limits for the maximum temperatures that a busbar conductor can operate within during normal operation, which influences conductor design selection and current carrying capacities.

1.3 The Problem

Despite the Australian Standards providing operational limits, they do not provide a detailed method for busbar conductor selection. As busbar arrangements are generally uninsulated within a switchboard enclosure, the operating temperature greatly depends on the busbar surroundings and air flow. Switchboard designs can vary greatly from board to board due to their application, and therefore busbar zones and conductor selection vary with this.

Type Tested switchboards are extensively tested to certify that their busbar operating temperature remains within allowable limits, however, Type Testing every switchboard is expensive and not commercially viable. Alternatively, verification of operating temperature of the busbars can be calculated by extrapolation of known data.

1.4 Project Objectives

The aim of this project was to simulate and model in Matlab the operating temperature of various current carrying copper busbar conductor arrangements in a specific bus zone of a low voltage switchboard to determine if the conductor selection meets Australian Standards.

The project addresses the following key objectives, tailored to meet the project aim.

1. Review of the current requirements in Australia for calculating Current Carrying Capacity of busbar in switchboards. This includes making references to Australian Standards such as:

   - **AS/NZS 3000:2007** Electrical Installations
   - **AS/NZS 3439.1:2002** Low-voltage switchgear and controlgear assemblies - Type-tested and partially type-tested assemblies
   - **AS 60890:2009** A method of temperature-rise assessment by extrapolation for partially type-test assemblies (PTTA) of low-voltage switchgear and controlgear

2. Review of the current methods of calculating Current Carrying Capacity of busbar arrangements in one commercial switchboard manufacturing factory.

3. Collation of some mathematical methods for the calculation of temperature of copper busbars carrying current with natural heat loss convection. State mathematical methods for the calculation of temperature loss of the switchboard cubical material incorporating effects caused by material finish.

4. Simulate and model in Matlab the temperature of copper busbars carrying 2500A in the specific bus zone and busbar arrangement.

5. Compare the Matlab simulation to real Type Test results for the specific bus zone and busbar arrangement.

6. Simulate and model in Matlab the temperature of copper busbars carrying various currents in a specific bus zone and with varying busbar arrangements. Varying currents would be of nominal switch sizes such as:

   - 630A
   - 800A
   - 1000A
   - 1250A
   - 1600A
   - 2000A
   - 3200A

   Busbar arrangements were varied in bar width and number of conductors in parallel per phase. Copper bar widths are of common commercially available sizes.

1.5 Overview

To achieve the aim of this project, Chapter 2 addresses Project Objectives 1, 2 and 3, reviewing literature, both public and private, to establish the background on what information is available for busbar design selection.

After establishing the background information, Chapter 3 will establish the specific bus zone system, its dimensions and assumptions made. Addressing Project Objectives 3, 4 and 6, this Chapter details the methodologies behind each method of calculating the operating temperature of current carrying copper busbars.

Implementing the methodologies detailed in Chapter 3, Chapter 4 presents the results of the four methods for calculating busbar operating temperatures or current carrying capacities detailed in the previous Chapter. This Chapter addresses Project Objectives 4 and 6.

Following the results, Chapter 5 presents an analysis and discussion of the developed Matlab Script's results verses the other three methods of calculating busbar operating temperatures or current carrying capacities, as describe in the Chapter 3. This Chapter addresses Project Objective 5.

Concluding the project, Chapter 6 summarises the project and the key discussions. This Chapter additionally discusses potential further work expanding on the findings of this project.

1.6 Project Outcomes

The outcomes of this project provide another method for switchboard manufactures to determine busbar current carrying capacities within the specific enclosure. The outcomes provide documentation that the design selection complies with Australian Standards.

2 Background

2.1 Introduction

This Chapter addresses Project Objectives 1, 2 and 3, reviewing literature, both public and private, to establish the background on what information is available for busbar design selection.

2.2 Standards Literature Review

2.2.1 AS/NZS 3000:2007 Electrical Installations

AS/NZS 3000:2007 Electrical Installations (AS 3000) is an Australian Standard that ‘sets out requirements for the design, construction and verification of electrical installations, including the selection and installation of electrical equipment forming part of such electrical installations’ (AS/NZS 3000:2007, p21). Clause 3.4.1 of AS 3000 states that ‘every conductor shall have a current-carrying capacity, in accordance with AS/NZS 3008.1’ (AS/NZS 3000:2007, p126). However, note 4 of this clause states that ‘current-carrying capacities for busbars should be obtained from the manufacturer’ (AS/NZS 3000:2007, p126), and also that AS 4388 provides a guide to this calculation. The manufacturer is the entity that designs and manufactures the switchboard. AS 4388:1996, A method of temperature-rise assessment by extrapolation for partially type-tested assemblies (PTTA) of low-voltage switchgear and controlgear was superseded by AS 60890:2009 of the same title in 2009.

Section 2.9.1 of AS 3000 relates to the construction of switchboards, and in addition to the calculation of current carrying capacities of busbars, AS 3000 states,

> Clause 2.9.3.2 Suitability. Switchboards shall be suitable to withstand the mechanical, electrical and thermal stresses that are likely to occur in service. Switchboards complying with the relevant requirements of the AS/NZS 3439 series of Standards are considered to meet the requirements of this clause 2.9.3 (AS/NZS 3000:2007, p115).

Summarising AS 3000, it states that the responsibility for the calculation of current carrying capacities of busbars lies with the manufacturer and AS 60890:2009 can be used as a guide. Additionally the construction of the switchboard is to comply with the relevant sections of AS/NZS 3439 with regards to thermal stresses that are likely to occur in service.

2.2.2 AS/NZS 3439.1:2002 Low-voltage switchgear and controlgear assemblies - Type-tested and partially type-tested assemblies

AS/NZS 3439.1:2002 (AS 3439) is an Australian Standard whose objective ‘is to lay down the definitions and to state the service conditions, construction requirements, technical characteristics and tests for low-voltage switchgear and control gear Assemblies’ (AS/NZS 3439.1:2002, p1).

AS 3439 states in its Preface that ‘Information regarding the current carrying capacity for copper busbars can be found in AS 4388:1996’ (AS/NZS 3439.1:2002, pii), which reiterates the statement made by AS 3000. As stated in Section 2.2.1 of this project, AS 4388:1996 was superseded by AS 60890:2009 of the same title in 2009.

Clause 7.8.2 of AS 3439 also reiterates the statement made by AS 3000 that the responsibility for the calculation of current carrying capacities of busbars lies with the manufacturer.

> Clause 7.8.2 Dimensions and rating of busbars and insulated conductors. The choice of the cross-sections of conductors inside the Assembly is the responsibility of the manufacturer. (AS/NZS 3439.1:2002, p48)

Clause 7.3 of AS 3439 defines the temperature rise limits in Table 2 of AS3439. Clause 7.3 and an extract of Table 2 relating only to the busbar components are shown in Table 2.1 on the following page. As stated in Table 2.1, the maximum copper busbar operational temperature under normal service conditions is 105°C.

Clause 7.3 Temperature rise. The Temperature-rise limits given in Table 2 apply for mean ambient air temperatures less than or equal to 35°C and shall not be exceeded for Assemblies when verified in accordance with 8.2.1. (AS/NZS 3439.1:2002, p27)

Table 2.1 Extract from AS3439.1 Table 2 - Temperature-rise limits

Parts of Assemblies	**Temperature rise** **K**
Busbars and conductors, plug-in contacts of removable or withdrawable parts which connect to busbars (6)	Limited by: – Mechanical strength of conducting material; – Possible effect on adjacent equipment; – Permissible temperature limit of the insulating material in contact with the conductor; – Effect of the temperature of the conductor on the apparatus connected to it; – For plug-in contacts, nature and surface treatment of the contact material.
6) The requirements for built-in components, busbars and conductors, plug-in contacts of removable or withdrawable parts which connect to busbars, limited by: – mechanical strength of conducting material; – possible effect on adjacent equipment; – permissible temperature limit of the insulating materials in contact with the conductors; – the effect of the temperature of the conductor on the apparatus connected to it; and – for plug-in contacts, the nature and surface treatment of the contact material would generally be considered to be complied with if temperature rises do not exceed 70 K for H.C. copper busbars and 55 K for H.C. aluminium busbars. The temperature rise limits of 70 K and 55 K are based on maximum temperatures of 105°C and 90°C, respectively, under the normal service conditions according to Clause 6.1.	

(AS/NZS 3439.1:2002, p28)

Clause 7.3 states that the temperature rise needs to be verified in accordance with Clause 8.2.1. Sub-clause 8.2.1.1 (below) states that verification of temperature rise limits shall be made either by test or by extrapolation.

> Clause 8.2.1.1 Verification of temperature rise.
>
> The Temperature-rise test is designed to verify that the temperature-rise limits specified in 7.3 for the different parts of the Assembly are not exceeded…
>
> … The verification of temperature-rise limits for PTTA shall be made
>
> - By test in accordance with 8.2.1, or
> - By extrapolation, for example in accordance with IEC 60890.
>
> (AS/NZS 3439.1:2002, p27)

AS 60890:2009 is a reproduction of the IEC 60890 standard, and is therefore the equivalent when referred to in AS 3439.

Summarising AS 3439, it states that the responsibility for the calculation of current carrying capacities of busbars lies with the manufacturer, and AS 60890:2009 can be used as a guide. Additionally, the maximum copper busbar operational temperature, under normal service conditions, is 105°C.

2.2.3 AS 60890:2009 A method of temperature-rise assessment by extrapolation for Partially Type-Test Assemblies (PTTA) of low-voltage switchgear and controlgear

AS/NZS 60890:2009 (AS 60890) is an Australian Standard whose objective is to provide one possible method to determine the temperature rise and prove compliance with the requirements of sub-clauses 8.2.1 of AS/NZS 3439.1:2002. Where the temperature rise is verified through calculation of extrapolated data, the Assembly is considered a Partially Type Tested Assembly (PTTA).

The scope of AS 60890 also defines the ambient air temperature as,

> Unless otherwise specified, the ambient air temperature outside the PTTA is the air temperature indicated for indoor installation of the PTTA (average value over 24 h) of 35°C. If the ambient air temperature outside the PTTA at the place of use exceeds 35°C, this higher temperature is deemed to be the ambient air temperature of the PTTA. (AS/NZS 60890:2009, p1)

AS 60890 provides a calculation procedure for one method of calculating the temperature rise of the air inside an enclosure. This method will be explored in Section 3.6.2.

2.3 Commercial Switchboard Manufacturing Workshop Review

Both AS/NZS 3000:2007 and AS/NZS 3439.1:2002 states that the responsibility for the calculation of current carrying capacities of busbars lies with the manufacturer. Therefore, a review of the current methods of calculating current carrying capacity of busbar arrangements in a commercial switchboard manufacturing workshop was conducted.

The review was performed on a company which has established its switchboard manufacturing facility over 45 years. They have their own engineering and design department that produces switchboard designs which are required to meet Australian Standards. The facility also incorporates a sheetmetal manufacturing workshop for the construction of metal clad switchboards, with its own paint shop for powder coating. The electrical manufacturing workshop facilitates the assembly and testing of the switchboards. It is essentially an all-in-one facility with little need for out sourcing of any manufacturing processes. Additionally, the company owns the Intellectual Property of a Motor Control Center Switchboard with Type Test certificates which documents compliance with the requirements of sub-clauses 8.2.1 of AS/NZS 3439.1:2002.

The aim of the project, as stated in Section 1.4, Project Objectives, is to simulate and model in Matlab the operating temperature of various current carrying copper busbar conductor arrangements in a specific bus zone. The specific bus zone is the horizontal bus zone which is used in the company reviewed's Type Tested Motor Control Center Switchboard. The details of specific bus zone can be found in Section 3.2.1, Bus Zone Specifics.

The commercial switchboard manufacturing workshop's method for calculation of current carrying capacities of busbars is to use a guide that was provided in AS 3000:1991 SAA Wiring Rules. Appendix C of AS 3000:1991 provides a method for the calculation of current carrying capacities which was removed from the 2000 and 2007 editions of AS 3000.

The method proposed in AS 3000:1991 is not a method for calculating the operating temperature of the busbars. This method assumes the bars are at their maximum possible rating of 105°C, this although gives a point of comparison between AS3000:1991 and AS 60890:2009 method. Therefore, this method will be explored in Section 3.6.1 AS 3000:1991 Method, please refer to this section for further details.

2.4 Mathematical Methods of Temperature Calculation

The law of conservation of energy states that the total energy of an isolated system cannot change. Energy can be neither created nor destroyed, but can change form. Energy can be transferred by interactions of a system and its surroundings, which is the case with the busbar system. Electrical energy enters the system, however, not all of the electrical energy leaves the system due to the resistance of the busbar conductors and Ohms Law. The remainder of the energy is dissipated as heat from the busbars into its surroundings.

‘Copper for Busbars’ is a publication maintained by the Copper Development Association in the United Kingdom. The publication itself is out of print, however, is maintained in a web based form and last updated in 1996. The preface states that the publication has long been accepted as the standard reference work on busbar design. This publication contains formulas for the calculation of convection, radiation and conduction heat loss from busbars which are further detailed in Section 3.4.

The free-convection flow phenomenon inside an enclosed space, although random, some very good generalisations can be made to determine average temperatures and heat flow. ‘Fundamentals of Heat and Mass Transfer’ by Incropera contains formulas for the calculation of heat transfer via convection, radiation and conduction in a range of scenarios, which is further detailed in Section 3.4.

The specified enclosure is a complex system of heat dissipation, absorption and conduction calculations, and the formulas used from the above publications and how they are inter-connected is detailed in Section 3.4.

2.5 Other Published Papers

Several other publications were assessed under the literature review for previous works relating to calculating the operating temperature of busbars within an enclosure. Two publications that relate to this project's aim were,

1. Calculations of Eddy Current, Fluid, and Thermal Fields in an Air Insulated Bus Duct System by Ho S., Li Y., Lin X. and Lo E. (2006), and

2. Temperature Rise Prediction in 3-Phase Busbar System at 20°C Ambient Temperature by Tebal N. and Pinang P. (2012).

Both of these publications are an analysis of a 3 phase bus duct system, which is similar in characteristics to a bus zone of a switchboard. They both used Finite Element Method (FEM) to model the temperature rise of the system. The Ho, Li, Lin and Lo method was developed in Fortran whilst the Tebal and Pinang method was modelled in Opera 2D.

Neither publication provided details of methodology or workings as they were essentially extended abstracts as part of conferences. Due to this lack of information, neither of these publications were used as sources of information for developing the Matlab Script of this project.

2.6 Conclusions

The review of the Australian Standards for high current switchboards identifies that the responsibility for the calculation of current carrying capacities of busbars lies with the manufacturer. AS 60890:2009 is stated as a method for the calculation of current carrying capacities of busbars and is further investigated in Section 3.6.2.

The manufacturer reviewed in this project does not use the AS 60890:2009 method referred to within AS/NZS 3439.1:2002 and AS/NZS 3000:2007. The use of a superseded version of AS3000:1991 and reliance on their Type Test certificate is used for their evidence of compliance with AS 3439. Additionally, AS 60890 does state that it is only one possible method to determine the temperature rise. The manufacture's method of AS 3000:1991 will be further investigated in Section 3.6.1.

Two publications have been identified as providing sufficient formulas for the calculation of the operating temperature of the busbars in the specific enclosure. The details of which are presented in Section 3.4, Mathematical Methods of Temperature Calculation.

It is also apparent that, because switchboard design can be fairly custom and designed on a board by board basis, it is difficult to write rules or methods that apply to all Assemblies. This is further evidenced by the statement that the responsibility of the calculation of current carrying capacities of busbars lies with the manufacturer.

3 Methodology

3.1 Introduction

This Chapter addresses Project Objectives 3, 4 and 6. A summary of these objectives are listed below:

3. Collation of mathematical methods for the calculation of temperature of copper busbars carrying current with natural heat loss convection.

4. Simulate and model in Matlab the temperature of copper busbars carrying 2500A in the specific bus zone and busbar arrangement.

6. Simulate and model in Matlab the temperature of copper busbars carrying various currents in a specific bus zone and with varying busbar arrangements.

This chapter also establishes the specific bus zone system, including its dimensions, assumptions and methodologies behind each method of calculating the operating temperature of current carrying copper busbars.

3.2 Specific Bus Zone System

3.2.1 Bus Zone Specifics

A bus zone is a designated section of an Assembly, specifically designed to facilitate busbars from which one or several distribution busbars and/ or incoming and outgoing units can be connected. The specific bus zone for this project is the horizontal bus zone. This horizontal bus zone is used in the company reviewed's Type Tested Motor Control Center Switchboard.

The reviewed company possesses a Type Test certificate and an accompanying report which details the extensive temperature rise testing performed. Figure 3.1 to Figure 3.4 show in detail the horizontal bus zone. The figures show the arrangement for which the test was performed. This arrangement consists of 3 by 125x6.3mm copper busbars per phase and 1 by 125x6.3mm copper busbar for neutral. This arrangement was tested up to 2450Amps.

In addition to the following figures, Appendix E contains the full Bus Zone General Arrangement Drawings obtained from the Type Test report, which details the locations of all the thermocouples used to measure temperature rise.

As stated in Assumption 6, found in Section 3.3, the horizontal bus zone is assumed to be infinite. Therefore, the worst case thermocouple readings from the Type Test report will be used. These thermocouples are located in the center of the tested Motor Control Center.

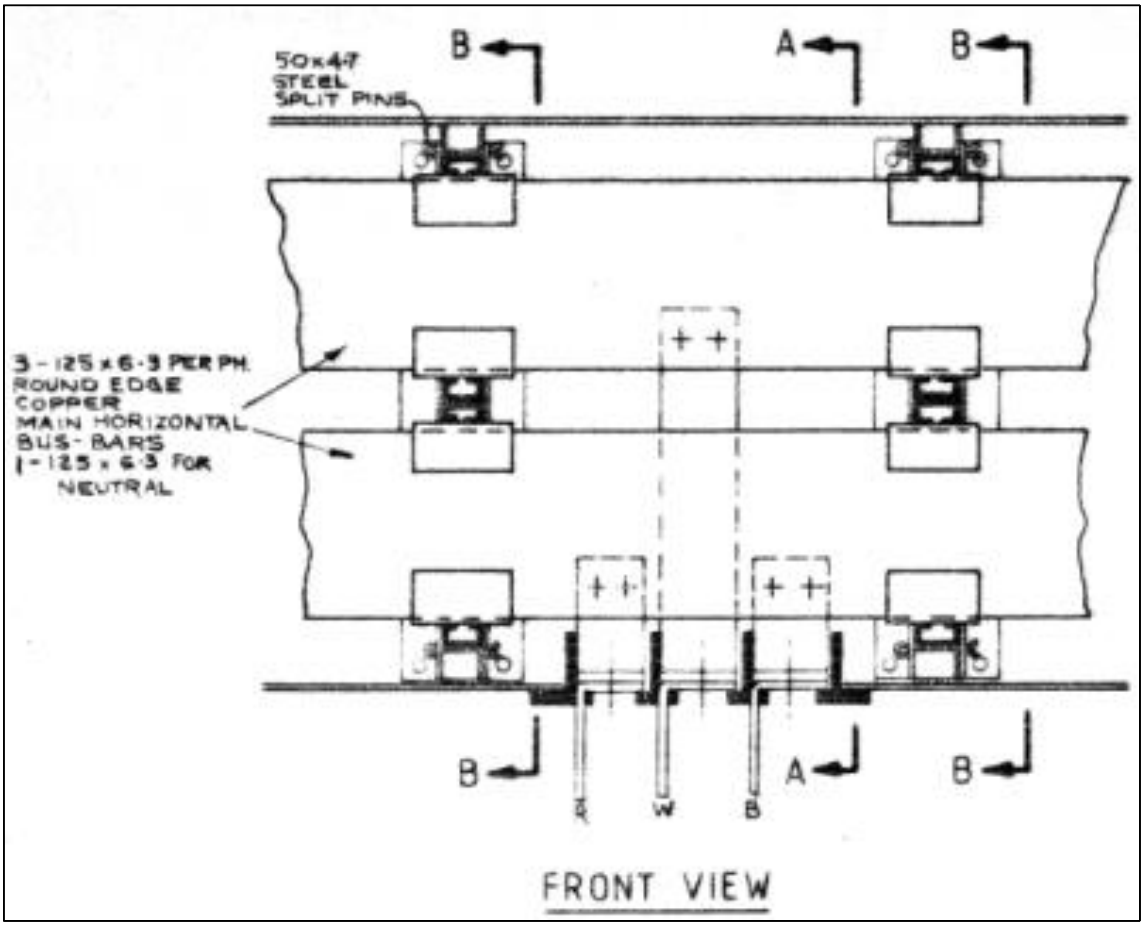


Figure 3.1 Front View of Bus Zone

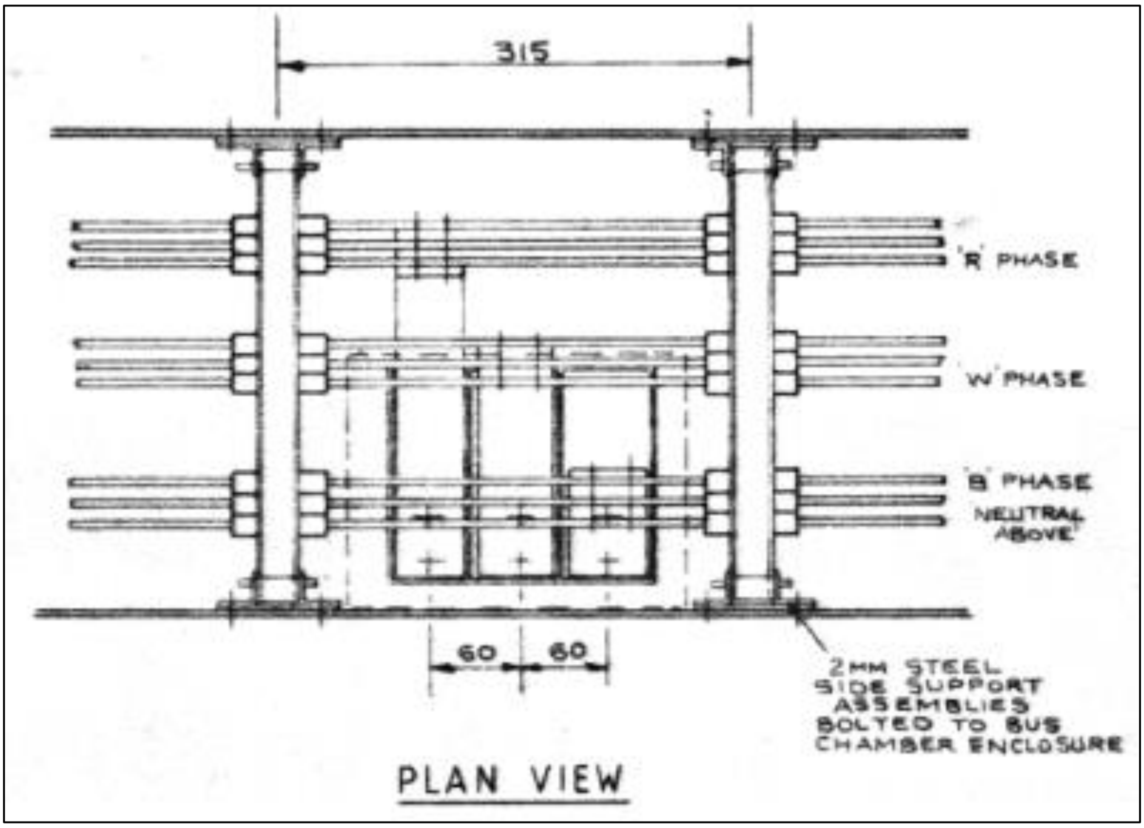


Figure 3.2 Plan View of Bus Zone

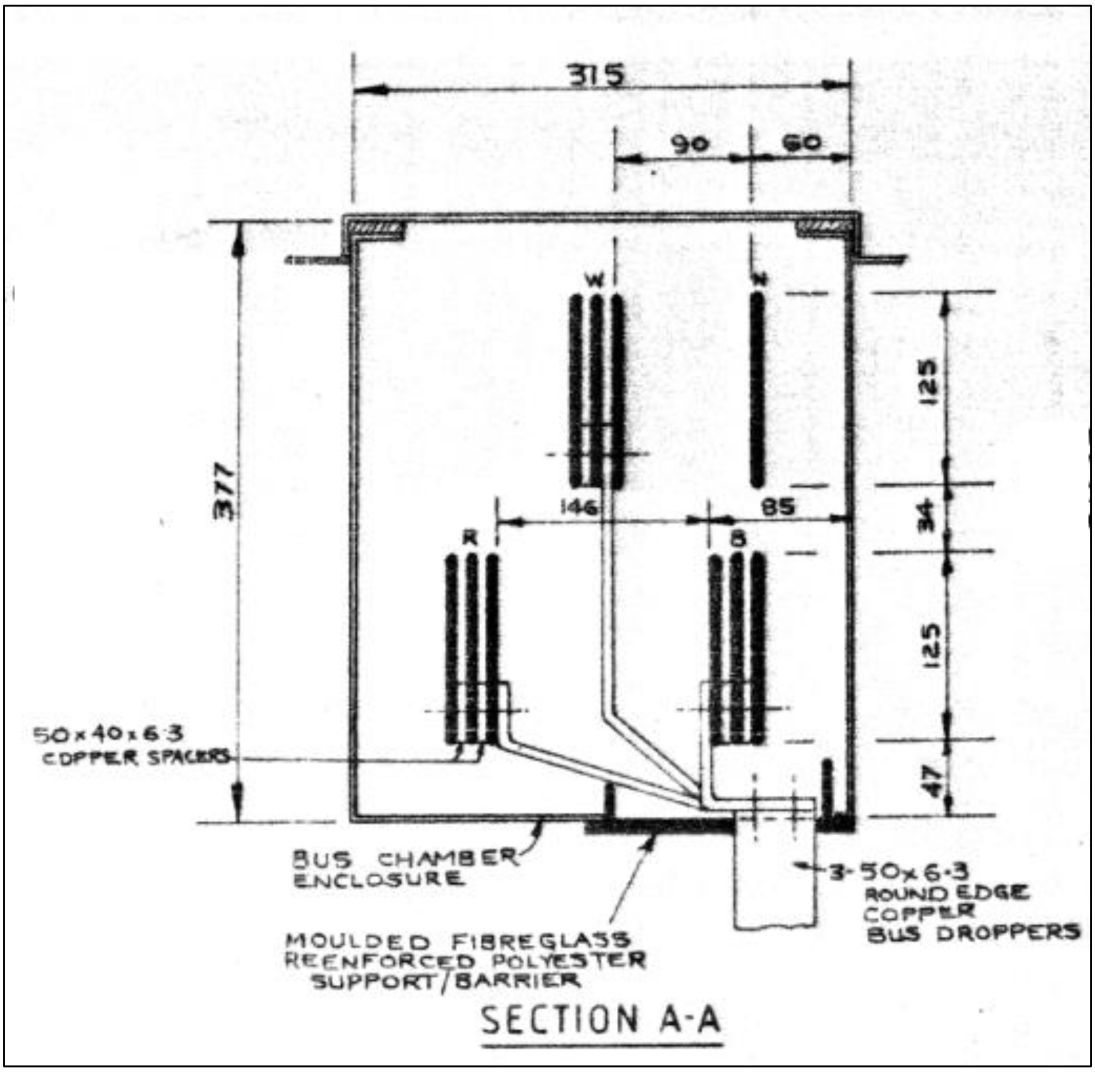


Figure 3.3 Sectional View of Bus Zone with Busbar Locations Dimensioned

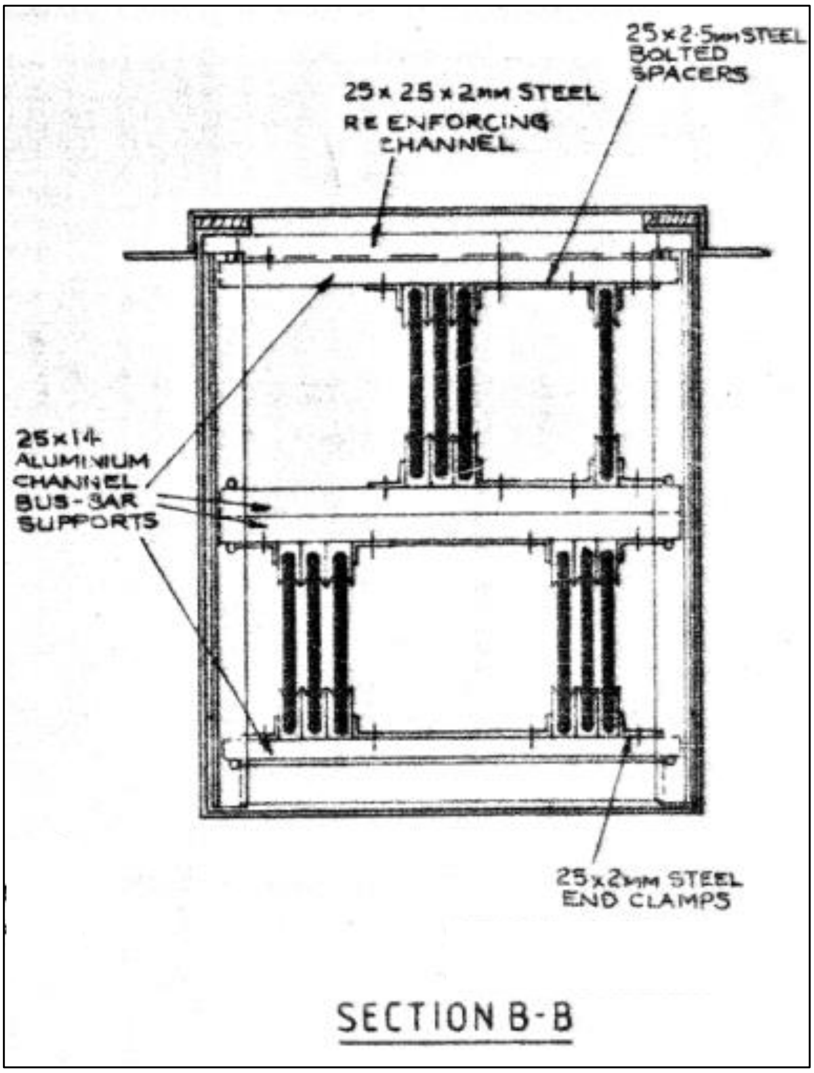


Figure 3.4 Sectional View of Bus Zone with Busbar Supports Shown

3.3 Assumptions

The following assumptions have been made in regards to the calculation of the operating temperature of various current carrying copper busbar conductor arrangements in a specific bus zone.

1. Assume all heat produced by the system is absorbed by the surrounding air.

2. Assume no heat loss through the bottom of the bus zone.

3. Assume busbars located below the bus zone do not contribute to heat generation.

4. Assume bight metal oxidize condition of busbars with emissivity of 0.1.

5. Assume the room temperature is held constant at ambient, and that heat transfer from the bus zone will have no effect on this temperature.

6. Assume the horizontal bus zone is infinite and current flow is constant along its length, so there is no transfer in the z-axis. i.e. section A-A = section B-B.

7. Assume the average air temperature within the enclosure is distributed equally and the busbar conductors are the same temperature.

8. Assume a balance 3 phase system with no negative or zero sequence voltages.

9. Assume still air within and outside the bus zone. i.e. no forced ventilation.

3.4 Mathematical Methods of Temperature Calculation

Energy can be transferred by interactions of a system and its surroundings, which is the case with the busbar system. Electrical energy enters the system, however, not all of the electrical energy leaves the system due to the resistance of the busbar conductors and Ohms Law. The remainder of the energy is dissipated as heat from the busbars into its surroundings.

The specified enclosure is a complex system of heat dissipation, absorption and conduction calculations, and the formulas used and their inter-connections are detailed within the following sections.

3.4.1 Heat Generated by Busbars

The rate at which electrical power is generated per unit length of busbar is the product of I^2R as described in Equation 3.1 below.

$$P = I^2 \times R \tag{3.1}$$

where P = power dissipated per unit length, W

I = current in the conductor, A

R = 415AC resistance per unit length of the conductor, Ω

3.4.2 Heat Dissipated by Busbars

Heat generated within a busbar can only be dissipated via the following methods:

1. Convection,
2. Radiation and
3. Conduction.

Heat dissipation via conduction depends on sections of the busbar system being at a lower temperature and acting like a heat sink. For the purpose of this report, heat dissipation via conduction will not be considered when determining the operating temperature of the busbar conductor arrangements. The rate at which heat is dissipated per unit length of busbar is equal to the rate at which electrical power is generated per unit length of busbar and is described in Equation 3.2 and 3.3 below.

$$P = q_{conv1} + q_{rad1} \qquad (3.2)$$

$$P = W_C A_C + W_R A_R \qquad (3.3)$$

where q_{conv1} = heat dissipated from busbars due to convection, W

q_{rad1} = heat dissipated from busbars due to radiation, W

W_C = heat dissipated per square meter due to convection, W/m^2

W_R = heat dissipated per square meter due to radiation, W/m^2

A_C = surface area of conductor, m^2 (convection)

A_R = surface area of conductor, m^2 (radiation)

3.4.2.1 Busbar Heat Dissipated by Convection

The rate at which heat is dissipated per unit length of busbar via convection depends on the shape, size and temperature rise above the surrounding air. Convection heat dissipation from the busbar differs from vertical to horizontal surfaces as described in Equation 3.4 and Figure 3.5 below.

$$q_{conv1} = W_C A_C = W_v A_{Cv} + W_h A_{Ch} \tag{3.4}$$

$$W_v = \frac{7.66\theta^{1.25}}{L^{0.25}} \tag{3.5}$$

$$W_h = \frac{5.920\theta^{1.25}}{L^{0.25}} \tag{3.6}$$

$$\theta \quad = \bar{T}_1 - \bar{T}_2 \tag{3.7}$$

where W_v = heat dissipated per vertical square meter due to convection, W/m^2

W_h = heat dissipated per horizontal square meter due to convection, W/m^2

A_{Cv} = vertical surface area of conductor, m^2

A_{Ch} = horizontal surface area of conductor, m^2

$\bar{T}_1$ = average temperature of busbar, K

$\bar{T}_2$ = average temperature of air within the enclosure, K

L = height or width of busbar, mm

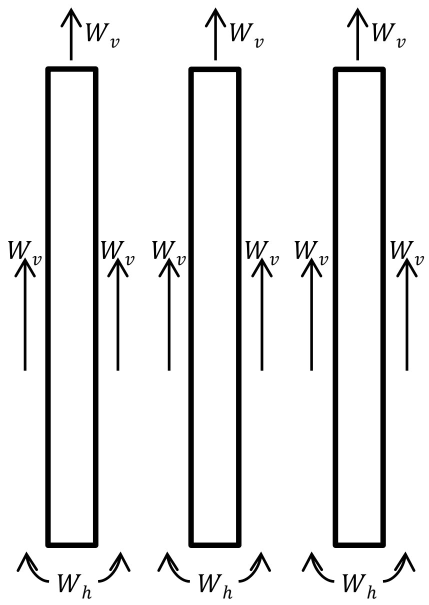


Figure 3.5 Convection Heat Loss from a Busbar Section

3.4.2.2 Busbar Heat Dissipated by Radiation

The rate at which heat is dissipated to its surroundings per unit length of busbar via radiation is proportional to the fourth power of their absolute temperatures and the relative emissivity between the busbar and its surroundings. Radiation heat dissipation from the busbar is described in Equation 3.8 and Figure 3.6 below.

$$q_{rad1} = W_R A_R = 5.70 \times 10^{-8} \times e(\bar{T}_1^4 - \bar{T}_3^4) \times A_R \quad (3.8)$$

$$e = \frac{\varepsilon_1 \varepsilon_2}{(\varepsilon_1 + \varepsilon_2) - (\varepsilon_1 \varepsilon_2)} \quad (3.9)$$

where e = relative emissivity

$\bar{T}_1$ = average temperature of busbar, K

$\bar{T}_3$ = average temperature of the enclosure inner surface, K

ε_1 = absolute emissivity of busbar

ε_2 = absolute emissivity of the enclosure inner surface

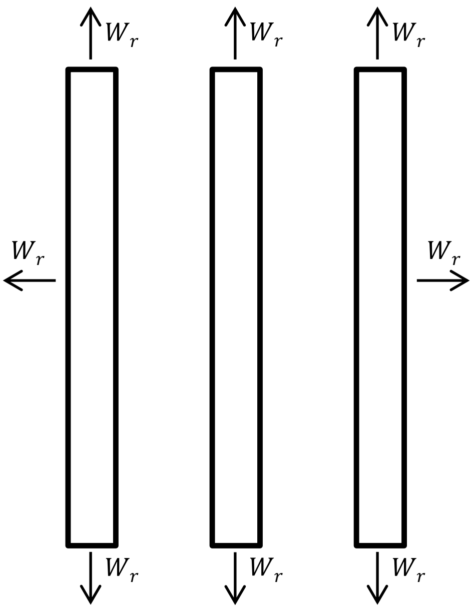


Figure 3.6 Radiation Heat Loss from a Busbar Section

Opposing busbar faces have no radiation heat dissipation as it is assumed (Assumption 7) their temperatures are approximately equal.

3.4.3 Heat Absorbed by Enclosure

Heat generated by the busbars is absorbed by the enclosure via the following methods:

1. Convection and
2. Radiation.

The rate at which heat is absorbed by the enclosure is equal to the rate at which electrical power is generated by the busbars, and is described in Equation 3.10 below.

$$P = q_{conv1} + q_{rad1} \tag{3.10}$$

where P = power dissipated per unit length of busbar, W

q_{conv1} = heat dissipated due to convection, W

q_{rad1} = heat dissipated due to radiation, W

3.4.3.1 Enclosure Heat Absorbed by Convection

The rate at which heat is transferred via convection within a cavity (dissipated by the busbars, absorbed via the enclosure) depends on the shape, size and temperature difference between surfaces. Convection heat absorbed by the enclosure differs from vertical to horizontal surfaces, as described in Equation 3.11 below.

$$q_{conv1} = \bar{h}_{v1} A_v + \bar{h}_{t1} A_t \tag{3.11}$$

where $\bar{h}_{v1}$ = average vertical convection heat transfer coefficient, W/m^2.K

$\bar{h}_{t1}$ = average top convection heat transfer coefficient, W/m^2.K

A_v = vertical surface area of enclosure, m^2

A_t = top surface area of enclosure, m^2

Convection heat absorbed by a vertical plane can be calculated through the use of Equations 3.12, 3.13 and 3.14 below.

$$Ra_{v1} = \frac{g\beta(\bar{T}_1 - \bar{T}_3)G_1^3}{v\alpha} \tag{3.12}$$

$$\overline{Nu}_{v1} = 0.22\left(\frac{Pr}{0.2+Pr}Ra_{v1}\right)^{0.28}\left(\frac{H}{G_1}\right)^{-1/4} \quad \begin{bmatrix} 2 \le \frac{H}{G_1} \le 10 \\ Pr \le 10^5 \\ 10^3 \le Ra \le 10^{10} \end{bmatrix} \tag{3.13}$$

$$\bar{h}_{v1} = \frac{\overline{Nu}_{v1}k}{H} \tag{3.14}$$

where Ra = Rayleigh number

$\overline{Nu}$ = average Nusselt number

g = gravity constant, 9.8m/s^2

β = volumetric thermal expansion coefficient, K^{-1}

$\bar{T}_1$ = average temperature of busbar, K

$\bar{T}_3$ = average temperature of the enclosure inner surface, K

H = height of the enclosure, m

G = gap between busbar and enclosure wall, m

v = kinematic viscosity, m^2/s

α = thermal diffusivity, m^2/s

Pr = Prandtl number

k = thermal conductivity, W/m.K

Similarly, convection heat absorbed by a horizontal plane, when heated from below, can be calculated through the use of Equations 3.15, 3.16 and 3.17 below.

$$Ra_{t1} = \frac{g\beta(\bar{T}_1 - \bar{T}_3)G_2^3}{v\alpha} \tag{3.15}$$

$$\overline{Nu}_{t1} = 0.069 Ra_{t1}^{1/3} Pr^{0.074} \qquad 3 \times 10^5 \leq Ra \leq 7 \times 10^9 \tag{3.16}$$

$$\bar{h}_{t1} = \frac{\overline{Nu}_{t1} k}{H} \tag{3.17}$$

3.4.3.2 Enclosure Heat Absorbed by Radiation

The rate at which heat is absorbed by the enclosure, via radiation dissipated by the busbars, is proportional to the fourth power of their absolute temperatures and the relative emissivity between the busbars and the enclosure. Enclosure radiation heat absorption is equal to the radiation heat dissipation from the busbar as described in Section 3.4.2.2.

3.4.4 Heat Conduction through Enclosure Wall

Heat generated within the enclosure passes through the enclosure walls via the following method:

1. Conduction

The rate at which heat is conducted through the walls of the enclosure is equal to the rate at which electrical power is generated by the busbars. This is described in Equation 3.18 and 3.19 below.

$$P = q_{cond} \tag{3.18}$$

$$q_{cond} = k_t A \frac{\Delta T}{\Delta x} \tag{3.19}$$

$$\Delta T \quad = \bar{T}_3 - \bar{T}_4 \tag{3.20}$$

where P = power dissipated per unit length of busbar, W

q_{cond} = heat conducted through enclosure wall, W

k_t = enclosure thermal conductivity, W/mK

A = surface area of enclosure, m^2

$\bar{T}_3$ = average temperature of the enclosure inner surface, K

$\bar{T}_4$ = average temperature of the enclosure outer surface, K

Δx = enclosure wall thickness, m

3.4.5 Heat Dissipated by Enclosure

Heat generated within the enclosure passes through the enclosure walls and is dissipated via the following methods:

1. Convection and
2. Radiation.

The rate at which heat is dissipated per unit length of enclosure is equal to the rate at which electrical power is generated per unit length of busbar, and is described in Equation 3.21 below.

$$P = q_{conv2} + q_{rad2} \tag{3.21}$$

where P = power dissipated per unit length of busbar, W

q_{conv2} = heat dissipated from enclosure due to convection, W

q_{rad2} = heat dissipated from enclosure due to radiation, W

3.4.5.1 Enclosure Heat Dissipated by Convection

The rate at which heat is dissipated via convection depends on the shape, size and temperature rise above ambient of the enclosure's outer surface temperature. Convection heat dissipation from the enclosure differs from vertical to horizontal surfaces as described in Equation 3.22 below.

$$q_{conv2} = \bar{h}_{v2} A_v + \bar{h}_{t2} A_t \tag{3.22}$$

where $\bar{h}_{v2}$ = vertical average convection heat transfer coefficient, W/m^2.K

$\bar{h}_{t2}$ = top average convection heat transfer coefficient, W/m^2.K

A_v = vertical surface area of enclosure, m^2

A_t = top surface area of enclosure, m^2

Convection heat dissipation from a vertical plane can be calculated through the use of Equations 3.23, 3.24 and 3.25 below.

$$Ra_{v2} = \frac{g\beta(\bar{T}_4 - T_5)H^3}{v\alpha} \tag{3.23}$$

$$\overline{Nu}_{v2} = 0.68 + \frac{0.670 Ra_{v2}^{1/4}}{\left[1 + (0.492/Pr)^{9/16}\right]^{4/9}} \qquad Ra_{v2} \leq 10^9 \tag{3.24}$$

$$\bar{h}_{v2} = \frac{\overline{Nu}_{v2} k}{H} \tag{3.25}$$

where Ra = Rayleigh number

$\overline{Nu}$ = average Nusselt number

g = gravity constant, 9.8m/s^2

β = volumetric thermal expansion coefficient, K^{-1}

$\bar{T}_4$ = average temperature of the enclosure outer surface, K

T_5 = temperature of the enclosure surroundings, K

H = height of the enclosure, m

v = kinematic viscosity, m^2/s

α = thermal diffusivity, m^2/s

Pr = Prandtl number

k = thermal conductivity, W/m.K

Similarly, convection heat dissipation from the top surface of a horizontal plane can be calculated through the use of Equations 3.26 below.

$$\overline{Nu}_{t2} = \frac{\bar{h}_{t2} L_c}{k} = 0.54 Ra_{t2}^{1/4} \tag{3.26}$$

$$L_c = A_t / P \tag{3.27}$$

where L_c = horizontal plane Nusselt correlation number

P = enclosure top surface area perimeter, m

3.4.5.2 Enclosure Heat Dissipated by Radiation

The rate at which the enclosure's heat is dissipated into its surroundings via radiation is proportional to the temperature difference between the enclosure and its surroundings, as described in Equation 3.28 and 3.29 below.

$$q_{rad2} = \bar{h}_{rad} A \tag{3.28}$$

$$\bar{h}_{rad2} = \varepsilon\sigma(\bar{T}_4 + T_5)(\bar{T}_4^2 + T_5^2) \tag{3.29}$$

where $\bar{h}_{rad2}$ = average radiation heat transfer coefficient, W/m^2.K

A = surface area of enclosure, m^2

ε = enclosure surface emissivity

σ = Stefan-Boltzmann constant, 5.67x10^{-8}W/m^2.K^4

$\bar{T}_4$ = average temperature of the enclosure outer surface, K

T_5 = temperature of the enclosure surroundings, K

The enclosure surface emissivity is determined by the enclosure surface finish. A surface finish emissivity closer to that of a black body will dissipate more heat via radiation into its surroundings.

3.4.6 Thermal Circuit of the Bus Zone System

Thermal resistances are the reciprocal multiplication of the heat transfer coefficient and the relative surface area, as shown in Equation 3.30 and 3.31. The convection components of the system consist of vertical and horizontal components which are in parallel, as shown in Equation 3.32. Combining Equations 3.01 to 3.32, a thermal circuit of the entire bus zone system can be developed, as depicted in Figure 3.7.

$$R_{conv2v} = 1/\bar{h}_{v2}A_v \tag{3.30}$$

$$R_{conv2t} = 1/\bar{h}_{t2}A_t \tag{3.31}$$

$$R_{conv2} = R_{conv2v}//R_{conv2t} \tag{3.32}$$

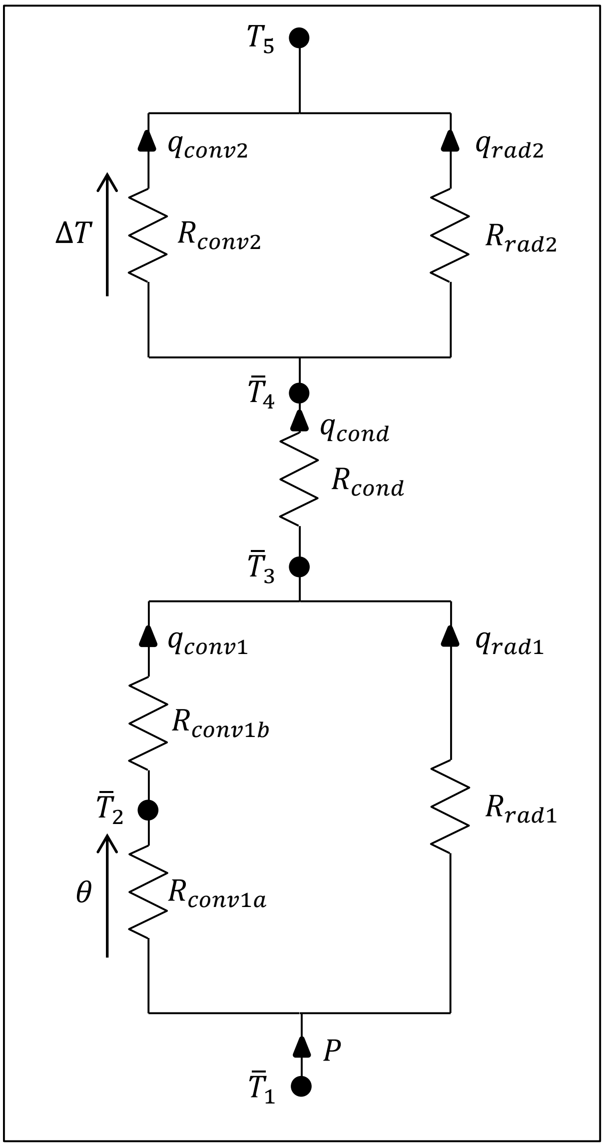


Figure 3.7 Thermal Circuit

3.5 Matlab Script

The Matlab Script program is designed to simulate and model the operating temperature of current carrying copper busbar conductors in the specified bus zone enclosure detailed in Section 3.2. The Matlab Script is written in functional blocks with the temperature and heat energy as the main inputs and outputs. The functional blocks are in line with the sub-sections of Section 3.4, Mathematical Methods of Temperature Calculation:

1. Heat Generated by Busbars
2. Heat Dissipated by Enclosure
3. Heat Conduction through Enclosure Wall
4. Heat Absorbed by Enclosure
5. Heat Dissipated by Busbars

A function flow chart in Figure 3.8 illustrates how each functional block interacts with each other. Looping is introduced around functional blocks due to approximations made on the first pass through. Program looping allows for large amounts of data to be generated automatically, without the need for user input for current settings or busbar arrangements. A full copy of the Matlab Script can be found in Appendix B.

All constants were gained from the ‘Fundamentals of Heat and Mass Transfer’ by Incropera publication and the resistances of the busbars were provided in AS 600890:2009. Parameters are specific to the enclosure or busbar dimensions determined from Section 3.2.

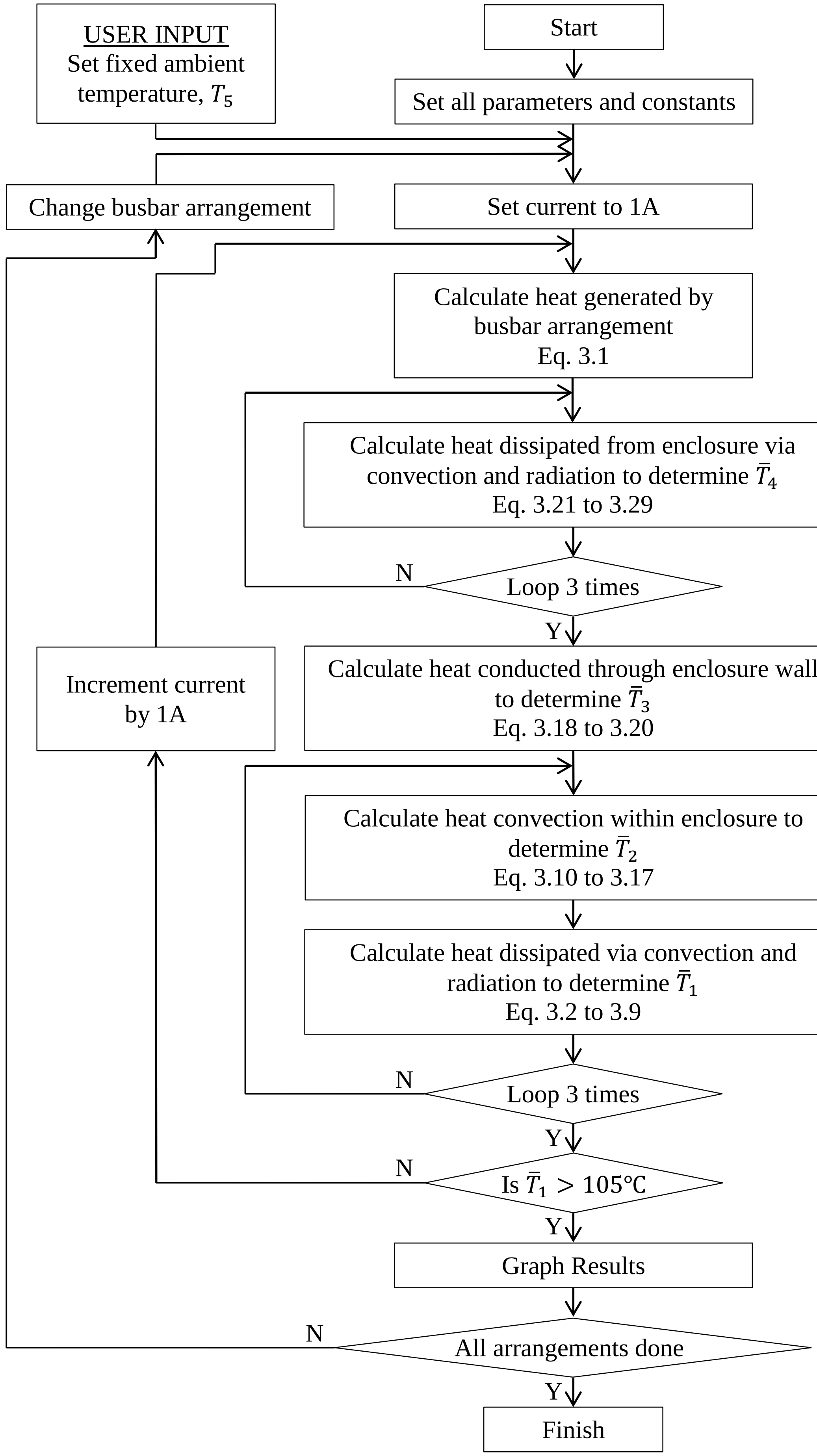


Figure 3.8 Matlab Script Functional Flow Chart

The Matlab script will produce the following outputs for any given bar size, number of bars per phase, and current flow:

- Average current in the conductors
- Power dissipated per unit length of busbar arrangement
- Total heat dissipated per unit length of enclosure

- Temperature of the enclosure surroundings
- Average temperature of the enclosure outer surface
- Average temperature of the enclosure inner surface
- Average temperature of air within the enclosure
- Average temperature of busbar

- Heat dissipated from busbars due to convection
- Heat dissipated from busbars due to radiation
- Heat conducted through enclosure wall
- Heat dissipated from enclosure due to convection
- Heat dissipated from enclosure due to radiation

3.6 Alternate Methods

The following methods will be utilised to produce results in the analysis of accuracy of the Matlab Script developed for this project.

3.6.1 AS 3000:1991 Method

AS/NZS 3000:1991 SAA Wiring Rules (AS 3000:1991) is a superseded Australian Standard that provides a means to calculate the current carrying capacity of copper and aluminium busbars. AS 3000:1991 provides a table of current carrying capacities of single and multiple busbars in a freely exposed, draught-free environment. The standard also provides tables of de-rating factors to be applied to the current carrying capacity of a selected busbar based on:

1. Ambient Temperature,
2. Temperature Rise and
3. (Busbar cross sectional area / enclosure cross sectional area) Ratio.

This method was removed by subsequent editions of AS3000 in 2000 and 2007.

The method provided in AS 3000:1991 is not a method for calculating the temperature of the busbars, which is the aim of this project. This method assumes the bars are at a specified operating temperature with a given ambient temperature, and provides an estimated maximum current carrying capacity of the busbar arrangement. However, the estimated current carrying capacity determined from the AS3000:1991 method for a given temperate can be compared with the calculated currents at the same temperatures determined by the Matlab Script.

The following procedure is followed to determine a busbar arrangement current carrying capacity using the AS3000:1991 method.

1. Select a busbar arrangement (e.g. 3 by 125x6.3mm copper busbars per phase and 1 by 125x6.3mm copper busbar for neutral)

2. Calculate the busbar cross sectional area (Busbar CSA).

3. Calculate the enclosure cross sectional area (Enclosure CSA).

4. Calculate the (Busbar CSA/ Enclosure CSA) ratio.

5. Determine the de-rating factor (read from Table C3 of AS 3000:1991) using the above Busbar CSA/ Enclosure CSA ratio.

6. Determine the de-rating factor for a given ambient temperature and desired temperature rise from Table C4 of AS 3000:1991.

7. Determine the free air current carrying capacity of the selected busbar arrangement from Table C1 of AS 3000:1991.

8. Multiply the free air current carrying capacity by the two de-rating factors, to determine the estimated current carrying capacity for the enclosure.

3.6.2 AS 60890:2009 Method

AS/NZS 60890:2009 (AS 60890) is an Australian Standard whose objective is to provide one possible method to determine the temperature rise of current carrying copper busbar conductors. Where the temperature rise is verified through calculation of extrapolated data, the Assembly is considered a Partially Type Tested Assembly (PTTA).

AS 60890 provides tables detailing the maximum operating current and its power loss for maximum temperature of the busbars and air temperature in the enclosure adjacent to the bars. The standard also provides tables and figures containing variables to be applied to the above values, to determine system compliance.

The following procedure is followed to determine a busbar arrangement current carrying capacity using the AS 60890 method:

1. Select a busbar arrangement (e.g. 3 by 125x6.3mm copper busbars per phase and 1 by 125x6.3mm copper busbar for neutral).

2. Calculate the enclosure effective cooling surface area.

3. Determine enclosure distribution factor and constants from Table I to V and Figures 3 to 8 of AS 60890.

4. Calculate the desired current carrying capacity and heat loss for the arrangement.

5. Calculate the internal temperature rise of the air at mid-height of the enclosure.

6. Calculate the internal temperature rise of the air at the top of the enclosure.

7. Produce a characteristic curve graph showing the temperature rise of air inside the enclosure.

8. Analyse if the temperature rises satisfy the requirements of AS 60890. If this is not so, change the parameters and repeat the calculation.

4 Results

4.1 Introduction

This Chapter presents the results for the four methods of calculating busbar operating temperatures or current carrying capacities as describe in the previous Chapter. These four methods are:

1. Matlab Script,
2. Type Test Certificate,
3. AS 3000:1991, and
4. AS 60890:2009.

This Chapter addresses Project Objectives 4 and 6. A summary of these objectives are listed below:

4. Simulate and model in Matlab the temperature of copper busbars carrying 2500A in the specific bus zone and busbar arrangement.

6. Simulate and model in Matlab the temperature of copper busbars carrying various currents in a specific bus zone, and with varying busbar arrangements.

4.2 Matlab Script Results

The Matlab Script developed simulates and models the operating temperature of current carrying copper busbar conductors in the specified bus zone enclosure. The script can be run to provide results for a single arrangement and current flow. This is the case in Table 4.1 below, where specific values are determined for comparison with the Type Test Certificate results in Section 5.2. The Type Test Certificate arrangement is 3 by 125x6.3mm copper busbars per phase and 1 by 125x6.3mm copper busbar for neutral. Table 4.1 below shows the results of the Matlab Script simulating under the same conditions as the Type Test Certificate

Table 4.1 3 by 125x6.3mm copper busbars Test Conditions

Description	Variable	Values
Average current in the conductors	I	2427A
Power dissipated per unit length of busbar arrangement	P	292.1W
Total heat dissipated per unit length of enclosure	P	292.1W
Temperature of the enclosure surroundings	T_5	23.6°C
Average temperature of the enclosure outer surface	$\bar{T}_4$	49.5°C
Average temperature of the enclosure inner surface	$\bar{T}_3$	49.5°C
Average temperature of air within the enclosure	$\bar{T}_2$	71.5°C
Average temperature of busbars	$\bar{T}_1$	94.0°C
Heat dissipated from busbars due to convection	q_{conv1}	274.1W
Heat dissipated from busbars due to radiation	q_{rad1}	18.0W
Heat conducted through enclosure wall	q_{cond}	292.1W
Heat dissipated from enclosure due to convection	q_{conv2}	118.0W
Heat dissipated from enclosure due to radiation	q_{rad2}	174.1W

The script was run to provide the operating temperature of busbar arrangements for a given ambient temperature and incrementing current flow. Current flow was incremented by one ampere per iteration until the operating temperature exceeded 105°C. The procedure was then repeated for all of the following busbar arrangements:

- Single, double and Triple by 63x6.3mm copper busbars per phase
- Single, double and Triple by 80x6.3mm copper busbars per phase
- Single, double and Triple by 100x6.3mm copper busbars per phase
- Single, double and Triple by 125x6.3mm copper busbars per phase
- Single, double and Triple by 160x6.3mm copper busbars per phase

For the following ambient temperatures:

- 40°C
- 35°C
- 30°C
- 25°C
- 20°C

Tables detailing the operating temperature of a busbar arrangement for a given current and ambient temperature can be generated by using the Matlab Script in Appendix B.

Switchboards are designed to current carrying capacities at specific ambient and operating temperatures as determined by the manufacture. Table 4.2 below provides a summary of the Matlab Script calculated current carrying capacities for a variety of ambient and operating temperatures conditions.

The ambient and operating temperatures chosen in the table are the same combinations available for calculation using the AS 3000:1991 method. A comparison between the Matlab Script and the AS 3000:1991 method results is detailed is Section 5.3.

Following Table 4.2, Figure 4.1 to Figure 4.5 graphs the operating temperature of busbar arrangements for a given current and ambient temperature up to a maximum operating temperature of 105°C.

Table 4.2 Matlab Script Results of Estimated Current Carrying Capacities for the Specified Enclosure.

Ambient	Operating	Busbar Width, mm														
		63			80			100			125			160		
		Number of Busbars per Phase														
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
°C		Estimated Maximum Current Carrying Capacity, Amperes														
40	**105**	872	1338	1722	1026	1523	1933	1191	1707	2139	1376	1900	2349	1671	2231	2732
40	**100**	830	1274	1640	977	1450	1842	1133	1626	2038	1310	1810	2238	1591	2125	2603
40	**90**	743	1141	1469	874	1299	1650	1014	1456	1825	1172	1621	2005	1423	1903	2332
40	**80**	648	996	1284	763	1135	1442	885	1272	1596	1023	1417	1753	1243	1664	2040
40	**70**	544	838	1080	641	954	1214	744	1070	1344	860	1192	1476	1045	1400	1718
35	**105**	909	1394	1793	1069	1586	2013	1240	1778	2226	1433	1978	2444	1739	2321	2842
35	**95**	827	1269	1633	973	1444	1833	1128	1618	2028	1303	1801	2226	1582	2113	2589
35	**85**	739	1136	1462	870	1293	1642	1009	1449	1817	1166	1613	1995	1415	1893	2319
35	**75**	645	992	1278	759	1130	1436	881	1266	1589	1018	1410	1745	1236	1655	2029
35	**65**	542	834	1075	638	950	1208	740	1065	1337	855	1186	1469	1039	1393	1709
30	**105**	945	1448	1862	1111	1647	2089	1288	1845	2311	1488	2053	2536	1805	2408	2947
30	**100**	905	1388	1785	1065	1579	2003	1234	1769	2216	1426	1969	2432	1730	2309	2826
30	**90**	823	1263	1626	968	1438	1825	1123	1611	2018	1297	1792	2215	1574	2102	2575
30	**80**	736	1131	1456	866	1287	1634	1004	1442	1808	1160	1605	1985	1408	1883	2307
30	**70**	642	988	1273	756	1124	1429	876	1260	1581	1013	1403	1736	1229	1646	2018
30	**60**	539	830	1071	635	945	1202	736	1060	1331	851	1180	1461	1033	1385	1699

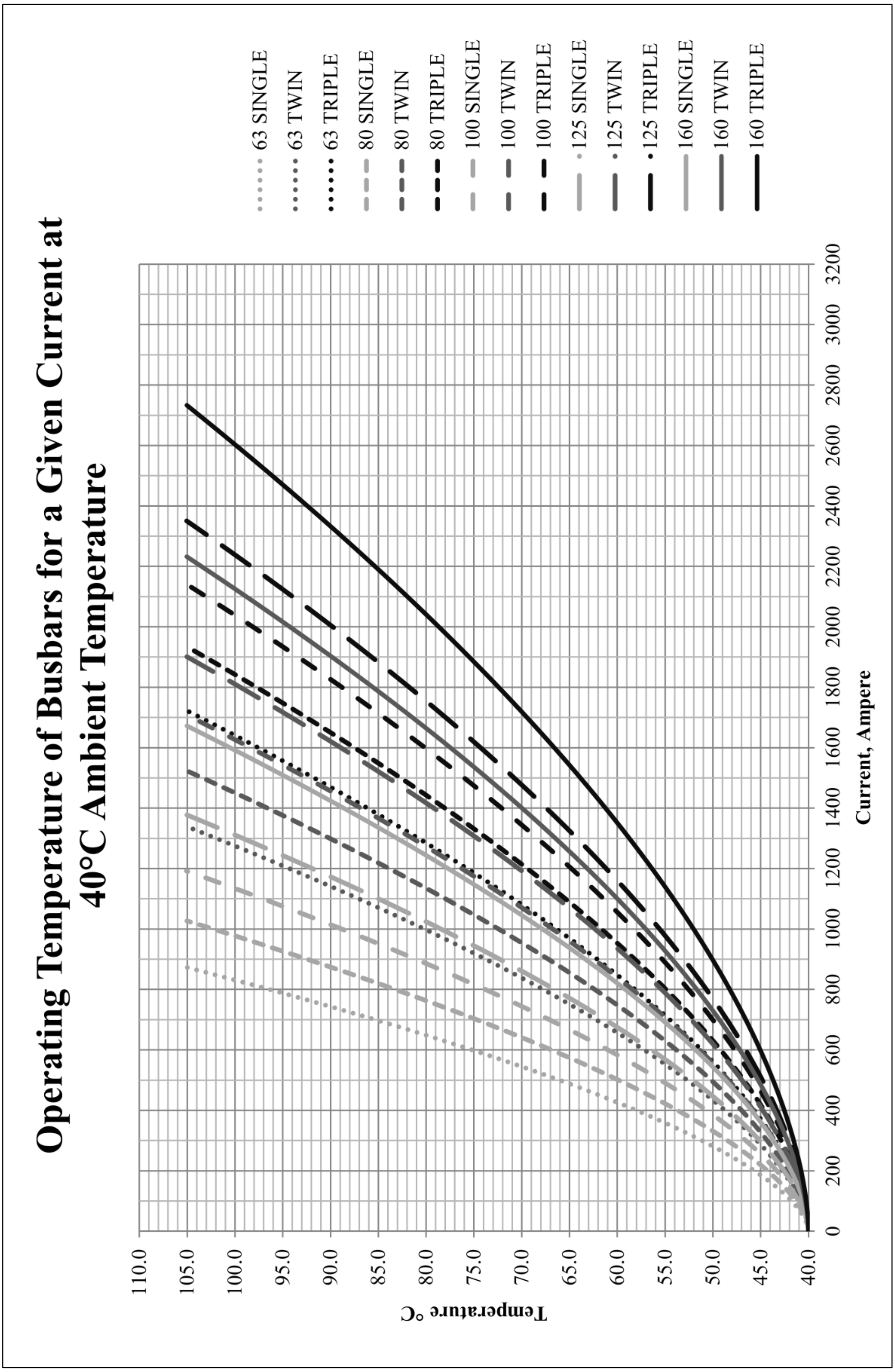


Figure 4.1 Operating Temperature of Busbars for a given Current at 40°C Ambient Temperature

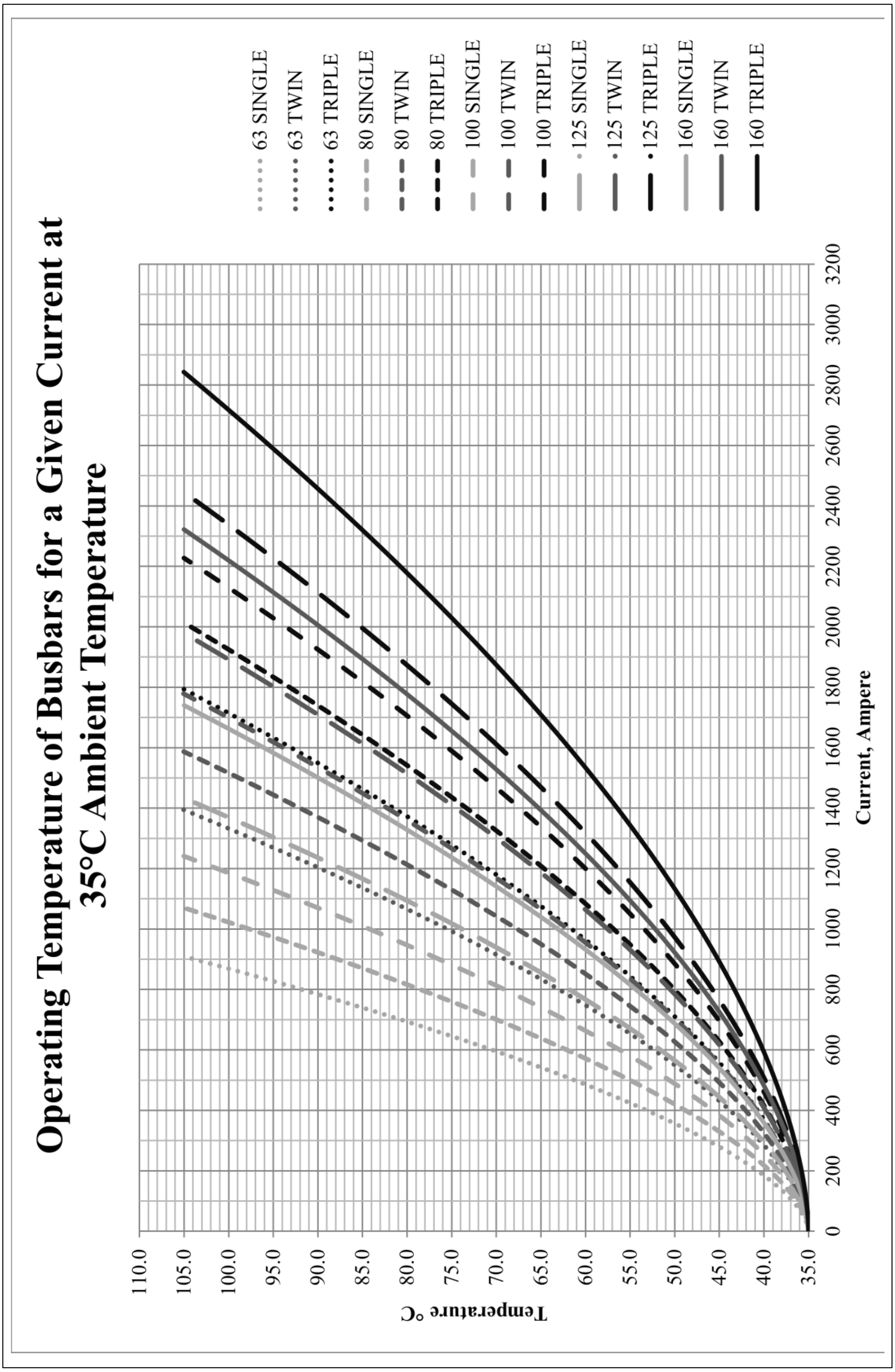


Figure 4.2 Operating Temperature of Busbars for a given Current at 35°C Ambient Temperature

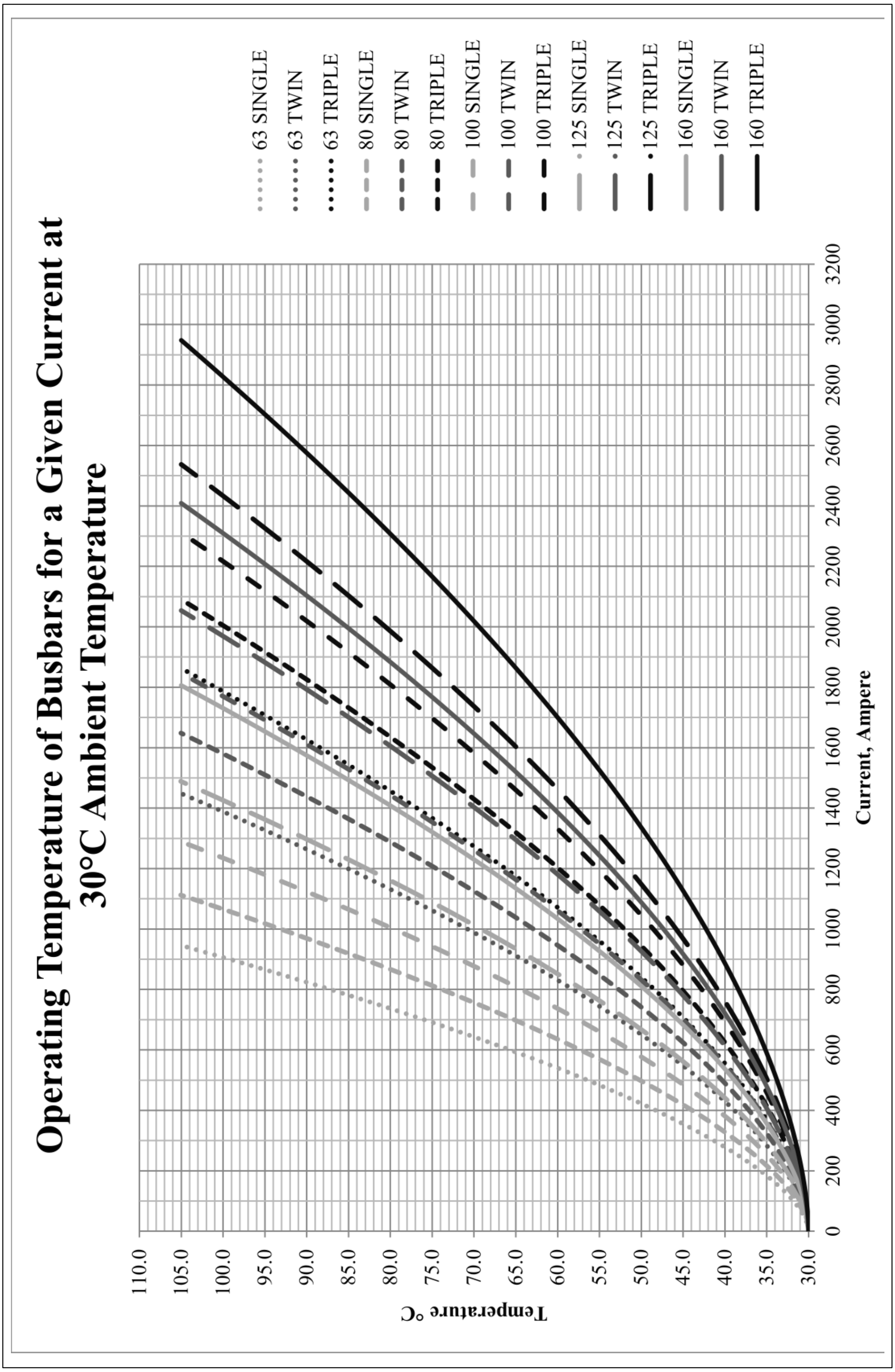


Figure 4.3 Operating Temperature of Busbars for a given Current at 30°C Ambient Temperature

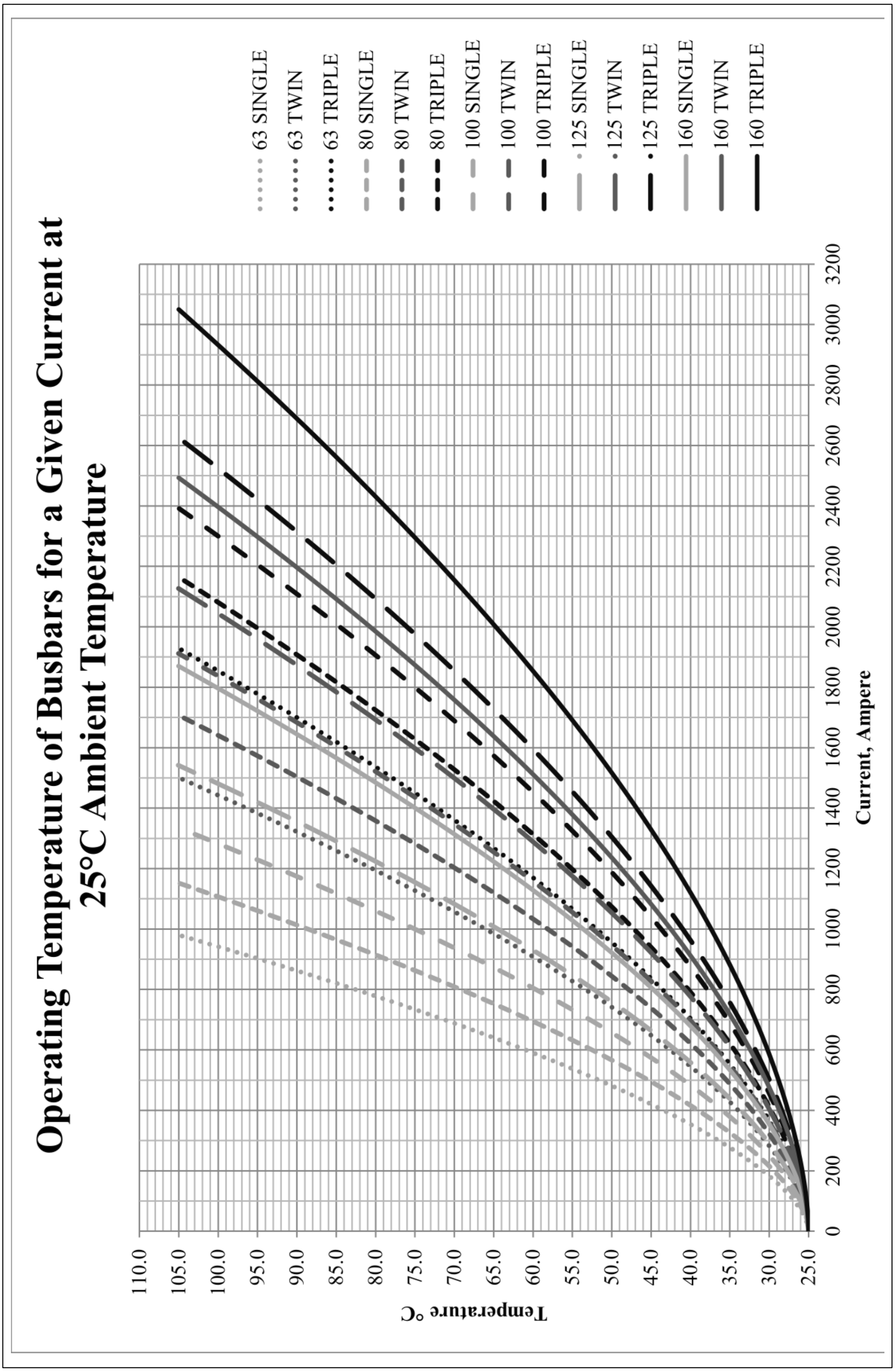


Figure 4.4 Operating Temperature of Busbars for a given Current at 25°C Ambient Temperature

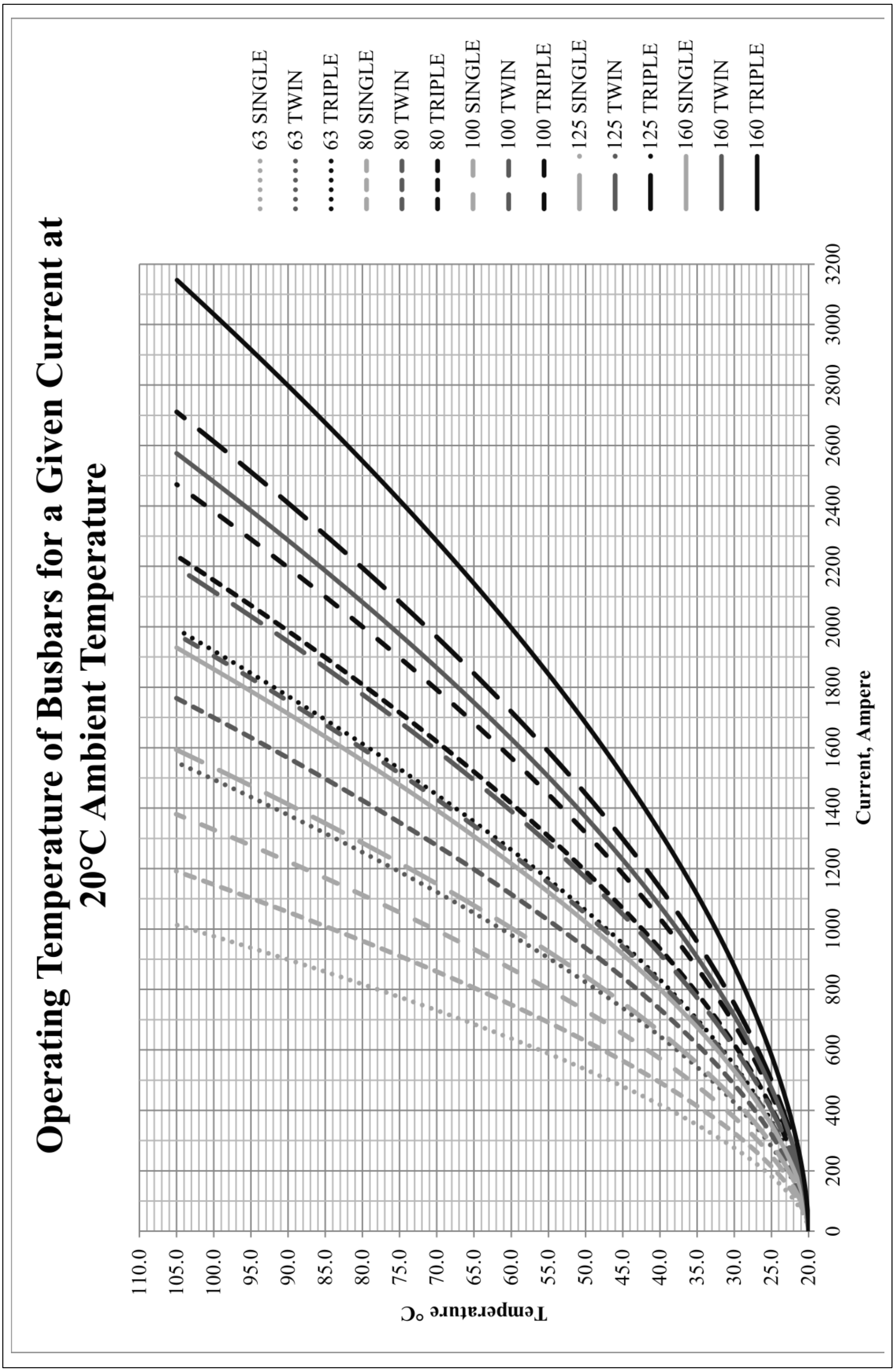


Figure 4.5 Operating Temperature of Busbars for a given Current at 20°C Ambient Temperature

Objective 6 was to simulate and model in Matlab the operating temperature of copper busbars carrying various currents in a specific bus zone and with varying busbar arrangements. Varying currents would be of nominal switch sizes such as:

- 630A
- 800A
- 1000A
- 1250A
- 1600A
- 2000A
- 3200A

Table 4.3 to Table 4.7 satisfies the requirements of Objective 6 as stated above. The busbar arrangements are sorted such that the highest temperature option is selected first for a nominal switch size. Commercially, this is usually the cheapest option to procure.

Table 4.3 Temperature of Busbars at Nominal Switch Sizes and 40°C Ambient

Bar Size, mm	**Number of Bars**	**Nominal Switch Size, Ampere**							
		630	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3200**
		Operating Temperature, °C							
63	1	78.1	96.4						
80	1	69.2	83.2	102.3					
100	1	62.8	73.8	88.9					
63	2	58.7	67.8	80.2	98.1				
125	1	57.8	66.6	78.5	95.5				
80	2	55.0	62.4	72.4	86.9				
160	1	52.8	59.2	67.9	80.3	100.5			
100	2	52.3	58.4	66.8	78.8	98.4			
63	3	52.2	58.2	66.4	78.2	97.6			
125	2	50.3	55.4	62.3	72.4	88.9			
80	3	50.0	54.9	61.7	71.5	87.5			
100	3	48.4	52.5	58.3	66.6	80.1	98.2		
160	2	47.8	51.7	57.0	64.8	77.5	94.3		
125	3	47.1	50.7	55.6	62.7	74.3	89.8		
160	3	45.5	48.2	52.0	57.5	66.6	78.7	96.1	

Table 4.4 Temperature of Busbars at Nominal Switch Sizes and 35°C Ambient

Bar Size, mm	**Number of Bars**	**Nominal Switch Size, Ampere**							
		630	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3200**
		Operating Temperature, °C							
63	1	70.5	91.8						
80	1	62.1	78.6	97.7					
100	1	56.2	69.1	84.2					
63	2	52.3	63.0	75.5	93.5				
125	1	51.6	61.8	73.8	91.0				
80	2	48.9	57.5	67.7	82.3				
160	1	46.9	54.4	63.1	75.7	96.1			
100	2	46.5	53.6	62.0	74.1	93.8			
63	3	46.3	53.3	61.6	73.5	93.0			
125	2	44.5	50.5	57.5	67.7	84.3			
80	3	44.3	50.0	56.9	66.7	82.9	104.2		
100	3	42.8	47.7	53.4	61.8	75.5	93.6		
160	2	42.3	46.8	52.2	60.0	72.8	89.8		
125	3	41.6	45.8	50.7	57.9	69.6	85.2		
160	3	40.1	43.3	47.1	52.7	61.9	74.0	91.6	

Table 4.5 Temperature of Busbars at Nominal Switch Sizes and 30°C Ambient

Bar Size, mm	**Number of Bars**	**Nominal Switch Size, Ampere**							
		630	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3200**
		Operating Temperature, °C							
63	1	65.7	87.2						
80	1	57.3	73.9	93.2					
100	1	51.3	64.4	79.6	101.4				
63	2	47.5	58.2	70.8	88.9				
125	1	46.7	57.0	69.1	86.5				
80	2	44.0	52.7	62.9	77.6	101.5			
160	1	42.1	49.6	58.4	71.1	91.6			
100	2	41.6	48.7	57.2	69.4	89.3			
63	3	41.4	48.4	56.8	68.8	88.4			
125	2	39.6	45.6	52.7	63.0	79.7	101.8		
80	3	39.3	45.2	52.0	62.0	78.2	99.8		
100	3	37.9	42.8	48.6	57.0	70.8	89.1		
160	2	37.3	41.9	47.4	55.2	68.1	85.2		
125	3	36.7	40.9	45.8	53.1	64.9	80.6	103.2	
160	3	35.2	38.4	42.3	47.9	57.1	69.4	87.1	

Table 4.6 Temperature of Busbars at Nominal Switch Sizes and 25°C Ambient

Bar Size, mm	**Number of Bars**	**Nominal Switch Size, Ampere**							
		630	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3200**
		Operating Temperature, °C							
63	1	61.0	82.6						
80	1	52.5	69.2	88.7					
100	1	46.5	59.7	75.0	97.0				
63	2	42.6	53.4	66.1	84.3				
125	1	41.9	52.3	64.5	81.9				
80	2	39.1	47.9	58.1	73.0	97.0			
160	1	37.2	44.7	53.6	66.5	87.2			
100	2	36.7	43.9	52.4	64.7	84.8			
63	3	36.5	43.6	52.0	64.1	83.8			
125	2	34.7	40.8	47.9	58.3	75.1	97.4		
80	3	34.4	40.3	47.2	57.2	73.6	95.3		
100	3	32.9	37.9	43.7	52.2	66.1	84.5		
160	2	32.4	37.0	42.5	50.5	63.5	80.7		
125	3	31.7	36.0	41.0	48.3	60.2	76.0	98.8	
160	3	30.2	33.5	37.4	43.0	52.3	64.7	82.6	

Table 4.7 Temperature of Busbars at Nominal Switch Sizes and 20°C Ambient

Bar Size, mm	**Number of Bars**	**Nominal Switch Size, Ampere**							
		630	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3200**
		Operating Temperature, °C							
63	1	56.2	78.0	103.2					
80	1	47.7	64.5	84.1					
100	1	41.7	54.9	70.4	92.5				
63	2	37.7	48.6	61.3	79.7				
125	1	37.0	47.5	59.8	77.4				
80	2	34.3	43.0	53.4	68.3	92.5			
160	1	32.3	39.9	48.9	61.8	82.7			
100	2	31.8	39.0	47.6	60.0	80.2			
63	3	31.6	38.7	47.1	59.4	79.2			
125	2	29.8	35.9	43.1	53.5	70.5	92.9		
80	3	29.5	35.4	42.4	52.5	69.0	90.8		
100	3	28.0	33.0	38.9	47.4	61.4	80.0		
160	2	27.5	32.1	37.7	45.7	58.8	76.2	101.1	
125	3	26.8	31.1	36.1	43.5	55.5	71.4	94.4	
160	3	25.3	28.6	32.5	38.2	47.6	60.1	78.1	105.1

4.3 Type Test Certificate Results

Temperature rise tests were conducted on the specific enclosure in 1982 and an accompanying report details the test arrangements and results. Of the eight tests detailed in the report, Test IIA was a temperature rise test conducted on the horizontal bus within the specific enclosure. The horizontal bus was connected as a series path for the current, with one end of the zone connected to a source and the other connected to the load, with a nominal current flowing the entire length of the bus zone. Table 4.8 details the test conditions. Table 4.9 provides the results of relevant thermocouple temperatures to be used in comparison with the Matlab Script. A drawing showing the locations of the relevant thermocouples is shown in Figure 4.6

Table 4.8 Test Conditions

Description	Values	Average
A Phase Current	2410A	2427A
B Phase Current	2440A	
C Phase Current	2430A	
Front Ambient Temperature	23.3°C	23.55°C
Rear Ambient Temperature	23.8°C	

Table 4.9 Results of Type Test Temperature Rise Test on Busbar Enclosure.

Thermo-couple Number	Thermocouple Location	Temp., °C	Temp. Rise, °C	Average Temp., °C	
A6	A Phase, Rear Busbar	92.0	68.4	90.23	93.14
A7	A Phase, Centre Busbar	94.5	70.9		
A8	A Phase, Front Busbar	84.2	60.6		
A12	B Phase, Rear Busbar	95.8	72.2	97.67	
A13	B Phase, Centre Busbar	98.3	74.7		
A14	B Phase, Front Busbar	98.9	75.3		
A19	C Phase, Rear Busbar	94.2	70.6	91.53	
A20	C Phase, Centre Busbar	91.6	68.0		
A21	C Phase, Front Busbar	88.8	65.2		
A24	Air Temp. at top of Busbar Enclosure	77.2	53.6	76.65	
A27	Air Temp. at top of Busbar Enclosure	76.1	52.5		

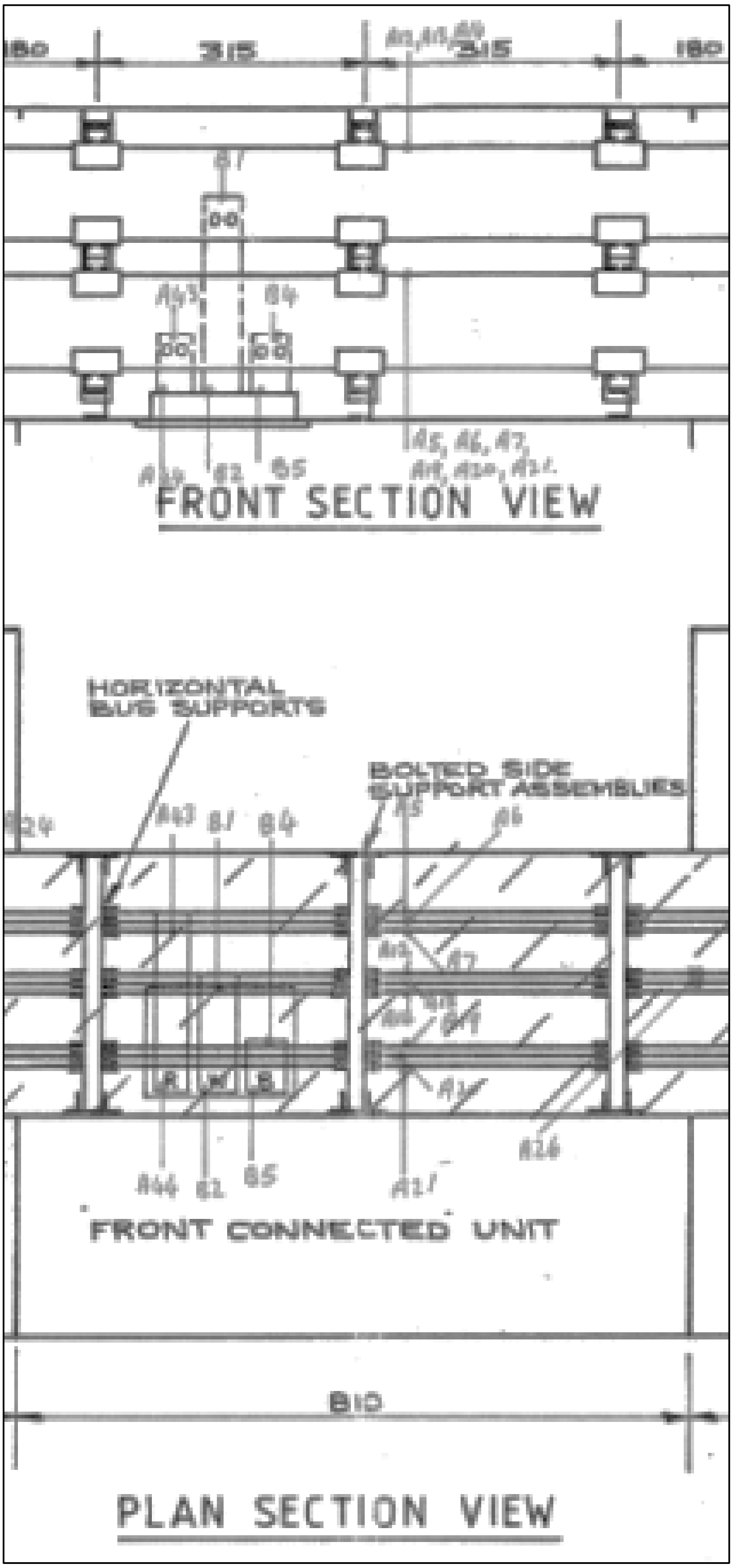


Figure 4.6 Type Test Temperature Rise Test Thermocouple Locations

4.4 AS 3000:1991 Results

The AS 3000:1991 method assumes that the busbars are at a specified operating temperature, with a given ambient temperature, and provides an estimated maximum current carrying capacity of the busbar arrangement.

The results of the estimated maximum current carrying capacities determined by the AS 3000:1991 method is shown in Table 4.10. The workings for all the combinations calculated with the AS 3000:1991 method can be found in Appendix C.

Table 4.10 AS3000:1991 Results of Estimated Current Carrying Capacities for the Specified Enclosure.

Ambient	Operating	Busbar Width, mm														
		63			80			100			125			160		
		Number of Busbars per Phase														
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
°C		Estimated Maximum Current Carrying Capacity, Amperes														
40	**105**	827	1353	1762	959	1591	2013	1173	1820	2277	1340	1991	2505	1652	2357	2874
40	**100**	786	1286	1673	911	1512	1912	1114	1729	2163	1273	1891	2380	1570	2240	2730
40	**90**	703	1150	1497	815	1353	1711	997	1547	1936	1139	1692	2129	1405	2004	2443
40	**80**	612	1001	1304	710	1178	1490	868	1347	1685	991	1473	1854	1223	1744	2127
40	**70**	513	839	1092	595	987	1248	727	1128	1412	831	1234	1553	1024	1462	1782
35	**105**	860	1407	1832	997	1655	2093	1220	1893	2368	1393	2070	2605	1718	2452	2989
35	**95**	786	1286	1673	911	1512	1912	1114	1729	2163	1273	1891	2380	1570	2240	2730
35	**85**	703	1150	1497	815	1353	1711	997	1547	1936	1139	1692	2129	1405	2004	2443
35	**75**	612	1001	1304	710	1178	1490	868	1347	1685	991	1473	1854	1223	1744	2127
35	**65**	513	839	1092	595	987	1248	727	1128	1412	831	1234	1553	1024	1462	1782
30	**105**	902	1475	1920	1045	1734	2194	1279	1984	2482	1460	2170	2731	1801	2570	3133
30	**100**	860	1407	1832	997	1655	2093	1220	1893	2368	1393	2070	2605	1718	2452	2989
30	**90**	786	1286	1673	911	1512	1912	1114	1729	2163	1273	1891	2380	1570	2240	2730
30	**80**	703	1150	1497	815	1353	1711	997	1547	1936	1139	1692	2129	1405	2004	2443
30	**70**	612	1001	1304	710	1178	1490	868	1347	1685	991	1473	1854	1223	1744	2127
30	**60**	513	839	1092	595	987	1248	727	1128	1412	831	1234	1553	1024	1462	1782

4.5 AS 60890:2009 Results

AS 60890 provides tables of current carrying capacities for busbars with specific air temperatures adjacent to the bars. With less current flowing through the conductors, the difference between air temperature adjacent to the busbars and the busbar operating temperature can be reduced. Figure 4.7 plots the extrapolated maximum operating current for an air temperature adjacent to the busbars when the operating temperature is 105°C. Figure 4.7 also plots the calculated air temperature adjacent to the busbars for a given current flow. The intersection of these two lines is the maximum operating current for the arrangement. The plots show in Figure 4.7 is for a 3 by 125x6.3mm copper busbars per phase arrangement with a conductor operating temperature of 105°C.

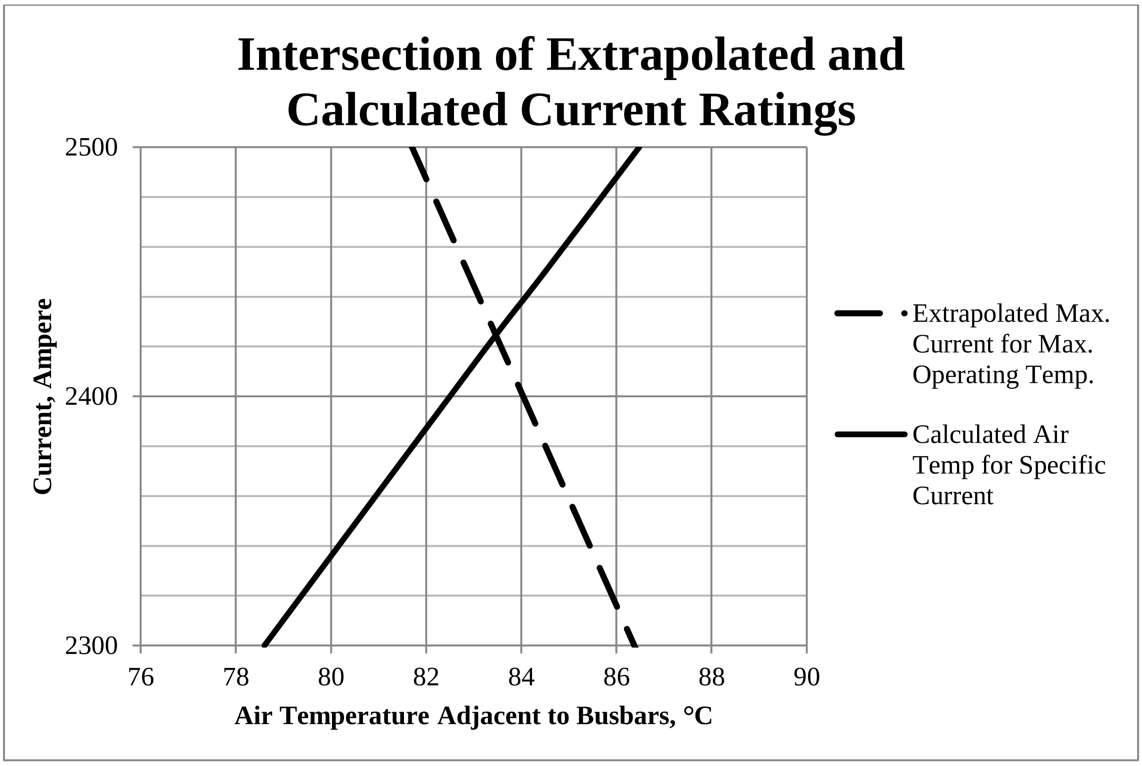


Figure 4.7 Intersection of Extrapolated and Calculated Current Ratings.

Figure 4.8 below shows the enclosure temperature characteristic curve for 2427A flowing through the 3 by 125x6.3mm copper busbars per phase arrangement.

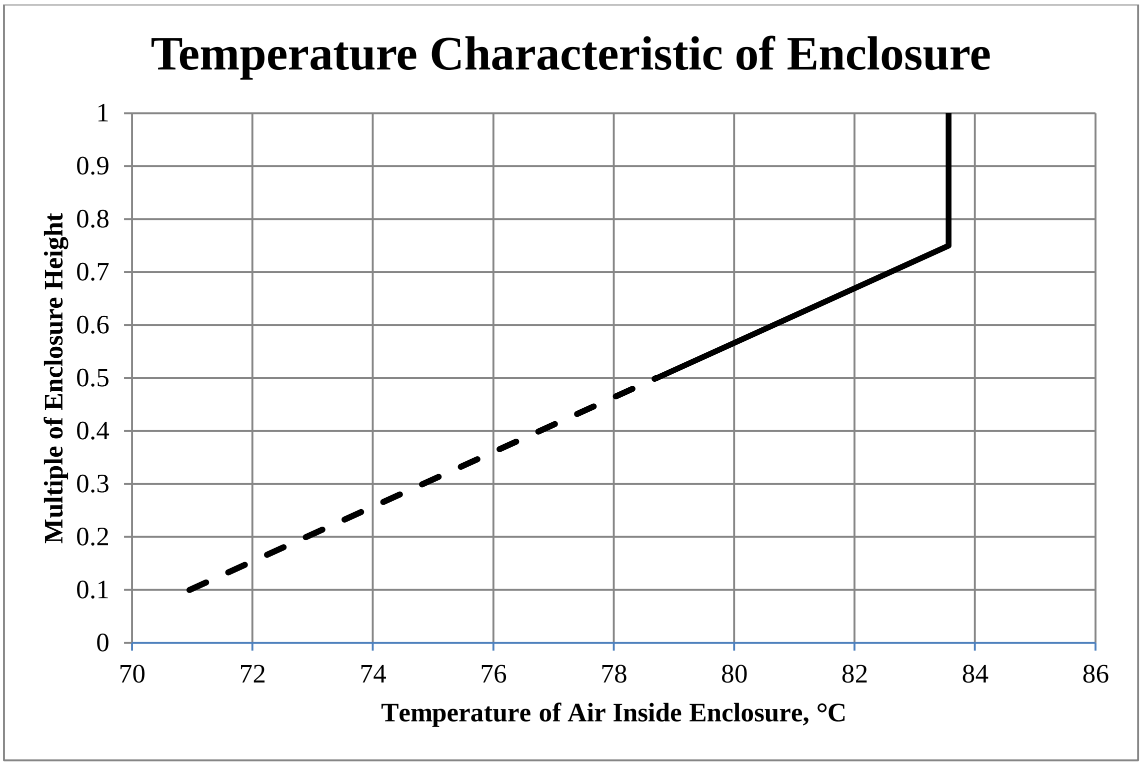


Figure 4.8 Enclosure Temperature Characteristic Curve

The results of the 3 by 125x6.3mm copper busbars per phase arrangement determined by the AS 60890 method is shown in Table 4.11 below. The workings for this arrangement can be found in Appendix D.

Table 4.11 Results of AS 60890 for 3 by 125x6.3mm copper busbars per phase.

Description	**Values**
Average current in the conductors	2427A
Power dissipated per unit length of busbar arrangement	292.1W
Temperature of the enclosure surroundings	23.6°C
Average temperature of air within the enclosure	78.7°C
Average temperature of air within at the top of the enclosure	83.6°C
Average temperature of busbars	105°C

5 Analysis and Discussion

5.1 Introduction

This Chapter presents an analysis and discussion of the Matlab Script results verses the other three methods of calculating busbar operating temperatures or current carrying capacities as describe in the Chapter 3. These comparisons are:

1. Matlab Script vs. Type Test Certificate
2. Matlab Script vs. AS 3000:1991
3. Matlab Script vs. AS 60890:2009

This chapter addresses Project Objective 5 and is summarised below:

5. Compare the Matlab simulation to real Type Test results for the specific bus zone and busbar arrangement.

5.2 Matlab Script vs. Type Test Results

The Matlab Script developed simulates and models the operating temperature of current carrying copper busbar conductors in the specified bus zone enclosure. The script was ran to provide results for a single arrangement and current flow for comparison with the arrangement of the Type Test Certificate results. This arrangement was:

3 by 125x6.3mm copper busbars per phase and

1 by 125x6.3mm copper busbar for neutral.

The results for both the Matlab script and the Type Test certificate are available in Chapter 4. Table 5.1 below summarises comparable results between the two methods.

Table 5.1 Matlab Script vs. Type Test Certificate Results

Description	Matlab Script	Type Test Certificate	% Error
Average Current in the conductors	2427A	2427A	0%
Temperature of the enclosure surroundings	23.6°C	23.6°C	0%
Average temperature of the enclosure outer surface	49.5°C		
Average temperature of the enclosure inner surface	49.5°C		
Average temperature of air within the enclosure	71.5°C	76.65°C	-6.7%
Average operating temperature of busbar	94.0°C	93.14°C	0.9%

As can be seen from the values detailed in Table 5.1, the average operating temperature of the busbars is within 0.9% error.

A percentage error value of 6.7% was obtained for the average temperature of the air within the enclosure. Although the error is a comparably large value in comparison to the operating temperature error, the physical location of the Type Test thermocouple may account for this. In the Type Test certificate testing, the air temperature within the enclosure was obtained by thermocouples that were soldered to small squares of copper plate suspended at the top of the bus zone, within the enclosure. Due to being located in the upper quadrant of the enclosure, it is expected that these thermocouples would have a higher temperature than the average for the air within the enclosure which was calculated by the Matlab script.

5.3 Matlab Script vs. AS 3000:1991 Results

Switchboards are designed to current carrying capacities at specific ambient and operating temperatures as determined by the manufacture. Table 4.2, in Section 4.2, provides the Matlab Script calculated current carrying capacities for a variety of ambient and operating temperature conditions. Similarly, Table 4.10, in Section 4.4, provides the AS 3000:1991 method calculated current carrying capacities for the same ambient and operating temperature conditions. Table 5.2 below provides a summary of differences in current carrying capacities between the two methods, whilst Table 5.3 provides a summary of the percentage errors.

Table 5.2 Current Carrying Capacity Differential of Matlab Script vs. AS3000 methods.

Ambient	Operating	Busbar Width, mm														
		63			80			100			125			160		
		Number of Busbars per Phase														
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
°C		Ampere														
40	**105**	45	-15	-40	67	-68	-80	18	-113	-138	36	-91	-156	19	-126	-142
40	**100**	44	-12	-33	66	-62	-70	19	-103	-125	37	-81	-142	21	-115	-127
40	**90**	40	-9	-28	59	-54	-61	17	-91	-111	33	-71	-124	18	-101	-111
40	**80**	36	-5	-20	53	-43	-48	17	-75	-89	32	-56	-101	20	-80	-87
40	**70**	31	-1	-12	46	-33	-34	17	-58	-68	29	-42	-77	21	-62	-64
35	**105**	49	-13	-39	72	-69	-80	20	-115	-142	40	-92	-161	21	-131	-147
35	**95**	41	-17	-40	62	-68	-79	14	-111	-135	30	-90	-154	12	-127	-141
35	**85**	36	-14	-35	55	-60	-69	12	-98	-119	27	-79	-134	10	-111	-124
35	**75**	33	-9	-26	49	-48	-54	13	-81	-96	27	-63	-109	13	-89	-98
35	**65**	29	-5	-17	43	-37	-40	13	-63	-75	24	-48	-84	15	-69	-73
30	**105**	43	-27	-58	66	-87	-105	9	-139	-171	28	-117	-195	4	-162	-186
30	**100**	45	-19	-47	68	-76	-90	14	-124	-152	33	-101	-173	12	-143	-163
30	**90**	37	-23	-47	57	-74	-87	9	-118	-145	24	-99	-165	4	-138	-155
30	**80**	33	-19	-41	51	-66	-77	7	-105	-128	21	-87	-144	3	-121	-136
30	**70**	30	-13	-31	46	-54	-61	8	-87	-104	22	-70	-118	6	-98	-109
30	**60**	26	-9	-21	40	-42	-46	9	-68	-81	20	-54	-92	9	-77	-83

Table 5.3 Percentage Error of Matlab Script vs. AS3000 Calculated Current Carrying Capacities with AS3000 as the Base.

Ambient	**Operating**	**Busbar Width, mm**														
		63			**80**			**100**			**125**			**160**		
		Number of Busbars per Phase														
		1	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
°C		**%**														
40	**105**	5.4	-1.1	-2.2	7.0	-4.3	-4.0	1.5	-6.2	-6.1	2.7	-4.6	-6.2	1.1	-5.4	-4.9
40	**100**	5.6	-0.9	-2.0	7.2	-4.1	-3.7	1.7	-6.0	-5.8	2.9	-4.3	-6.0	1.4	-5.1	-4.7
40	**90**	5.7	-0.8	-1.9	7.2	-4.0	-3.6	1.7	-5.9	-5.7	2.9	-4.2	-5.8	1.3	-5.0	-4.5
40	**80**	5.9	-0.5	-1.5	7.5	-3.6	-3.2	2.0	-5.6	-5.3	3.2	-3.8	-5.4	1.7	-4.6	-4.1
40	**70**	6.1	-0.1	-1.1	7.8	-3.3	-2.7	2.3	-5.2	-4.8	3.5	-3.4	-5.0	2.0	-4.2	-3.6
35	**105**	5.7	-0.9	-2.1	7.2	-4.2	-3.8	1.6	-6.1	-6.0	2.9	-4.5	-6.2	1.2	-5.3	-4.9
35	**95**	5.2	-1.3	-2.4	6.8	-4.5	-4.1	1.2	-6.4	-6.3	2.4	-4.8	-6.5	0.8	-5.6	-5.2
35	**85**	5.1	-1.2	-2.4	6.7	-4.4	-4.0	1.2	-6.3	-6.1	2.4	-4.7	-6.3	0.7	-5.5	-5.1
35	**75**	5.4	-0.9	-2.0	7.0	-4.0	-3.6	1.5	-6.0	-5.7	2.7	-4.3	-5.9	1.1	-5.1	-4.6
35	**65**	5.7	-0.6	-1.6	7.3	-3.7	-3.2	1.8	-5.6	-5.3	2.9	-3.9	-5.4	1.4	-4.7	-4.1
30	**105**	4.8	-1.8	-3.0	6.3	-5.0	-4.8	0.7	-7.0	-6.9	1.9	-5.4	-7.1	0.2	-6.3	-5.9
30	**100**	5.2	-1.4	-2.6	6.8	-4.6	-4.3	1.2	-6.5	-6.4	2.4	-4.9	-6.7	0.7	-5.8	-5.5
30	**90**	4.7	-1.8	-2.8	6.3	-4.9	-4.6	0.8	-6.8	-6.7	1.9	-5.2	-6.9	0.3	-6.1	-5.7
30	**80**	4.7	-1.7	-2.8	6.2	-4.8	-4.5	0.7	-6.8	-6.6	1.9	-5.2	-6.8	0.2	-6.0	-5.6
30	**70**	4.9	-1.3	-2.3	6.5	-4.5	-4.1	0.9	-6.4	-6.2	2.2	-4.8	-6.4	0.5	-5.6	-5.1
30	**60**	5.1	-1.1	-1.9	6.8	-4.2	-3.7	1.2	-6.1	-5.7	2.5	-4.4	-5.9	0.8	-5.2	-4.7

Over the 240 different combinations presented above, all the percentages are within a ±7.8% error, with an average error window of +3.4% to -4.4%. However, it is worth noting that the AS3000.1991 method is also an approximation via calculation and simplification, therefore, an exact match is not required, but the trend of results being within a small margin of error is desirable as this was an Australian Standard. To further support this statement, two thirds of the above results shows that the AS 3000:1991 method is more conservative than the Matlab Script, which would be expected when developing an approximation method, such as the AS 3000:1991 method.

5.4 Matlab Script vs. AS 60890:2009 Results

The results given by the AS 60890 method in Section 4.5 is for the same arrangement and conditions as the Type Test Certificate Results. This arrangement was:

3 by 125x6.3mm copper busbars per phase and

1 by 125x6.3mm copper busbar for neutral.

The results for both the Matlab script and the AS60890 method are available in Chapter 4. Table 5.4 Matlab Script vs. AS60890 Results below summarises comparable results between the two methods.

Table 5.4 Matlab Script vs. AS60890 Results

Description	**Matlab Script**	**AS 60890**	**% Error**
Average Current in the conductors	2427A	2427A	0%
Temperature of the enclosure surroundings	23.6°C	23.6°C	0%
Average temperature of the enclosure outer surface	49.5°C		
Average temperature of the enclosure inner surface	49.5°C		
Average temperature of air within the enclosure	71.5°C	78.7°C	9.1%
Average operating temperature of busbar	94.0°C	105°C	10.5%

As can be seen from the values detailed in Table 5.1, the average operating temperature of the busbars has an error difference of 10.5% and the average temperature of the air within the enclosure error of 9.1%. Similarly to the AS 3000:1991 method, the AS 60890 method is also an approximation via calculation and simplification, and the values obtained are more conservative than that of the Matlab script.

As detailed in Section 5.2, the Matlab Script is within 1% error of the real Type Test Certificate results, and therefore, relatively accurate. As the AS 60890 method is over 10% in error with the Matlab Script, it will not be analysed any further.

5.5 Matlab Script

The aim of this project was to simulate and model in Matlab the operating temperature of various current carrying copper busbar conductor arrangements in a specific bus zone of a low voltage switchboard, to determine if the conductor selection meets Australian Standards.

This section discusses the Matlab Script and how the real world results could potentially vary from that of the developed model.

5.5.1 Accuracy of Model

Table 5.1 in Section 5.2 identified that the Matlab Script solution was within 0.9% error for the average operating temperature of the busbars compared with the Type Test certificate results. However, the problem is not linear and the Type Test Results only provides one point of temperature reference for one current, for one arrangement at one ambient air temperature. This raises the question, how accurate is the model at other,

1. currents,
2. busbar arrangements and
3. ambient air temperatures?

Without other real test data to compare the Matlab Script to, the Matlab Script may be simulating, as shown in Figure 5.1, where the intersection of the two lines in the graph is the 0.9% error obtained in Section 5.2. In this potential solution scenario, the Matlab Script is accurate for a small window and larger errors are obtained at other currents.

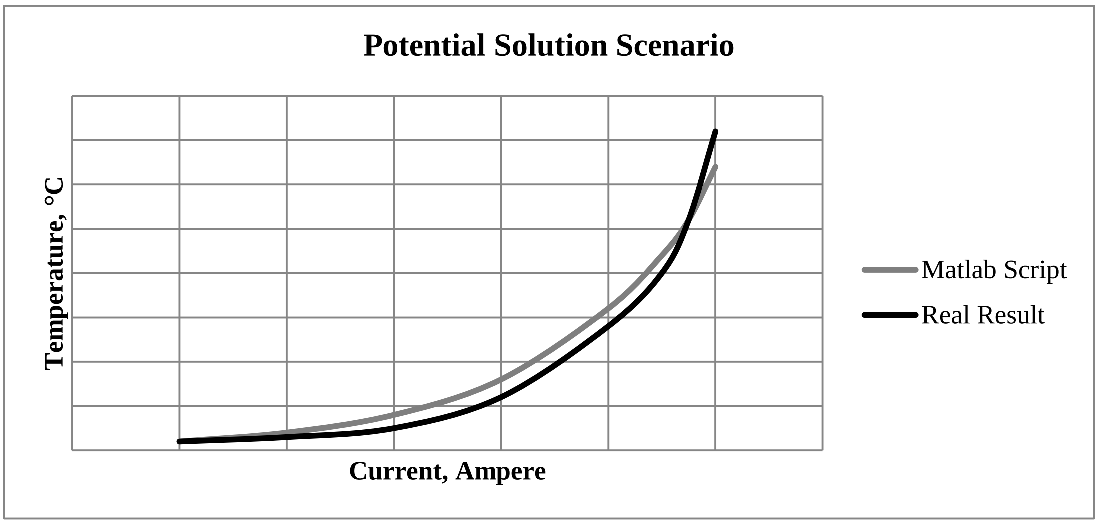


Figure 5.1 Potential Solution Scenario

5.5.2 Assumption Relaxation

Section 3.3 sets out assumptions made to simplify the Busbar system to a one dimensional problem. The following 2 assumptions below from Section 3.3 will be discussion on what is typical of a real world situation:

Assumption 6. Assume the horizontal bus is infinite and current flow is constant along its length, so there is no transfer in the z-axis.
i.e. section A-A = section B-B

Assumption 7. Assume the average air temperature within the enclosure is distributed equally and the busbar conductors are the same temperature.

Firstly, Assumption 6 assumes that the bus zone is infinitely long, however, no switchboard is infinitely long. Unless the ends of the switchboard are perfect insulators, they will provide additional cooling surfaces, which will facilitate lower thermal resistances in the bus zone thermal circuit. This would create a differential in busbar temperatures at the ends of a switchboard compared to the middle, and would create heat flow in the z-axis. This therefore makes the Matlab Script more conservative when calculating operating temperature to determine compliance with Australian Standards.

The second half of Assumption 6 assumes that the current flow is constant along the entire length of the bus zone. In reality, the full current rating will enter the bus zone at a single point (i.e. above the incomer tier) which may be located at the end or in the middle of the bus zone. Worst case scenario, the incoming point is located at one end and the full current rating will flow until the first distribution tap off point in the adjacent tier. Distribution tap off points will continue to decrease the current continuing past each point.

As described in Section 3.4.1, the rate at which electrical power is generated per unit length of busbar is the product of I^2R as described. The resistance of the busbar has not changed but the current has reduced. This leads to less heat dissipated and a lower temperature of the busbar. This then creates a differential in busbar temperatures at the ends furthest away from the incoming source point compared to the incoming source point. The busbars at the end away from the incoming source point become effectively heat sinks and would create heat flow in the z-axis. This therefore makes the Matlab Script more conservative when calculating operating temperature to determine compliance with Australian Standards.

Assumption 7 was implemented to simplify the problem, however, real world predictions can be made regarding these temperatures. The air temperature within the enclosure would not be uniform with the air at the top being hotter, and the air at the bottom cooler, than the enclosure average temperature. This air temperature differential is essential for the mechanics of causing the buoyancy forces for heat convection.

Two phases of the busbar system are located in the lower half of the bus zone and one phase is located in the top half. As the heat loss formulas are a calculation of heat loss to the air temperature adjacent to the busbar, the two lower phases will have lower average operating temperatures compared to the upper.

Additionally, in a three bars per phase system, the centre bar of a phase will have a higher operating temperature compared to its two flanking bars. This is due to the centre bar having severely reduced heat dissipation via radiation as the two larger surfaces face the two flanking bars at approximately the same temperature. Therefore, the two flanking busbars will be slightly less than the average operating temperature and the centre busbar will be higher.

6 Conclusions

The developed Matlab Script successfully models and simulates the operating temperature of various current carrying copper busbar conductor arrangements in a specific bus zone of a low voltage switchboard. Comparisons with the Type Test Certificate results for the 3 by 125x6.3mm copper busbars per phase arrangement shows that the Matlab Script is within 0.9% error for the same conditions.

A commercial switchboard manufacturing workshop method for calculating current carrying capacities of busbars is to use a guide that was provided in AS 3000:1991 SAA Wiring Rules. An extensive comparison of 240 different combinations of the AS 3000:1991 method and the Matlab Script was carried out. The largest error of all the combinations was ±7.8%, with an average error window of +3.4% to -4.4%.

AS/NZS 60890:2009 is an Australian Standard whose objective is to provide one possible method to determine the temperature rise of current carrying copper busbar conductors. This method was also compared with the Matlab Script using the 3 by 125x6.3mm copper busbars per phase arrangement. The average operating temperature of the busbars has an error difference of 10.5% and the average temperature of the air within the enclosure error of 9.1%.

Similarly to the AS 3000:1991 method, the AS 60890 method is an approximation via calculation and simplification, therefore, an exact match is not required, but the trend of results being within a small margin of error is desirable as this these are Australian Standards.

Due to the large error of the AS 60890 method of over 10% with the Matlab Script, it was not analysed any further. The AS 60890 method result and two thirds of the AS 3000:1991 method were more conservative than the Matlab Script, which would be expected when developing an approximation method such as the Australian Standards methods.

The final half of the project aim was to determine if the conductor selection meets Australian Standards. AS 3439.1:2002 stipulates that the maximum copper busbar operational temperature under normal service conditions is 105°C. An output of the Matlab Script was tables detailing the operating temperature of a busbar arrangement for a given current and ambient temperature. Using these tables thus satisfies the requirements of AS 3439.

The outcomes of this project will be used to assist the design selection of busbar conductors within the specified bus zone to document that design selections complies with Australian Standards.

6.1 Potential Future Work

All of the core objectives of this project have been completed successfully. However, the Matlab Script model could be further improved with further development into the following areas:

1. Further comparison with real test results to validate Matlab Script model for the specified bus zone.

2. Increase complexity of the Matlab Script by modelling each busbar operating temperature independently and is location dependant.

3. Increasing the dimensionality of the problem with the addition of heat transfer in the z-axis. This would include investigation into load sheading along the bus zone, hence sections of busbar acting as a heat sink.

4. Addition of functionality to allow alternative enclosure dimensions, busbar arrangements (trefoil, 3 in a row horizontally, vertically, etc.) and busbar orientation (horizontal or vertical). Comparison with real test results would be required to validate Matlab Script model.

5. Investigate the effect of contaminates introduced to a busbar system in a non-sealed bus zone.

6. Investigate the effect of cyclic loads to determine if a cyclic rating is applicable.

7. Investigate the effect of busbar and cable joints and their heat distribution effect on the busbar system.

8. Addition of a Graphical User Interface (GUI) for the Matlab Script.

7 Appendix A

7.1 Project Specification

University of Southern Queensland

Faculty of Health, Engineering & Sciences

ENG 4111/4112 Research Project

Project Specification

FOR: Roland BARRETT

TOPIC: Temperature of Current Carrying Copper Busbars Conductors

SUPERVISOR: Dr Tony Ahfock

PROJECT AIM: To Simulate and Model in Matlab the Temperature of Current Carrying Copper Busbars Conductors in a Specific Bus Zone.

PROGRAMME: Issue A, 11th March 2013

1. Research the current requirements in Australia for calculating Current Carrying Capacity of Busbar in switchboards. This will include making references to Australian Standards such as:

    - **AS/NZS 3000:2007** Electrical Installations
    - **AS/NZS 3439.1:2002** Low-voltage switchgear and controlgear assemblies - Type-Tested and Partially Type-Tested Assemblies
    - **AS 60890:2009** A method of temperature-rise assessment by extrapolation for Partially Type-Test Assemblies (PTTA) of low-voltage switchgear and controlgear

    Additional Standards may be found as a result of further investigation.

2. Investigate current methods of calculating Current Carrying Capacity of Busbar arrangements in a commercial switchboard manufacturing factory.

3. Research mathematical methods for the calculating the temperature of Copper Busbars carrying current with natural heat loss convection. Research mathematical methods for the calculating the temperature loss of the switchboard cubical material incorporating effects caused by material finish (i.e. natural or painted).

4. Simulate and model in Matlab the temperature of copper busbars carrying 2500A in a specific bus zone and busbar arrangement.

5. Compare the Matlab simulation to real Type Test results for the specific bus zone and busbar arrangement.

6. Simulate and model in Matlab the temperature of copper busbars carrying various currents in a specific bus zone and with varying busbar arrangements. Varying currents would be of nominal switch sizes such as:

   - 630A
   - 800A
   - 1000A
   - 1250A
   - 1600A
   - 2000A
   - 3200A

   Varying busbar arrangements will vary in bar width and number of conductors in parallel per phase. Copper bar widths will be of common commercially available sizes.

As time permits:

7. Simulate and model in Matlab the temperature of copper busbars carrying various currents in a non-specific enclosure and busbar arrangement.
   i.e. Custom Enclosure, Custom Arrangement.

AGREED Issue A, 11th March 2013

(Student) Roland Barrett Date: 11 / 03 / 2013

(Supervisor) ______________________ Date: / / 2013

(Examiner / Co-examiner) Chris Snook Date: 16 / 4 / 2013

8 Appendix B

8.1 Matlab Script

```
% USQ ENG4111/4112 - Project - S1/S2 2013
% busbar_temp.m
% Created 20th April 2013
%---------------------------------------------------------------------------
% Authors
% Initials Name           StudentNo. Mobile     Email
% RB       Roland Barrett 0050070099 0422535956 romiba@hotmail.com
%---------------------------------------------------------------------------
% Version  Date         Author    Comments
%  1.0     20 Apr 2013  RB        Initial file
%  2.0     11 Aug 2013  RB        Alpha Release
%  3.0      5 Oct 2013  RB        Final Release
%---------------------------------------------------------------------------
%% Script Description
%
%   The Matlab Script program is designed to simulate and model the
%   operating temperature of current carrying copper busbar conductors in
%   the specified bus zone enclosure detailed in Section 3.2 of the
%   dissertation. The Matlab Script is written in functional blocks with
%   the temperature and heat energy as the main inputs and outputs.
%   The functional blocks are in line with the sub-sections of Section
%   3.4, Mathematical Methods of Temperature Calculation of the
%   dissertation:
%
%   1.  Heat Generated by Busbars
%   2.  Heat Dissipated by Enclosure
%   3.  Heat Conduction through Enclosure Wall
%   4.  Heat Absorbed by Enclosure
%   5.  Heat Dissipated by Busbars
%
%   A function flow chart in Figure 3.8 of the dissertation illustrates
%   how each functional block interacts with each other. Looping is
%   introduced around functional blocks due to approximations made on the
%   first pass through. Program looping allows for large amounts of data
%   to be generated automatically without the need for user input for
%   current settings or busbar arrangements.
%
%   All constants were gained from the ‘Fundamentals of Heat and Mass
%   Transfer’ by Incropera publication and the resistances of the busbars
%   were provided in AS 600890:2009. Parameters are specific to the
%   enclosure or busbar dimensions determined from Section 3.2 of the
%   dissertation.
%
%   The Matlab script will produce the following outputs for any given
%   bar size, number of bars per phase and current flow:
%
%   •   Average Current in the conductors
%   •   Power dissipated per unit length of busbar arrangement
%   •   Total heat dissipated per unit length of enclosure
%
%   •   Temperature of the enclosure surroundings
%   •   Average temperature of the enclosure outer surface
%   •   Average temperature of the enclosure inner surface
%   •   Average temperature of air within the enclosure
%   •   Average temperature of busbar
%
%   •   Heat dissipated from busbars due to convection
%   •   Heat dissipated from busbars due to radiation
%   •   Heat conducted through enclosure wall
%   •   Heat dissipated from enclosure due to convection
%   •   Heat dissipated from enclosure due to radiation
%
%
```

```
% Bus Zone Cross-Section
%
%         |      315       |
%                  | 90 |60|
%      _   ________________   _
%         |       W     N  |   _46
%         |      |||    |  |
%         |      |||    |  |   125
%         |      |||    |  |   _
%    377  |   R        B   |   _34
%         |  |||      |||  |
%         |  |||      |||  |   125
%         |  |||      |||  |   _
%      _  |________________|   _47
%
%              |  146 | 85 |
%
%
%% Assumptions
%   1.  Assume all heat produced is absorbed by the surrounding air.
%   2.  Assume no heat loss through the bottom of the bus zone.
%   3.  Assume busbars located below bus zone do not contribute to heat
%       generation.
%   4.  Assume bight metal oxidize condition of busbars with emissivity
%       of 0.1.
%   5.  Assume the room temperature is held constant at ambient and heat
%       transfer from the bus zone will have no effect on this temperature.
%   6.  Assume the horizontal bus is infinite and current flow is constant
%       along its length, so there is no transfer in the z-axis.
%       i.e. section A-A = section B-B.
%   7.  Assume the average air temperature within the enclosure is
%       distributed equally and the busbar conductors are the same
%       temperature.
%   8.  Assume a balance 3 phase system with no negative or zero sequence
%       voltages.
%   9.  Assume still air within and outside the bus zone. i.e. no forced
%       ventilation.

%% Clear Workspace
clc
clear all
close all
hold all

%% Parameters
global bpp bp bw bh bt e K T2

Br  =  [0.063,0.000060265,0.000036215,0.000025868;...
        0.080,0.000048273,0.000030213,0.000021868;...
        0.100,0.000039394,0.000025770,0.000018900;...
        0.125,0.000032286,0.000022219,0.000016531;...
        0.160,0.000026058,0.000019111,0.000014458];
        %Table of Busbar resistances

f   =   50              ;   %Frequency, hertz
bt  =    0.0063         ;   %Busbar thickness, m
gap =    0.0063         ;   %Gap between parallel bars, m
be  =    0.1            ;   %Emissivity of bight copper busbar

E1  =    0.315          ;   %Enclosure lid width, m
E2  =    0.377          ;   %Enclosure upper vertical section, m
Eei =    0.47           ;   %Enclosure inner surface emissivity
Eeo =    0.93           ;   %Enclosure outer surface emissivity
Et  =    0.002          ;   %Enclosure sheetmetal thickness, m
Ek  =   43              ;   %Enclosure sheetmetal conductivity, W/m.K

g   =    9.8            ;   %Gravity, m/s²
sb  =    5.67   *10^-8  ;   %StefanBoltzmann Constant, W/m²*K^4
K   =  273              ;   %Kelvin at 0°C, K
```

```
T5  =   20              ;   %Ambient Temperature of room, °C

%Thermo physical Properties of Air at Atmospheric Pressure
p300 =   1.1614         ;   %Density @300K, kg/m³
cp300=   1.007          ;   %Specific Heat Capacity @300K, kJ/kg*K
u300 = 184.6   *10^-7   ;   %Dynamic Viscosity @300K, N*s/m²
v300 =  15.89  *10^-6   ;   %Kinematic Viscosity @300K, m²/s
k300 =  26.3   *10^-3   ;   %Thermal Conductivity @300K, W/m*K
a300 =  22.5   *10^-6   ;   % @300K, m²/s
Pr300=   0.707          ;   % @300K

p400 =   0.8711         ;   %Density @400K, kg/m³
cp400=   1.014          ;   %Specific Heat Capacity @400K, kJ/kg*K
u400 = 230.1   *10^-7   ;   %Dynamic Viscosity @400K, N*s/m²
v400 =  26.41  *10^-6   ;   %Kinematic Viscosity @400K, m²/s
k400 =  33.8   *10^-3   ;   %Thermal Conductivity @400K, W/m*K
a400 =  38.3   *10^-6   ;   % @400K, m²/s
Pr400=   0.690          ;   % @400K

%Parameters required for single loop
bc  = 2427              ;   %Busbar current, ampere
bw  =    0.125          ;   %Busbar width, m
bpp =    3              ;   %Busbars per phase
bp  =    3              ;   %Number of phases

% Start Program
%% 0.0 Arrangement Loop
sizematrix = [0.063,0.063,0.063,0.080,0.080,0.080,0.100,0.100,0.100,...
              0.125,0.125,0.125,0.160,0.160,0.160;...
              1,2,3,1,2,3,1,2,3,1,2,3,1,2,3;...
              E2,E2,E2,E2,E2,E2,E2,E2,E2,E2,E2,E2,E2+0.070,E2+0.070,...
              E2+0.070];    %Matrix to alternate busbar arrangements

for sizeloop = 1:15
    bw = sizematrix (1,sizeloop);   %Set busbar width for loop
    bpp= sizematrix (2,sizeloop);   %Set number of busbars per phase for
                                    %loop
    E2 = sizematrix (3,sizeloop);   %Set the size of the bus zone height
                                    %for loop

    bc = 1;                         %Set initial Current of 1 amp for loop
    T1 = 0;                         %Set initial busbar temperature at 0°C
    finish = 0;                     %Set initial loop condition
    for plotloop = 1:4000           %Start loop from 1A up to 4000A
        if T1 < 105                 %Execute only if busbar operating
                                    %temperature is less than 105°C
            %% 1.0 Heat Generated by the Busbars
            bro = interp1(Br(:,1),Br(:,bpp+1),bw);
                   %Busbar resistance, ohms
            bh  = bp*((bc)^2)*bro;
                   %Busbar heat generation, W/m

            %% 2.0 Heat Loss from Enclosure
            T4   =  T5+50;
                     %Initial Guess of Temperature of outside surface of
                     %enclosure, °C
            for loop = 1:3  %Loop 3 times to improve result accuracy
                % 2.1 Thermo physical Properties of Air at Enclosure Lid
                Tf45 = (T4+T5)/2 + 273;
                        %Average temp between T4 and T5
                Tf45a= (Tf45-300)/100;
                p45  = ( p400- p300)*Tf45a+ p300;
                cp45 = (cp400-cp300)*Tf45a+cp300;
                u45  = ( u400- u300)*Tf45a+ u300;
                v45  = ( v400- v300)*Tf45a+ v300;
                k45  = ( k400- k300)*Tf45a+ k300;
                a45  = ( a400- a300)*Tf45a+ a300;
                Pr45 = (Pr400-Pr300)*Tf45a+Pr300;
                B45  = 1/Tf45;
```

```
    % 2.2 Convection Heat Loss from Enclosure
    % 2.2.1 Vertical Sides of Bus Zone
    RaV  = g*B45*(T4-T5)*(E2^3)/(v45*a45);
            %Enclosure Vertical Rayleigh Number

    %Laminar flow 10^4<Ra<10^9
    NuV  = 0.68+(0.670*RaV^(1/4))/((1+(0.492/Pr45)^(9/16))...
           ^(4/9));
            %Enclosure vertical Nesselt Number
    hV   = NuV*k45/E2;
            %Enclosure vertical Free convection, W/m²K

    % 2.2.2 Horizontal Top of Bus Zone
    LcH  = (E1*(1))/(2*E1+2*(1));
            %Horizontal surface correlation constant
    RaH  = (g*B45*(T4-T5)*LcH^3)/(v45*a45);
            %Enclosure horizontal Rayleigh Number

    %Upper Surface of a Hot Plate where 10^4<Ra<10^7,
    %NuH = 0.54Ra^(1/4)
    NuH  = 0.54*RaH^(1/4);
            %Enclosure horizontal Nesselt Number
    hH   = NuH*k45/LcH;
            %Enclosure horizontal Free convection, W/m²K

    % 2.3 Radiation Heat Loss from Enclosure
    hRAD = Eeo*sb*((T4+K)+(T5+K))*((T4+K)^2+(T5+K)^2);
            %Enclosure radiation, W/m²K

    % 2.4 Calculation of Enclosure Surface Temperature
    Rcvo = 1/(hH*E1*1+2*hV*E2*1);
            %Free convection thermal resistance
    Rrad = 1/(hRAD*(E1+2*E2)*1) ;
            %Radiation thermal resistance
    Rpar = 1/((1/Rcvo)+(1/Rrad));
            %Equivilant parallel resistance
    T4   = T5+bh*Rpar;
            %Temperature of the outer surface of the enclosure
end

%% 3.0 Heat Conduction through Enclosure
T3 = T4+bh*Et/(Ek*(E1+2*E2)*1);
      %Temperature of the inner surface of the enclosure

%% 4.0 Heat Transfer within the Enclosure
T1a = T3 + 60;  %Initial Guess of Temperature of outside surface
                %of enclosure, °C
Qr  = 0.1*bh ;  %Initial Busbar radiation heat loss
for loop = 1:3  %Loop 3 times to improve result accuracy
    %% 4.1 Heat Absorbed by the Enclosure
    Tf13 = (T1a+T3)/2 + 273;
            %Average temp between T2 and T3
    Tf13a= (Tf13-300)/100  ;
    p12  = ( p400- p300)*Tf13a+ p300;
    cp13 = (cp400-cp300)*Tf13a+cp300;
    u13  = ( u400- u300)*Tf13a+ u300;
    v13  = ( v400- v300)*Tf13a+ v300;
    k13  = ( k400- k300)*Tf13a+ k300;
    a13  = ( a400- a300)*Tf13a+ a300;
    Pr13 = (Pr400-Pr300)*Tf13a+Pr300;
    B13  = 1/Tf13;

    % 4.2 Convection Heat Loss from Enclosure
    % 4.2.1 Inner Rayleigh Numbers for Bus Zone
    RaLH = g*B13*(T1a-T3)*(E1^3)/(v13*a13);
            %Enclosure Horizontal Rayleigh Number
    RaLV = g*B13*(T1a-T3)*(E2^3)/(v13*a13);
            %Enclosure Vertical Rayleigh Number

    % 4.3 Cellular flow in a cavity
```

```
        % 4.3.1 Horizontal cellular flow in a cavity
        Egap1= E2;
        NuLH = 0.069*(RaLH^(1/3))*(Pr13^0.074);
                %Enclosure horizontal Nesselt Number
        hLH  = NuLH*k13/Egap1;
                %Inner enclosure horizontal free convection, W/m²K

        % 4.3.1 Vertical cellular flow in a cavity
        Egap2= 0.10917;
                %Gap between Red or Blue phase and the enclosure
                %wall, m
        NuLV = 0.22*((Pr13*RaLV/(0.2+Pr13))^0.28)*((E2/Egap2)...
               ^(-1/4));
                %Enclosure vertical Nesselt Number
        hLV   = NuLV*k13/Egap2;
                %Inner enclosure vertical free convection, W/m²K

        % 4.4 Calculation of Enclosure Surface Temperature
        RcLH = 1/(hLH*E1*1);
                %Horizontal free convection thermal resistance
        RcLV = 1/(2*hLV*(E2)*1);
                %Vertical free convection thermal resistance
        RparLV= 1/((1/RcLH)+(1/RcLV));
                %Equivalent parallel resistance

        % 4.5 Calculation of Enclosure average air Temperature
        T1a  = T3+(bh-Qr)*RparLV;
                %Effective average temperature of busbars
        T2   = (T1a+T3)/2;
                %Average air temperature within the enclosure

        %% 4.6 Heat Transfer from the Busbars
        e    = (be*Eei)/((be+Eei)-(be*Eei));
                %Busbar/enclosure relative emissivity

        x0   = [110 180 20 20 100];
                %Starting guess for solution
        [x,fval] = fsolve(@busbarheatloss,x0);
                %Call solver

        Qcv  = 2*bpp*bp*x(1)*bw ;
                %Heat dissipated from busbars vertically via conv.
        Qch  = 2*bpp*bp*x(2)*bt ;
                %Heat dissipated from busbars horizontally via conv.
        Qc   = Qcv+Qch          ;
                %Heat dissipated from busbars via convection
        Qrv  = 2*bp*x(3)*bw     ;
                %Heat dissipated from busbars vertically via rad.
        Qrh  = 2*bpp*bp*x(4)*bt ;
                %Heat dissipated from busbars horizontally via rad.
        Qr   = Qrv+Qrh          ;
                %Heat dissipated from busbars via radiation
        Qt   = Qcv+Qch+Qrv+Qrh  ;
                %Total heat dissipated from busbars
        T1   = x(5)             ;
                %Average operating temperature of busbars

        clc     %Clear workspace for loop
    end

    %% 5.0 Outputs
    EQc  = (T4-T5)/Rcvo;
    EQr  = (T4-T5)/Rrad;

    fprintf('\nBusbar Size
%4.0f mm',bw*1000);
    fprintf('\nNumber of Bars per Phase
%4.0f   '    ,bpp);
    fprintf('\nAverage Current in the Conductors
%4.0f Amperes',bc);
```

```
            fprintf('\nPower dissipated per unit length of busbar arrangement
%3.1f Watts'   ,Qt);
            fprintf('\nTotal heat dissipated per unit length of enclosure
%3.1f Watts'   ,bh);
            fprintf('\n');
            fprintf('\nTemperature of the enclosure surroundings
%3.1f°C',T5);
            fprintf('\nAverage temperature of the enclosure outer surface
%3.1f°C',T4);
            fprintf('\nAverage temperature of the enclosure inner surface
%3.1f°C',T3);
            fprintf('\nAverage temperature of air within the enclosure
%3.1f°C',T2);
            fprintf('\nAverage temperature of busbar
%3.1f°C',T1);
            fprintf('\n');
            fprintf('\nHeat dissipated from busbars due to convection
%3.1f Watts',Qc);
            fprintf('\nHeat dissipated from busbars due to radiation
%3.1f Watts',Qr);
            fprintf('\nHeat conducted through enclosure wall
%3.1f Watts',bh);
            fprintf('\nHeat dissipated from enclosure due to convection
%3.1f Watts',EQc);
            fprintf('\nHeat dissipated from enclosure due to radiation
%3.1f Watts',EQr);
            fprintf('\n');

            results(plotloop,1) = bc;
            results(plotloop,sizeloop+1) = T1;
                  %Record the results of the Busbar operating temperature
                  %vs. the current
            bc = bc + 1;
                  %Increment the current for next loop

        elseif finish ~= 1
            plot(results(1:plotloop-1,1),results(1:plotloop-1,sizeloop+1))
                  %Graph the results for the current arrangement
            finish = 1;
                  %Execute this function only once per arrangement
        end
    end
end
grid              %Add Grid to graphs
% End Program
```

9 Appendix C

9.1 AS 3000:1991 Method Calculations

(A) BUSBAR DETAILS	Units															
Width of Phase Bar	mm	63	63	63	80	80	80	100	100	100	125	125	125	160	160	160
Number of Bars per Phase		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Thickness of Phase Bar	mm	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3
Width of Neutral Bar	mm	63	63	63	80	80	80	100	100	100	125	125	125	160	160	160
Number of Bars per Neutral		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Thickness of Neutral Bar	mm	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3
Number of Phases		3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Busbar Cross Sectional Area	mm^2	1587.6	3175.2	4762.8	2016	4032	6048	2520	5040	7560	3150	6300	9450	4032	8064	12096
(B) KNOWN DATA																
Current Carrying Capacity (Table C1)	A	1165	1990	2710	1370	2375	3190	1700	2800	3715	1970	3155	4275	2430	3790	5060
Ambient Temperature	°C	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
Temperature Rise	°C	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65
Operating Temperature	°C	105	105	105	105	105	105	105	105	105	105	105	105	105	105	105
(C) ENCLOSURE DETAILS (Bus Zone)																
Height	mm	377	377	377	377	377	377	377	377	377	377	377	377	377	377	377
Width	mm	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315
Enclosure Cross Sectional Area	mm^2	118755	118755	118755	118755	118755	118755	118755	118755	118755	118755	118755	118755	118755	118755	118755
Magnetic Material		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Non-Magnetic Material		No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Outdoors		No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Indoors - Poorly Ventilated		No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
Indoors - Well Ventilated		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
(D) RATIO BUSBAR/ENCLOSURE CSA'S		1.34%	2.67%	4.01%	1.70%	3.40%	5.09%	2.12%	4.24%	6.37%	2.65%	5.31%	7.96%	3.40%	6.79%	10.19%
(E) DEGREE OF ENCLOSURE																
De-rating Factor (Table C3)		0.71	0.68	0.65	0.7	0.67	0.631	0.69	0.65	0.613	0.68	0.631	0.586	0.68	0.622	0.568
(F) TEMPERATURE RATING																
De-rating Factor (Table C4)		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
(G)"ADJUSTED RATING"																
Arrangement Current Carrying Capacity	A	827.15	1353.2	1761.5	959	1591.25	2012.89	1173	1820	2277.3	1339.6	1990.81	2505.15	1652.4	2357.38	2874.08

Ambient	Operating	Temperature De-rating	Busbar Width, mm														
			63			80			100			125			160		
			Number of Busbars per Phase														
			1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
			Degree of Enclosure De-rating														
			0.71	0.68	0.65	0.7	0.67	0.631	0.69	0.65	0.613	0.68	0.631	0.586	0.68	0.622	0.568
°C			Estimated Maximum Current Carrying Capacity, Amperes														
40	**105**	**1**	827	1353	1762	959	1591	2013	1173	1820	2277	1340	1991	2505	1652	2357	2874
40	**100**	**0.95**	786	1286	1673	911	1512	1912	1114	1729	2163	1273	1891	2380	1570	2240	2730
40	**90**	**0.85**	703	1150	1497	815	1353	1711	997	1547	1936	1139	1692	2129	1405	2004	2443
40	**80**	**0.74**	612	1001	1304	710	1178	1490	868	1347	1685	991	1473	1854	1223	1744	2127
40	**70**	**0.62**	513	839	1092	595	987	1248	727	1128	1412	831	1234	1553	1024	1462	1782
35	**105**	**1.04**	860	1407	1832	997	1655	2093	1220	1893	2368	1393	2070	2605	1718	2452	2989
35	**95**	**0.95**	786	1286	1673	911	1512	1912	1114	1729	2163	1273	1891	2380	1570	2240	2730
35	**85**	**0.85**	703	1150	1497	815	1353	1711	997	1547	1936	1139	1692	2129	1405	2004	2443
35	**75**	**0.74**	612	1001	1304	710	1178	1490	868	1347	1685	991	1473	1854	1223	1744	2127
35	**65**	**0.62**	513	839	1092	595	987	1248	727	1128	1412	831	1234	1553	1024	1462	1782
30	**105**	**1.09**	902	1475	1920	1045	1734	2194	1279	1984	2482	1460	2170	2731	1801	2570	3133
30	**100**	**1.04**	860	1407	1832	997	1655	2093	1220	1893	2368	1393	2070	2605	1718	2452	2989
30	**90**	**0.95**	786	1286	1673	911	1512	1912	1114	1729	2163	1273	1891	2380	1570	2240	2730
30	**80**	**0.85**	703	1150	1497	815	1353	1711	997	1547	1936	1139	1692	2129	1405	2004	2443
30	**70**	**0.74**	612	1001	1304	710	1178	1490	868	1347	1685	991	1473	1854	1223	1744	2127
30	**60**	**0.62**	513	839	1092	595	987	1248	727	1128	1412	831	1234	1553	1024	1462	1782

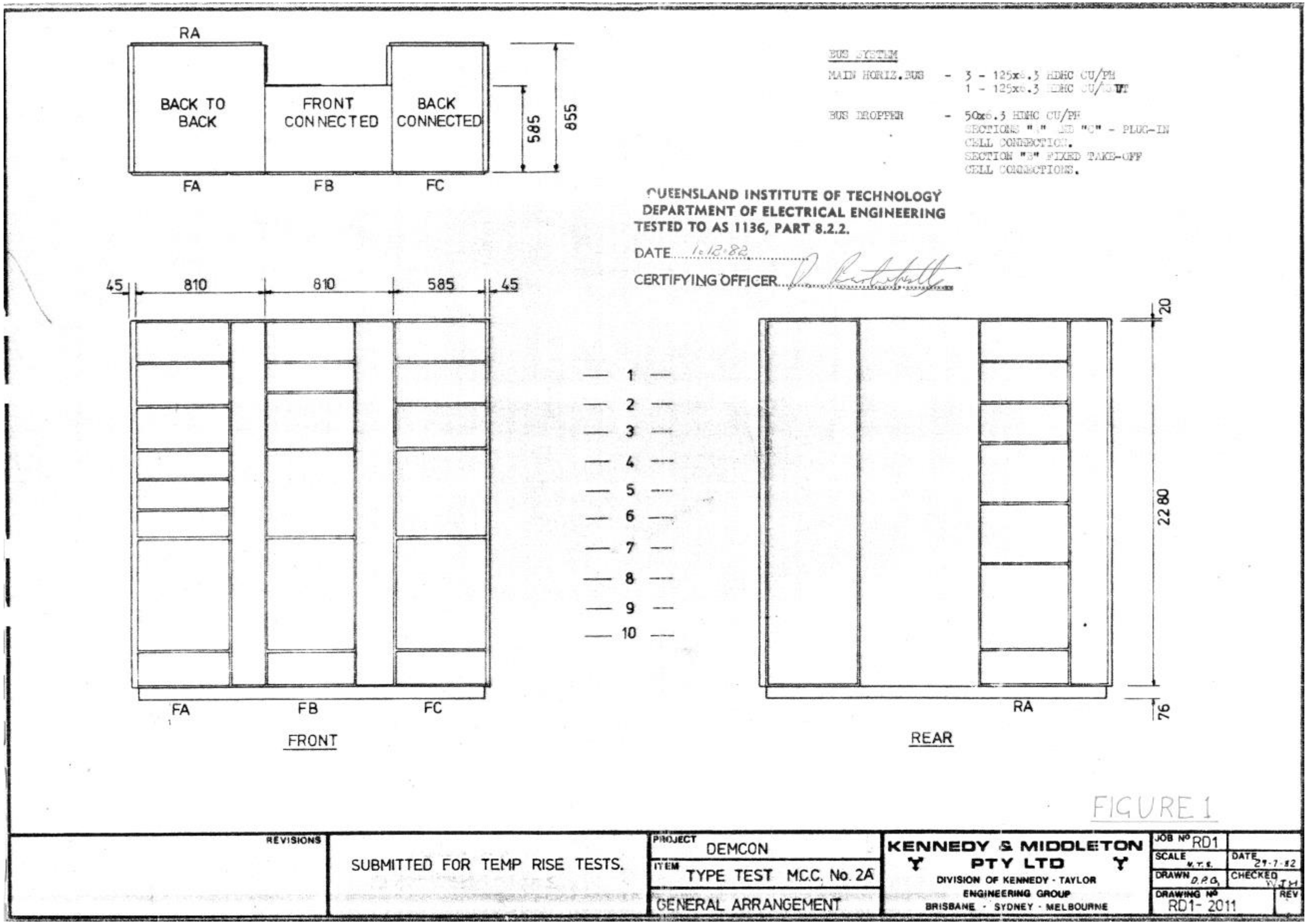
10 Appendix D

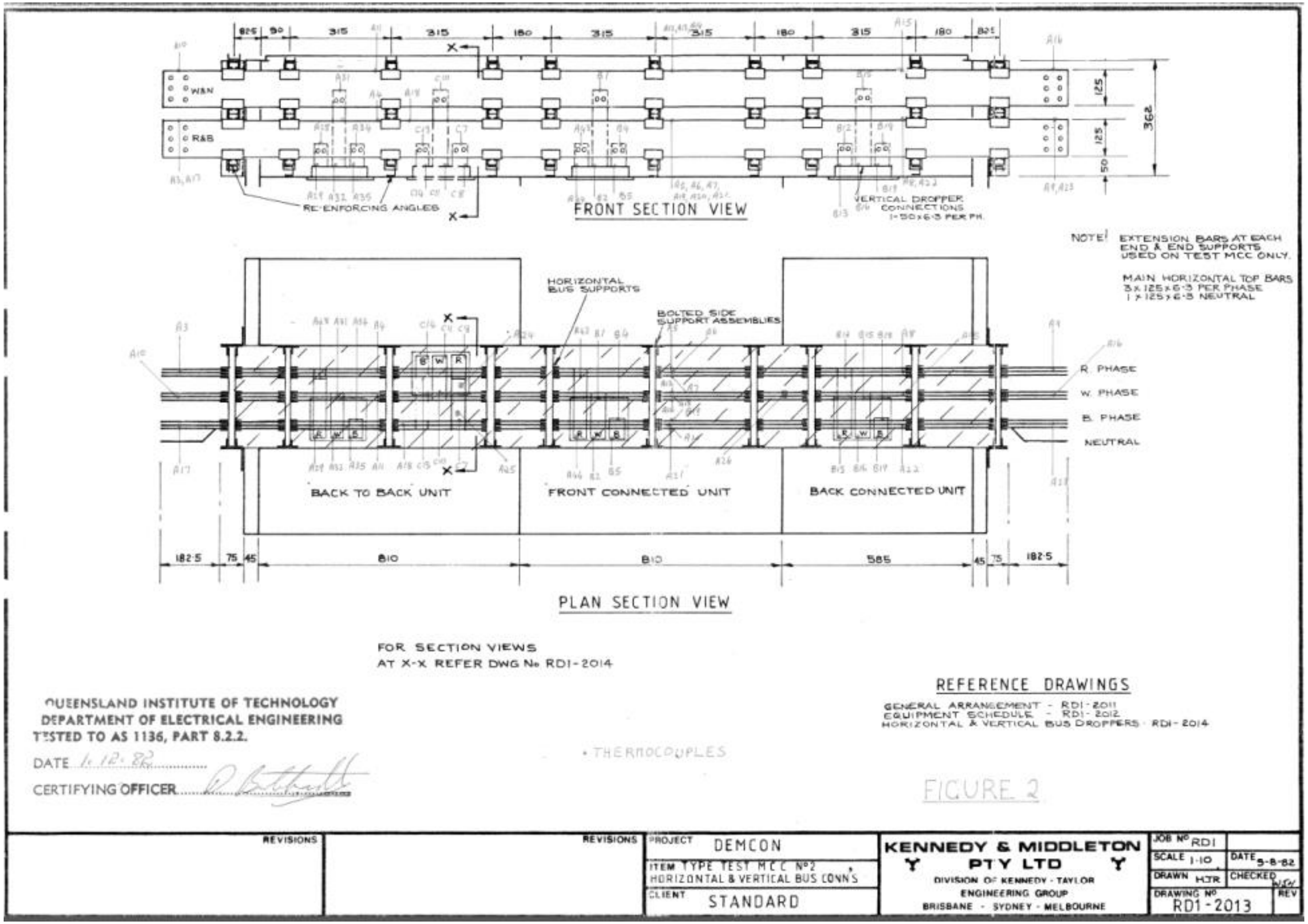
10.1 AS 60890:2009 Method Calculations

(A) BUSBAR DETAILS			
Width of Phase Bar		125	mm
Number of Bars per Phase		3	
Thickness of Phase Bar		6.3	mm
Width of Neutral Bar		125	mm
Number of Bars per Neutral		1	
Thickness of Neutral Bar		6.3	mm
Number of Phases		3	
Maximum Operating Current (Table ZA.6)		3416	A
Power Loss per Phase Conductor (Table ZA.6)		192.9	W/m
Power Loss at Operating Current		97.37244076	W/m
(B) KNOWN DATA			
Operating Current		**2427**	**A**
Ambient Temperature		23.6	°C
Temperature Rise		60	°C
Operating Temperature		105	°C
(C) ENCLOSURE DETAILS (Bus Zone)			
Height		377	mm
Width		810	mm
Depth		315	mm
Number of Horizontal Partitions		0	
Ventilation		NO	
Inlet Ventilation		0	cm^2
Outlet Ventilation		0	cm^2
(D) ENCLOSURE EFFECTIVE COOLING SURFACE	**AREA m^2**	**SURFACE FACTOR**	
	A_0	b	$A_0 * b$
Top	0.25515	1.4	0.35721
Front	0.30537	0.9	0.274833
Rear	0.30537	0.9	0.274833
Left Hand Side	0.118755	0	0
Right Hand Side	0.118755	0	0
$A_E = \sum(A_0 * b)$=Total			**0.906876**
$A_e > 1.25 m^2$	$f = h^{1.35}/A_b$	~~1.050183644~~	
$A_e < 1.25 m^2$	$g = h/w$	0.465432099	
Enclosure Constant (Figure 7)	k	0.68	
Factor of Horizontal Partitions	d	1	
Temperature Distribution Factor (Figure 8)	c	1.088	
Effective Power Loss	P	236.615031	Watt
Exponent	x	0.804	
	P^x	81.04571037	
	$\Delta t_{0.5} = k * d * P^x$	55.11108305	
	$\Delta t_{1.0} = c * \Delta t_{0.5}$	59.96085836	
Air Temperature Adjacent to the Busbars		83.56085836	

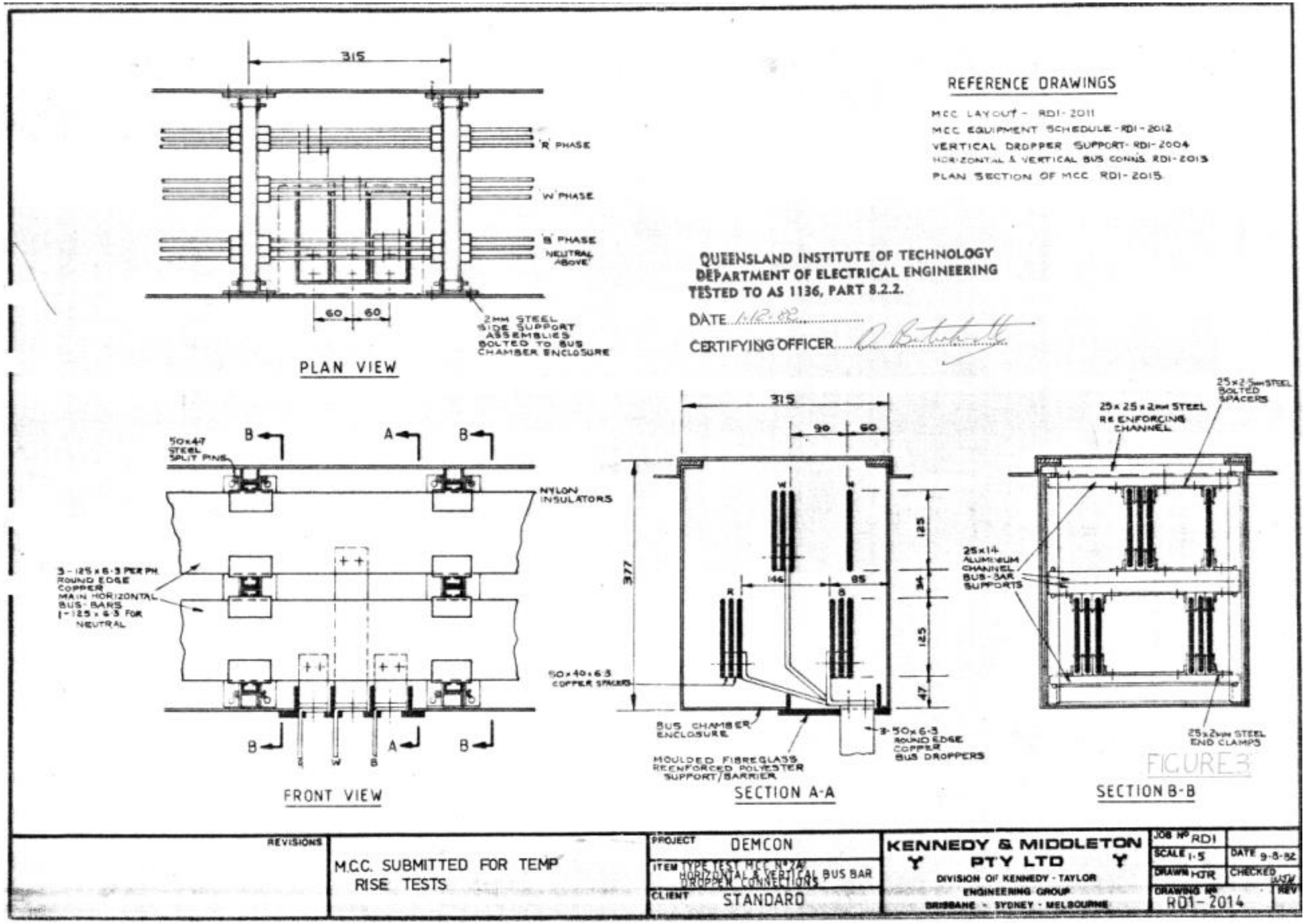
11 Appendix E

11.1 Bus Zone General Arrangement Drawings

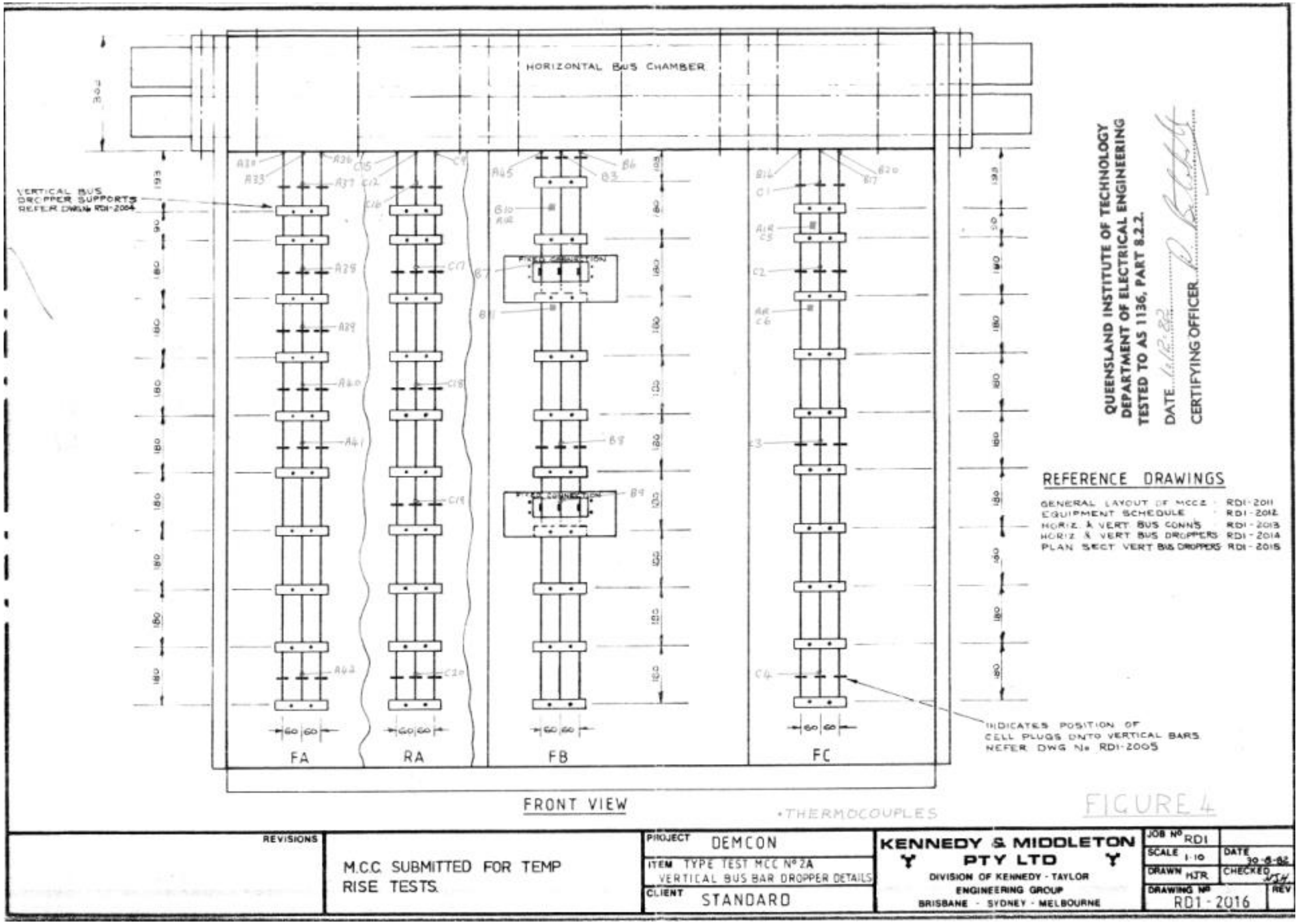

RA
BACK TO BACK
FRONT CONNECTED
BACK CONNECTED
585
855
FA
FB
FC
BUS SYSTEM
MAIN HORIZ. BUS - 3 - 125x6.3 HDHC CU/PH
1 - 125x6.3 HDHC CU/
BUS DROPPER - 50x6.3 HDHC CU/PH
SECTIONS "C" - PLUG-IN
CELL CONNECTION.
SECTION FIXED TAKE-OFF
CELL CONNECTIONS.
QUEENSLAND INSTITUTE OF TECHNOLOGY
DEPARTMENT OF ELECTRICAL ENGINEERING
TESTED TO AS 1136, PART 8.2.2.
DATE 1.12.82
CERTIFYING OFFICER
45
810
810
585
45
1
2
3
4
5
6
7
8
9
10
20
2280
76
FA
FB
FC
FRONT
RA
REAR
FIGURE 1
REVISIONS
SUBMITTED FOR TEMP RISE TESTS.
PROJECT DEMCON
ITEM TYPE TEST M.C.C. No. 2A
GENERAL ARRANGEMENT
KENNEDY & MIDDLETON PTY LTD
DIVISION OF KENNEDY - TAYLOR ENGINEERING GROUP
BRISBANE · SYDNEY · MELBOURNE
JOB Nº RD1
SCALE N.T.S.
DATE 27-7-82
DRAWN
CHECKED
DRAWING Nº RD1- 2011
REV



FRONT SECTION VIEW
RE-ENFORCING ANGLES
VERTICAL DROPPER CONNECTIONS 1-50x6·3 PER PH.
W&N
R&B
NOTE: EXTENSION BARS AT EACH END & END SUPPORTS USED ON TEST MCC ONLY.
MAIN HORIZONTAL TOP BARS 3x125x6·3 PER PHASE 1x125x6·3 NEUTRAL
HORIZONTAL BUS SUPPORTS
BOLTED SIDE SUPPORT ASSEMBLIES
R PHASE
W PHASE
B PHASE
NEUTRAL
BACK TO BACK UNIT
FRONT CONNECTED UNIT
BACK CONNECTED UNIT
PLAN SECTION VIEW
FOR SECTION VIEWS AT X-X REFER DWG No RDI-2014
REFERENCE DRAWINGS
GENERAL ARRANGEMENT - RDI-2011
EQUIPMENT SCHEDULE - RDI-2012
HORIZONTAL & VERTICAL BUS DROPPERS - RDI-2014
QUEENSLAND INSTITUTE OF TECHNOLOGY
DEPARTMENT OF ELECTRICAL ENGINEERING
TESTED TO AS 1136, PART 8.2.2.
DATE 1.12.82
CERTIFYING OFFICER
• THERMOCOUPLES
FIGURE 2
REVISIONS
REVISIONS
PROJECT DEMCON
ITEM TYPE TEST MCC No2 HORIZONTAL & VERTICAL BUS CONN'S
CLIENT STANDARD
KENNEDY & MIDDLETON PTY LTD
DIVISION OF KENNEDY - TAYLOR ENGINEERING GROUP
BRISBANE - SYDNEY - MELBOURNE
JOB No RDI
SCALE 1:10
DATE 5-8-82
DRAWN HJR
CHECKED
DRAWING No RD1-2013
REV



315
'R' PHASE
'W' PHASE
'B' PHASE
NEUTRAL ABOVE
60
60
2MM STEEL SIDE SUPPORT ASSEMBLIES BOLTED TO BUS CHAMBER ENCLOSURE
PLAN VIEW
REFERENCE DRAWINGS
MCC LAYOUT - RDI-2011
MCC EQUIPMENT SCHEDULE - RDI-2012
VERTICAL DROPPER SUPPORT - RDI-2004
HORIZONTAL & VERTICAL BUS CONNS RDI-2013
PLAN SECTION OF MCC RDI-2015
QUEENSLAND INSTITUTE OF TECHNOLOGY
DEPARTMENT OF ELECTRICAL ENGINEERING
TESTED TO AS 1136, PART 8.2.2.
DATE 1.12.82
CERTIFYING OFFICER
50x4.7 STEEL SPLIT PINS
NYLON INSULATORS
3-125x6.3 PER PH. ROUND EDGE COPPER MAIN HORIZONTAL BUS-BARS 1-125x6.3 FOR NEUTRAL
FRONT VIEW
315
90
60
377
125
34
125
47
146
85
50x40x6.3 COPPER SPACERS
BUS CHAMBER ENCLOSURE
MOULDED FIBREGLASS REENFORCED POLYESTER SUPPORT/BARRIER
3-50x6.3 ROUND EDGE COPPER BUS DROPPERS
SECTION A-A
25x2.5mm STEEL BOLTED SPACERS
25x25x2mm STEEL REENFORCING CHANNEL
25x14 ALUMINIUM CHANNEL BUS-BAR SUPPORTS
25x2mm STEEL END CLAMPS
FIGURE 3
SECTION B-B
REVISIONS
M.C.C. SUBMITTED FOR TEMP RISE TESTS
PROJECT DEMCON
ITEM TYPE TEST MCC No2 HORIZONTAL & VERTICAL BUS BAR DROPPER CONNECTIONS
CLIENT STANDARD
KENNEDY & MIDDLETON PTY LTD
DIVISION OF KENNEDY-TAYLOR ENGINEERING GROUP
BRISBANE - SYDNEY - MELBOURNE
JOB No RDI
SCALE 1:5
DATE 9-8-82
DRAWN HJR
CHECKED
DRAWING No RD1-2014
REV


HORIZONTAL BUS CHAMBER
VERTICAL BUS DROPPER SUPPORTS REFER DWG No RDI-2004
QUEENSLAND INSTITUTE OF TECHNOLOGY
DEPARTMENT OF ELECTRICAL ENGINEERING
TESTED TO AS 1136, PART 8.2.2.
DATE
CERTIFYING OFFICER
REFERENCE DRAWINGS
GENERAL LAYOUT OF MCCs RDI-2011
EQUIPMENT SCHEDULE RDI-2012
HORIZ. & VERT. BUS CONN'S RDI-2013
HORIZ & VERT BUS DROPPERS RDI-2014
PLAN SECT VERT BUS DROPPERS RDI-2015
INDICATES POSITION OF CELL PLUGS ONTO VERTICAL BARS REFER DWG No RDI-2005
FA
RA
FB
FC
FRONT VIEW
•THERMOCOUPLES
FIGURE 4
REVISIONS
M.C.C. SUBMITTED FOR TEMP RISE TESTS.
PROJECT DEMCON
ITEM TYPE TEST MCC No 2A VERTICAL BUS BAR DROPPER DETAILS
CLIENT STANDARD
KENNEDY & MIDDLETON PTY LTD
DIVISION OF KENNEDY - TAYLOR
ENGINEERING GROUP
BRISBANE - SYDNEY - MELBOURNE
JOB No RDI
SCALE 1:10
DATE 30-8-82
DRAWN HJR
CHECKED
DRAWING No RD1-2016
REV

12 References

Copper Development Association 1996, *Copper for Busbars*, Pub 22, Copper Development Association, United Kingdom, Viewed 17 March 2013 <http://www.copperinfo.co.uk/busbars/pub22-copper-for-busbars/homepage.shtml>

Ho S., Li Y., Lin X., Lo E. 2006, *Calculations of Eddy Current, Fluid, and Thermal Fields in an Air Insulated Bus Duct System*, Electromagnetic Field Computation, pages 101, Viewed 30 June 2013, IEEE Xplore, 10.1109/CEFC-06.2006.1632893

Tebal N., Pinang P. 2012, *Temperature Rise Prediction in 3-Phase Busbar System at 20°C Ambient Temperature*, Power and Energy (PECon), 2012 IEEE International Conference on 2-5 Dec. 2012, pages 736 – 740, Viewed 30 June 2013, IEEE Xplore, 10.1109/PECon.2012.6450313

Standards Australia 1991, *SAA Wiring Rules*, AS/NZS 3000:1991, Standards Australia, Sydney, viewed 3 March 2013 <http://www.saiglobal.com/online/autologin.asp>

Standards Australia 2002, *Low-voltage switchgear and controlgear assemblies - Type-tested and partially type-tested assemblies*, AS/NZS 3439.1:2002, Standards Australia, Sydney, viewed 3 March 2013 <http://www.saiglobal.com/online/autologin.asp>

Standards Australia 2007, *Electrical Installations*, AS/NZS 3000:2007, Standards Australia, Sydney, viewed 3 March 2013 <http://www.saiglobal.com/online/autologin.asp>

Standards Australia 2009, *A method of temperature-rise assessment by extrapolation for partially type-test assemblies (PTTA) of low-voltage switchgear and controlgear*, AS 60890:2009, Standards Australia, Sydney, viewed 3 March 2013 <http://www.saiglobal.com/online/autologin.asp>

Standards Australia 2009, *Electrical Installations - Selection of Cables*, AS/NZS 3008.1.1:2009, Standards Australia, Sydney, viewed 3 March 2013 <http://www.saiglobal.com/online/autologin.asp>