energyline
Electricity Networks Expertise

REVISE – WP2: MOVING CLOSER TO REAL-WORLD APPLICATION

ALPHA PHASE

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EXECUTIVE SUMMARY

In order to meet the Net Zero targets of the UK government, there is an increasing requirement to integrate renewable energy sources into the existing transmission network. However, it is constrained by the limited amount of current that can be transferred by the existing overhead line circuits which leads to significant monetary losses. The current methodology for rating overhead lines in the UK is based on TGN26 which uses historical environmental data captured in the 1980s and is applied uniformly across the UK disregarding local/regional climate variations. Improving the understanding of line ratings, based on latest generation high resolution weather data combined with latest system modelling techniques will offer the potential to revise line ratings without the requirement for physical modifications.

Energyline have been commissioned to review the effects of changing key parameters within the ratings calculations in line with 'real world' meteorological data. This report documents the findings of Work Package 2 of the Alpha phase of the Strategic Innovation Fund 'REVISE' project (Revisiting and Evaluating Environmental Inputs On-Line Ratings).

The report aims to demonstrate the impacts of changing specific parameters within the Cigre TB 601 ratings calculation within the bounds of real-world meteorological observations and 'coincident events'. This will enable greater focus on specific areas for further research and validation in subsequent phases of the project.

Additionally, to inform the work packages of the REVISE alpha phase, review of the appropriate time resolution for the ratings methodology has been undertaken specifically in how the real-world sag response of conductors may correlate with changing temperatures.

Heating and cooling effects play an important role in conductor performance and thermal rating. With the forced convection from high wind speeds improving cooling and increasing thermal rating. However, with weather parameters being unpredictable, it is difficult to estimate when wind speeds will be high and consistent and therefore the level of cooling is unpredictable.

From the results discussed it can be concluded that wind speed along with ambient temperature had the greatest effect on thermal rating as they have the biggest effect on temperature fluctuation leading to changes in potential rating. With this fluctuation it is also important to further consider the conductor sag reaction times and rate of change to gain a more detail and accurate reading on the response times for different conductor systems.

CONTENTS

1. INTRODUCTION

In order to meet the Net Zero targets of the UK government, there is an increasing requirement to integrate renewable energy sources into the existing transmission network. However, it is constrained by the limited amount of energy that can be transferred by the existing overhead line circuits – which leads to significant monetary losses.

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1.1. TERMS OF REFERENCE

The terms of reference for Work Package 2 were developed through scoping sessions with SSEN and other collaborators.

The Alpha phase deliverable D2.2 is for a report submitted detailing the findings of the literature review and calculations carried out as part of WP2.

1.2. OVERHEAD LINE RATINGS

The following section is intended to give the reader a general understanding of the current approach to OHL ratings.

Overhead line ratings refer to the current carrying capacity of the circuit without exceeding the temperature limit of the conductor system, this is a critical parameter in the design, operation, and maintenance of transmission and distributions circuits.

In Great Britain the ratings methodology that has been used since the 1980s is defined by National Grid in TGN26 "Circuit Ratings for Overhead Lines". These are a set of standard 'static line ratings' which are defined seasonally for pre-fault and post-fault conditions. The ratings are derived using a probabilistic approach to the exceedance of the thermal limit of the conductor and adopt conservative meteorological parameters in the calculation for the steady-state heat balance equation.

There are three principal components to the static line ratings used in the GB transmission network:

- Assumed seasonal meteorological parameters i.e. ambient temperature, wind speeds etc. These are ultimately not dictated however, the UK has adopted a set of parameters documented in TGN 26.
- The heat balance equation for steady state conditions described in Cigre TB 601 "Guide for Thermal Rating Calculations of Overhead Lines" which is a thermodynamics calculation with meteorological parameters as well as additional assumptions regarding the physics of conductor heating and cooling.
- Exceedance values – can be thought of similarly to a safety factor which are standardised by the transmission system operator and limit the probability that a conductor will exceed it's maximum rated temperature so as not to cause electrical clearance infringements.

This report is concerned mainly with the meteorological assumptions and their effects on line ratings, the time response of the conductor to these changes ultimately feeds into the calculation of exceedance values.

It should be noted in relation to bullet point 2, that other methods are widely used, Figure 1 shows a comparison between calculated and measured conductor temperatures in accordance with the Cigre 601 and IEEE 738-2012 calculations. It shows that although not identical the values between the calculations and recorded temperatures are similar and follow the same pattern therefore Cigre TB 601 is used throughout this report.

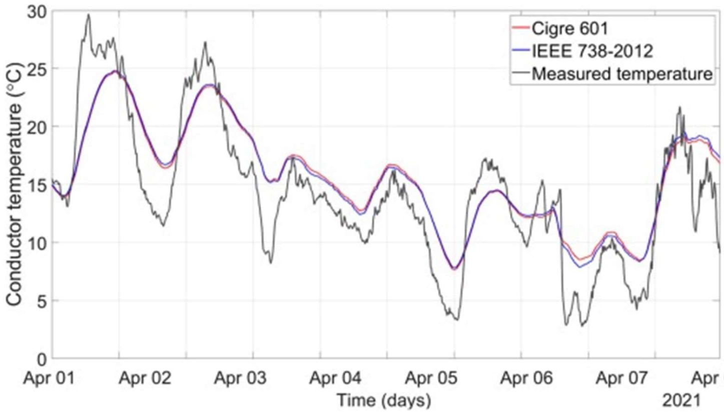

Figure 1- Comparison between calculated and measured conductor temperature, (Sterc, 2023).

2. HEAT BALANCE – STEADY STATE

In the steady state, the heat produced by the current, solar radiation, magnetic heating, and corona heating is equal to heat dissipated by convective, radiative and evaporative cooling. Figure 2 presents the conductor heating and cooling. The heat balance can be written as below:

PJ + PS + PM + Pi = PC + Pr + Pw

Where PJ is the joule heating, PS the solar heating, PM is the magnetic heating, Pi the corona heating, PC is the convective cooling, Pr is the radiative cooling and Pw is the evaporative cooling. Figure 2 below is a graphic of the heating and cooling parameters.

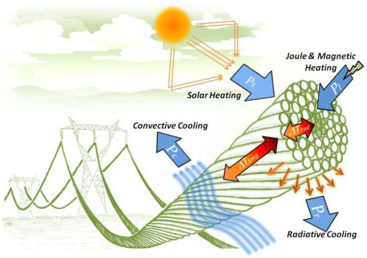

Figure 2 - Heating and cooling of an Overhead Line conductor (Cigre TB 601)

The heat balance is therefore a thermodynamics problem which requires the quantification of physical terms to the equation.

The assumed summer conditions for the calculation of ratings are presented in Table 1.

Table 1 - Ambient Condition – Summer

Parameter	Value	Unit
Wind	0.5	m/s
Ambient Temperature	20	°C
Wind angle	90	°
Albedo 1	0.2	
Thermal Conductivity of Air	0.027	
Altitude	50	m

Changing the parameters will affect the conductor rating and each parameter will affect the rating to a lesser or greater degree. By altering these parameters the percentage change to the rating can be calculated and compared. The range of values and coincident values are to be informed by data provided by the MetOffice.

2.1. JOULE HEATING

Joule heating refers to the energy generated by current flow through the conductor. It considers the current resistance and the “skin effect”. The skin effect is the increase of current density towards the surface of the conductor when alternating currents are used. The joule heating can be calculated using the following equation.

$$P_J = I^2 \times R_{dc}$$

I = Total Direct Current

R_{dc} = Current resistance per unit length

Joule heating is the production of heat by passing an electrical current through a medium, in this case the conductor, with finite conductivity, (Anvari, 2020). As this is a physical phenomenon of the conductor itself, any review of the calculations of this effect are considered to be out with the scope of this study.

2.2. SOLAR HEATING

The thermal rating of overhead power conductors depends on the maximum allowable temperature, if the temperature of the conductor is already being increased by environmental parameters such as solar heating, then this lowers the overall rating of the conductor. The greater the absorptivity of the conductor the greater the solar heating will be. Similarly with the size of the conductor, as a larger conductor diameter means a larger surface area for the solar heating to occur, (Riba, 2024).

$$P_S = a_S \times I_T \times D$$

a_S = Absorptivity of conductor surface

I_T = Global radiation intensity

D = Conductor Diameter

Of these parameters, it is only the global radiation intensity which may be subject to review within this study. For instance, the current ratings methodology in the UK does not account for day and nighttime differences in solar heating, which is a self-evident difference which can be explored as well as the magnitude of radiation and it’s effects.

2.3. MAGNETIC HEATING

Magnetic heating refers to the increase in temperature of conductors due to their exposure to alternating magnetic fields. This phenomenon is typically associated with inductive coupling and eddy current losses. As this is a physical phenomena of the conductor itself, any review of the calculations of this effect are considered to be out with the scope of this study.

2.4. CONVECTIVE COOLING

Two types of convection are considered: natural convection, which occurs when wind speed is zero; and forced convection which depends on wind speed and direction relative to the line.

At moderate-to-high wind speeds, forced convection dominates and natural convection can be ignored. At low wind speeds, natural convection may have a significant effect, becoming the dominant convection mechanism at very low wind speeds. Wind variability, even within a single span, makes it very difficult to assess the thermal behaviour of overhead lines, particularly at low wind speeds and high current densities.

The chimney effect also known as Natural Convective Cooling (NCC) on a conductor is the convection process where heat is dissipated from a conductor due to the movement of air, even in the absence of external airflow (still air). This occurs because of differences in air density caused by temperature gradients causing buoyancy force shown in Figure 3.

$$P_C = \pi \times \lambda_f \times (T_S - T_a) \times Nu$$

λ_f = Thermal Conductivity of air

T_S = Temperature of conductor

T_a = Temperature of air#

Nu = Nusselt Number

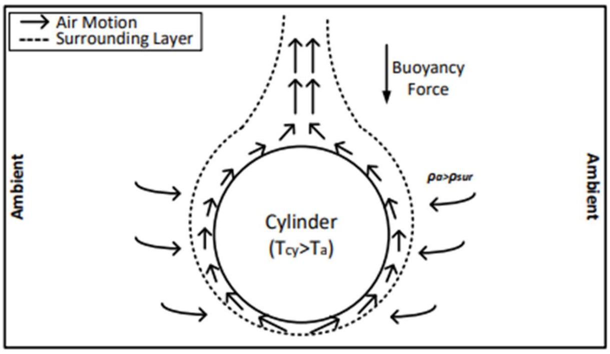

Figure 3- Illustration of natural convective cooling on cylindrical conductor, (Rahman, 2018)

Conductors generate heat when carrying high load. This is due to resistive losses which heat up the surrounding air forming a density gradient or surrounding film layer between the warm air around the conductor and the cooler ambient air. Therefore, close to the conductor the air becomes less dense. This density change means that the air rises. As the warmer air rises, cooler air from the surrounding environment replaces it, creating upward airflow. This ongoing process establishes an airflow, which enhances heat transfer away from the conductor, (Rahman, 2018).

Most of the parameters/ assumptions which form the basis to the convective cooling of conductors. Of these parameters, the thermal conductivity of air has been particularly difficult to determine as described in the following section.

2.4.1. Thermal Conductivity of Air – Humidity

The thermal conductivity of air is relevant to convective cooling as it describes the property of the air which enables it to carry heat away from the conductor, the thermal conductivity is calculated in Cigre TB 601:

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$$\lambda_f = 2.368 \times 10^{-2} + 7.23 \times 10^{-5} \times T_f - 2.763 \times 10^{-8} \times T_f^2$$

Where the film temperature is assumed to be the film temperature and is calculated using the following.

$$T_f = 0.5 \times (T_s + T_a)$$

With T_s being the surface temperature of the conductor and T_a being the air temperature. The equations show the increase of air temperature causing an increase in thermal conductivity.

There are multiple different calculation methods and results linking the effects of humidity on the thermal conductivity of surrounding air. This effect on thermal conductivity has the potential to affect the thermal rating of the line. Two Coinciding examples can be seen in Figure 4 and Figure 5 both indicate an increase in thermal conductivity with temperature as expected. However, as ambient air reaches 50°C, the effects of humidity begin to become more prominent.

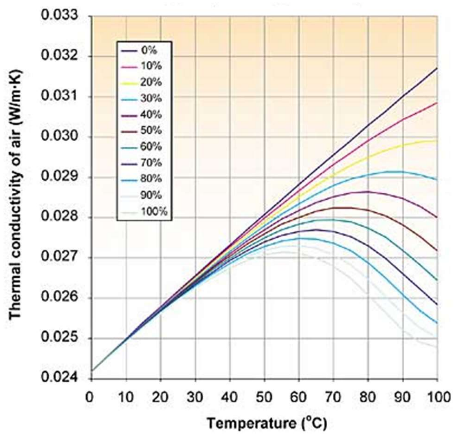

Figure 4 - Change in thermal conductivity of air with temperature, (Lasance, 2003)

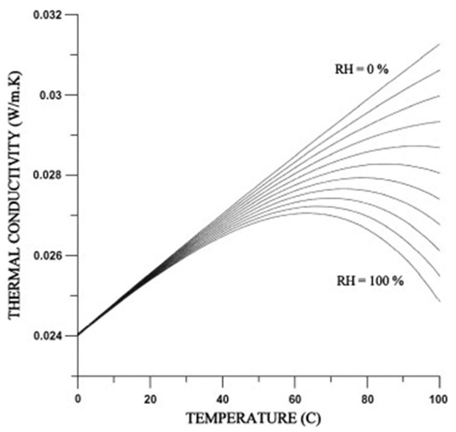

Figure 5 - The thermal conductivity of moist air as a function of temperature with the relative humidity as a parameter ranging between dry air, (Tsilingiris, 2008).

Both figures show an incremental increase in humidity. The impact of humidity on the thermal rating is shown to be the same, with the increase in humidity decreasing the thermal conductivity when a temperature above 50°C is reached.

The software used to generate the graph shown in Figure 4 employs kinetic theory describing a mixture of both dry air and water vapour; in this case, atmospheric air and water vapor in order to generate the results. The results show that with increasing moisture content the thermal conductivity decreases. The results in Figure 5 utilise equations of a similar method to Figure 4 utilising the thermal conductivity of both dry air and water vapour in order to generate a thermal conductivity for a mixture of the two as these are the most important factors along with the ration of water vapor to ambient air, (PowerProcess, 2024).

Both figures show a maximum value of thermal conductivity is developed for each fixed relative humidity curve, which moves towards higher temperatures as the relative humidity decreases. This maximum moves typically from the temperature of 63 °C to about 94 °C as the relative humidity decreases from saturation level conditions to about RH = 40%, (Tsilingiris, 2008).

Although Figure 4 and Figure 5 indicate a decrease in thermal conductivity under high humidity and temperatures, Figure 6 and Figure 7 showed the opposite. With thermal conductivity increasing with humidity and temperature, with the effects of humidity becomung more prominent with the increase in temperature which is incidcated in Figure 4 - Figure 7.

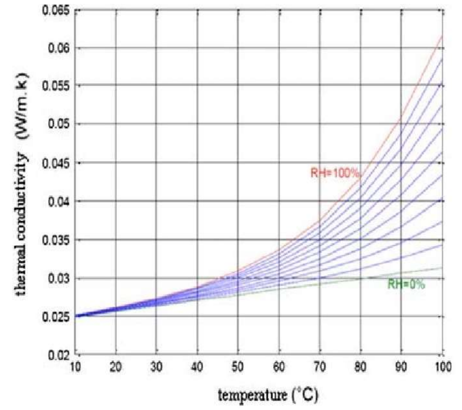

Figure 6- The thermal conductivity of moist air relative humidity between 0 and 100%, (Boukhriss, 2013)

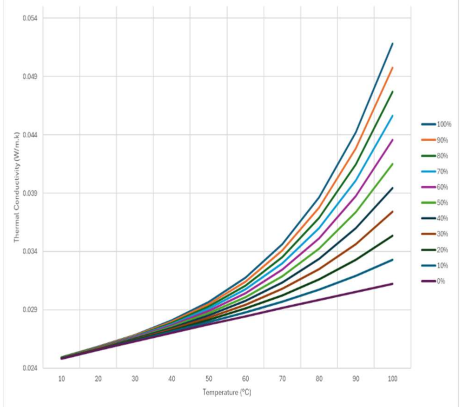

Figure 7- Humidity and Thermal Conductivity change with temperature.

Figure 7 was a recreation of the thermal conductivity calculations using generic weather values whilst changing the relative humidity and ambient air temperature. The equations and calculations were then implemented into the Cigre 601 calculations. Generally, the effect of humidity on air properties is small enough that it can be neglected. However, at high ambient temperatures and low pressure, humidity effects may need to be addressed in applications such as free air cooling or cooling of outdoor equipment, (Wilcoxon, 2024). This is also indicated in the previous figures with the change in thermal conductivity being more pronounced at higher ambient temperatures. When discussing the reasoning for the effects of humidity on thermal rating it is worth noting that impact of humidity on thermal properties is minimal at lower temperatures, particularly for thermal conductivity. However, as hot air has the potential to hold more moisture, the effects do become more pronounced at higher temperatures and lower pressures, particularly for viscosity, (Wilcoxon, 2024).

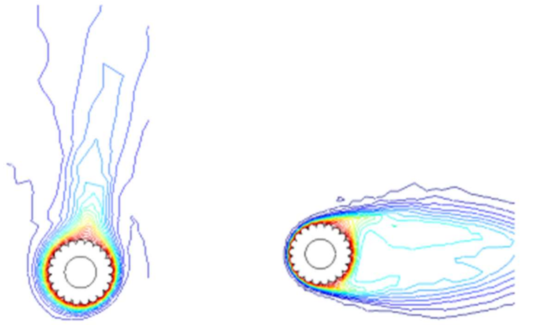

Figure 8- Illustration of natural and forced convection along an overhead line conductor, (Chen, 2012)

Figure 8 shows the natural and force convection of an overheat line conductor. Similarly to Figure 3 it shows the surrounding air being heated up by the conductor causing it to rise and cool causing the chimney effect. It is also shown that the layer of hot air shown in red, is significantly thinner in Figure 8 – a than in Figure 8 – b. This is due to the airflow from the wind causing significant cooling effects.

2.4.2. Film Effect

The film effect of the conductor refers to the impact of a thin layer of air that forms around the surface of a conductor during heat transfer processes. This film can influence the efficiency of heat dissipation from the conductor to the surrounding environment. When a conductor generates heat, the temperature gradient between its surface and the surrounding air causes a layer to form adjacent to the conductor this can be seen in Figure 3. This layer is the boundary layer, which has a temperature increase that transfers from the surface of the conductor to the cooler ambient temperature. The film increases thermal resistance, this is caused when the heat is transferred from the conductor to the ambient air as it must pass through this layer. The effectiveness of heat transfer depends on the thickness of the film and its thermal conductivity.

In still air, the film thickness increases, reducing heat transfer efficiency. Forced convection such as wind reduces the film effects on the conductor improving cooling. The cooling properties, such as thermal conductivity, significantly impact the film's behaviour. The film effect is an essential consideration for conductor heating and cooling and the impact that wind speeds and ambient temperatures have on reducing the effects.

2.5. RADIATIVE COOLING

The net radiative heat loss from a conductor is the total radiative energy transmitted from its surface. It can be divided into two components. The heat radiated to the ground and surroundings, and the heat radiated directly to the sky. Applying the Stefan-Boltzmann law. The level of radiative cooling can be calculated using the following equation.

$$P_r = \pi \times D \times \sigma_B \times F_{c-g} \times \varepsilon_s \times [(T_s + 273)^4 - (T_g + 273)^4] +$$
$$\pi \times D \times \sigma_B \times F_{c-sky} \times \varepsilon_s \times [(T_s + 273)^4 - (T_{sky} + 273)^4]$$

D = Outer Diameter of Conductor

σ_B = Stefan-Boltzmann constant

ε_s = Emissivity of conductor surface

T_s = Conductor Surface Temperature

T_g = Temperature of ground below conductor

T_{sky} = Temperature of sky above conductor

F_{c-g} = Fraction of radiated energy from conductor to ground

F_{c-sky} = Fraction of radiated energy from conductor to sky

3. RELAXATION TIME

Relaxation time refers to the time taken for the conductor to reach maximum sag for a given temperature, this can also be thought of as the thermal inertia of the conductor system.

3.1. HEATING AND COOLING RATES

The pre-fault loading of a circuit is generally 80% or less of the rated continuous capability. It is this pre-fault loading that is the true continuous line loading, and it is possible to consider postfault loads that would have a risk of temperature excursion, if they were applied continuously. The risk of conductor temperature increasing beyond the design maximum can be modified by the time constant of the temperature change following an increase in load. The time constant for conductor temperature adjustment is generally considered to be 20 minutes, (Price, 1983).

The findings of an experiment undertaken by Queen's university of Belfast showed that this time constant is variable with changing wind speeds. The results of this study are shown in Figure 9 and indicate the increase in core temperature under different wind speeds over the course of 60 minutes. This data shows that the cooling effect of the wind limits the conductor temperature and also the time taken to reach steady state. This may indicate possible increases in the time constant to be considered in conductor ratings because of the assumption of low wind speed events.

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To produce the graph a step current of 0 to 550 amps was applied in order to generate a level of joule heating. The current was not adjusted to be constant during the tests, so that the Joule heating from the conductor (1x175mm2 ACSR (Lynx)) would be slightly less than that of a constant current condition. The initial ambient temperature in each test was within 23.1 ± 1.3 ˚ C. The selected wind speeds were 0, 1, 3, 5, 10 and 15 m/s with a wind angle of 90°, 'normal' to the conductor axis.

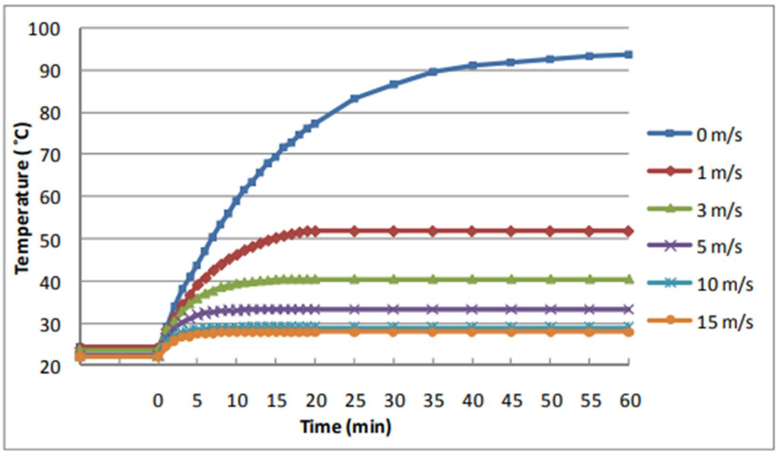

Figure 9- Wind cooling of conductor for various wind speeds, (Fu, 2010)

The graph shows that from the ambient temperature of 23°C the conductors take around 20 minutes to reach and maintain a steady operating temperature. However, the conductor undergoing no forced convection increases in temperature until the end of the experiment and the results reach a steady state. As the ratings project is mostly concerned with exceedance events, i.e. temperatures potentially in excess of 90°C it could be postulated that these time periods change subject to the degree of current change and as the temperature differential to ambient temperature increases.

It is important to note that the conductor construction may play a significant role in the heating rate of a conductor. Simplistically there are 3 common types of conductor constructions in use in the UK : All Aluminium, Steel Core and Composite core. The specific heat capacities of steel and aluminium are: 460 J/kg°K and 921 MJ/kg°K respectively, meaning that aluminium requires more energy to raise it's temperature by 1°K. Correcting for the density of steel and using the volumetric specific heat the values are 3.616 MJ/m^3K and 2.485 MJ/m^3K respectively (Thermtest.com). The volumetric specific heat is a better comparative property in the application of conductors and it can therefore be considered that an ACSR conductor of an equivalent size to an AAAC with have a higher heat capacity and therefore take longer to heat and cool.

Furthermore, the conductor bundle configuration (i.e. number of conductors in a bundle) may play a role in heating and cooling rates due to the volume/ surface ratio effect.

3.2. SAG RESPONSE

It is ultimately the probability that a conductor will exceed its 'profiled' design sag that is the risk being mitigated in the existing ratings methodology so as not to infringe electrical clearances and cause harm to the public.

No literature has been identified to quantify the latency of the sag response to the conductor temperature (if such a phenomena exists). It is hypothesised that the conductors final sag will be achieved at some point after the conductor has reached its final temperature and this is because of the internal friction between the layers of a stranded conductor.

In AAAC conductors the conductor is homogeneous, however, a temperature differential exists between the core and outer strands, due to the effects of linear thermal expansion this should mean that there is a time period the distribution of tension within the conductor is being distributed by elastic elongation of the layers.

In ACSR conductors there is a greater differential in the coefficient of thermal expansion and therefore the time period for settlement may take longer than for AAAC conductors. For GAP type ACSR this mechanism may be even more complex due to the load share of the pre-tensioned steel core and outer aluminium strands, there may also be slower heating rates due to the reduced thermal conduction between core and outer strands.

The temperature differential between core and outer strands increases as the core temperature increases relative to the ambient temperature. This may mean that HTLS conductors have greater sag settlement times.

Due to a lack of available literature it was identified early in the Alpha phase that real world Dynamic Line Rating Data may provide the answers to the theories posited above as often conductor sag is being measured to infer temperature and circuit loading data is available. This data has not been forthcoming at the time of writing.

4. FINDINGS

4.1. HEAT BALANCE PARAMETERS

The following figures highlight results from the ratings calculation. The changing parameters were applied to three conductors, 3 x 700mm2 AAAC (triple Araucaria) at 400kV as one of the highest capacity bundles in use in the GB transmission system, 1 x 300mm^2 (single Upas) at 132kV as it is commonly the smallest transmission voltage conductor, and also 1 x 229 ACCC (single Monte Carlo ULS) to test the effects of the parameters on a HTLS conductor. The choice in conductor selection allows for different conductor attributes to be tested with different voltages, bundle sizes and conductors being tested in order to identify any disparate behaviour.

4.1.1. Wind Speed

The following wind speeds have been selected for the study as they are realistic, conservative cases. The selected wind speeds also consider recorded Met Office wind speed data displaying most frequently occurring wind 'summer day' speeds to be 1m/s – 10m/s indicated in Figure 10.

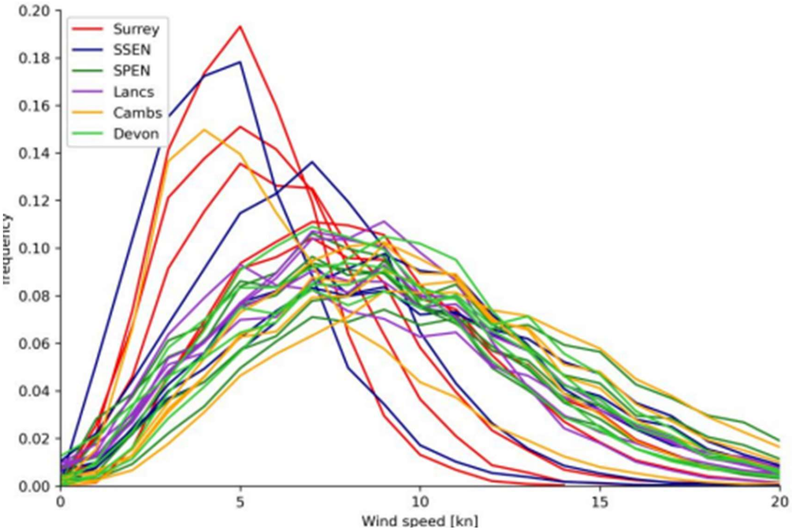

Figure 10- MET office Summer Day Wind Speed data

Figure 11 - Figure 13 show the change in rating for each conductor.

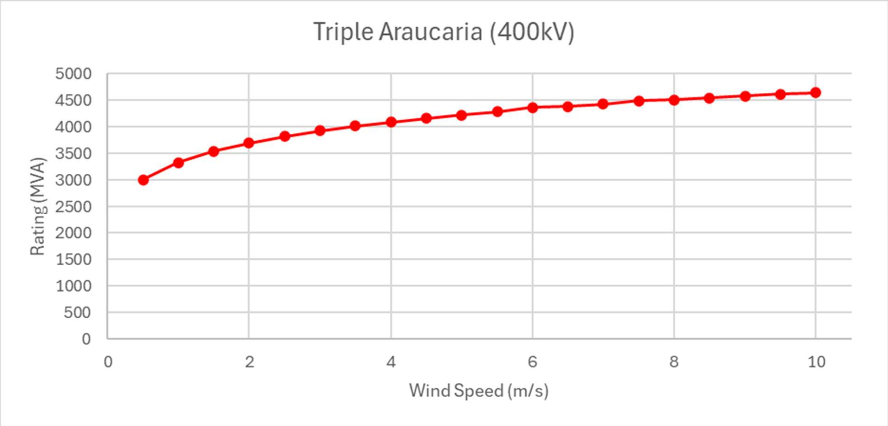

Figure 11 - Wind speed effect on conductor rating, Triple Araucaria

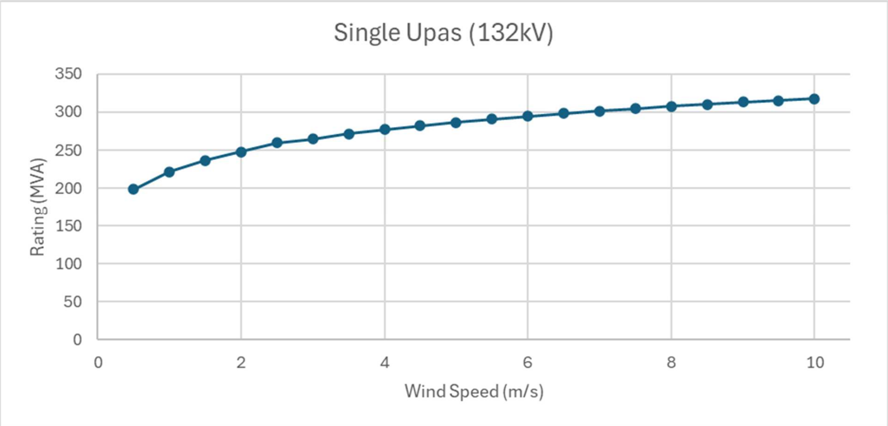

Figure 12 - Wind speed effect on conductor rating, Single Upas

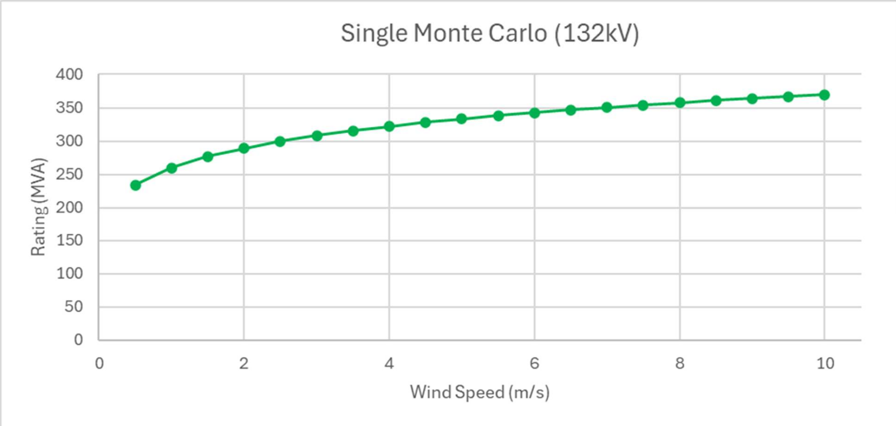

Figure 13- Wind speed effect on conductor rating, Monte Carlo

The results in the graphs are shown to be similar. As well as Table 2 showing all conductors to have similar percentage rating change between wind speeds.

Table 2- Conductor Rating Percentage Change with Wind Speed

Conductor	Wind Speed, 0.5 m/s	Wind Speed, 10m/s	Percentage Change
Upas Rating (MVA)	198	318	60.2%
Araucaria Rating (MVA)	3007	4639	54.3%
Monte Carlo Rating (MVA)	234	369	57.7%

4.1.2. Ambient Air Temperature

The range of ambient temperature values were selected for study to gather a wide range of values. Based on MET office data the range of realistic temperature values is likely to be a range of 5°C to 30°C this indicated in Figure 14.

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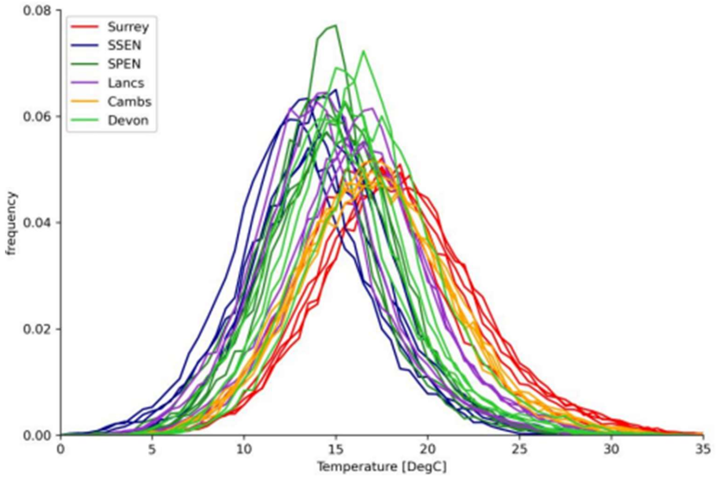

Figure 14- MET office Summer day Ambient Temperature data

Results indicate if the ambient air temperature is increased, the thermal conductivity decreases in turn causing the rating to decease as indicated in Figure 15 - Figure 17.

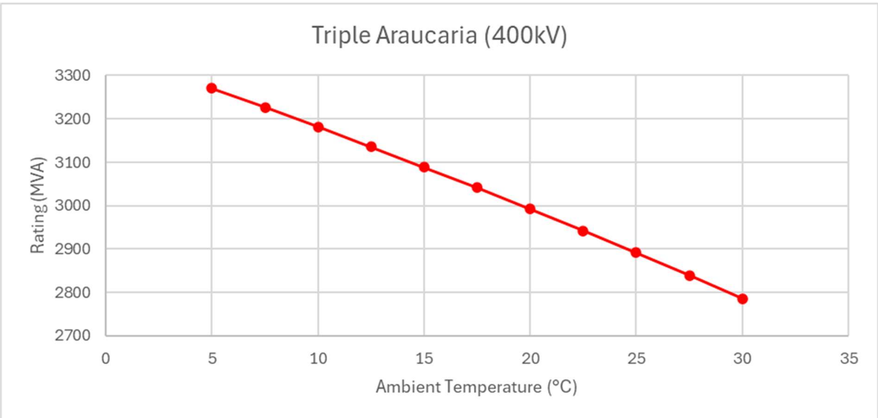

Figure 15- Ambient Air Temperature effect on conductor rating, Triple Araucaria

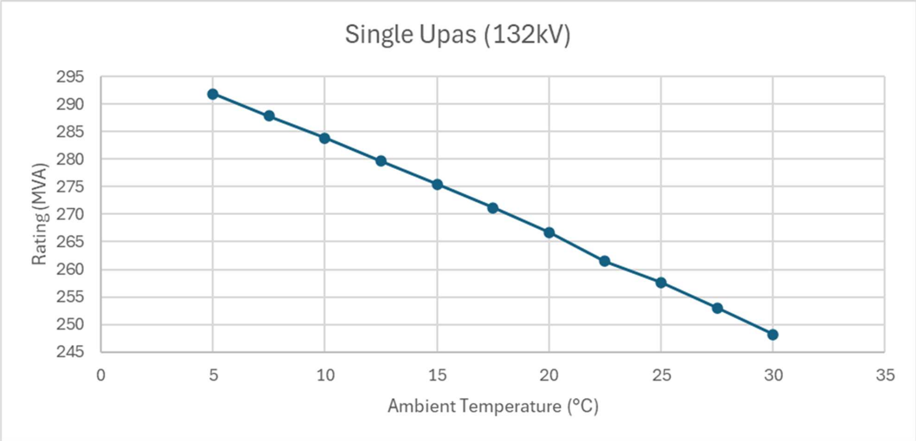

Figure 16- Ambient Air Temperature effect on conductor rating, Single Upas

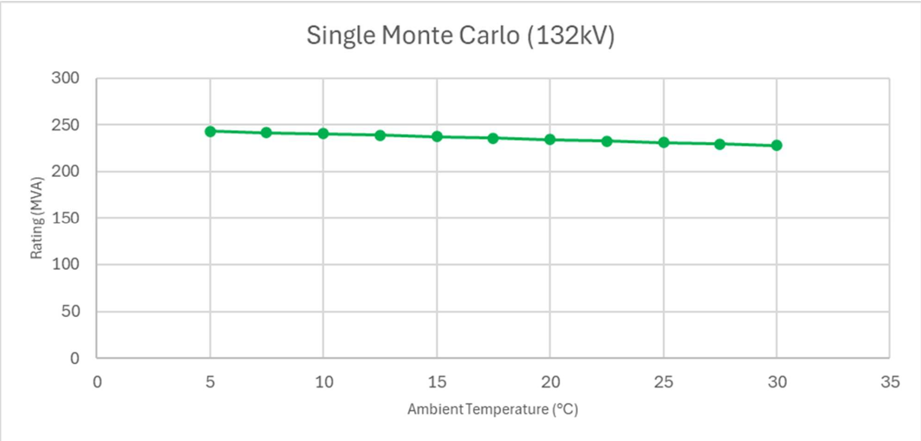

Figure 17- Ambient Air Temperature effect on conductor rating, Single Monte Carlo

The rating change showed to be similar in all figures. Table 3 shows the percentage rating change, between 5°C to 30°C.

Table 3- Conductor Rating Percentage Change with Ambient Air Temperature (5°C - 30°C)

Conductor	Temperature, 5°C	Temperature, 30°C	Percentage Change
Upas Rating (MVA)	292	248	-15.0%
Araucaria Rating (MVA)	3271	2786	-14.8%
Monte Carlo Rating (MVA)	243	228	- 6.3%

4.1.3. Direct Solar Radiation

The range of solar radiation values were selected based on MET office data the range of realistic irradiance is shown to be a range of 0 to 100 w/m^2.

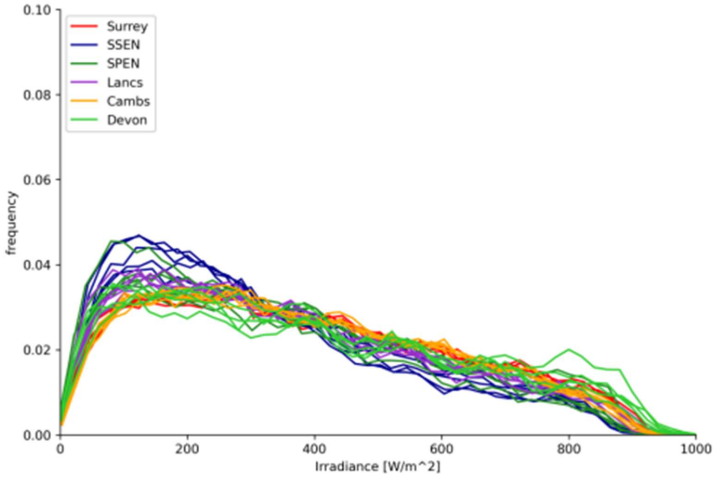

Figure 18- MET office Summer day Solar Irradiance data

Figure 19 - Figure 21 show the change in thermal rating with solar radiation.

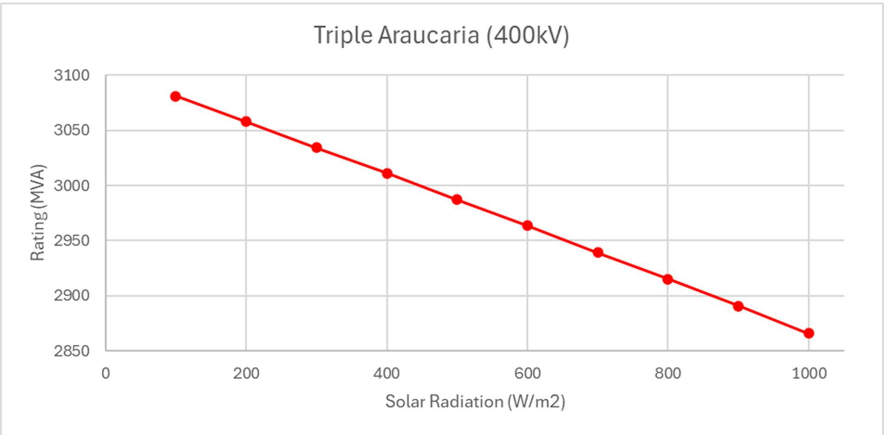

Figure 19- Direct Solar Radiation effect on conductor rating, Triple Araucaria

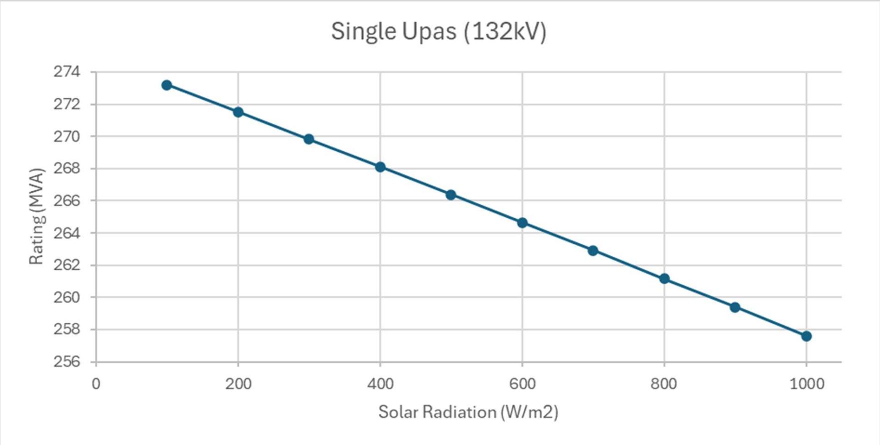

Figure 20- Direct Solar Radiation effect on conductor rating, Single Upas

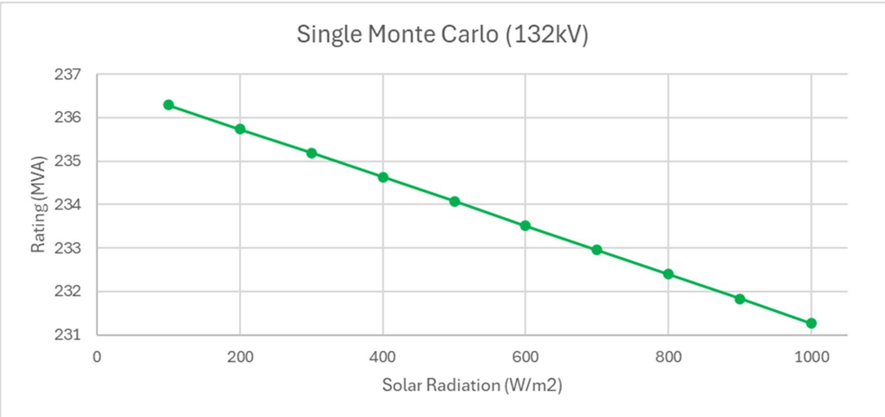

Figure 21- Direct Solar Radiation effect on conductor rating, Single Monte Carlo

The percentage decrease is shown to be less than that of the wind speed and ambient air temperature. Showing that although it contributes to the rating, it does not contribute as much as other parameters. A smaller decrease was shown to occur during the analysis of the HTLS conductor as indicated in Table 4.

Table 4- Conductor Rating Percentage Change with Direct Solar Radiation

Conductor	Solar Radiation, 100	Solar Radiation, 1000	Percentage Change
Upas Rating (MVA)	273	258	-5.7%
Araucaria Rating (MVA)	3081	2866	-7.0%
Monte Carlo Rating (MVA)	236	231	- 2.1%

4.1.4. Atmospheric Humidity

The percentage humidity impacts the thermal conductivity of the air. The calculations for change in humidity were done at an ambient air temperatures of 20°C in line with the Cigre 601 standard ambient air temperature.

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The humidity calculations were done from 0% to 100% humidity, Figure 22 indicates the recorded humidity data for six different site location on a 'summers day' indicating humidity largely never falls below 20% and is likely above 40%.

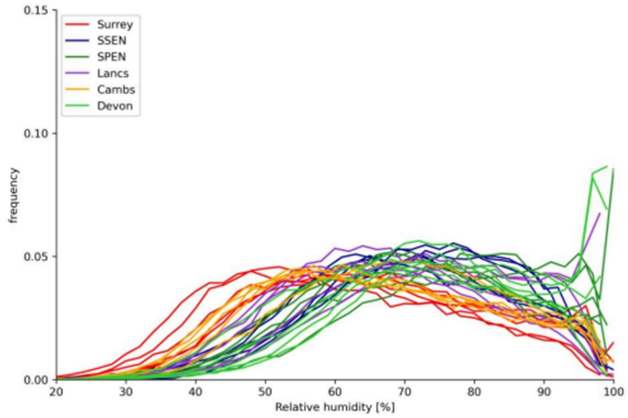

Figure 22- MET office summer day humidity data

Figure 23 - Figure 25 show the change in thermal conductivity and thermal rating with each humidity percentage change at 20°C.

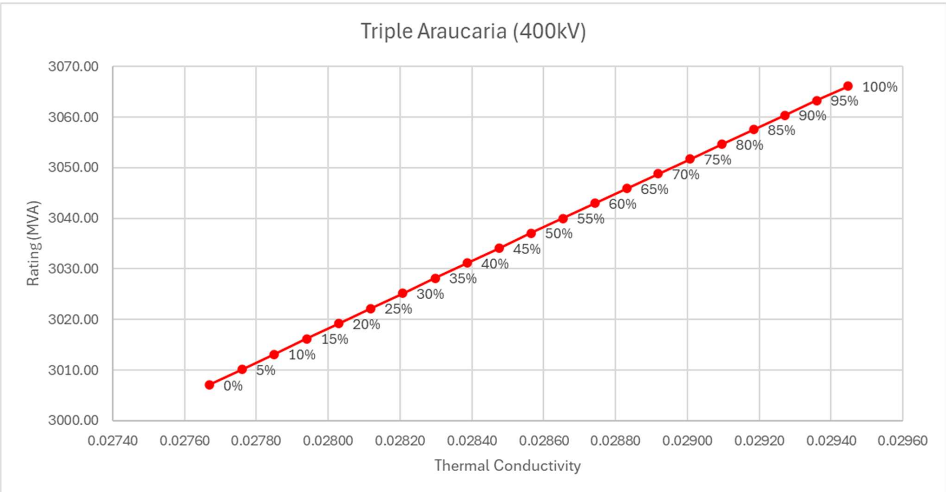

Figure 23- Humidity effect on conductor rating, Triple Araucaria

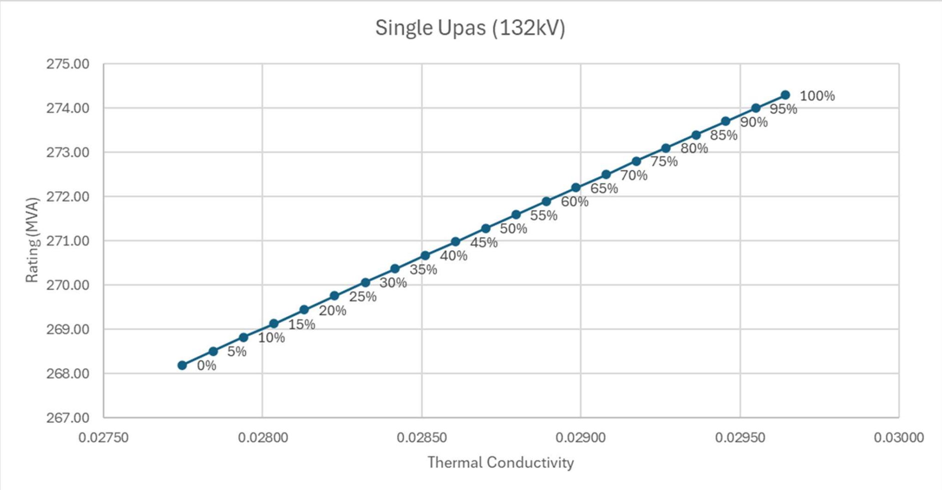

Figure 24- Humidity effect on conductor rating, Single Upas

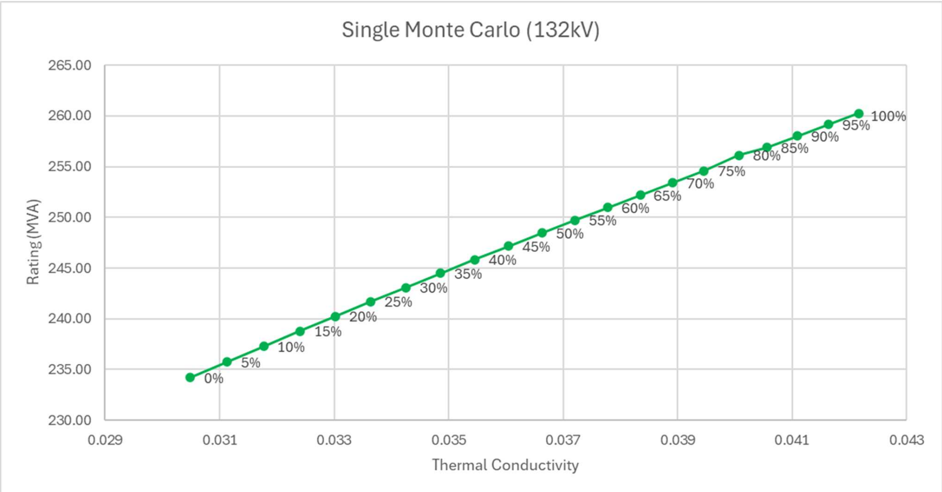

Figure 25- Humidity effect on conductor rating, Single Monte Carlo

The results showed an increase in the thermal conductivity of air with the increase of humidity in turn causing an increase in the conductor rating. Notably, there is a significant difference in the rating of the high temperature conductor.

Table 5- Conductor Rating Percentage Change with Humidity at 20°C

Conductor	Humidity Change, 0%	Humidity Change, 100%	Percentage Change
Upas Rating (MVA)	268.19	274.29	2.3%
Araucaria Rating (MVA)	3007.11	3066.15	2.0%
Monte Carlo Rating (MVA)	234.19	260.23	11.1%

4.1.5. Wind Angle

The wind angle impacts the rating of the conductor under the effects of forced convective cooling. This is shown in Figure 8 with the wind angle being perpendicular to the conductor a greater impact of cooling occurs. The following calculations were done at a wind angle of 0° in increments of 10 until the wind direction was perpendicular to the line.

The results in Figure 26 - Figure 28 show the impact of wind angle on the conductor rating.

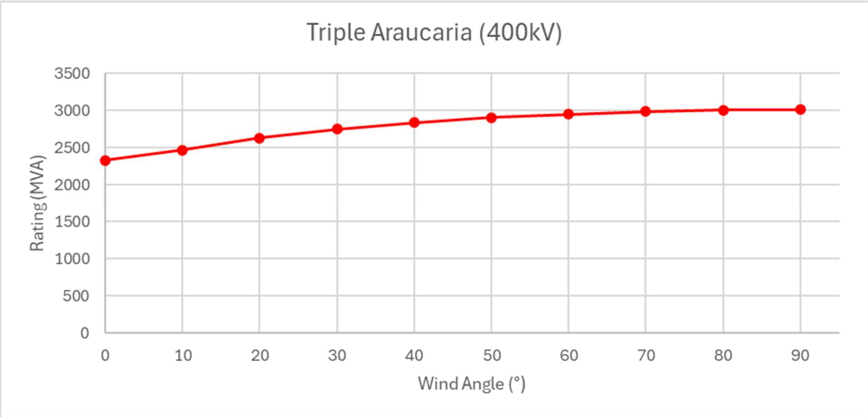

Figure 26- Wind angle effect on conductor rating, Triple Araucaria

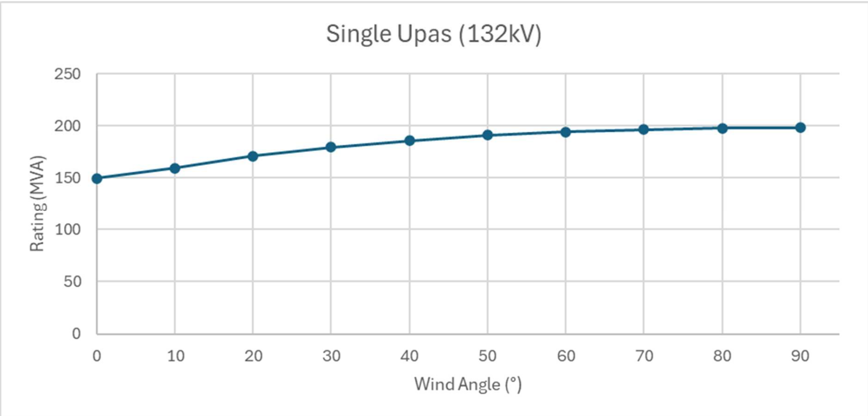

Figure 27- Wind angle effect on conductor rating, Single Upas

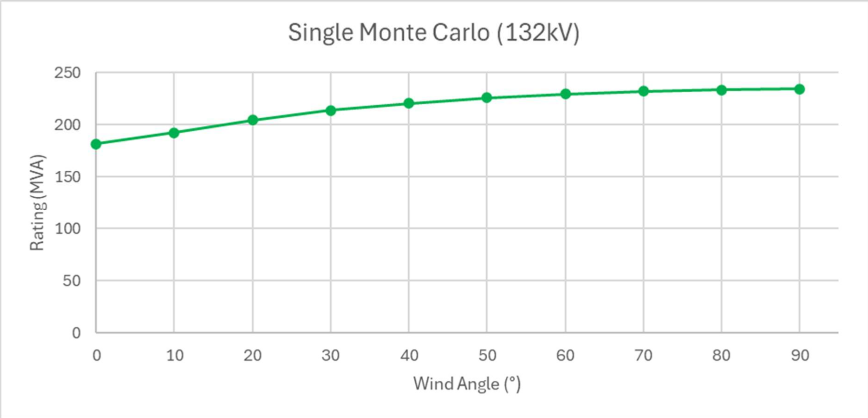

Figure 28- Wind angle effect on conductor rating, Single Monte Carlo

As expected, the rating of the conductor increased the closer the wind angle was to perpendicular with the line.

Table 6- Conductor Rating Percentage Change with wind angle

Conductor	Wind angle, 0°	Wind Angle, 90°	Percentage Change
Upas Rating (MVA)	150	198	25%
Araucaria Rating (MVA)	2330	3007	23%
Monte Carlo Rating (MVA)	182	234	22%

5. DISCUSSION

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When considering all selected 'Real World' parameters, it becomes evident that wind speed has the greatest impact in changing the conductor rating. The most critical events are typically defined by their duration and average temperature generally periods of low wind, such as during calm, hot summer days.

The methodology of Cigre 601 assumes 0% humidity in its calculations. Introducing new iterative methods to account for the effects of humidity on conductor ratings may therefore be a valuable consideration for subsequent phases. The results from the analysis showed humidity to have the largest impact on HTLS conductors. However, further analysis is likely required to evaluate the extent to which humidity affects conductor ratings and to assess the potential benefits of incorporating this variable. Additionally, the influence of precipitation and how humidity interacts with other weather parameters such as during hot, dry days or wet conditions should be considered to improve model accuracy.

Incorporating new iterative calculations presents challenges, especially when these involve iterative loops such as those where film temperature depends on conductor temperature. Experimental validation may be useful to determine whether the proposed calculations produce meaningful results.

The values in Table 7 represent the change in rating with changed to 'real-world' values

Commented [JS8]: Are you sure? You've said wind is the biggest elsewhere?

Table 7 - Summary of Weather parameters impact on rating

Weather Parameter	Generic weather values	Real-World Weather values	Percentage change between weather Values	Percentage Rating Change		
				Araucaria	Upas	Monte Carlo
Wind Speed	0.5 m/s	2 m/s	300%	22.9%	25.1%	23.6%
Ambient Temperature	20 °C	15°C	-25.0%	3.1%	3.2%	1.3%
Solar Radiation	500 W/m^2	200 W/m^2	-60%	2.3%	1.9%	0.7%
Humidity, 20 °C	0%	75%	-	1.48%	1.72%	8.71%

The analysis presented in this study demonstrates that humidity has a measurable impact on HTLS (High-Temperature Low-Sag) conductors, in this case Monte Carlo. This increased sensitivity in HTLS conductors could be attributed to elevated film temperatures, which intensify the interaction between conductor surface conditions and surrounding air moisture content. Under these conditions, film temperature is a key variable. Humidity affects the thermal conductivity and specific heat capacity of air, altering convective cooling dynamics. Despite its influence, modelling humidity in rating calculations is not straightforward. It introduces additional complexity, particularly where iterative loops may occur, such as when conductor temperature affects film temperature, which in turn modifies heat transfer coefficients that determine the final conductor temperature. Accurately resolving these interdependencies may require iterative numerical solutions, and potentially, the development of empirical models validated by field or lab-based experimentation.

6. CONCLUSIONS

The work undertaken for Work Package 2 of the Alpha phase of the REVISE project, has been detailed in this report and provided valuable insights into the impact of real-world meteorological parameters on overhead line thermal ratings. In pursuit of the REVISE project's overarching goal to update and improve the accuracy of overhead line ratings in the UK, moving away from the limitations of the historical TGN26 methodology, this study has specifically examined the effects of varying key parameters within the Cigre TB 601 ratings calculation using contemporary meteorological data and considering 'coincident events'.

Our analysis of real-world weather parameters has definitively shown that wind speed exerts the most significant influence on conductor thermal ratings. The most critical scenarios for line rating occur during low-wind, high-temperature conditions, underscoring the necessity for precise thermal modelling. Conversely, higher wind speeds and weather conditions promoting cooling were observed to increase the thermal rating. This aligns with the fundamental principles of heat transfer in overhead lines, where convective cooling due to wind plays a crucial role in dissipating heat generated by electrical current and solar radiation.

While the Cigre 601 guidance offers a foundational approach to thermal rating calculations, its assumption of 0% humidity represents a simplification of actual environmental conditions. This study has indicated that humidity, particularly for HTLS conductors, can have a significant impact on thermal ratings ~10%. Despite this, the effect of humidity remains generally less pronounced compared to wind speed and ambient air temperature. This may be a key area for further investigation in the Beta phase.

Insight into the sag relaxation time for conductors has been limited due to a lack of published literature and the inaccessibility of dynamic line rating data from trial installations. The temperature time constant response of conductors appears to increase at elevated temperatures (partially due to the increasing cooling effect of ambient air temperatures on hotter bodies), no data has been identified to quantify the time response above normal operating temperatures i.e. in the case of exceedance events, this may be a worthy area of research as well as investigating the assumed latency of the sag response to the conductor temperature change.

The move away from static ratings based on historical, geographically uniform data has the potential to unlock additional energy transfer capacity on existing overhead line circuits, thereby contributing to meeting the UK's Net Zero targets and mitigating significant monetary losses associated with current transmission constraints.

7. REFERENCES

Anvari, A., 2020. State-of-the-art methods for overcoming temperature polarization in membrane distillation process: A review. *Journal of Memebrane science,* 616(1).
Boukhriss, M., 2013. Study of thermophysical properties of a solar desalination system using solar energy. *Desalination and Water Treatment,* 51(4-6), pp. 1290-1295.
Chen, L., 2012. Thermal Grading around Overhead Transmission Line under Various Environments and its Influence to Load Capacity. *IEEE International Symposium on Electrical Insulation,* 1(1), pp. 545-548.
Cigre, 2014. GUIDE FOR THERMAL RATING CALCULATIONS OF OVERHEAD LINES. *Cigre 601,* 1(1), pp. 1-95.
Fu, J., 2010. Wind cooling effect on dynamic overhead line ratings. *Conference Paper,* 1(1), pp. 1-7.
Lasance, C. J. M., 2003. *The Thermal Conductivity of Moist Air.* [Online]
Available at: https://www.electronics-cooling.com/2003/11/the-thermal-conductivity-of-moist-air/
[Accessed 31 December 2024].
Lindberg, E., 2011. The Overhead Line Sag Dependence on weather parameters and line current. *Examensarbete,* 1(1), pp. 1-70.
Lindberg, E., 2011. The Overhead Line Sag Dependence on Weather Parameters and Line Current. *UPTEC W11 017,* 1(1), pp. 1-70.
Maksić, M., 2019. Cooling of overhead power lines due to the natural convection. *International Journal of Electrical Power & Energy Systems,* 113(1), pp. 333-343.
Numan, M., 2021. Coordinated operation of reconfigurable networks with dynamic line rating for optimal utilization of renewable generation. *International Journal of Electrical Power & Energy Systems,* 125(1).
PowerProcess, 2024. *Humid Air : Specific heat capacity.* [Online]
Available at: https://powderprocess.net/Tools_html/Air/Air_Humid_Specific_Heat.html
[Accessed 30 December 2024].
Price, C., 1983. Statistical approach to thermal rating of overhead lines for power transmission and distribution. *IEE Proceedings C (Generation, Transmission and Distribution),* 130(5), pp. 1-12.
Rahman, S. A., 2018. Re-Assessing the Current-Temperature Calculation for Bare Overhead Conductors at Low Wind Conditions. *Electrical Energy and Power Systems Group,* 1(1), pp. 1-170.
Riba, J.-R., 2024. Analyzing the role of emissivity in stranded conductors for overhead power lines. *International Journal of Electrical Power & Energy Systems,* 159(1).
Sterc, T., 2023. Methods for estimation of OHL conductor temperature based on ANN and regression analysis. *International Journal of Electrical Power & Energy Systems,* 151(1).
Tsilingiris, P., 2008. Thermophysical and transport properties of humid air at temperature range between 0 and 100 °C. *Energy Conversion and Management,* 49(5), pp. 1098-1110.
Wilcoxon, R., 2024. *Properties of Humid Air.* [Online]
Available at: https://www.electronics-cooling.com/2024/02/calculation-corner-properties-of-humid-air/#:~:text=These%20properties%20of%20the%20mixture,%2FmK%2C%20and%20%CE%BCm.
[Accessed 11 February 2025].
Zemljarič, B., 2024. Calculating a conductor's temperature-related sag as the limiting value for a Dynamic Line Rating. *Electric Power Systems Research,* 234(1).