

TNSP OPERATIONAL LINE RATINGS

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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 practices¹. 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

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.

In some circumstances there will be operational benefits from applying real time thermal ratings to a transmission circuit. To determine under which circumstances such a benefit may occur, historical weather data of average wind speed and direction, and ambient temperature along the transmission circuit should be obtained and analysed. If for a majority of the time, wind speeds are higher than the assumption used in calculation of the static rating, the application of measured wind speed (and direction where applicable) and ambient temperature will, in most scenarios, increase the thermal rating of a transmission circuit. Operational benefits will only be realised if the thermal static rating is the limiting constraint on the particular transmission circuit and the ambient conditions are more favourable than the static rating assumptions at the time the additional capacity is required. It must be emphasised that the real time rating is determined by the actual weather conditions and these may not always give an increased thermal rating to the line.

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 a cost effective operational benefit to allow improved 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 static² 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

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)

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-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; or
- 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:

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

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:

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

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. TRANSMISSION LINE REAL TIME THERMAL RATINGS

To determine real time thermal ratings for a transmission circuit the environment in which the transmission line operates must be well understood and the input parameters to the heat balance of the conductor adequately measured. These inputs are the fixed physical characteristics of the transmission line as well as the variable parameters of ambient weather conditions. Alternatively, effective conductor temperature, tension or sag monitoring can also be used to determine real time ratings.

With inputs of ambient weather conditions along the length of the transmission line, the current carrying capacity of the circuit must be calculated continuously in real-time. The methodology used for normal ratings (as described in section 4 and Appendix A) is used for the calculation. Rating information needs to be provided to the calculation engine at least every minute or more often if available. The real-time rating should be calculated from data typically averaged over a 10-minute period to provide a stable value. The measured data and calculations then have to be provided to an energy control centre in a suitable format to realise any potential benefits. Suitable real time telecommunications systems must be available for the transfer of data from the measurement sites to the control centre and then to the dispatch centre to allow the use of real time ratings. Temporary unavailability of these telecommunications systems must also be considered in the design and implementation of the real time ratings system.

It should be noted that real time rating systems will show occasions where the real time rating is below the normal static thermal rating. These reduced rating periods must be considered once the information is available.

More information on real time rating methodologies and requirements is in Appendix D.

7. 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.

8. REFERENCES

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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 ($^{\circ}\text{C}$)
I	Conductor current (A)
I_{DR}	Deterministic Conductor Rating (A)
α	Temperature coefficient of dc resistance at 20°C (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 ($^{\circ}\text{C}$)
T_G	Ground temperature ($^{\circ}\text{C}$)
T_D	Sky temperature ($^{\circ}\text{C}$)
V	Wind speed (m/s) (assumed to be horizontal)
Ψ	Angle of attack to the wind to the conductor axis ($^{\circ}$)
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 = $5.67 \times 10^{-8} \text{ (W/m}^2 \text{ K}^4)$

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 ($^{\circ}\text{C}$) = $\frac{(T_C + T_A)}{2}$

λ_f Thermal conductivity of the air film (W/mK) = $2.42 \times 10^{-2} + 7.2 \times 10^{-5} \times T_f$
p 124 Ref [2]

ν_f Viscosity of the air film (m^2/s) = $1.32 \times 10^{-5} + 9.5 \times 10^{-8} \times T_f$ 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 ($^{\circ}$)

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 ($^{\circ}$)

Re^* Reynolds Number of the effective wind speed, V_{eff}

A.2.7 Solar Heating Parameters

Φ	Latitude ($^{\circ}$) (e.g. -19.3° in Townsville, -33.8° in Sydney, -34.9° in Adelaide, -42.9° in Hobart)
χ	Longitude ($^{\circ}$) (e.g. 146.8° in Townsville, 151.1° in Sydney, 138.9° in Adelaide, 147.4° in Hobart)
N	Day number in the year (from $N = 1$ on 1st January)
δ_s	Solar declination ($^{\circ}$)
ω_{SR}	Solar angle at sunrise ($^{\circ}$)
T_{actual}	Time at location (hours AEST)
$T_{sunrise}$	Sunrise time (hours AEST)
T_s	Solar time (hours)
ω_s	Hour angle ($^{\circ}$)
H_s	Solar angle ($^{\circ}$) (i.e. angle between the Sun's beam and a horizontal plane)
γ_s	Azimuth angle of the direct solar beam ($^{\circ}$)
γ_L	Azimuth angle of the conductor ($^{\circ}$)
η	Angle between the Sun's beam and the conductor ($^{\circ}$)
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 $20^{\circ}C$)
$R_{dc}(T_c)$	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]:

$$P_s = a D \left[I_{B0} \left(\sin \eta + \frac{\pi F}{2} \sin H_s \right) + \frac{\pi}{2} I_d (1 + F) \right] \quad (3.1)$$

where:

D = Conductor diameter (m)

a = Solar absorptivity of the conductor surface

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

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

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

$$H_s = \sin^{-1} [\sin \delta_s \sin \phi + \cos \delta_s \cos \phi \cos \omega_s] \quad \text{from Eq (14) in Ref [2]} \quad (3.4)$$

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

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

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

$$T_s = T_{\text{actual}} - T_{\text{sunrise}} \quad (3.8)$$

$$\omega_s = \omega_{SR} - 15 \times T_s \quad \text{Eq (17) in Ref [2]} \quad (3.9)$$

$$\gamma_s = \sin^{-1} [-\cos \delta_s \times \sin \omega_s / \cos H_s] \quad \text{p124 in Ref [2]} \quad (3.10)$$

$$\eta = \cos^{-1} [\cos H_s \cos (\gamma_s - \gamma_L)] \quad \text{from Eq 11 in Ref [3]} \quad (3.11)$$

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:

$$P_s = a D \left[I_{B0} \left(1 + \frac{\pi F}{2} \sin H_s \right) + \frac{\pi}{2} I_d (1 + F) \right] \quad (3.12)$$

A.4 Power-Loss Rate Due to Radiation

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

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

where

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

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

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:

$$Nu_{nat} = \text{Nusselt Number due to natural convection} \\ = A \times (G_r \times P_r)^m \text{ Eq (21) of Ref [2]} \quad (5.2)$$

and

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

$$P_r = \text{Prandtl Number} = 0.715 - 2.5 \times 10^{-4} \times T_f \quad \text{p124 Ref [2]} \quad (5.4)$$

$$\text{If } (G_r \times P_r) \leq 10^4 : A = 0.850, m = 0.188$$

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

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:

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

Where:

$$Nu_{wind} = \text{Nusselt Number due to the wind alone} \\ = B (Re)^n [0.42 + C(\sin \psi)^P] \quad \text{From Eq (6) of Ref [4]} \quad (5.6)$$

and

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

$$\text{If } Re \leq 2650 : B = 0.641, n = 0.471$$

$$\text{If } Re > 2650 : B = 0.048, n = 0.800$$

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 $0^\circ \leq \psi \leq 24^\circ : C = 0.68, P = 1.08$

$$24^\circ < \psi \leq 90^\circ : C = 0.58, P = 0.90$$

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):

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

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

$$V_{eff} = \sqrt{V^2 + V_z^2} \quad (5.9)$$

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

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

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

- Finding ϕ from:

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

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

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

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

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

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

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

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 :

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

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 ($^\circ\text{C}^{-1}$)
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.:

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

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
1/2	+0.99934	+ 1.9608×10 ⁻⁴	- 2.0493×10 ⁻⁵	+ 8.9859×10 ⁻⁷	+ 1.8572×10 ⁻⁸
3/9	+0.99979	+6.2538×10 ⁻⁵	- 6.4912×10 ⁻⁶	+ 2.8143×10 ⁻⁷	+ 1.4862×10 ⁻⁸
2/7	+0.99992	+2.6909×10 ⁻⁵	- 2.9508×10 ⁻⁶	+ 1.3297×10 ⁻⁷	+ 1.2010×10 ⁻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 mm²), Olive (508 mm²), Orange (438 mm²) and Mango (373 mm²).

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:

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

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:

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

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:

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

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):

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

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:

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

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 $(t + \Delta t)$:

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

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 Δt 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, $\rho_A = 2700 \text{ kg/m}^3$
- For zinc-coated steel wire, $\rho_S = 7800 \text{ kg/m}^3$

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, $C_p = 929.4 + 0.32236 \times T_c \text{ J/(kg } ^\circ\text{C)}$
- For zinc-coated steel wire, $C_p = 441.2 + 0.47517 \times T_c \text{ J/(kg } ^\circ\text{C)}$

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:

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

where k_s is the skin effect multiplier.

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

$$\text{let } z = \sqrt{\frac{8\pi \cdot f}{10^4 \cdot R_{dc}}} \quad \text{where } f \text{ is in Hz and } R_{dc} \text{ in } \Omega / \text{km}$$

$$\text{then } k_s = \frac{z}{2} \left(\frac{\text{ber}(z) \cdot \text{bei}'(z) - \text{bei}(z) \cdot \text{ber}'(z)}{\text{ber}'(z)^2 + \text{bei}'(z)^2} \right) \quad (B.2)$$

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

$$\text{let } dd = \frac{id^2}{od^2 - id^2} \quad \text{let } ee = \frac{od^2}{od^2 - id^2}$$

where id and od are inside and outside diameters of conductor

$$\text{let } mr = \sqrt{\frac{8\pi \cdot f \cdot ee}{10^4 \cdot R_{dc}}} \quad \text{let } mq = \sqrt{\frac{8\pi \cdot f \cdot dd}{10^4 \cdot R_{dc}}}$$

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

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

$$\text{let } g = e \cdot \text{ker}(mr) - f \cdot \text{kei}(mr)$$

$$\text{let } h = f \cdot \text{ker}(mr) + e \cdot \text{kei}(mr)$$

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

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

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

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

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

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

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

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

I Functions (from Ref [8])

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

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

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

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

C= Euler constant = 0.5772156649.....

II Derivatives

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

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

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

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

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:

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

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 20°C. 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 20°C) values of k_m or the Australian Standard ACSR, the results of Figure C.1 were obtained.

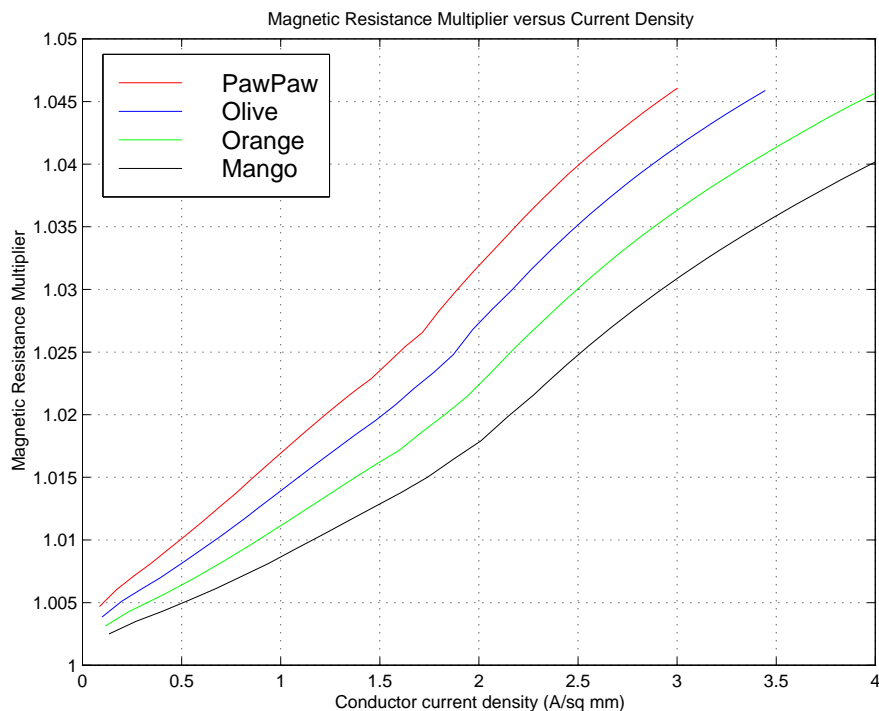


Figure C.1 Calculated values of k_m obtained from the method of Reference [9] for AS ACSR 54/7 & 54/19 Conductors at 20°C plotted against current density in the aluminium layers.

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

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

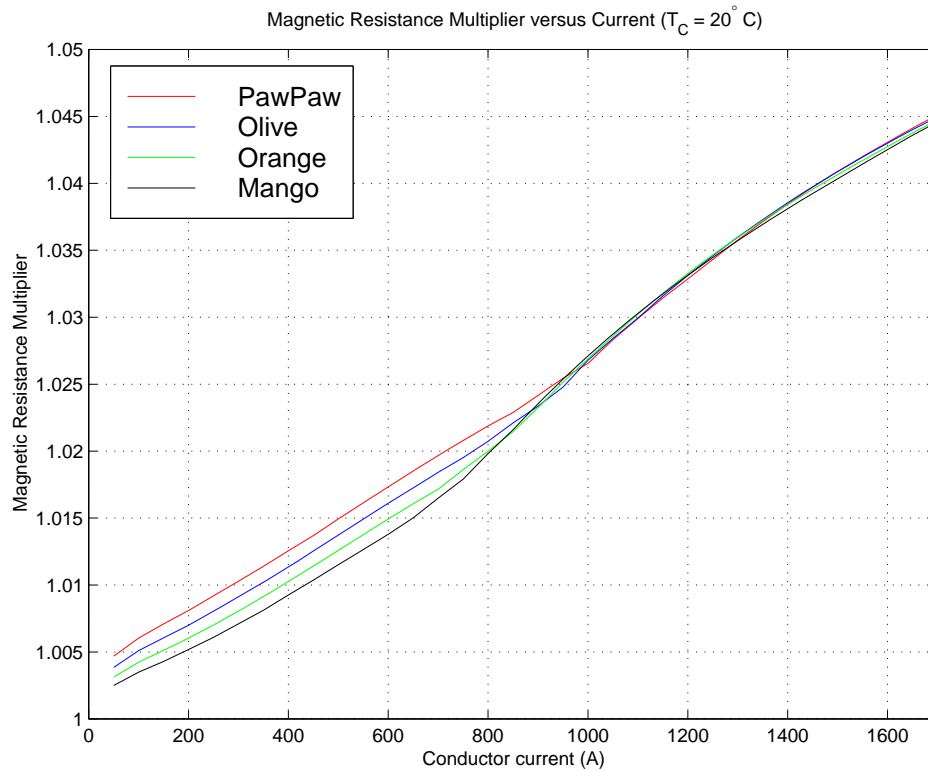


Figure C.2 Calculated values of k_m obtained from the method of Reference [9] for AS ACSR 54/7 & 54/19 Conductors at 20°C plotted against conductor current.

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 20°C.

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

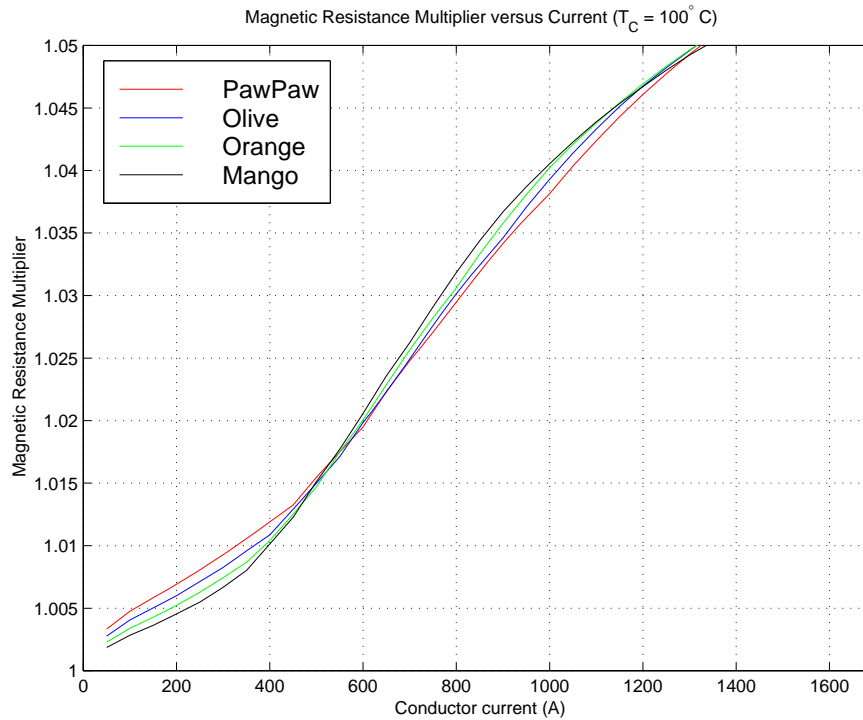


Figure C.3 Calculated values of k_m obtained from the method of Reference [9] for AS ACSR 54/7 & 54/19 Conductors at 100°C plotted against conductor current.

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 100°C.

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:

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

Where:

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

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

APPENDIX D – Real Time Rating Methodologies and Requirements

D.1 Introduction

The following sections provide information on the common real time rating methods that are supported and used by electricity transmission companies.

Table D1 is a simplified comparison of the common methods available for real time ratings. A detailed assessment, including site specific considerations must be carried out for any individual application of real time ratings.

Table D1. Comparison of assessment methods

Monitor	Cost				Accuracy				
	Purchase Cost	Install Cost	Maintain Cost	Line Outage	Measurement Reach	Normal Wind High Load	Normal Wind Low Load	High Load Low Wind	High Load High Wind
Weather	low	low	low	no	variable	good	good	low	good
Temperature	high	medium	high	no	point	good	low	good	good
Tension	high	high	high	yes	multi span	good	low	high	good
Combined	low	medium	medium	yes	multi span	good	good	high	good
Dummy	low	low	low	no	variable	good	good	good	good
Sag	high	medium	high	no	multi span	good	low	high	good

D.2 Weather monitoring based Methods

The weather-based model is the method that is most closely related to the traditional static rating methodology. These systems measure weather parameters for use in equations to estimate the cooling effects of radiation, natural convection and forced cooling of conductors.

There are a range of matters that need to be considered in the implementation of weather based systems for determination of real time thermal line ratings. It should be noted however that prior to any consideration of detailed implementation matters an assessment of the most relevant historical weather information should be carried out to assess whether there is likely to be any benefit from weather monitoring at the times when additional thermal capacity is likely to be required by the power system.

To determine the conductor temperature the heating parameters, the line current and solar radiation must also be measured or calculated. The final temperature of the conductor is the value of temperature that provides a balance between the heating and cooling equations which are the same equations used for determining the static thermal rating. This corresponds to the current that heats the line to the design limit. This can be converted to an MVA rating as required.

The minimum weather parameters to be measured are ambient temperature and wind speed. The heating parameter to be measured is current and the heating parameter to be calculated is solar radiation.

D.2.1 Data requirements

Regional weather stations must be installed along with SCADA monitoring of the weather measurements to provide accurate and timely input data. For the derivation of real-time thermal ratings, the minimum information that is required is both ambient temperature and wind speed. Additional information and techniques that may be useful in determining real-time ratings include:

- measurement of wind direction;
- direct and indirect solar input;
- ultrasonic wind measurement instruments, including consideration of wind measurement accuracy requirements and reliability;
- ambient temperature – range and performance;
- SCADA scan rate less than 1 minute;
- data averaging – local measurement equipment and algorithmic;
- drift detection – self monitoring (redundancy of instrumentation to allow cross checking of measurement accuracy); and
- calibration.

High-quality instruments providing a high standard of reliability, a robustly designed power source and reliable communication links are vital to effective real-time rating determination. The existence and availability of communication links to (potentially remote) locations along a transmission line need to be considered in the design of the scheme. Redundancy of instruments, power sources and communications links may also need to be considered.

- Wind – speed and direction

Heat loss of the conductor due to wind is probably the most important factor in determining real-time ratings. Therefore accurate measurement of wind speed is vital. Based on experience to date, a minimum sample rate of at least six times per minute is necessary to obtain a representative wind speed value for each minute.

Low wind speeds provide the highest area of risk to the transmission network and it is highly recommended that sensitive ultrasonic wind anemometers be used in preference to cup-type anemometers as the latter have inertia that makes them inaccurate at low wind speeds. Cup type anemometers also have high maintenance requirements. Ultrasonic anemometers are available that can accurately measure wind speed down to close to 0 m/s, compared with the cup-type instruments that are inaccurate below 0.5 m/s.

When using any wind speed measurement device, the corrections for instrument calibration mounting versus conductor height, angle of incidence variation and topographic uncertainties as well as instrument inertia (as described in the manufacturer's technical manual) need to be carefully applied.

Regardless of the measurement issues, there can be a large variability in the wind factor across the length of the transmission line. To minimise this risk and balance the need to install an excessive number of weather stations, the following practice can be adopted for wind speeds applied in the model calculations of ratings:

- Apply a wind speed multiplier of 0.5 (where wind direction is not included in the algorithm).
- Apply a wind speed multiplier to compensate for other measurement uncertainties such as terrain and distance from the measurement site.
- Maximum wind speed may be clipped at an upper limit.
- Install accurate ultrasonic or similar wind instrumentation.

- Wind speed data can be manipulated (smoothed) on site before transmission but there is still some statistical modelling required to confirm the accuracy of the treatment of multiple readings per minute. Adopting moving average smoothing over about 10 minutes (or the thermal constant time period of the conductor) to reduce the 'noise' introduced by the variability of the wind's speed and direction is considered to be reasonable.

The line rating calculation methodology uses a mathematical model of the temperature behaviour of a conductor (see Appendix A).

Wind direction is a factor that should be measured and where possible related to the orientation of the transmission line. Wind has a maximum cooling effect at 90 degrees to the line axis, with the cooling effect of wind blowing axially along the conductor reduced to 45%. A mathematical equation (see equation 5.6, Appendix A) may be used to estimate the cooling effectiveness at any angle to the line axis. This can be used for transmission circuits which have a dominant aspect in relation to prevailing winds, but is not useful for transmission circuits which change direction over their length.

- Ambient temperature

The ambient air temperature is the second of the important input parameters that needs to be considered when assigning a real-time thermal rating. It can be sampled as often as the station is scanned. Unlike wind, it does not change rapidly. Along the line, some ambient temperature variation may occur with altitude. Consideration should be given to temperature measurement redundancy to ensure that subtle instrumentation error drifts are detected.

- Solar inputs

It is considered more appropriate that solar parameters are calculated rather than measured to avoid unreliability in direct measurements which would result from slow moving cloud patters. The parameters should be calculated based on no cloud cover for the whole line length.

D.2.2 Implementation guidelines for weather monitoring

There are a range of matters that need to be considered in the implementation of weather based systems for determination of real time thermal line ratings. It should be noted however that prior to any consideration of detailed implementation matters an assessment of the most relevant historical weather information should be carried out to assess whether there is likely to be any benefit from weather monitoring at the times when additional thermal capacity is likely to be required by the power system.

- Distance between measurement sites

This is perhaps the most difficult and most critical element in the design of a real-time line rating system. Consideration needs to be given to the way the climate and geography of the easement varies over the length of a transmission line. For example, weather conditions across an open, flat grass plain will be much more constant than weather along an easement that traverse forests, hills and/or valleys. Telecommunications will be required from each weather station to make any use of the data.

In designing real-time rating systems consideration must be given to synoptic weather behaviour. Synoptic atmospheric variations change relatively slowly. For example a typical pressure variation would be about 1 hPa per 100 km creating a wind of about 3.8 m/s. Low pressure systems are typically more intense and may have pressure drops

of 3 hPa per 100 km with winds around 12 m/s. High pressure systems may result in constant pressures and low wind speeds over hundreds of kilometres.

The use of real-time rating systems is particularly relevant when wind is in the low to normal wind speed range. For measurement separation of 33 km and converting pressure differential into wind speed at normal conditions; 33 km = 0.33 hPa = 1.3 m/s. This implies that a maximum average wind error of about 1.3 m/s could occur over a 33 km distance. Figure D.1 shows the correlation of instantaneous wind speed at two weather stations 35 km apart. The spread of values for any average midpoint value is about ± 1 m/s.

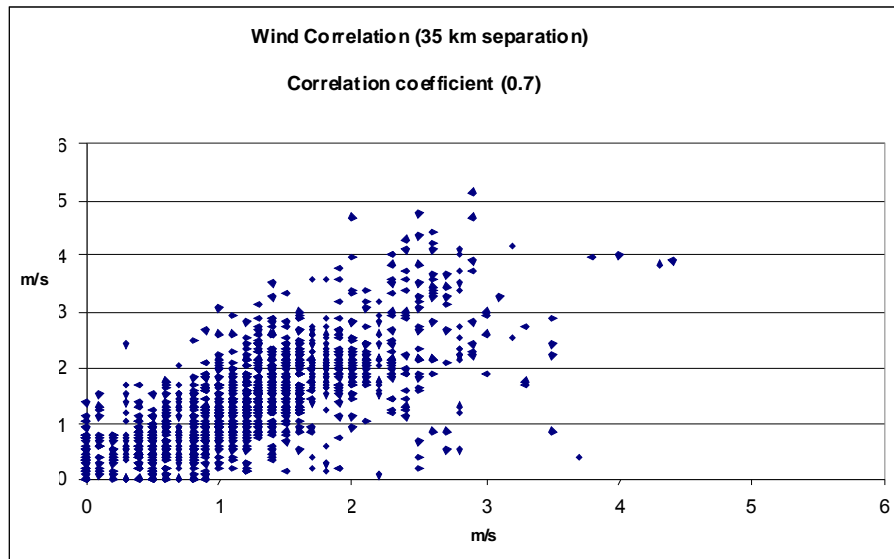


Figure D.1: Wind correlation of two stations 35 km apart

Another important consideration is the time lag for a change to propagate over distance. For example a cool change propagates at approximately 15-55 km/hr over land so it is possible for conditions to be quite different over varying sections of the easement for a period longer than the line thermal time constant. This is another reason the spacing of measurements should not be too far apart.

It appears from experience in Southern Australia to date that a measurement interval of 30-50 km is a reasonable choice for weather stations along a transmission line easement where conditions are relatively uniform. This conclusion is supported by a number of studies of wind site correlation [11, 12, 13] that show data supporting wind correlation at these distances.

While this provides a useful guide the actual interval used needs to be assessed on a case-by-case basis and modified according to the climate and topography of the particular easement being investigated.

It should be noted that this interval will also present challenges in getting the data from the weather station into the calculation algorithm for transmission circuits which are longer than 35 km, particularly if the transmission circuit traverses uninhabited spaces without telecommunications systems.

- Geography and atmospheric modelling

Where a line easement passes across geographical features that would influence wind speed, atmospheric models that consider the topography of the land surface may be used to evaluate these effects. Programs are available that can generate a map of average

wind speeds along the easement. This map can then be used to carefully site weather stations or allow a ratio factor to be calculated to estimate wind speeds in protected areas e.g. valleys.

- Use of barometric pressure

Barometric pressure can be used to improve measurement confidence across the transmission line easement. Synoptic scale winds are directly proportional to the barometric pressure gradients that exist over a region.

Some experience shows that a group of differential barometric measurements across a weather region, for example, 50–200 km in diameter provides an additional source of regional wind speed estimation that improves the confidence in the combined direct local measurements. Four pressure drop measurements taken at locations arranged symmetrically across a region in a star formation i.e. at 45 degree intervals around the compass is preferred as shown in figure D.2.

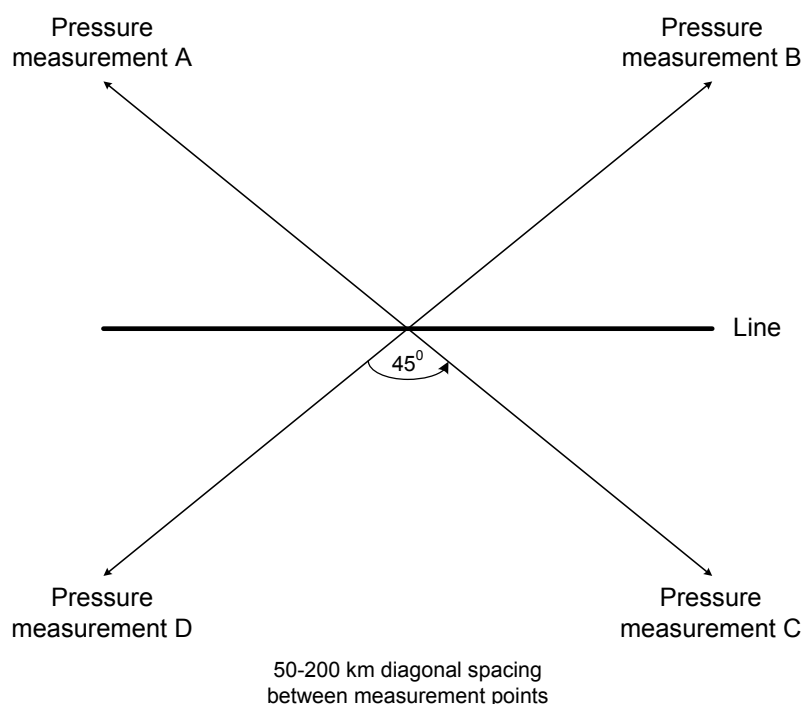


Figure D.2: Wind speed estimation with four measurement points

A minimal arrangement with three pressure drop measurements taken at locations arranged in a triangular configuration could also be used. The pressure based wind estimate can be used to provide an upper bound 'reasonability check' on the measured wind speeds. For line lengths greater than 50 km, a triangle of barometers, as shown in Figure D.3. allows the pressure gradients over the line to be measured and the wind speed over the line easement to be estimated for reasonability check purposes.

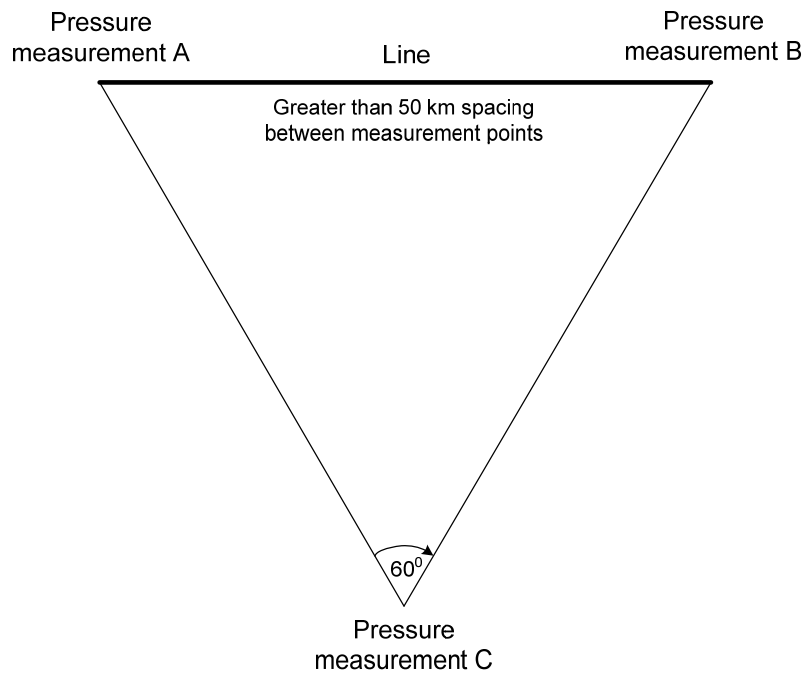


Figure D.3: Wind speed estimation with three measurement points

Wind speed can be estimated using the approximation that a pressure-drop of 1 hPa over 100 km creates approximately a 3.8 m/s wind. Each of the pressure drops over the distances AB, AC and BC are evaluated and can be used as a reasonability check on the direct wind speed measurement from the weather stations.

- Selection of weather regions

Regional weather patterns need to be well understood when positioning weather monitoring stations relative to the location of transmission lines. Using this information it may be possible to determine weather regions for the network so that information from one monitoring station can be applied to multiple circuits with little increase in the risk to the accuracy of real-time rating calculations. Interaction with local Bureau of Meteorology specialists can prove to be helpful in determining reasonable regional weather patterns.

- Telemetry, Automation and Operational interface

The weather measurement transducers used at the weather station sites should preferably be of the moving average type. Some transducers allow the averaging period to be adjusted and it is preferable for the averaging period to be set longer than the SCADA scan rate interval to ensure that the integrated value applied to the conductor model is reasonably accurate. Instantaneous weather values are quite variable and may lead to unwanted and quite large scale movement in the rating values at each calculation interval if used unprocessed. The values that are uploaded into the SCADA system should in turn be integrated over the model calculation interval with a moving average interval of at least 10 minutes to smooth the wind speed variation.

Example of a suitable setup:

1. Wind speed anemometer averaging period = 6 seconds
2. SCADA analogue scan rate = 2-5 seconds
3. Algorithm wind speed moving average period = 10 minutes
4. Rating model execution interval = 1 minute

The heating time constant of transmission line conductors is in the order of minutes, typically 3-20 minutes. For mathematical stability the calculation interval should be around one third of the shortest time constant i.e. 1 minute or less.

The variability of the other measured values should also be considered.

- Wind direction is as variable as wind speed so an identical averaging treatment is required.
- Ambient temperature has a change rate that is much slower than wind speed and therefore requires a different identical averaging treatment.
- Barometric pressure also has a change rate that is much slower than wind speed.
- The load current can change by a large amount instantaneously therefore this should be measured at the SCADA rate and a moving average taken over the calculation interval. Normally current transducers do not have an averaging capability.

D.3 Direct measurement methods

D.3.1 Direct conductor temperature measurement method

These systems measure conductor temperature directly which is then used as the operational limit. The method requires the installation of a measurement device directly on the conductor. This measurement is very local but is highly accurate. A line rating cannot be calculated unless weather data is available in addition to the measured temperature.

D.3.2 Tension method

These systems measure conductor tension allowing a direct calculation of sag and an indirect calculation of conductor temperature. The tension method requires the installation of a strain gauge between a tower structure and a conductor strain insulator assembly. Tension has the advantage that it responds to the average of the heating effects along a number of suspension spans. It has a measurement reach of about two to three kilometres along a run of suspension towers.

Conductor tension is directly related to sag, but the thermal operation of lines is also limited by temperature and current rating. As a result the tension sensor outputs must be augmented with ambient temperature and wind speed, or a representative conductor temperature is obtained from a non-energised (dummy) piece of conductor. A line rating cannot be calculated unless weather data is available in addition to the measured temperature.

While the tension sensor itself is quite sensitive, the geometry of the spans between strain towers can have a significant effect on the sensitivity of the system as a whole. For example, a short section between strain towers with no elevation change will respond sharply to variations in other parameters. However, a line section with a mix of long and short spans, significant elevation changes and 'as built' tensioning and sagging errors or non-plumb suspension strings, could produce an almost meaningless result if the span of interest is more than about three spans away from the tension monitor. The tension sensor must also be installed at a rigid support structure to avoid being corrupted by measurements of the structure movement.

D.3.3 Conductor sag monitoring systems

These systems measure conductor sag. This is a direct measurement of the ultimate limiting parameter at one point but conductor temperature is determined by an indirect calculation. The method requires the installation of a sag measurement assembly. Sag measurement in

one span is a point measurement in that span however, it does respond to the average of the heating effects along a number of suspension spans.

A line rating cannot be calculated unless weather data is available in addition to the measured temperature.

D.3.4 Dummy conductor methods

These systems measure the ambient air temperature, solar radiation and the temperature of a dummy conductor oriented in the same direction as the axis of the line at the point of measurement.

This data can be used to estimate the environmental cooling effects and can be improved by the inclusion of a heating element of known power in the dummy conductor. Without a heater, there will normally be a very small difference between the dummy conductor and the ambient temperature, therefore the certainty of the cooling parameter estimations may not be adequate. When a heater system is provided the accuracy of the system is strongly dependent on the accuracy and reliability of the power output of the heater and the provision of such a power source at remote sites can be expensive.

The dummy conductor temperature is balanced against the ambient temperature with a known current from which a conductor rating can be calculated.

D.3.5 Calculation for direct measurement methods

Site measured parameters such as tension or sag do not provide data that is directly useable in the rating calculations set out in Appendix A. It is necessary to convert these measurements into a temperature value.

The 'as built' lines rarely have conductor sags that agree precisely with 'as designed' values due to errors in temperature measurement during sagging, sagging errors, clamping in errors and variability of conductor creep. Because of this, a field verification of the 'as built' state of the line is required to provide a temperature calibration point for tension or sag. This verification may be done via a ground based survey or it may be viable to undertake an Airborne Laser Survey to provide the 'as built' data.

A reference point needs to be established by calibration before any meaningful calculations can be done to convert tension or sag to temperature. Typical methods used to establish this reference point are for surveyors to measure conductor support and mid-span levels in a number of spans and record dates, times, wind, sun/cloud. Line loads for those dates and times are then obtained from system SCADA. There is practical difficulty in obtaining a precise temperature measure as some parameters will always be estimates. Airborne laser surveys are an alternative to provide the same information as surveyors if a large number of spans need checking. Such aerial laser scanning can also be performed at night such that the effects of direct and indirect solar influences can be removed from the equations.

If tension monitors are used to measure a critical span remote from the measurement site then modelling becomes very important as the tension changes are attenuated by longitudinal insulator string deflections. In this regard it should be noted that it is always assumed that the environmental conditions are global in the zone being monitored. No system will give reliable data with differential in the environmental conditions. Line design programs with a Finite Element analysis option appear to be the best way of modelling the state of a line particularly when it is in undulating terrain, has variable span lengths and insulator clipping offsets are involved.

- Tension to temperature

Once a reference calibration point has been established, an equation to describe temperature as a function of tension is required. A polynomial of the form:

$$\text{Temperature} = a + bt + ct^2 + dt^3 \text{ (where } t = \text{tension)};$$

will provide sufficient accuracy.

The tensions at a minimum of four temperature values over the range of interest will be required to establish the values of a, b, c and d using standard curve fitting mathematical techniques such as the 'least squares' method and would ideally be established from field measurements over a wide temperature range although this may be difficult to implement. The temperature values can be predicted from the line design program. Suppliers of equipment may have other methods.

- Sag to temperature

The process is very similar to the tension to temperature conversion described above. Once a reference calibration point has been established, an equation to describe temperature as a function of sag is required. A polynomial of the form:

$$\text{Temperature} = a + bs + cs^2 \text{ (where } s = \text{sag)};$$

will provide sufficient accuracy.

The sags at a minimum of three temperature values over the range of interest will be required to establish the values of a, b & c using standard curve fitting mathematical techniques such as the 'least squares' method and would ideally be established from field measurements over a wide temperature range although this may be difficult to implement. The sag values can be predicted from the line design program. Suppliers of equipment may have other methods.

D.4 Combined methods

The measurement of weather parameters for use in equations to estimate the cooling effects of radiation and a direct measurement method in parallel, using a direct calculation of sag or conductor temperature and an indirect calculation of conductor temperature can be combined together to reap the benefits of both systems and provide high quality assessments of real time thermal line ratings. To reduce the complexity and cost of applying this method, it would not be necessary to make direct measurements on all circuits in multi-circuit easement.