TNSP OPERATIONAL LINE RATINGS

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TABLE OF CONTENTS

1. INTRODUCTION

This document describes the calculation and methods which are used for determining thermal ratings for transmission lines. It should be noted that thermal ratings are only one of several aspects of transmission network operation which determine the network capability. Other aspects are not discussed in this document but include transient stability, dynamic stability and voltage support capability. All of these elements must be maintained in operating a transmission system. As such the actual capability of the system is determined by the lowest of these elements and therefore, in many cases transmission capability is not actually determined by the thermal transmission line ratings.

An overhead transmission line thermal rating (“line rating”) is a limit on the combination of the line-current magnitude and duration, for the purpose of restricting conductor temperature. Conductor temperature, in turn is restricted in order to limit one or more of the following:

- The clearance between the conductor and ground
- The clearance to other conductors
- Protection from loss of tensile strength or permanent conductor damage by heat.

There are some significant differences in networks that operate in the NEM. These differences are derived predominantly from the geography, climate, topography, distribution of load and the distribution and types of generation source available in each NEM region.

While recognising the constraints imposed by network differences, a common approach to the calculation of line ratings across the NEM has been agreed so that all TNSPs in the NEM use the same equations and the same secondary environmental variables (i.e. excluding wind speed and ambient temperature) when calculating line ratings. The only source of differing rating outcomes in each region or state arises from differing ambient conditions.

2. LINE RATING PRINCIPLES

A transmission line is designed for the conductors to be operated up to a defined maximum temperature (i.e. its “design temperature”). The design temperature and the minimum ground clearance are key factors in line design parameters. The conductor type and size are important in determining the mechanical strength and the energy transfer capability of the line. The aim of this section of the report is to describe the factors that determine the energy transfer at the design temperature of the line.

The design temperature determines the limit of expansion of the conductor and this in turn sets the ground clearance at this temperature. The limit on the design temperature of the conductor is normally determined by the material properties of the conductor, the span length between towers and the tower height. Loss of conductor strength due to annealing always needs to be avoided to ensure that the conductor and the transmission line have a reasonable life expectancy.

The conductor ground clearance is stipulated by legislation and/or public safety clearance practices[1]. The energy transferred by the line must be limited to ensure that the conductor does not infringe these clearances by operating at above its design temperature.

In operation the conductor temperature is increased by electrical losses (due to the conducted current) and by the incidence of solar radiation, whereas it is cooled by combined natural and forced convection (wind) and radiation. The conductor temperature is determined by the

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[1] Jurisdictional legislation applies.

balance of the heat-gain and heat-loss processes, the ambient temperature and by the thermal capacity of the conductor.

Weather conditions can vary significantly throughout a day. The ambient temperature changes relatively slowly but it is common for substantial changes in the speed and the direction of the wind to occur over short periods of time. In the line design process an ambient temperature, solar radiation, wind speed and direction are selected to calculate the design value for the energy transfer rate or “current rating” required of the line. The design values are chosen so that the designed energy transfer rate is available for most of the period specified (day, night, summer, winter etc). Conditions of high ambient temperature and/or low wind speed may require the line rating to be reduced, i.e. the design temperature is reached when the energy transfer rate is less than the original design value.

3. TYPES OF LINE RATINGS

It has been agreed that line ratings be defined predominantly under the following two categories.

a. Normal – a continuous rating applicable to normal system operation
b. Real-time – a rating dependent on appropriate measurements of ambient temperature and wind conditions

Each TNSP provides **Normal** ratings for operational and operational planning purposes. These ratings are provided as at least a **Day-time** and a **Night-time** rating for at least each **month** of the year (i.e. at least 24 Normal ratings on each line). TNSPs may also provide other ratings where there is an operational benefit in doing so, such as short time ratings or contingency ratings.

All TNSPs are developing the application of **Real-time** ratings where those ratings would provide an operational benefit to allow best utilisation of critical transmission lines in the long term.

3.1 Normal Ratings

This has also been known as a “Continuous” rating.

A line rating that can be applied at any time. It is a static[2] rating that may vary on a monthly (or seasonal basis) and between night and day. It is a line rating which remains constant over a defined period. It is independent of the prevailing ambient conditions during the defined period. In assigning this rating, it is recognised that the conductor may be subjected to the rated current for very long periods of time (theoretically for 100% of the time)

Normal ratings of lines are used for network planning and operational planning purposes and for operational circumstances where another form of rating is not available or necessary. Each Normal rating is a constant, value and is a reflection of the average, “adverse” weather conditions for the particular period that it is applied, in a particular geographical region.

3.2 Real-time Ratings

A line rating, which is determined either from appropriate measured wind speed and air temperature, or from direct measurement of conductor parameters. To be classified as a Real-

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[2] **Static** – not real-time (independent of prevailing weather conditions) and not short-time (meaning it is applicable over time frames greater than the time constant of the conductor)

time rating, the data on weather conditions must be measured to an acceptable accuracy and at an acceptable frequency.

The rating can be:

- Calculated from measurement of the two major ambient parameters of wind speed and ambient temperature;
- Determined from measured conductor parameters, such as:
    - Conductor temperature;
    - Conductor tension;
    - Conductor sag; or
    - Conductor ground clearance.

It is recognised that other ambient parameters such as solar radiation and wind direction may also be measured and incorporated into the calculation, but it is necessary for both wind speed and air temperature to be appropriately measured in order for a rating to qualify as a Real-time rating and represent conditions over the entire length of the transmission line.

Real-time ratings are used to maximise use of the transmission system under favourable weather conditions where energy transfer capacity would otherwise be limited by the Normal rating. Appropriate weather details are communicated to the dispatch or control centre and the rating for each line calculated. This approach usually provides a higher rating but may result in a reduced rating if weather conditions are extreme and unfavourable i.e. low wind and high ambient temperature.

Accurate and timely measurement of ambient temperature and wind conditions which are representative of the entire length of the transmission line are essential in applying Real-time ratings to lines.

4. CALCULATION OF TRANSMISSION LINE NORMAL RATINGS

All TNSPs in the NEM use the same equations and the same secondary environmental variables (i.e. excluding wind speed and ambient temperature) to determine the line ratings. This section provides the equations used to determine the normal line (steady-state) ratings.

Normal (or continuous) ratings are the most widely used. They use a deterministic approach where the actual continual variation in climatic factors is ignored, and certain fixed values of parameters such as wind speed and ambient temperature are adopted.

The normal current rating, I_{DR}, is calculated from the following formula:

$$I_{DR} = \sqrt{\frac{P_C + P_R - P_S}{R_{ac}}} \qquad (1)$$

Where:

P_S = Solar heat-gain rate;

R_{ac} = Effective ac resistance;

P_C = Convection heat-loss rate;

P_R = Radiation heat-loss rate;

and these parameters have been evaluated for the condition that the conductor temperature is equal to the conductor design temperature.

This formula is based on the assumption that the steady conductor current is equal to the normal rating, I_{DR}, and in that steady-state condition of the conductor, the sum of the heat-gain rates is equal to the sum of the heat-loss rates. The following equilibrium condition applies:

$$I^2 R_{ac} + P_S - P_C - P_R = 0 \qquad (2)$$

A normal line rating for a chosen type of conductor can then be determined based on:

- A known value of the conductor design temperature;
- A known set of conductor parameters;
- An assumed, fixed set of ambient parameters; and
- The assumption that the steady value of conductor temperature is equal to the design temperature.

Detailed formulae for calculating each of these parameters is contained in Appendix A. Other formulae used in calculation of non steady state ratings are also included in Appendix A.

The list of conductor parameters, physical parameters and recommended values contained in Attachment A provides a detailed guideline to others using the rating-calculation method. It removes doubt about the selection of parameters and shows how some parameters vary across regions. Weather conditions prevailing in each geographic area can then be used by the TNSP to calculate the appropriate line rating for a region.

5. REGIONAL WEATHER CONDITIONS

There is a wide range of ambient weather conditions across the NEM, which necessitates different rating treatment.

In **Queensland** ambient temperatures have greater variations west of the Great Dividing Range. Day-time wind speeds tend to increase with increasing ambient temperature, but there is some evidence that extreme temperatures inland can be associated with still conditions. The majority of Bureau of Meteorology weather stations are on the coast, while significant lengths of the electrical network are inland.

Also in **NSW** ambient temperatures have greater variations west of the Great Dividing Range. Day-time wind speeds tend to increase with increasing ambient temperature, while most commonly wind speed is significantly lower at night. NSW has many lines that are 150 to 300km long. These lines can traverse a wide variety of terrain and be subjected to major differences in ambient conditions along the line route.

The **Victorian** weather changes can be often and the ambient temperature can vary significantly during the day and from day to day. Hot summer days are normally associated with hot winds. There are windy areas south of the Great Dividing Range and warmer areas with more sunlight north of the range. Low winter temperatures in some areas can be co-incident with low wind speed conditions.

Records indicate that **South Australian** weather conditions can vary substantially at any time or season of the year. Very hot conditions experienced during the summer months are generally accompanied by windy conditions. However, there are occasions where most of the state can experience temperatures of over 40°C with relatively still air conditions.

The **Tasmanian** weather is changeable and influenced by the 'roaring forties' environment. Summer temperatures beyond 25°C are often associated with hot N-NW winds from mainland Australia. Winters are cool to cold and, between calm frosty spells, associated with storms from the W-SW. Snow at elevations above 400m is not uncommon in winter.

6. CONCLUSION

There are some significant differences in networks that operate in the NEM. These differences are derived predominantly from the geography, climate, topography, distribution of load and the distribution and types of generation source available in each NEM region.

While recognising the constraints imposed by network differences, a common approach to the calculation of line ratings across the NEM has been agreed so that all TNSPs in the NEM use the same equations and the same secondary environmental variables (i.e. excluding wind and ambient temperature) when calculating line ratings. The only source of differing rating outcomes in each region or state arises from differing ambient conditions.

All TNSPs in the NEM have jointly developed a common approach to calculate the thermal rating of transmission lines. This document describes the common calculation and methods which are used for determining thermal ratings for transmission lines

7. REFERENCES

[1] ESAA Document D(b)5 –1988, “Current Rating of Bare Overhead Line Conductors”, Electrical Supply Association of Australia.

[2] V T Morgan, “The thermal rating of overhead-line conductors Part 1. The steady-state thermal model”, Electric Power Systems Research, Vol 5, pp 119 –139, 1982.

[3] V T Morgan, “Rating of bare overhead conductors for continuous currents”, Proceedings of the IEE, Vol 114, No 10, pp 1473 – 1482, 1967.

[4] V T Morgan, “Some factors which influence the continuous and dynamic thermal ratings of overhead-line conductors”, Paper 230-08, CIGRE Symposium 06-95, Brussels 1985.

[5] AS 3607-1989, “Conductors – Bare overhead, aluminium and aluminium alloy – Steel reinforced”.

[6] EPRI Final Report EL-5707 for Project 2546-1, “Conductor Temperature Research”, Georgia Institute of Technology, Atlanta, May 1988.

[7] W A Lewis and P D Tuttle, “The resistance and reactance of aluminium conductors, steel reinforced”, AIEE Transactions, Part III, Vol 77, February 1959, pp 1189 – 1210.

[8] Gradshteyn & Ryzhik, Tables of Integrals, Series and Products.

[9] J S Barrett, O Nigol, C J Fehervari, R D Findlay, “A new model of resistance in ACSR conductors”, IEEE Transactions on Power Systems, PWRD-1, No 2, pp 198-208 (1986).

[10] D A Douglass, L A Kirkpatrick and L S Rathbun, “AC resistance of ACSR – magnetic and temperature effects” IEEE Transactions on Power Apparatus and Systems, Vol PAS-104, No 6, June 1985, pp 1578 – 1684.

APPENDIX A - TNSP Conductor Rating Calculation Method

A.1 Introduction

The following sections present the equations that are recommended for use to evaluate the (per unit length) heat-gain and heat-loss powers of transmission line conductors.

A.2 Parameter Definitions

A.2.1 Conductor Parameters

D	Diameter of conductor (m)
T_c	Conductor temperature (ºC)
I	Conductor current (A)
I_{DR}	Deterministic Conductor Rating (A)
α	Temperature coefficient of dc resistance at 20ºC (K^{-1})
ε	Emissivity of the conductor surface (Recommended value = 0.8)
a	Solar absorption coefficient of the conductor surface (Recommended value = 0.8)
m	Mass per one metre of conductor length (kg m^{-1})
C_p	Heat capacity per kg of conductor (J kg^{-1})
ρ_A, ρ_S	Densities of aluminium and steel (kg m^{-3})

A.2.2 Ambient Parameters

T_A	Ambient temperature (ºC)
T_G	Ground temperature (ºC)
T_D	Sky temperature (ºC)
V	Wind speed (m/s) (assumed to be horizontal)
Ψ	Angle of attack to the wind to the conductor axis (º)
I_{B0}	Direct-beam solar intensity under standard conditions (W/m^2)
I_d	Diffuse solar intensity (W/m^2)
F	Albedo (ground reflectance) (Recommended value = 0.2)

A.2.3 Physical Constants

g	acceleration due to gravity = 9.81 m/s^2
σ	Stefan-Boltzmann constant = 5.67×10^{-8} (W/m^2 K^4)

A.2.4 Power-Loss Rates

P_N	Power-loss rate per metre of conductor due to natural convection (W/m)
P_F	Power-loss rate per metre of conductor due to forced convection due to the wind (W/m)
P_C	Power-loss rate per metre of conductor due to convection (both natural and forced)
P_R	Power-loss rate per metre of conductor due to radiation (W/m)

A.2.5 Power-Gain Rates

P_S	Power-gain rate per metre of conductor due to solar heating (W/m)
P_{cur}	Power-gain rate per metre of conductor due to Joule and magnetic heating caused by conduction of the current, I (W/m)

A.2.6 Convection Parameters

T_f	Temperature of the air film (ºC) = $\frac{(T_C + T_A)}{2}$
λ_f	Thermal conductivity of the air film (W/mK) = $2.42\times10^{-2} + 7.2\times10^{-5}\times T_f$ p 124 Ref [2]
ν_f	Viscosity of the air film (m^2/s) = $1.32\times10^{-5} + 9.5\times10^{-8}\times T_f$ p124 Ref [2]
G_r	Grashof Number
P_r	Prandtl Number
Nu	Nusselt Number
Re	Reynolds Number of the wind speed V
Ψ	Angle of attack of the wind to the axis of the conductor (°)
B, n, C, P	Parameters in relationship between Nusselt Number due to the wind alone, Reynolds number and angle of attack,. i.e. $Nu_{wind} = B\,(Re)^n\,[\,0.42 + C(\sin\psi)^P]$
V_{eff}	Effective speed of the net air flow due to the combination of natural and forced convection (m/s)
V_x, V_y	Horizontal components of the net air flow respectively perpendicular to and along the axis of the conductor.
V_z	Vertical component of the net air flow (m/s)
Φ	Angle of attack of the effective wind speed V_{eff} to the axis of the conductor (°)
Re^*	Reynolds Number of the effective wind speed, V_{eff}

A.2.7 Solar Heating Parameters

Φ	Latitude (º) (e.g. –19.3º in Townsville, –33.8º in Sydney, -34.9º in Adelaide, -42.9º in Hobart)
χ	Longitude (º) (e.g. 146.8º in Townsville, 151.1º in Sydney, 138.9º in Adelaide, 147.4º in Hobart)
N	Day number in the year (from $N = 1$ on 1st January)
δ_s	Solar declination (º)
ω_{SR}	Solar angle at sunrise (º)
T_{actual}	Time at location (hours AEST)
T_{sunrise}	Sunrise time (hours AEST)
T_S	Solar time (hours)
ω_S	Hour angle (º)
H_S	Solar angle (º) (i.e. angle between the Sun's beam and a horizontal plane)
γ_S	Azimuth angle of the direct solar beam (º)
γ_L	Azimuth angle of the conductor (º)
η	Angle between the Sun's bean and the conductor (º)
I_{B0}	Direct solar beam intensity under standard conditions, (W/m^2)
I_d	Diffuse solar intensity (W/m^2)

A.2.8 Conductor Resistance Parameters

f	Power frequency (Hz) = 50 Hz in Australia
T_{ref}	Reference conductor temperature (usually 20ºC)
$R_{dc}(T_c)$	Conductor dc resistance per unit length at conductor temperature, T_c
$R_{ac}(T_c)$	Conductor (50Hz) ac resistance per unit length at conductor temperature, T_c
k_s	Skin effect resistance multiplier
X	$\sqrt{f / R_{dc}}$ = Parameter applied in the evaluation of the skin effect resistance multiplier
ID	Inner diameter of a tubular conductor (m)
T/D	Ratio of the thickness of the aluminum layers to the conductor diameter in an ACSR Conductor = $(D - ID)/(2 \times D)$

a_0 a_1 a_2, a_3, a_4 Coefficients for polynomial approximation for skin-effect multiplier k_s

k_m Magnetic effect resistance multiplier (applicable to ACSR conductors)

G, H Parameters used in the estimation of the magnetic effect resistance multiplier.

A.3 Power-Gain Rate Due to Solar Heating

A.3.1 Computation Method

Solar gain (per unit length) for a horizontal conductor at sea level is given by Eq (12) in Ref [2]:

$$P_S = a\, D\, [I_{B0} (\sin \eta + \frac{\pi F}{2} \sin H_S) + \frac{\pi}{2} I_d\ (1 + F)] \tag{3.1}$$

where:

D = Conductor diameter (m)

a = Solar absorptivity of the conductor surface

$I_{B0} = 1280 \sin H_S / (\sin H_S + 0.314)$ (W/m^2) from Eq (18) in Ref [2] (3.2)

$I_d = (570 - 0.47 \times I_{B0}) (\sin H_S)^{1.2}$ p123 in Ref [2] (3.3)

F = Albedo (i.e. the reflectance) of the ground.

$H_S = \sin^{-1} [\sin \delta_s \sin \varphi + \cos \delta_s \cos \varphi \cos \omega_S]$ from Eq (14) in Ref [2] (3.4)

$\delta_s = 23.45^\circ \times \sin \left[360^\circ \times \frac{(284 + N)}{365} \right]$ Eq (15) in Ref [2] (3.5)

$\omega_{SR} = \cos^{-1} [- \tan \delta_s \tan \varphi]$ Eq (16) in Ref [2] (3.6)

$T_{sunrise} = 12 - [\omega_{SR} + \text{Longitude} (^\circ) - 150^\circ]/15 + 0.223$ (3.7)

$T_S = T_{actual} - T_{sunrise}$ (3.8)

$\omega_S = \omega_{SR} - 15 \times T_S$ Eq (17) in Ref [2] (3.9)

$\gamma_S = \sin^{-1} [- \cos \delta_s \times \sin \omega_S / \cos H_S]$ p124 in Ref [2] (3.10)

$\eta = \cos^{-1} [\cos H_S \cos (\gamma_S - \gamma_L)]$ from Eq 11 in Ref [3] (3.11)

If the conductor azimuth angle (γ_L) is not known, or varies significantly along the length of the line, then the worst-case assumption that $(\gamma_S - \gamma_L) = \pm 90^\circ$, results in $\sin \eta = 1$ and Equation (3.1) becomes:

$$P_S = a\, D\, [I_{B0} (1 + \frac{\pi F}{2} \sin H_S) + \frac{\pi}{2} I_d\ (1 + F)] \tag{3.12}$$

A.4 Power-Loss Rate Due to Radiation

The power-loss rate P_R due to radiation is given by (Eq (35) Ref [2]):

$$P_R = \pi D \sigma \varepsilon [(T_C + 273)^4 - \tfrac{1}{2}(T_G + 273)^4 - \tfrac{1}{2}(T_D + 273)^4] \qquad (4.1)$$

where

$$T_D = 0.0552\ (T_A + 273)^{1.5} - 273 \qquad \text{p 130 Ref [2]} \qquad (4.2)$$

$T_G = T_A + 5°\text{C}$ for day-time or = $T_A - 5°\text{C}$ for night-time conditions (4.3)

A.5 Power-Loss Rate Due to Convection

A.5.1 Natural Convection

The power loss rate due to natural convection P_N, (in the absence of wind) is then given by

$P_N = \pi\ \lambda_f\ (T_C - T_A)\ Nu_{nat}$ Eq (20) Ref [2] (5.1)

Where:

Nu_{nat} = Nusselt Number due to natural convection

= $A \times (G_r \times P_r)^m$ Eq (21) of Ref [2] (5.2)

and

$$G_r = \text{Grashof Number} = \frac{D^3 g\,(T_C - T_A)}{[T_f + 273]\nu_f^2} \qquad \text{p124 Ref [2]} \qquad (5.3)$$

P_r = Prandtl Number = $0.715 - 2.5\times10^{-4} \times T_f$ p124 Ref [2] (5.4)

If $(G_r \times P_r) \le 10^4$: $A = 0.850$, $m = 0.188$

If $(G_r \times P_r) > 10^4$: $A = 0.480$, $m = 0.250$

A.5.2 Forced Convection (Due to the Wind)

The power loss rate due to forced convection P_F, (in the absence of natural convection) is then given by:

$P_F = \pi\ \lambda_f\ (T_C - T_A)\ Nu_{wind}$ Eq (8) Ref [4] (5.5)

Where:

Nu_{wind} = Nusselt Number due to the wind alone

= $B\ (Re)^n\ [0.42 + C(\sin\psi)^P]$ From Eq (6) of Ref [4] (5.6)

and

$$Re = \text{Reynolds Number due to the wind} = \frac{V D}{\nu_f} \qquad (5.7)$$

If $Re \le 2650$: $B = 0.641$, $n = 0.471$

If $Re > 2650$: $B = 0.048$, $n = 0.800$

It should be noted that the values of Re, B & n above are for circular stranded conductors only. The coefficients would change for smooth body conductors. Refer to Table 3 in Ref [2].

and If $0° \le \psi \le 24°$: $C = 0.68$, $P = 1.08$

$24° < \psi \le 90°$: $C = 0.58$, $P = 0.90$

A.5.3 Mixed Convection (Combined Effects of Wind and Natural Convection)

In the general case, where both natural convection and forced convection contribute to the flow, then the applied approach is to:

- Find a vertical component of an effective, vertical, component of wind speed V_z due to natural convection using Equations (5.2) and (5.6):

$$V_z = \frac{\nu_f}{D}\left[\frac{Nu_{nat}}{B}\right]^{\frac{1}{n}} \qquad \text{with } B = 0.641,\ n = 0.471 \qquad (5.8)$$

- Combine this effective vertical component with the horizontal component due to the wind speed V to find an effective wind speed V_{eff};

$$V_{eff} = \sqrt{V^2 + V_Z^2} \qquad (5.9)$$

- Find the angle of attack of the effective wind speed to the axis of the conductor (φ) by:

  a Finding the component of the wind speed along the axis of the conductor (V_y) from:

$$V_y = V \cos(\psi) \qquad (5.10)$$

  b Finding φ from:

$$\varphi = \cos^{-1}\left[\frac{V_y}{V_{eff}}\right] \qquad (5.11)$$

- Use Equation (5.7) to find the Reynolds Number, Re^* of the effective wind speed V_{eff};

$$Re^* = \frac{V_{eff}\, D}{\nu_f} \qquad (5.12)$$

- Use Equation (5.6) to find the Nusselt Number for the combined flow at angle φ to the conductor axis:

$$Nu_{eff} = B\,(Re^*)^n\,[\,0.42 + C(\sin\varphi)^P] \qquad (5.13)$$

- Use Equation (5.5) to find the mixed-flow convection power loss rate, P_C

$$P_C = \pi\,\lambda_f\,(T_C - T_A)\,Nu_{eff} \qquad (5.14)$$

A.6 Power-Gain Rate Due to Conduction of Current

A.6.1 Power-Gain Processes

The following processes affect the input power when the conductor conducts current:

- The resistive losses in the conducting wires of the conductor;
- The increase of the resistance of the conducting wires with increasing conductor temperature;

- The 50Hz radial magnetic field within the conductor produces a higher current density in the outer layers. This process is known as the “skin effect”. Its influence increases as conductor diameter increases. Its influence decreases as the conductor temperature increases;

- The conduction via helically-wound wires in the different layers make contributions to a 50Hz axial magnetic field. The constraint that the voltage drops along the conductor are the same in each layer produces a non-uniform current per wire in the different layers. The effect is greatest in ACSR conductors with three aluminium layers, where an increase in the current per wire in the middle aluminium layer produces an increase in the conductor resistance. This process is known as the “transformer effect” because of the tendency to maintain an “amp-turn balance” in the aluminium layers. This process is dependent on the conductor temperature, conductor type, and the conductor current; and

- The current distribution that results from the transformer effect in an ACSR conductor produces a non-zero 50Hz axial magnetic field in its steel core. The steel of the core is selected for its tensile strength and it has a large hysteresis loop. The application of the 50Hz axial magnetic field therefore produces magnetic heating in the steel core. This process is also dependent on the conductor temperature, conductor type and conductor current.

A.6.2 Resistance of Conductors

The dc resistance of conductors is generally quoted in standards or manufacturer’s data in Ω/km at a particular reference temperature T_{ref}, which is usually 20°C.

A.6.3 Increase in dc Resistance with Conductor Temperature

The dc resistance increases with conductor temperature. At conductor temperature T_C.:

$$R_{dc}(T_C) = R_{dc}(T_{ref})[1 + \alpha (T_C - T_{ref})] \quad (\Omega / \mathrm{m}) \qquad (6.1)$$

Table A.6.1 shows the values listed in Ref [5] for the temperature coefficient of resistance for different conductor materials.

Material	Resistance coefficient, α (°C^{-1})
Aluminium 1350	0.00403
Aluminium Alloy 1120	0.00390
Aluminium Alloy 6201	0.00360
Copper	0.00381

Table A.6.1 Temperature co-efficient of resistance

A.6.4 Calculation of a.c. Resistance

Two types of methods have been developed that aim to assign conductor a.c. resistances that include the effects described in Section A.6.1. They are:

- Analytic methods (such as that described in Reference [9]) that aim to model all these processes in order to evaluate the conductor resistance at a chosen combination of conductor current and conductor temperature; and

- Semi-empirical methods that (such as that described in Reference [10]):
    - Identify the factor by which the conductor dc resistance needs to be multiplied to account for the skin effect; and
    - For ACSR conductors, assign a further correction factor, which is based measurements and plotted against the current density in the aluminium wires.

The main problem with the first approach is that the calculation method is reasonably complex.

The problem with the semi-empirical approach is that the "transformer effect" is not simply a function of current density.

A.6.5 Skin Effect Resistance Multiplier, k_s

Transmission line conductors have one of the following forms:

- Layers of wires of the one material (e.g. AAC and AAAC conductors); and
- Layers of wires, where the inner layers form a steel core and the outer layers provide the path for current conduction (e.g. ACSR/GZ and AACSR/GZ/1120).

For the computation of the skin effect resistance multiplier, both types of conductor can be considered to be hollow conductors, with an outer diameter D and an inner diameter ID. An alternative description is an outer diameter D and a thickness T of the conductor such that $T = (D - ID)/2$. The homogeneous conductor is an example with $T/D = 0.5$.

Appendix B presents the formula (from Reference [7]) to compute the skin-effect resistance multiplier, k_s.

One approach to assigning the value of k_s is its evaluation from direct usage of the equations of Appendix B.

An alternative method is as follows It is found that k_s is dependent only on the ratio T/D and the factor $X = \sqrt{f / R_{dc}}$, where f is the system frequency (i.e. 50Hz in Australia) and R_{dc} has the units of Ω/km. It should be noted that X and therefore k_s are dependent on the conductor temperature. Most Australian Standard conductors have one of the following values of T/D:

- $T/D = 0.5$ for all AAC, AAAC and Copper conductors;
- $T/D = 3/9 = 0.3333$ for all 54/7 and 54/19 conductors with steel cores; and
- $T/D = 2/7 = 0.2857$ for all 30/7 conductors with steel cores.

In the range of values of X expected for overhead line conductors, the variation of k_s can be fitted quite well (for each of these three values of T/D) with a fourth-order polynomial in X i.e.:

$$k_s = a_0 + a_1 X + a_2 X^2 + a_3 X^3 + a_4 X^4 \qquad (6.2)$$

Where the values of the coefficients for each of the three values of T/D are shown in Table A.6.2.

T/D	Values of Coefficients				
	a_0	a_1	a_2	a_3	a_4
½	+0.99934	$+ 1.9608\times10^{-4}$	$- 2.0493\times10^{-5}$	$+ 8.9859\times10^{-7}$	$+ 1.8572\times10^{-8}$
3/9	+0.99979	$+6.2538\times10^{-5}$	$- 6.4912\times10^{-6}$	$+ 2.8143\times10^{-7}$	$+ 1.4862\times10^{-8}$
2/7	+0.99992	$+2.6909\times10^{-5}$	$- 2.9508\times10^{-6}$	$+ 1.3297\times10^{-7}$	$+ 1.2010\times10^{-8}$

Table A.6.2 Coefficients used to find the value of the skin effect multiplier, k_s

A.6.6 Magnetic-Effect Resistance Multiplier, k_m for 54/7 and 54/19 ACSR

For ACSR conductors with three aluminium layers (e.g. 54/7 and 54/19 ACSR), there is a need for another (current-dependent and conductor-temperature-dependent) factor by which R_{dc} is multiplied in order to assign the value of R_{ac} with reasonable accuracy.

As shown in Reference [9], the process that dominates the contribution to the increased ac resistance in the redistribution of the currents in the three aluminium layers from that which applied for when dc is conducted. The other process is the magnetic losses in the steel wires.

The method described in Reference [9] has been applied at 50Hz to find (at different values of conductor temperature) the values of R_{ac} of Australian Standard ACSR conductors PawPaw (538 mm^2), Olive (508 mm^2), Orange (438 mm^2) and Mango (373 mm^2).

By repeating the calculations with the steel wires replaced by a non-conducting material with a relative permeability of one, the value of k_s produced by the Barrett method for each conductor/temperature combination was calculated.

The value of the magnetic-effect resistance multiplier (k_m) was then found for a range of combinations of:

- Conductor type;
- Conductor current; and
- Conductor temperature.

Some of the results are presented in Appendix C. One outcome is that quite a good approximation in the ranges of conductor current and temperature of practical interest is that an acceptable approximation for k_m for any of these ACSR conductors with three aluminum layers is:

$$k_m = 1 + [G + H \times (T_C - 20)] \times I \qquad (6.3)$$

Where:

$G = 2.7 \times 10^{-5}\ \text{A}^{-1}$

$H = 1.5 \times 10^{-7}\ (\text{A}\ ^{\circ}\text{C})^{-1}$

A.7 Calculation of Deterministic Ratings

A.7.1 Objective

A deterministic line rating for a chosen type of conductor is based on:

- A known value of the conductor design temperature;
- A known set of conductor parameters;
- An assumed, fixed set of ambient parameters;
- The steady conductor current is equal to the deterministic rating, I_{DR}; and
- The assumption that the steady value of conductor temperature is equal to the design temperature.

A.7.2 Calculation Method

For the assumed steady-state condition of the conductor, the sum of the heat-gain rates is equal to the sum of the heat-loss rates. Therefore, for this equilibrium condition:

$$I^2 R_{ac} + P_S - P_C - P_R = 0 \tag{7.1}$$

Where:

P_S = Solar heat-gain rate;

R_{ac} = Effective ac resistance;

P_C = Convection heat-loss rate;

P_R = Radiation heat-loss rate

and have all been evaluated for the condition that the conductor temperature is equal to the conductor design temperature.

From equation (7.1), the deterministic current rating, I_{DR} is found from:

$$I_{DR} = \sqrt{\frac{P_C + P_R - P_S}{R_{ac}}} \tag{7.2}$$

A.8 Calculations of Conductor-Temperature Transients

A.8.1 Transient Conductor-Temperature Calculation Method

For non-steady conditions, the heat balance equation for a conductor that has:

- Uniform conditions along its length; and
- A negligible radial temperature gradient,

is given by (at time = *t*):

$$P_S(t) + I^2 R_{ac}(t) - P_C(t) - P_R(t) - mC_P \frac{dT_C(t)}{dt} = 0 \tag{8.1}$$

where:

P_S = Solar heat-gain rate;

R_{ac} = Effective ac resistance;

P_C = Convection heat-loss rate;

P_R = Radiation heat-loss rate;

m = Mass per one metre of conductor length (kg m^{-3});

C_p = Heat capacity per metre of conductor (J kg^{-1})

For a small time increment, Δt the following approximation can be made for the time differential: of the conductor temperature:

$$\frac{dT_C(t)}{dt} \approx \frac{T_C(t+\Delta t) - T_C(t)}{\Delta t} \tag{8.2}$$

By substituting Equation (8.2) into (8.1) leads to the following approximation for $T_C(t+\Delta t)$, i.e. the conductor temperature at time $(t+\Delta t)$:

$$T_C(t+\Delta t) = T_C(t) + \frac{\Delta t}{mC_P}[\, P_S(t) + I^2 R_{ac}(t) - P_C(t) - P_R(t)] \tag{8.3}$$

Application of the methods described in the sections above to assign values to $P_S(t), I^2 R_{ac}(t), P_C(t)$ and $P_R(t)$ at values of time *t* separated, by a small value of time-increment Δ*t* provides a method that is expected to accurately follow the variation of the conductor temperature.

A.8.3 Assigning the Heat Capacity of Conductors

The mass per metre of the conductor requires:

- The density of the materials used in the wires;
- The number of wires in the different layers; and

- The lengths of the wires in the different layers that includes the influence of the lay lengths.

The following densities (from Reference [5]) have been used:

- For aluminium and aluminium alloy, $\rho_A = 2700$ kg/m^3
- For zinc-coated steel wire, $\rho_S = 7800$ kg/m^3

The specific heat at constant pressure (C_P) for the different materials were taken from Reference [6] to have the following variation with conductor temperature, T_c:

- For aluminium and aluminium alloy, $C_P = 929.4 + 0.32236 \times T_c$ J/(kg ºC)
- For zinc-coated steel wire, $C_P = 441.2 + 0.47517 \times T_c$ J/(kg ºC)

For ACSR conductors, the heat capacities for the steel layers and the aluminum layers need to be combined to produce one value of mC_p for one metre of the conductor

APPENDIX B – Increase in Conductor Resistance Due to Skin Effect

The following method is derived from Ref (7), which applies to a solid or hollow round conductor, with no steel core:

$R_{ac} = R_{dc} \times k_s$ (B.1)

where k_s is the skin effect multiplier.

For homogeneous conductor constructions (AAC etc) k_s can be expressed as follows:

let $z = \sqrt{\dfrac{8\pi.f}{10^4.R_{dc}}}$ where f is in Hz and R_{dc} in Ω/km

then $k_s = \dfrac{z}{2}\left(\dfrac{\mathrm{ber}(z).\mathrm{bei}'(z)-\mathrm{bei}(z).\mathrm{ber}'(z)}{\mathrm{ber}'(z)^2+\mathrm{bei}'(z)^2}\right)$ (B.2)

For hollow conductors (concentric ACSR can be treated as hollow),

let $dd = \dfrac{id^2}{od^2 - id^2}$ let $ee = \dfrac{od^2}{od^2 - id^2}$

where *id* and *od* are inside and outside diameters of conductor

let $mr = \sqrt{\dfrac{8\pi.f.ee}{10^4.R_{dc}}}$ let $mq = \sqrt{\dfrac{8\pi.f.dd}{10^4.R_{dc}}}$

let $a = \mathrm{ker}'(mq)$ let $b = \mathrm{kei}'(mq)$ let $c = -\mathrm{ber}'(mq)$ let $d = -\mathrm{bei}'(mq)$

let $e = \dfrac{ac+bd}{a^2+b^2}$ let $f = \dfrac{ad-bc}{a^2+b^2}$

let $g = e.\mathrm{ker}(mr) - f.\mathrm{kei}(mr)$

let $h = f.\mathrm{ker}(mr) + e.\mathrm{kei}(mr)$

let $i = e.\mathrm{ker}'(mr) - f.kei'(mr)$

let $j = f.\mathrm{ker}'(mr) + e.\mathrm{kei}'(mr)$

let $k = g + \mathrm{ber}(mr)$

let $l = h + \mathrm{bei}(mr)$

let $m = i + \mathrm{ber}'(mr)$

let $n = j + \mathrm{bei}'(mr)$

$k_s = \dfrac{mr}{2.ee}\left(\dfrac{kn-ml}{m^2+n^2}\right)$

The ber, bei, ker, kei functions and their derivatives are defined by the following series expansions.

I Functions (from Ref [8])

$$ber(x) = 1 + \sum_{k=1}^{\infty} \frac{(-1)^k \left(\frac{x}{2}\right)^{4k}}{[(2k)!]^2}$$

$$bei(x)=\sum_{k=1}^{\infty}\frac{(-1)^{k+1}\left(\frac{x}{2}\right)^{4k-2}}{\left[(2k-1)!\right]^{2}}$$

$$ker(x)=\left(\ln(\frac{2}{x})-C\right).ber(x)+\frac{\pi}{4}.bei(x)+\sum_{k=1}^{\infty}\frac{(-1)^{k}\left(\frac{x}{2}\right)^{4k}}{\left[(2k)!\right]^{2}}.\sum_{m=1}^{2k}\frac{1}{m}$$

$$kei(x)=\left(\ln(\frac{2}{x})-C\right).bei(x)-\frac{\pi}{4}.ber(x)+\sum_{k=0}^{\infty}\frac{(-1)^{k}\left(\frac{x}{2}\right)^{4k+2}}{\left[(2k+1)!\right]^{2}}.\sum_{m=1}^{2k+1}\frac{1}{m}$$

C= Euler constant = 0.5772156649......

II Derivatives

$$ber'(x)=\sum_{k=1}^{\infty}\frac{(-1)^{k}.2k\left(\frac{x}{2}\right)^{4k-1}}{\left[(2k)!\right]^{2}}$$

$$bei'(x)=\sum_{k=1}^{\infty}\frac{(-1)^{k+1}(2k-1)\left(\frac{x}{2}\right)^{4k-3}}{\left[(2k-1)!\right]^{2}}$$

$$ker'(x)=\left(\ln(\frac{2}{x})-C\right).ber'(x)-\frac{1}{x}.ber(x)+\frac{\pi}{4}.bei'(x)+\sum_{k=1}^{\infty}\frac{(-1)^{k}.2k\left(\frac{x}{2}\right)^{4k-1}}{\left[(2k)!\right]^{2}}.\sum_{m=1}^{2k}\frac{1}{m}$$

$$kei'(x)=\left(\ln(\frac{2}{x})-C\right).bei'(x)-\frac{1}{x}bei(x)-\frac{\pi}{4}.ber'(x)+\sum_{k=0}^{\infty}\frac{(-1)^{k}(2k+1)\left(\frac{x}{2}\right)^{4k+1}}{\left[(2k+1)!\right]^{2}}.\sum_{m=1}^{2k+1}\frac{1}{m}$$

APPENDIX C - Magnetic Resistance Multiplier for 54/7 & 54/19 ACSR Conductors

The calculation method described in Reference [9], plus some data derived from magnetisation tests on steel wires, were used to compute the 50Hz ac resistance of some Australian Standard 54/7 and 54/19 ACSR conductors.

By replacing the steel core with a non-conducting material with a relative permeability of one for each combination of conductor type and conductor temperature, the value of the "skin-effect resistance multiplier", k_s was found.

For the different combinations of:

- Conductor type;
- Conductor temperature; and
- Conductor current

The "magnetic resistance multiplier", k_m was found from:

$$k_m = R_{ac} /(k_s \times R_{dc}) \qquad (C.1)$$

When a similar approach (as described in Reference [2]) was applied to measured values of R_{ac} to find the current-dependency of k_m, it was plotted against current density for a conductor temperature of 20ºC. The outcome was a high level of scatter, as seen from Figure 4 of Reference [10].

When this approach was applied to the calculated (50Hz at 20ºC) values of k_m or the Australian Standard ACSR, the results of Figure C.1 were obtained.

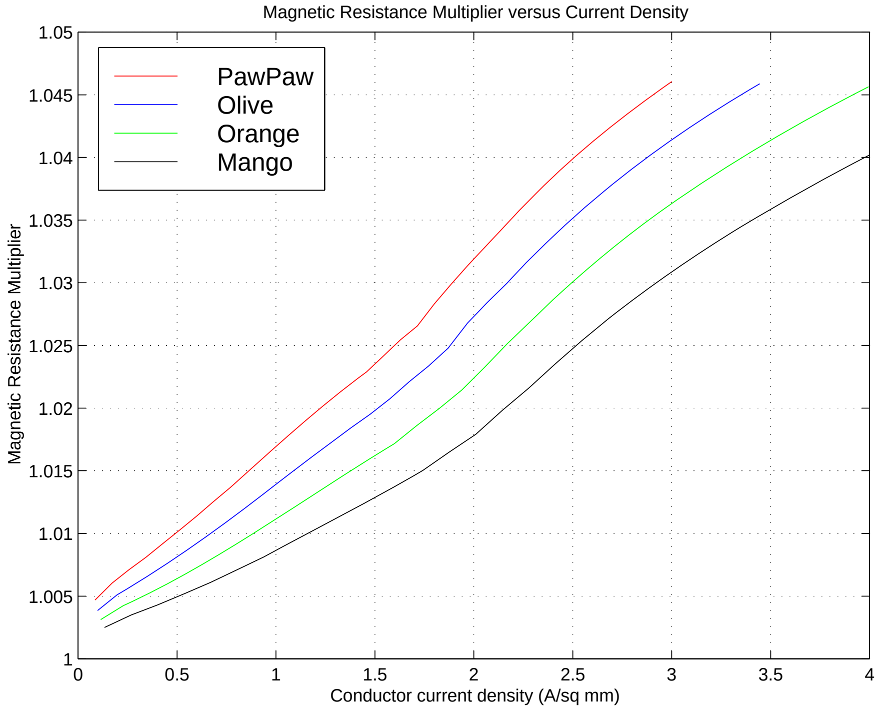

Figure C.1 Calculated values of k_m obtained from the method of Reference [9] for AS ACSR 54/7 & 54/19 Conductors at 20ºC plotted against current density in the aluminium layers.

The calculated results of Figure C.1 show a spread of results quite similar to that of the (60Hz at 20ºC) measured results of Figure 4 of Reference [10] .

However, when the calculated 50Hz values k_m at 20ºC are plotted against conductor current, the results shown in Figure C.2 are obtained.

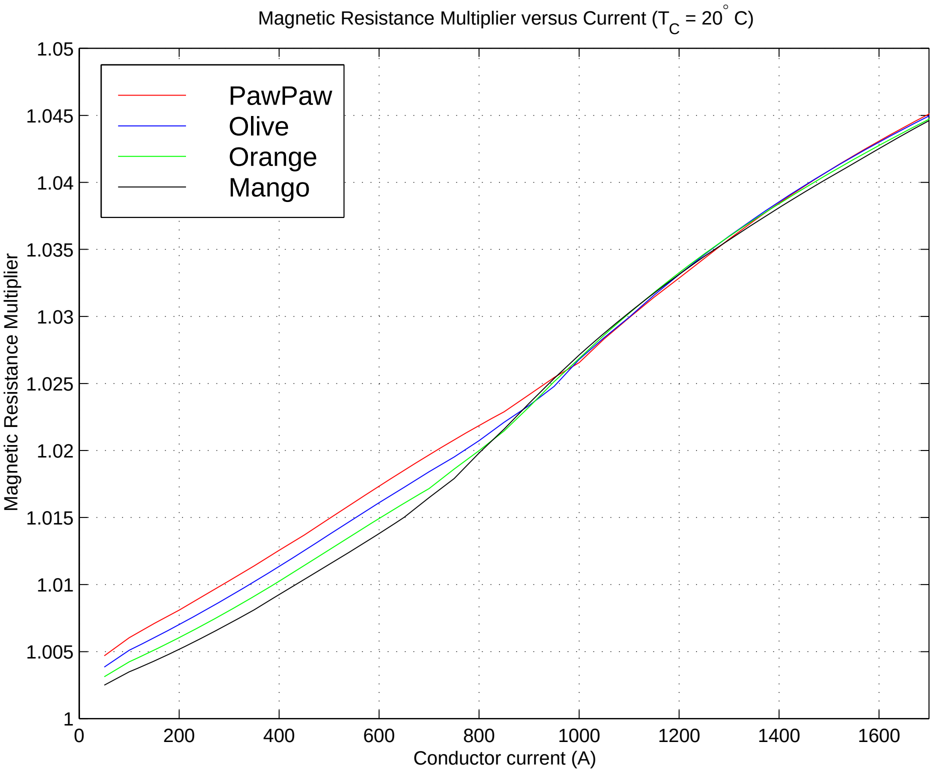

Figure C.2 Calculated values of k_m obtained from the method of Reference [9] for AS ACSR 54/7 & 54/19 Conductors at 20ºC plotted against conductor current.

The results of Figure C.2 suggest that a simple linear approximation for the variation of k_m against conductor current would fit the results quite well for a conductor temperature of 20ºC.

The calculation process was repeated for a conductor temperature of 100ºC and the results shown in Figure C.3 were obtained,

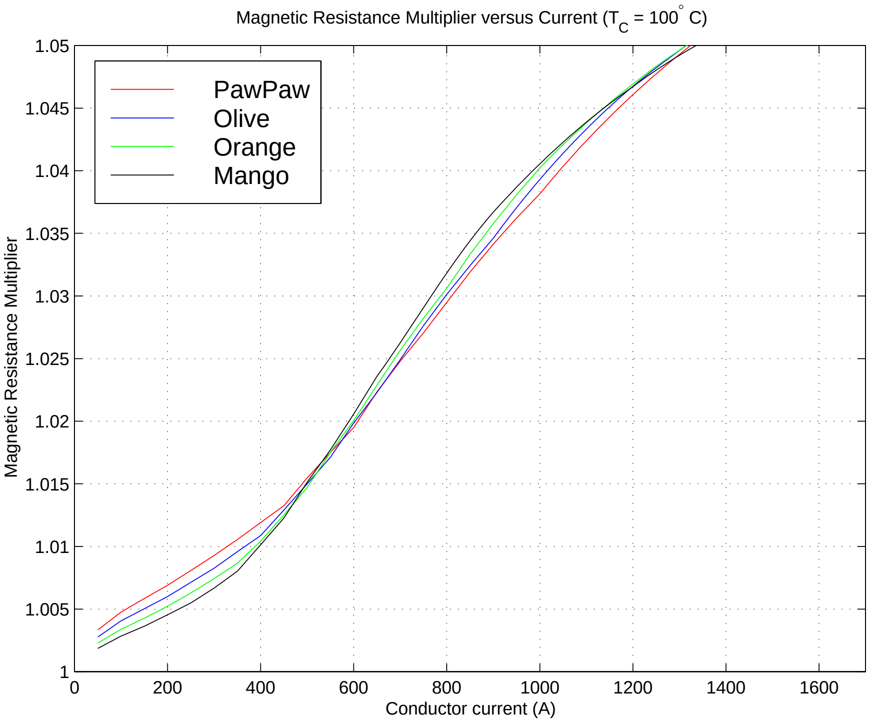

Figure C.3 Calculated values of k_m obtained from the method of Reference [9] for AS ACSR 54/7 & 54/19 Conductors at 100ºC plotted against conductor current.

Again, the results of Figure C.3 suggest that a simple linear approximation for the variation of k_m against conductor current would fit the results quite well for a conductor temperature of 100ºC.

Comparison of the results of Figure C.2 and C.3 show that the linear coefficient chosen to fit the variation of k_m is dependent on the conductor temperature.

A simple approximation that assigns the value of k_m with sufficient accuracy is as follows:

$$k_m = 1 + [G + H \times (T_C - 20)] \times I \qquad \text{(C.3)}$$

Where:

$G = 2.7 \times 10^{-5}\ \mathrm{A}^{-1}$

$H = 1.5 \times 10^{-7}\ (\mathrm{A\ ^\circ C})^{-1}$