Operating Temperature of Current Carrying

Copper Busbar Conductors

A dissertation submitted by

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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.
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# Table of Contents

Abstract ...........................................................................................................................................ii

Acknowledgements .........................................................................................................................v

Table of Contents .............................................................................................................................vi

List of Figures ...................................................................................................................................x

List of Tables .....................................................................................................................................xi

Glossary of Terms ............................................................................................................................xii

1 Introduction .....................................................................................................................................1

1.1 Outline of the Project ..................................................................................................................1

1.2 Introduction .................................................................................................................................1

1.3 The Problem ...............................................................................................................................2

1.4 Project Objectives .......................................................................................................................2

1.5 Overview ....................................................................................................................................5

1.6 Project Outcomes .......................................................................................................................6

2 Background ....................................................................................................................................7

2.1 Introduction .................................................................................................................................7

2.2 Standards Literature Review .....................................................................................................7

2.2.1 AS/NZS 3000:2007 Electrical Installations ............................................................................7
2.2.2 AS/NZS 3439.1:2002 Low-voltage switchgear and controlgear assemblies
- Type-tested and partially type-tested assemblies.................................................9

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.................................................................................................................................12

2.3 Commercial Switchboard Manufacturing Workshop Review .......................13

2.4 Mathematical Methods of Temperature Calculation........................................15

2.5 Other Published Papers ..................................................................................16

2.6 Conclusions ....................................................................................................17

3 Methodology ......................................................................................................18

3.1 Introduction .....................................................................................................18

3.2 Specific Bus Zone System ..............................................................................19

3.2.1 Bus Zone Specifics.....................................................................................19

3.3 Assumptions ...................................................................................................24

3.4 Mathematical Methods of Temperature Calculation........................................25

3.4.1 Heat Generated by Busbars .......................................................................25

3.4.2 Heat Dissipated by Busbars ......................................................................26

3.4.3 Heat Absorbed by Enclosure ....................................................................30

3.4.4 Heat Conduction through Enclosure Wall ...............................................33

3.4.5 Heat Dissipated by Enclosure ...................................................................34

3.4.6 Thermal Circuit of the Bus Zone System .................................................37

3.5 Matlab Script ..................................................................................................39
3.6 Alternate Methods ................................................................. 42

3.6.1 AS 3000:1991 Method ........................................................... 42

3.6.2 AS 60890:2009 Method .......................................................... 44

4 Results .......................................................................................... 46

4.1 Introduction ............................................................................... 46

4.2 Matlab Script Results ............................................................... 47

4.3 Type Test Certificate Results ..................................................... 59

4.4 AS 3000:1991 Results .............................................................. 62

4.5 AS 60890:2009 Results ............................................................. 64

5 Analysis and Discussion ............................................................. 67

5.1 Introduction ............................................................................... 67

5.2 Matlab Script vs. Type Test Results .......................................... 68

5.3 Matlab Script vs. AS 3000:1991 Results .................................... 70

5.4 Matlab Script vs. AS 60890:2009 Results ................................ 72

5.5 Matlab Script ........................................................................... 74

5.5.1 Accuracy of Model ............................................................ 74

5.5.2 Assumption Relaxation ....................................................... 75

6 Conclusions .................................................................................. 78

6.1 Potential Future Work .............................................................. 80

7 Appendix A .................................................................................. 82

7.1 Project Specification ............................................................... 82

8 Appendix B ................................................................................. 86
8.1 Matlab Script ................................................................. 86

9 Appendix C ....................................................................... 93

9.1 AS 3000:1991 Method Calculations .................................. 93

10 Appendix D ..................................................................... 96

10.1 AS 60890:2009 Method Calculations ................................ 96

11 Appendix E ..................................................................... 98

11.1 Bus Zone General Arrangement Drawings ....................... 98

12 References ..................................................................... 103
List of Figures

Figure 3.1 Front View of Bus Zone ................................................................. 20
Figure 3.2 Plan View of Bus Zone ................................................................. 21
Figure 3.3 Sectional View of Bus Zone with Busbar Locations Dimensioned ....... 22
Figure 3.4 Sectional View of Bus Zone with Busbar Supports Shown .................. 23
Figure 3.5 Convection Heat Loss from a Busbar Section ................................... 28
Figure 3.6 Radiation Heat Loss from a Busbar Section ...................................... 29
Figure 3.7 Thermal Circuit ............................................................................. 38
Figure 3.8 Matlab Script Functional Flow Chart .............................................. 40
Figure 4.1 Operating Temperature of Busbars for a given Current at 40°C Ambient Temperature ................................................................. 51
Figure 4.2 Operating Temperature of Busbars for a given Current at 35°C Ambient Temperature ................................................................. 52
Figure 4.3 Operating Temperature of Busbars for a given Current at 30°C Ambient Temperature ................................................................. 53
Figure 4.4 Operating Temperature of Busbars for a given Current at 25°C Ambient Temperature ................................................................. 54
Figure 4.5 Operating Temperature of Busbars for a given Current at 20°C Ambient Temperature ................................................................. 55
Figure 4.6 Type Test Temperature Rise Test Thermocouple Locations ................ 61
Figure 4.7 Intersection of Extrapolated and Calculated Current Ratings .............. 64
Figure 4.8 Enclosure Temperature Characteristic Curve .................................... 65
Figure 5.1 Potential Solution Scenario ............................................................. 75
List of Tables

Table 2.1 Extract from AS3439.1 Table 2 - Temperature-rise limits .......................... 10
Table 4.1 3 by 125x6.3mm copper busbars Test Conditions .................................. 47
Table 4.2 Matlab Script Results of Estimated Current Carrying Capacities for the Specified Enclosure ................................................................. 50
Table 4.3 Temperature of Busbars at Nominal Switch Sizes and 40°C Ambient .......... 56
Table 4.4 Temperature of Busbars at Nominal Switch Sizes and 35°C Ambient ........ 57
Table 4.5 Temperature of Busbars at Nominal Switch Sizes and 30°C Ambient .......... 57
Table 4.6 Temperature of Busbars at Nominal Switch Sizes and 25°C Ambient .......... 58
Table 4.7 Temperature of Busbars at Nominal Switch Sizes and 20°C Ambient .......... 58
Table 4.8 Test Conditions ......................................................................................... 59
Table 4.9 Results of Type Test Temperature Rise Test on Busbar Enclosure ........... 60
Table 4.10 AS3000:1991 Results of Estimated Current Carrying Capacities for the Specified Enclosure ................................................................. 63
Table 4.11 Results of AS 60890 for 3 by 125x6.3mm copper busbars per phase .......... 66
Table 5.1 Matlab Script vs. Type Test Certificate Results ............................................. 68
Table 5.2 Current Carrying Capacity Differential of Matlab Script vs. AS3000 methods. .............................................................................................................. 70
Table 5.3 Percentage Error of Matlab Script vs. AS3000 Calculated Current Carrying Capacities with AS3000 as the Base ................................................. 71
Table 5.4 Matlab Script vs. AS60890 Results .............................................................. 72
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.


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, piii), 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

<table>
<thead>
<tr>
<th>Parts of Assemblies</th>
<th>Temperature rise K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Busbars and conductors, plug-in contacts of removable or withdrawable parts which connect to busbars (6)</td>
<td>Limited by:</td>
</tr>
<tr>
<td>(6) The requirements for built-in components, busbars and conductors, plug-in contacts of removable or withdrawable parts which connect to busbars, limited by:</td>
<td></td>
</tr>
<tr>
<td>– mechanical strength of conducting material;</td>
<td></td>
</tr>
<tr>
<td>– possible effect on adjacent equipment;</td>
<td></td>
</tr>
<tr>
<td>– permissible temperature limit of the insulating materials in contact with the conductors;</td>
<td></td>
</tr>
<tr>
<td>– the effect of the temperature of the conductor on the apparatus connected to it;</td>
<td></td>
</tr>
<tr>
<td>– for plug-in contacts, the nature and surface treatment of the contact material.</td>
<td></td>
</tr>
</tbody>
</table>

(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


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:


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 bright 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.

\[
P = P = I^2 \times R
\]  

(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.

\[
P = q_{\text{conv}1} + q_{\text{rad}1}
\]

\[
P = W_C A_C + W_R A_R
\]

where

- \( q_{\text{conv}1} \) = heat dissipated from busbars due to convection, W
- \( q_{\text{rad}1} \) = 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.

\[
q_{\text{conv}1} = W_C A_C = W_V A_{CV} + W_H A_{CH} \tag{3.4}
\]

\[
W_V = \frac{7.66\theta^{1.25}}{L^{0.25}} \tag{3.5}
\]

\[
W_H = \frac{5.92\theta^{1.25}}{L^{0.25}} \tag{3.6}
\]

\[
\theta = \bar{T}_1 - \bar{T}_2 \tag{3.7}
\]

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.

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

(3.8)

\[ e = \frac{\varepsilon_1 \varepsilon_2}{(\varepsilon_1 + \varepsilon_2) - (\varepsilon_1 \varepsilon_2)} \]  

(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
\[ \varepsilon_1 = \text{absolute emissivity of busbar} \]

\[ \varepsilon_2 = \text{absolute emissivity of the enclosure inner surface} \]

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.

\[ P = q_{\text{conv}1} + q_{\text{rad}1} \]  

(3.10)

where

- \( P \) = power dissipated per unit length of busbar, W
- \( q_{\text{conv}1} \) = heat dissipated due to convection, W
- \( q_{\text{rad}1} \) = 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.

\[ q_{\text{conv}1} = \tilde{h}_v A_v + \tilde{h}_t A_t \]  

(3.11)
where \( \bar{h}_{v1} = \text{average vertical convection heat transfer coefficient, W/m}^2\cdot\text{K} \)

\( \bar{h}_{t1} = \text{average top convection heat transfer coefficient, W/m}^2\cdot\text{K} \)

\( A_v = \text{vertical surface area of enclosure, m}^2 \)

\( A_t = \text{top surface area of enclosure, m}^2 \)

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

\[
Ra_{v1} = \frac{g \beta (T_1 - T_3) G_1^2}{v \alpha} \tag{3.12}
\]

\[
\bar{N}u_{v1} = 0.22 \left( \frac{Pr}{0.2 + Pr} Ra_{v1} \right)^{0.28} \left( \frac{H}{G_1} \right)^{-1/4} \begin{bmatrix} 2 \leq \frac{H}{G_1} \leq 10 \\ Pr \leq 10^5 \\ 10^3 \leq Ra \leq 10^{10} \end{bmatrix} \tag{3.13}
\]

\[
\bar{h}_{v1} = \frac{\bar{N}u_{v1} k}{H} \tag{3.14}
\]

where  
\( Ra = \text{Rayleigh number} \)

\( N\text{u} = \text{average Nusselt number} \)

\( g = \text{gravity constant, 9.8m/s}^2 \)

\( \beta = \text{volumetric thermal expansion coefficient, K}^{-1} \)

\( \bar{T}_1 = \text{average temperature of busbar, K} \)

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

\( H = \text{height of the enclosure, m} \)

\( G = \text{gap between busbar and enclosure wall, m} \)

\( v = \text{kinematic viscosity, m}^2/\text{s} \)

\( \alpha = \text{thermal diffusivity, m}^2/\text{s} \)
\[ Pr = \text{Prandtl number} \]
\[ k = \text{thermal conductivity, W/m.K} \]

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.

\[ Ra_{t_1} = \frac{g \beta (\bar{T}_{1} - \bar{T}_3) \rho_2^3}{\nu \alpha} \quad (3.15) \]

\[ \bar{N}u_{t_1} = 0.069Ra_{t_1}^{1/3}Pr^{0.074} \quad 3 \times 10^5 \leq Ra \leq 7 \times 10^9 \quad (3.16) \]

\[ \bar{h}_{t_1} = \frac{\bar{N}u_{t_1} k}{H} \quad (3.17) \]

### 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.

\[
P = q_{\text{cond}} \tag{3.18}
\]

\[
q_{\text{cond}} = k_t A \frac{\Delta T}{\Delta x} \tag{3.19}
\]

\[
\Delta T = \bar{T}_3 - \bar{T}_4 \tag{3.20}
\]

where

- \( P \) = power dissipated per unit length of busbar, W
- \( q_{\text{cond}} \) = heat conducted through enclosure wall, W
- \( k_t \) = enclosure thermal conductivity, W/mK
- \( A \) = surface area of enclosure, m²
- \( \bar{T}_3 \) = average temperature of the enclosure inner surface, K
- \( \bar{T}_4 \) = average temperature of the enclosure outer surface, K
- \( \Delta x \) = 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.

\[ P = q_{\text{conv2}} + q_{\text{rad2}} \]  

where \( P \) = power dissipated per unit length of busbar, W
\( q_{\text{conv2}} \) = heat dissipated from enclosure due to convection, W
\( q_{\text{rad2}} \) = 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.
\[ q_{\text{conv}2} = \bar{h}_{v2} A_v + \bar{h}_{t2} A_t \]  \hspace{1cm} (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.

\[ Ra_{v2} = \frac{g \beta (\bar{T}_4 - T_5) H^3}{\nu \alpha} \]  \hspace{1cm} (3.23)

\[ \bar{N}_u_{v2} = 0.68 + \frac{0.670Ra_{v2}^{1/4}}{[1+(0.492/Pr)^{9/16}]^{4/3}} \quad Ra_{v2} \leq 10^9 \]  \hspace{1cm} (3.24)

\[ \bar{h}_{v2} = \frac{\bar{N}_u_{v2} k}{H} \]  \hspace{1cm} (3.25)

where

\( Ra = \) Rayleigh number

\( \bar{N}_u = \) average Nusselt number

\( g = \) gravity constant, 9.8m/s\(^2\)

\( \beta = \) 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

\( \nu = \) kinematic viscosity, m\(^2\)/s
\[ \alpha = \text{thermal diffusivity, m}^2/\text{s} \]
\[ Pr = \text{Prandtl number} \]
\[ k = \text{thermal conductivity, W/m.K} \]

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

\[ \overline{Nu}_{t2} = \frac{\overline{h}_{Lc}L_c}{k} = 0.54Ra^{1/4} \] (3.26)

\[ L_c = A_t/P \] (3.27)

where \( L_c = \text{horizontal plane Nusselt correlation number} \)
\[ P = \text{enclosure top surface area perimeter, m} \]

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.

\[ q_{rad2} = \overline{h}_{rad}A \] (3.28)

\[ \overline{h}_{rad2} = \varepsilon\sigma(\overline{\theta}_4 + \overline{\theta}_5)(\overline{\theta}_4^2 + \overline{\theta}_5^2) \] (3.29)
where $\bar{h}_{rad2} = \text{average radiation heat transfer coefficient, W/m}^2\text{K}$

$A = \text{surface area of enclosure, m}^2$

$\varepsilon = \text{enclosure surface emissivity}$

$\sigma = \text{Stefan-Boltzmann constant, 5.67x10}^{-8}\text{W/m}^2\text{K}^4$

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

$T_5 = \text{temperature of the enclosure surroundings, K}$

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.
Set all parameters and constants

Set fixed ambient temperature, $T_5$

Change busbar arrangement

Calculate heat generated by busbar arrangement
Eq. 3.1

Calculate heat dissipated from enclosure via convection and radiation to determine $\bar{T}_4$
Eq. 3.21 to 3.29

Loop 3 times

N
Y

Increment current by 1A

Calculate heat conducted through enclosure wall to determine $\bar{T}_3$
Eq. 3.18 to 3.20

Calculate heat convection within enclosure to determine $\bar{T}_2$
Eq. 3.10 to 3.17

Calculate heat dissipated via convection and radiation to determine $\bar{T}_1$
Eq. 3.2 to 3.9

Loop 3 times

N
Y

Is $\bar{T}_1 > 105°C$

Y

Graph Results

N

All arrangements done

Y

Finish

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

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

<table>
<thead>
<tr>
<th>Description</th>
<th>Variable</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average current in the conductors</td>
<td>( I )</td>
<td>2427A</td>
</tr>
<tr>
<td>Power dissipated per unit length of busbar arrangement</td>
<td>( P )</td>
<td>292.1W</td>
</tr>
<tr>
<td>Total heat dissipated per unit length of enclosure</td>
<td>( P )</td>
<td>292.1W</td>
</tr>
<tr>
<td>Temperature of the enclosure surroundings</td>
<td>( T_5 )</td>
<td>23.6°C</td>
</tr>
<tr>
<td>Average temperature of the enclosure outer surface</td>
<td>( T_4 )</td>
<td>49.5°C</td>
</tr>
<tr>
<td>Average temperature of the enclosure inner surface</td>
<td>( T_3 )</td>
<td>49.5°C</td>
</tr>
<tr>
<td>Average temperature of air within the enclosure</td>
<td>( T_2 )</td>
<td>71.5°C</td>
</tr>
<tr>
<td>Average temperature of busbars</td>
<td>( T_1 )</td>
<td>94.0°C</td>
</tr>
<tr>
<td>Heat dissipated from busbars due to convection</td>
<td>( q_{\text{conv1}} )</td>
<td>274.1W</td>
</tr>
<tr>
<td>Heat dissipated from busbars due to radiation</td>
<td>( q_{\text{rad1}} )</td>
<td>18.0W</td>
</tr>
<tr>
<td>Heat conducted through enclosure wall</td>
<td>( q_{\text{cond}} )</td>
<td>292.1W</td>
</tr>
<tr>
<td>Heat dissipated from enclosure due to convection</td>
<td>( q_{\text{conv2}} )</td>
<td>118.0W</td>
</tr>
<tr>
<td>Heat dissipated from enclosure due to radiation</td>
<td>( q_{\text{rad2}} )</td>
<td>174.1W</td>
</tr>
</tbody>
</table>
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 in 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>
<thead>
<tr>
<th>Ambient Operating</th>
<th>Busbar Width, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Number of Busbars per Phase</td>
<td>1</td>
</tr>
<tr>
<td>°C</td>
<td>Estimated Maximum Current Carrying Capacity, Amperes</td>
</tr>
<tr>
<td>40 105</td>
<td>872  1338  1722</td>
</tr>
<tr>
<td>40 100</td>
<td>830  1274  1640</td>
</tr>
<tr>
<td>40 90</td>
<td>743  1141  1469</td>
</tr>
<tr>
<td>40 80</td>
<td>648  996   1284</td>
</tr>
<tr>
<td>40 70</td>
<td>544  838   1080</td>
</tr>
<tr>
<td>35 105</td>
<td>909  1394  1793</td>
</tr>
<tr>
<td>35 95</td>
<td>827  1269  1633</td>
</tr>
<tr>
<td>35 85</td>
<td>739  1136  1462</td>
</tr>
<tr>
<td>35 75</td>
<td>645  992   1278</td>
</tr>
<tr>
<td>35 65</td>
<td>542  834   1075</td>
</tr>
<tr>
<td>30 105</td>
<td>945  1448  1862</td>
</tr>
<tr>
<td>30 100</td>
<td>905  1388  1785</td>
</tr>
<tr>
<td>30 90</td>
<td>823  1263  1626</td>
</tr>
<tr>
<td>30 80</td>
<td>736  1131  1456</td>
</tr>
<tr>
<td>30 70</td>
<td>642  988   1273</td>
</tr>
<tr>
<td>30 60</td>
<td>539  830   1071</td>
</tr>
</tbody>
</table>
Figure 4.1 Operating Temperature of Busbars for a Given Current at 40°C Ambient Temperature

Temperature (°C) vs. Current (Ampere) for different busbar configurations:
- 63 SINGLE
- 63 TWIN
- 63 TRIPLE
- 80 SINGLE
- 80 TWIN
- 80 TRIPLE
- 100 SINGLE
- 100 TWIN
- 100 TRIPLE
- 125 SINGLE
- 125 TWIN
- 125 TRIPLE
- 160 SINGLE
- 160 TWIN
- 160 TRIPLE
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

<table>
<thead>
<tr>
<th>Bar Size, mm</th>
<th>Number of Bars</th>
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### Table 4.4 Temperature of Busbars at Nominal Switch Sizes and 35°C Ambient

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

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

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Page 58
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

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

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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.
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<td>90</td>
<td>786</td>
</tr>
<tr>
<td>30</td>
<td>80</td>
<td>703</td>
</tr>
<tr>
<td>30</td>
<td>70</td>
<td>612</td>
</tr>
<tr>
<td>30</td>
<td>60</td>
<td>513</td>
</tr>
</tbody>
</table>

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

![Intersection of Extrapolated and Calculated Current Ratings](image)

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.

<table>
<thead>
<tr>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average current in the conductors</td>
<td>2427A</td>
</tr>
<tr>
<td>Power dissipated per unit length of busbar arrangement</td>
<td>292.1W</td>
</tr>
<tr>
<td>Temperature of the enclosure surroundings</td>
<td>23.6°C</td>
</tr>
<tr>
<td>Average temperature of air within the enclosure</td>
<td>78.7°C</td>
</tr>
<tr>
<td>Average temperature of air within at the top of the enclosure</td>
<td>83.6°C</td>
</tr>
<tr>
<td>Average temperature of busbars</td>
<td>105°C</td>
</tr>
</tbody>
</table>
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

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

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

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.

<table>
<thead>
<tr>
<th>Ambient °C</th>
<th>Operating Current, Ampere</th>
<th>Number of Busbars per Phase</th>
<th>Busbar Width, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>105</td>
<td>2</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>-15</td>
<td></td>
<td>-12</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>-68</td>
<td>80</td>
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<tr>
<td></td>
<td>70</td>
<td>-80</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>113</td>
<td>125</td>
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<tr>
<td></td>
<td>85</td>
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<td>160</td>
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<td>100</td>
<td>80</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>-12</td>
<td>-33</td>
<td>-12</td>
</tr>
<tr>
<td></td>
<td>66</td>
<td>-62</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>-103</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>-125</td>
<td>125</td>
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<td></td>
<td>17</td>
<td>-81</td>
<td>160</td>
</tr>
<tr>
<td>40</td>
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<td>-111</td>
<td>-12</td>
</tr>
<tr>
<td></td>
<td>59</td>
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<td>63</td>
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<tr>
<td></td>
<td>17</td>
<td>-91</td>
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<tr>
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<td>125</td>
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<td>-77</td>
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<td>35</td>
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<td>-115</td>
<td>-12</td>
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<td>-39</td>
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<td>63</td>
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<td>-69</td>
<td>-142</td>
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<td>95</td>
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<td>27</td>
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<tr>
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<td>29</td>
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<td>-109</td>
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<td>24</td>
<td>-84</td>
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<tr>
<td></td>
<td>-17</td>
<td>15</td>
<td>-69</td>
</tr>
<tr>
<td>30</td>
<td>105</td>
<td>28</td>
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<td>43</td>
<td>-139</td>
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</tr>
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<td></td>
<td>66</td>
<td>28</td>
<td>163</td>
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<td>30</td>
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<td>30</td>
<td>-117</td>
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<td>28</td>
<td>-195</td>
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<tr>
<td></td>
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<td>12</td>
<td>163</td>
</tr>
<tr>
<td>30</td>
<td>80</td>
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</tr>
<tr>
<td></td>
<td>-21</td>
<td>9</td>
<td>-83</td>
</tr>
</tbody>
</table>
Table 5.3 Percentage Error of Matlab Script vs. AS3000 Calculated Current Carrying Capacities with AS3000 as the Base.

<table>
<thead>
<tr>
<th>Ambient °C</th>
<th>Operating °C</th>
<th>Number of Busbars per Phase</th>
<th>Busbar Width, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40 105</td>
<td>63  80 100 125 160</td>
<td></td>
</tr>
<tr>
<td>40 100</td>
<td>40 90</td>
<td>80 105 95 85 75 105 75 65 105</td>
<td></td>
</tr>
<tr>
<td>40 80</td>
<td>40 70</td>
<td>70 105 95 85 75 65 105 65 105</td>
<td></td>
</tr>
<tr>
<td>40 70</td>
<td>35 105</td>
<td>105 95 85 75 65 105 75 75 105</td>
<td></td>
</tr>
<tr>
<td>35 95</td>
<td>35 85</td>
<td>95 85 75 65 105 75 75 65 105</td>
<td></td>
</tr>
<tr>
<td>35 75</td>
<td>35 65</td>
<td>75 75 65 105 75 75 65 75 105</td>
<td></td>
</tr>
<tr>
<td>30 105</td>
<td>30 100</td>
<td>105 100 90 80 70 90 70 60 90</td>
<td></td>
</tr>
<tr>
<td>30 90</td>
<td>30 80</td>
<td>90 80 70 60 70 60 70 60 70 60</td>
<td></td>
</tr>
<tr>
<td>30 70</td>
<td>30 60</td>
<td>70 60 70 60 70 60 70 60 70 60</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Percentage Error</th>
<th>1  2  3  1  2  3  1  2  3  1  2  3</th>
</tr>
</thead>
<tbody>
<tr>
<td>±7.8% error</td>
<td>%</td>
</tr>
</tbody>
</table>

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>
<thead>
<tr>
<th>Description</th>
<th>Matlab Script</th>
<th>AS 60890</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Current in the conductors</td>
<td>2427A</td>
<td>2427A</td>
<td>0%</td>
</tr>
<tr>
<td>Temperature of the enclosure surroundings</td>
<td>23.6°C</td>
<td>23.6°C</td>
<td>0%</td>
</tr>
<tr>
<td>Average temperature of the enclosure outer surface</td>
<td>49.5°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average temperature of the enclosure inner surface</td>
<td>49.5°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average temperature of air within the enclosure</td>
<td>71.5°C</td>
<td>78.7°C</td>
<td>9.1%</td>
</tr>
<tr>
<td>Average operating temperature of busbar</td>
<td>94.0°C</td>
<td>105°C</td>
<td>10.5%</td>
</tr>
</tbody>
</table>
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.

![Potential Solution Scenario](image)

**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
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) ___________________________ Date: 11 / 03 / 2013

(Supervisor) ___________________________ Date: / / 2013

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

Roland Barrett

Chris Snook
8 Appendix B

8.1 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 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

% Bus Zone Cross-Section
|
| 315 |
| 90 | 60 |

<table>
<thead>
<tr>
<th>W</th>
<th>N</th>
<th>46</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>377</td>
<td>R</td>
<td>B</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
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<td></td>
</tr>
<tr>
<td>146</td>
<td>85</td>
<td>47</td>
</tr>
</tbody>
</table>

%% 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 bright 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 bright 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
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,...
               0.125,0.125,0.125,0.160,0.160,0.160;...
               1,2,3,1,2,3,1,2,3,1,2,3;...
               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

% 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
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 Nusselt 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 Nusselt 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

%% 5.0 Outputs
EQc = (T4-T5)/Rcvo;
EQr = (T4-T5)/Rrad;
fprintf('Busbar Size
%4.0f mm',bw*1000);
fprintf('Number of Bars per Phase
%4.0f ,bpp);
fprintf('Average Current in the Conductors
%4.0f Amperes',bc);
% Power dissipated per unit length of busbar arrangement
fprintf('\nPower dissipated per unit length of busbar arrangement %3.1f Watts' , Qt);
% Total heat dissipated per unit length of enclosure
fprintf('\nTotal heat dissipated per unit length of enclosure %3.1f Watts' , bh);
fprintf('\n\n\nTemperature of the enclosure surroundings %3.1f°C', T5);
% Average temperature of the enclosure outer surface
fprintf('\nAverage temperature of the enclosure outer surface %3.1f°C', T4);
% Average temperature of the enclosure inner surface
fprintf('\nAverage temperature of the enclosure inner surface %3.1f°C', T3);
% Average temperature of air within the enclosure
fprintf('\nAverage temperature of air within the enclosure %3.1f°C', T2);
% Average temperature of busbar
fprintf('\nAverage temperature of busbar %3.1f°C', T1);
fprintf('\n\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);
% Heat dissipated from enclosure due to convection
fprintf('\nHeat dissipated from enclosure due to convection %3.1f Watts', EQc);
% Heat dissipated from enclosure due to radiation
fprintf('\nHeat dissipated from enclosure due to radiation %3.1f Watts', EQr);
fprintf('\n\n\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
grid
% Add Grid to graphs
% End Program
9 Appendix C

9.1 AS 3000:1991 Method Calculations
### (A) BUSBAR DETAILS

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width of Phase Bar</td>
<td>mm</td>
<td>63, 63, 63, 80, 80, 80, 100, 100, 100, 125, 125, 125, 125, 160, 160, 160</td>
</tr>
<tr>
<td>Number of Bars per Phase</td>
<td></td>
<td>1, 2, 3, 1, 2, 3, 1, 2, 3, 1, 2, 3</td>
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<tr>
<td>Width of Neutral Bar</td>
<td>mm</td>
<td>63, 63, 63, 80, 80, 80, 100, 100, 100, 125, 125, 125, 125, 160, 160, 160</td>
</tr>
<tr>
<td>Number of Bars per Neutral</td>
<td></td>
<td>1, 2, 3, 1, 2, 3, 1, 2, 3</td>
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<tr>
<td>Number of Phases</td>
<td></td>
<td>3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3</td>
</tr>
<tr>
<td>Busbar Cross Sectional Area</td>
<td>mm²</td>
<td>1587.6, 3175.2, 4762.8, 2016, 4032, 6048, 2520, 5040, 5750, 3150, 6300, 9430, 4032, 8064, 12096</td>
</tr>
</tbody>
</table>

### (B) KNOWN DATA

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Carrying Capacity (Table C1)</td>
<td>A</td>
<td>1165, 1990, 2710, 1370, 2375, 3190, 1700, 2800, 3715, 1970, 3155, 4275, 2430, 3790, 5060</td>
</tr>
<tr>
<td>Ambient Temperature</td>
<td>°C</td>
<td>40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40, 40</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>°C</td>
<td>105, 105, 105, 105, 105, 105, 105, 105, 105, 105, 105, 105, 105, 105, 105, 105, 105</td>
</tr>
</tbody>
</table>

### (C) ENCLOSURE DETAILS (Bus Zone)

<table>
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<tr>
<th>Description</th>
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<th>Values</th>
</tr>
</thead>
<tbody>
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<td>Enclosure Cross Sectional Area</td>
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<tr>
<td>Magnetic Material</td>
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<tr>
<td>Non-Magnetic Material</td>
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<td>No, No, No, No, No, No, No, No, No, No, No, No, No, No, No, No, No</td>
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<tr>
<td>Outdoors</td>
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<td>No, No, No, No, No, No, No, No, No, No, No, No, No, No, No, No, No</td>
</tr>
<tr>
<td>Indoors - Poorly Ventilated</td>
<td></td>
<td>No, No, No, No, No, No, No, No, No, No, No, No, No, No, No, No, No</td>
</tr>
<tr>
<td>Indoors - Well Ventilated</td>
<td></td>
<td>Yes, Yes, Yes, Yes, Yes, Yes, Yes, Yes, Yes, Yes, Yes, Yes, Yes, Yes, Yes, Yes, Yes</td>
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### (D) RATIO

<table>
<thead>
<tr>
<th>Description</th>
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<th>Values</th>
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</thead>
<tbody>
<tr>
<td>BUSBAR/ENCLOSURE CSA'S</td>
<td></td>
<td>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%</td>
</tr>
</tbody>
</table>

### (E) DEGREE OF ENCLOSURE

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
<th>Values</th>
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</thead>
<tbody>
<tr>
<td>De-rating Factor (Table C3)</td>
<td></td>
<td>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</td>
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### (F) TEMPERATURE RATING

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<th>Values</th>
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</thead>
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<td>De-rating Factor (Table C4)</td>
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<td>1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1</td>
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### (G)"ADJUSTED RATING"

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<th>Units</th>
<th>Values</th>
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</thead>
<tbody>
<tr>
<td>Arrangement Current Carrying Capacity</td>
<td>A</td>
<td>827.15, 1353.2, 1761.5, 959, 1591.25, 2012.89, 1173, 1820, 2277.3, 1339.6, 1990.81, 2905.15, 1652.4, 2357.38, 2874.08</td>
</tr>
<tr>
<td>Busbar Width, mm</td>
<td>Ambient</td>
<td>Operating</td>
</tr>
<tr>
<td>------------------</td>
<td>---------</td>
<td>-----------</td>
</tr>
<tr>
<td>63</td>
<td>1</td>
<td>0.71</td>
</tr>
<tr>
<td>80</td>
<td>2</td>
<td>0.67</td>
</tr>
<tr>
<td>100</td>
<td>3</td>
<td>0.69</td>
</tr>
<tr>
<td>125</td>
<td>4</td>
<td>0.7</td>
</tr>
<tr>
<td>150</td>
<td>5</td>
<td>0.68</td>
</tr>
<tr>
<td>160</td>
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</table>

<table>
<thead>
<tr>
<th>Busbar Width, mm</th>
<th>Number of Busbars per Phase</th>
<th>Number of Busbars per Phase</th>
<th>Degree of Endurance Decrating</th>
</tr>
</thead>
<tbody>
<tr>
<td>63</td>
<td>1</td>
<td>0.715</td>
<td>0.65</td>
</tr>
<tr>
<td>80</td>
<td>2</td>
<td>0.675</td>
<td>0.65</td>
</tr>
<tr>
<td>100</td>
<td>3</td>
<td>0.69</td>
<td>0.63</td>
</tr>
<tr>
<td>125</td>
<td>4</td>
<td>0.7</td>
<td>0.65</td>
</tr>
<tr>
<td>150</td>
<td>5</td>
<td>0.685</td>
<td>0.65</td>
</tr>
<tr>
<td>160</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Busbar Width, mm</th>
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<td>0.675</td>
<td>0.65</td>
</tr>
<tr>
<td>100</td>
<td>3</td>
<td>0.69</td>
<td>0.63</td>
</tr>
<tr>
<td>125</td>
<td>4</td>
<td>0.7</td>
<td>0.65</td>
</tr>
<tr>
<td>150</td>
<td>5</td>
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<tr>
<th>Busbar Width, mm</th>
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10 Appendix D

10.1 AS 60890:2009 Method Calculations
### (A) BUSBAR DETAILS

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Width of Phase Bar</td>
<td>125 mm</td>
</tr>
<tr>
<td>Number of Bars per Phase</td>
<td>3</td>
</tr>
<tr>
<td>Thickness of Phase Bar</td>
<td>6.3 mm</td>
</tr>
<tr>
<td>Width of Neutral Bar</td>
<td>125 mm</td>
</tr>
<tr>
<td>Number of Bars per Neutral</td>
<td>1</td>
</tr>
<tr>
<td>Thickness of Neutral Bar</td>
<td>6.3 mm</td>
</tr>
<tr>
<td>Number of Phases</td>
<td>3</td>
</tr>
<tr>
<td>Maximum Operating Current</td>
<td>3416 A</td>
</tr>
<tr>
<td>Power Loss per Phase</td>
<td>192.9 W/m</td>
</tr>
<tr>
<td>Power Loss at Operating Current</td>
<td>97.37244076 W/m</td>
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</table>

### (B) KNOWN DATA

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Operating Current</td>
<td>2427 A</td>
</tr>
<tr>
<td>Ambient Temperature</td>
<td>23.6 °C</td>
</tr>
<tr>
<td>Temperature Rise</td>
<td>60 °C</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>105 °C</td>
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### (C) ENCLOSURE DETAILS (Bus Zone)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Height</td>
<td>377 mm</td>
</tr>
<tr>
<td>Width</td>
<td>810 mm</td>
</tr>
<tr>
<td>Depth</td>
<td>315 mm</td>
</tr>
<tr>
<td>Number of Horizontal Partitions</td>
<td>0</td>
</tr>
<tr>
<td>Ventilation</td>
<td>NO</td>
</tr>
<tr>
<td>Inlet Ventilation</td>
<td>0 cm²</td>
</tr>
<tr>
<td>Outlet Ventilation</td>
<td>0 cm²</td>
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</tbody>
</table>

### (D) ENCLOSURE EFFECTIVE COOLING SURFACE

<table>
<thead>
<tr>
<th>Area</th>
<th>Surface Factor</th>
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<tbody>
<tr>
<td>$A_o$</td>
<td>$b$</td>
</tr>
<tr>
<td>Top</td>
<td>0.25515</td>
</tr>
<tr>
<td>Front</td>
<td>0.30537</td>
</tr>
<tr>
<td>Rear</td>
<td>0.30537</td>
</tr>
<tr>
<td>Left Hand Side</td>
<td>0.118755</td>
</tr>
<tr>
<td>Right Hand Side</td>
<td>0.118755</td>
</tr>
<tr>
<td>$A_e = \sum (A_o*b)=Total$</td>
<td>0.906876</td>
</tr>
</tbody>
</table>

$A_e > 1.25m^2$

$$f = h^{0.35}/A_o$$

$A_e < 1.25m^2$

$$g = h/w$$

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enclosure Constant (Figure 7)</td>
<td>k</td>
</tr>
<tr>
<td>Factor of Horizontal Partitions</td>
<td>d</td>
</tr>
<tr>
<td>Temperature Distribution Factor (Figure 8)</td>
<td>c</td>
</tr>
<tr>
<td>Effective Power Loss</td>
<td>P</td>
</tr>
<tr>
<td>Exponent</td>
<td>x</td>
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$$P^* = 81.04571037$$

$$At_0.5 = k^*d^*P^*$$

$$At_{1.0} = c^*At_0.5$$

Air Temperature Adjacent to the Busbars | 83.56085836 |
11 Appendix E

11.1 Bus Zone General Arrangement Drawings
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>


<http://www.saiglobal.com/online/autologin.asp>


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