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Sensitivity Effects of High Temperature Overhead Conductors to Line Rating Variables

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SUMMARY

For traditional overhead transmission lines, the maximum allowable conductor operating temperature on ASCR, AAC, or AAAC lines for determining the static line ratings can be quite low, typically well under 100 C. At these low temperatures, the primary driver for determining static line ratings are assumptions made about the wind speed and direction and the ambient temperature. Assumptions for solar loading and emitted thermal radiation, driven by line emissivity and absorptivity, are secondary factors, and only provide small changes to the static ratings. However, when considering newer high temperature conductors such as ACSS, ACCR, ZTACIR, and ACCC® the maximum allowable conductor temperatures can be significantly higher, up to 250° C. This higher temperature shifts the importance of the emissivity assumptions of the overhead transmission line, due to the nature of the T^4 dependence of the radiative heat loss compared to the T^1 dependence of the convective heat loss, as well as shifting the dependency on local wind conditions.

Typical assumptions in the United States for the emissivity/absorptivity of overhead transmission lines in determining the static ratings are to use a value of 0.5 for both parameters or set a value in the range of 0.7 to 0.9. Recent experimental tests at EPRI have shown that higher emissivity aging assumptions may not be valid in some regions of the US, and that actual values may be much lower (0.25-0.45) than older studies have predicted (0.8-0.9).

Here, the assumptions of different US Regional Transmission Operators (RTOs) and different utilities within RTOs are examined for the static ratings for traditional lower operating temperatures up to 100° C as well as with the higher maximum temperature conductors associated with newer conductor designs at 250° C. The sensitivity of the static ratings is examined at both lower and higher

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temperature conductors with respect to overhead line emissivity and absorptivity, wind speed, wind direction, and solar loading, and ambient temperature. It is shown that the effects of the conductor absorptivity, solar flux and ambient temperature on the static rating are increased when the transmission line has a lower maximum conductor temperature. The effects of the conductor emissivity, wind direction and wind speed have increased effects on the static rating when the transmission line has a higher maximum conductor temperature. In addition, example weather data is used to calculate the conductor temperature with different line emissivity and absorptivity assumptions. This shows the effect of assumptions made for emissivity only has a minor impact for low temperature lines, but for high temperature transmission lines can cause a 150-200° C temperature swing.

KEYWORDS

Dynamic line ratings – Static line ratings – Overhead transmission lines – High temperature conductors

1. INTRODUCTION

The line ratings are based on an ampacity that corresponds to a maximum conductor temperature for assumed environmental assumptions and have standard models developed by the International Council on Large Electric Systems (CIGRE) [1,2,3], the International Electrochemical Commission (IEC) [4], and the Institute of Electrical and Electronics Engineers (IEEE) [5,6]. The conductor maximum operating temperature is established to avoid sagging or clearance issues of the line segments between structures due to thermal expansion and to avoid damage to the conductor and equipment from excessive conductor temperature. To avoid these issues, overhead conductor line ratings are typically calculated as constant values using conservative assumptions for the weather conditions in the calculations.

Historically, transmission owners have built lines with conductors such as ACSR, AAC and AAAC with maximum operating temperatures of under 100°C. Increasingly, transmission owners are reconductoring, rebuilding, and building greenfield projects with high temperature conductors such as such as ACSS, ACCR, ZTACIR, and ACCC® for increased capacity and to accommodate the many constraints in line design. These conductors are often rated for continuous use with maximum operating temperatures from 180°C-250°C. As conductor temperatures increase, the relative impact of the line rating variables changes. Assumptions that were suitably conservative at lower temperatures may no longer be so at higher temperatures.

Recent studies have shown that older assumptions on the emissivity and absorptivity of overhead transmission lines may not be valid [7]. Recent values of aging lines measured 0.25-0.45 emissivity, as opposed to older studies showing much higher emissivity with aging [8]. In addition, the range of emissivity and absorptivity assumptions between different US Independent System Operators (ISOs) varies widely [9,10,11]. While for low temperature conductors, the impact of these discrepancies has only a minimal effect on an overhead line's temperature, for high temperature lines, the impact has a much larger effect as the sensitivity to the parameters shifts significantly.

2. THEORY

The temperature of a conductor can be calculated though a simple heat balance of the Joule heating, and solar heating terms with the heat loss through convective cooling and thermal radiation heat loss. This is illustrated in Figure 1.

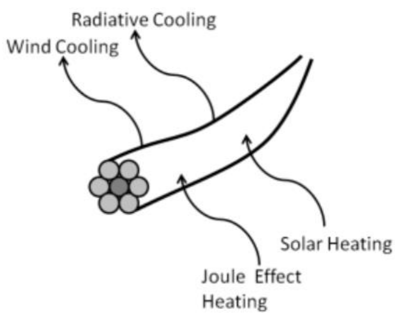


Figure 1. Heat balance of a conductor.

The heat balance equation is used to solve for the maximum current, I, to get [5]

$$I = \sqrt{\frac{q_c + q_r - q_s}{R(T_c)}} \quad (6)$$

Where q_c, q_r, and q_s are the convective, radiative and solar contributions, and *R* is the conductor resistance as a function of the conductor temperature T_c. The radiated heat loss per unit length in units of W/m is given by

$$q_r = 17.8D\epsilon\left[\left(\frac{T_c + 273.15}{100}\right)^4 - \left(\frac{T_a + 273.15}{100}\right)^4\right] \tag{7}$$

Where ϵ is the emissivity, T_a is the ambient air temperature and *D* is the conductor diameter. The heat gain through solar irradiance is given by

$$q_s = \alpha Q_{se}\sin(\theta)A' \tag{8}$$

Where α is the solar absorptivity, Q_{se} is the total solar and sky radiated heat flux corrected by elevation, θ is the effective angle of incidence of the sun's rays and A' is the projected area of the conductor. The convective heat loss is calculated using one of three equations for high wind speeds, low wind speed (below 3 mph) or natural convective cooling. For high wind speed the equation is given by

$$q_{c1} = \left[1.01 + 1.35\left(\frac{DV_w\rho_f}{\mu_f}\right)^{0.52}\right]k_f K_{angle}(T_c - T_a) \tag{9}$$

For low wind speed the equation is given by

$$q_{c2} = 0.754\left(\frac{DV_w\rho_f}{\mu_f}\right)^{0.6} k_f K_{angle}(T_c - T_a) \tag{10}$$

Or for natural convection the equation is given by

$$q_{cn} = 3.645\rho_f^{0.5}D^{0.75}(T_c - T_a)^{1.25} \tag{11}$$

Where V_w is the speed of air, with fluid parameters density ρ_f, viscosity μ_f and thermal conductivity k_f calculated at the ambient temperature. And K_{angle} is the wind direction factor which can vary from about 0.3 to 1.0 based on parallel or perpendicular wind flow to the transmission line, given by

$$K_{angle} = 1.194 - \cos(\phi) + 0.194\cos(2\phi) + 0.368\sin(2\phi) \tag{12}$$

Where ϕ is the angle of incidence between the wind and the transmission line midpoint. For the study here, three conductors are studied: a medium sized 796 kcmil Drake conductor (1.108 in) –a small sized 336.4 kcmil Linnet conductor (0.72 in), and a large size 2156 kcmil Bluebird conductor (1.762 in) with line properties from [12].

2.1 Aged Conductor Emissivity/Absorptivity

In an older publication [8], plots were created for emissivity and absorptivity correlations for aging conductors. These types of correlations have been in use for decades across various RTO/ISOs in the United States as accepted values. However, in recent studies, one such set of data was measured by EPRI and was presented at the IEEE738 Task Force meeting, have shown different correlations [13]. A plot of some data samples is shown in Figure 2 overlaid on the original data set. This shows that for some measured values in the ERCOT region, emissivities of old transmission lines may be much lower than previously assumed. The assumptions used by utilities for emissivity/absorptivity of lines may need to be revisited, especially for higher temperature conductors.

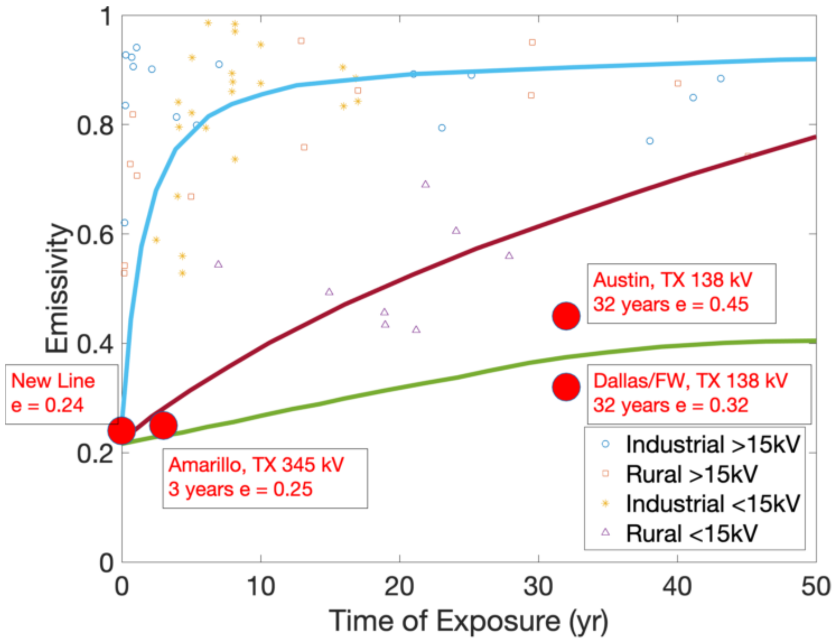


Figure 2. Recent emissivity measurements from ERPI [13] plotted against data reproduced from Rigdon, et al. [8]. The blue, red, and green line are fits to corresponding industrial, rural low voltage, and the updated datasets, respectively.

3. RESULTS AND DISCUSSION

3.1 US RTO/ISO Sensitivities

For demonstration of how line ratings may change between US Transmission Operators, data for how various entities calculate their line ratings are shown in Table I. The emissivity and absorptivity assumptions vary widely between the operators, as shown from a maximum of 1.0/0.9 to a minimum of 0.23/0.43, but even other variables have wide variations such as maximum conductor temperatures with a range of 45° C, and the wind speed assumptions varying by a factor of 5.

Table I. Summary of RTO/ISO Conditions [9,10,11,14,15,16,17].

Rating Input Conditions	NYISO Summer	MISO Utility #1	CA Utility #1	CA Utility #2	FL Utility #1	ISO-NE	PJM	SPP	SPP Utility #1	SPP Utility #2
Conductor Temperature (°C/°F)	95 / 203	100 / 212	100 / 212	80 / 176	115 / 239	100 / 212	125 / 257	85 / 185	100 / 212	90 / 194
Ambient Air Temperature (°C/°F)	30 / 86	40 / 104	40 / 104	43 / 109	35 / 95	38 / 100.4	35 / 95	40 / 104	40 / 104	40 / 104
Emissivity	0.6	0.8	0.5	0.5	0.9	0.75	0.7	0.23	0.5	0.85
Absorptivity	0.6	0.8	0.5	0.5	0.9	0.5-0.7	0.9	0.43	0.5	1.0
Wind speed normal to	3 / 0.9144	1.2 / 0.366	4 / 1.2192	2 / 0.6096	2.933 /	3 / 0.9144	0 / 0	2 / 0.6096	6 / 1.8288	6 / 1.8288

conductor (fps/mps)					0.894 0					
Solar radiated heat flux (W/ft^2 or W/m^2)	93 / 1001	93 / 1001	97.5 / 1050	93 / 1001	93 / 1001	93 / 1001	92.7 / 998	93 / 1001	93 / 1001	93 / 1001

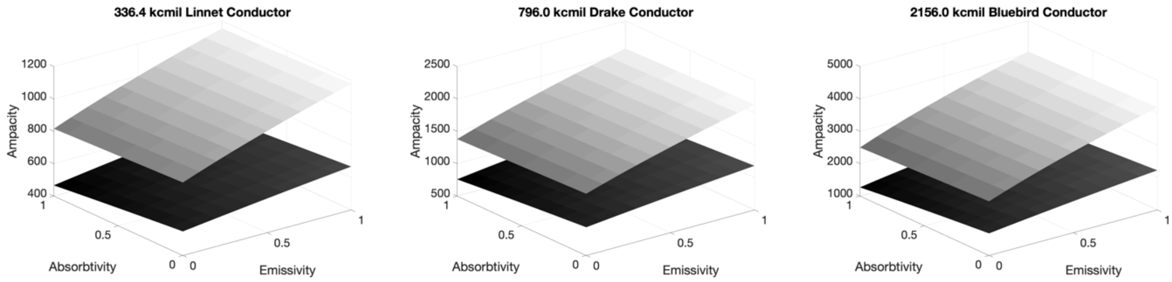
The resulting ampacity calculation between the different RTO/ISOs is shown in Table II for the three conductors discussed previously. The ACSR data uses the RTO/ISO maximum conductor temperature from Table I. For the ACSS data, a maximum conductor temperature of 250° C is used across the RTO/ISOs. From lower to higher temperature conductors the spread between the RTO/ISO static ratings changes, going from 275 to 301 A with a small Linnet conductor, 490 to 429 A with the Drake conductor and 931 to 773 A with a large Bluebird conductor – with lower values coming from a result of eliminating the 45° C maximum conductor temperature spread for ACSS calculations. The benefit of the high temperature lines increases with the conductor size, with an 85% change on the 336.4 kcmil Linnet, a 92% change on the 796.0 kcmil Drake and a 103% change with the 2156.0 kcmil Bluebird.

Table II. Summary of RTO/ISO Ampacity Calculations.

Conductor Type	NYISO Summer	MISO Utility #1	CA Utility #1	CA Utility #2	FL Utility #1	ISO-NE	PJM	SPP	SPP Utility #1	SPP Utility #2
ACSR Linnet	669	531	675	444	700	681	556	522	719	652
ACSS Linnet (250° C)	1140	1023	1153	1007	1086	1208	939	1079	1177	1240
ACSR Drake	1149	923	1161	756	1202	1187	1017	904	1246	1126
ACSS Drake (250° C)	2013	1839	2022	1779	1909	2158	1738	1923	2037	2167
ACSR Bluebird	2106	1701	2145	1352	2194	2204	1983	1654	2283	2047
ACSS Bluebird (250 °C)	3856	3598	3857	3413	3635	4186	3491	3725	3868	4157

3.2 Emissivity/Absorptivity Sensitivity

To further illustrate the impact of the weather variables on ampacity calculations, sensitivity of the variables over an extended range is examined. For the sensitivity to all of the variables relevant to the line rating calculations, similar assumptions to the weather conditions in the IEEE738 standards are utilized. These are 40° C ambient temperature, 0.61 m/s wind speed perpendicular to the conductor, and a solar irradiance of 1000 W/m^2. The full range of the emissivity/absorptivity values are shown in Figure 3a for 336.4 kcmil Linnet, 3b for 796.0 kcmil Drake and 3c for 2156.0 kcmil Bluebird. The lower surface in each shows the ACSR with 100 °C max, and the upper surface shows the ACSS values with 250 °C max. At low conductor temperatures, the slope in the emissivity and absorptivity is similar, but at higher temperatures this shifts dramatically from the T^4 dependency of the radiative heat loss, and also the I^2 Joule heating rate causing the heat gain from absorptivity to become more minimal. For side-by-side comparison of this increase, the case with emissivity equal to absorptivity is shown in Figure 4 for the conductors. Here, a 54 A, 112 A, and 249 A range for the 336.4 kcmil Linnet, 796.0 kcmil Drake and 2156.0 kcmil Bluebird conductors are seen for the low temperature ACSR transmission lines. However, the range of these values increases to 304 A, 622 A and 1386 A for the same sized lines as ACSS with the maximum temperature set to 250 °C.



(a) **(b)** **(c)**

Figure 3. Sensitivity of the ampacity calculations to absorptivity and emissivity for (a) 100 °C ACSR and 250 °C ACSS Linnet (b) 100 °C ACSR and 250 °C ACSS Drake (c) 100 °C ACSR and 250 °C ACSS Bluebird.

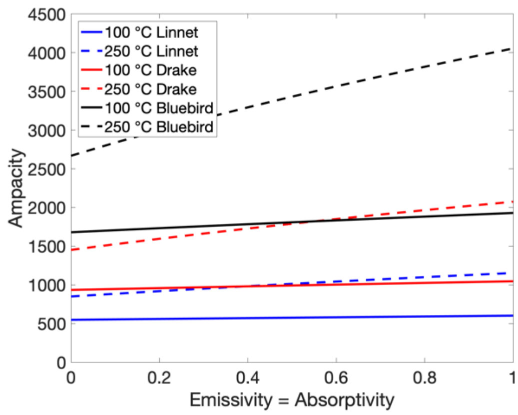


Figure 4. Sensitivity of the ampacity calculations to absorptivity equal to emissivity for the six transmission lines.

3.3 Weather Variable Sensitivity

Similar plots can be constructed for the weather variables used to determine the transmission line rating. The weather variables are shown in Figure 5a for the wind speed, Figure 5b for the wind direction, Figure 5c for the solar irradiance and Figure 5d for the ambient temperature. For the weather variables, the wind speed shows considerable change in ampacity. For the wind direction, as the parallel wind flow is neared at the low wind speed considered, the ampacity flatlines, as natural convection becomes more dominant than forced convection. This effect is increased with larger conductor sizes. In comparison, the solar irradiance only shows minor changes in the ampacity values.

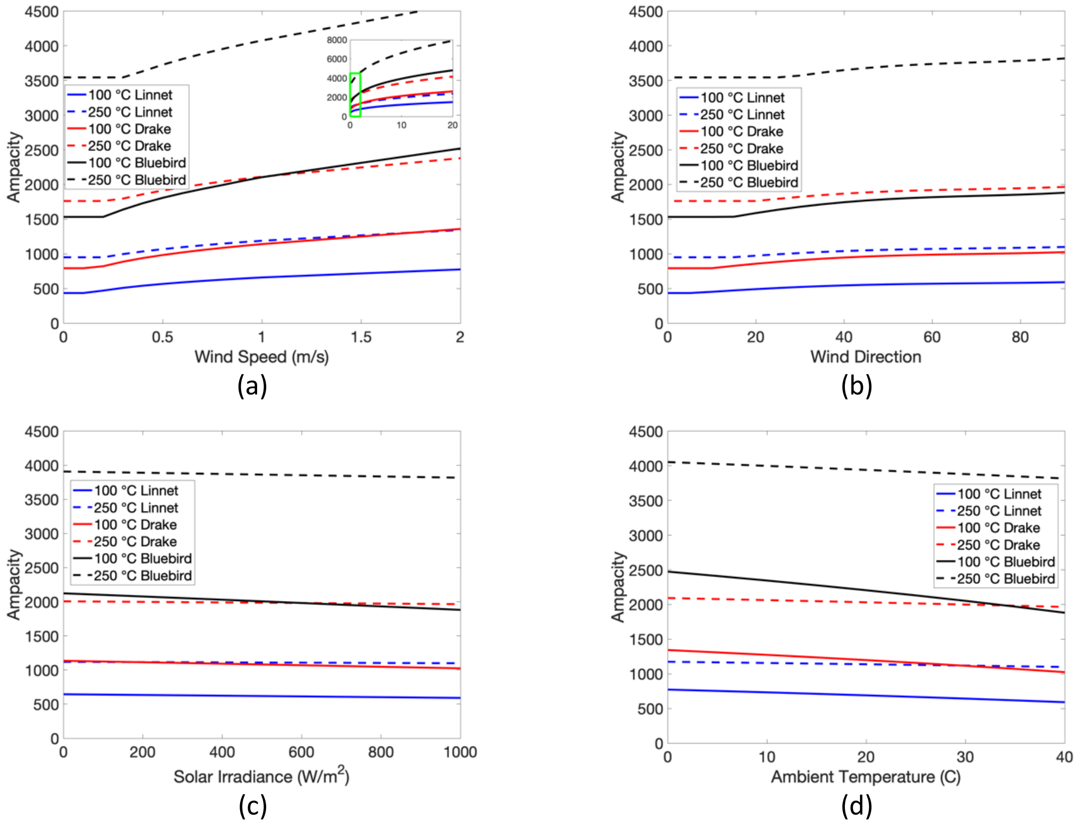


Figure 5. The sensitivity of the six transmission lines to (a) wind speed, (b) wind direction, (c) solar irradiance and (d) ambient temperature for 100 °C ACSR and 250 °C ACSS lines.

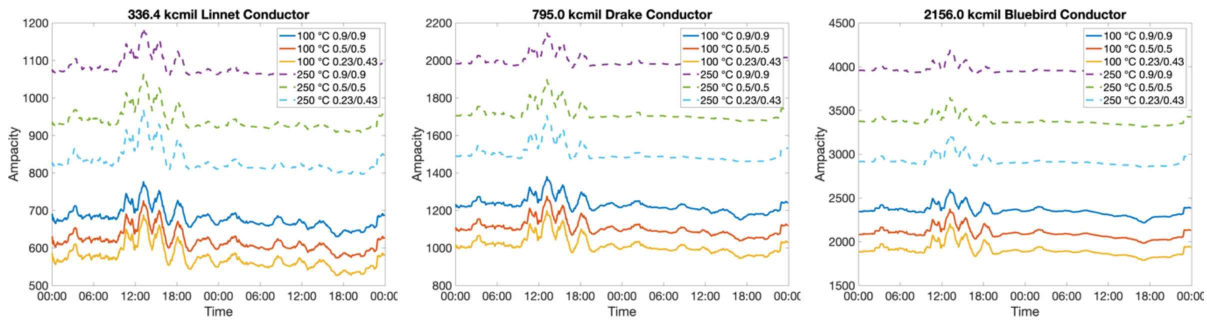
For some of the sensitivity variables the range over the values tested actually drops when moving from a low temperature to a high temperature conductor. This occurs with ambient temperature and solar heat gain, as with the higher current on higher temperature conductors, the Joule heating effect overwhelms the heating effect from solar irradiance. The decrease with respect to ambient temperatures indicates less ampacity gain from ambient adjusted ratings (AARs) with high temperature conductors. The ranges are summarized in Table III.

Table III. Change of ampacity over sensitivity range for each variable.

Variable ▸ Conductor ▾	Emissivity = Absorptivity	Wind Speed	Wind Direction	Solar Ampacity	Ambient Temperature
ACSR Linnet	54	1064	156	54	182
ACSS Linnet	304	1417	149	21	75
ACSR Drake	112	1820	232	111	319
ACSS Drake	622	2397	203	42	128
ACSR Bluebird	249	3276	348	242	593
ACSS Bluebird	1389	4348	273	91	237

3.4 DLR Ampacity with Emissivity/Absorptivity

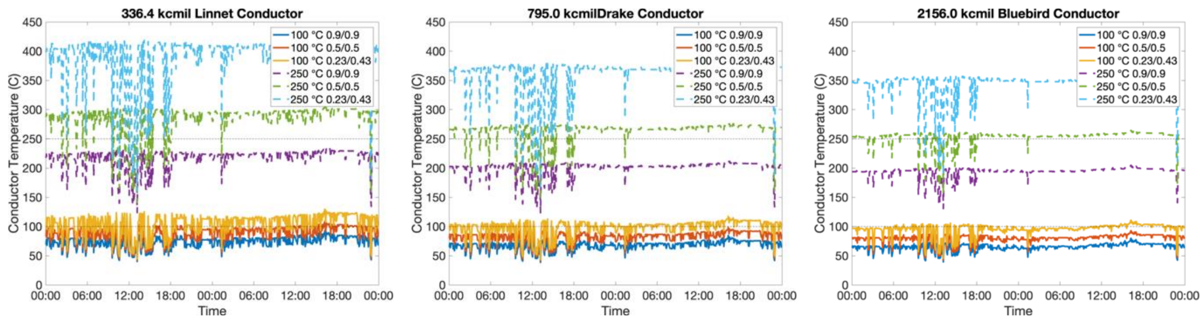
Using weather data from a previous study [18], the DLR ampacity of the transmission lines was plotted over a day long span in Figure 6 utilizing three different assumptions for the emissivity and absorptivity of the lines, corresponding to the RTO/ISO assumptions in Table I. This is plotted for conservative assumptions - 0.23/0.43 values from SPP, mid-range assumptions – 0.5/0.5 values from California Utility #1 and aggressive assumptions – 0.9/0.9 values from Florida Utility #1. This weather data mainly consists of north-south wind flow on a north-south running line, leading to a conservative set of ampacity values. The days selected show one high-wind day with additional ampacity followed by one low-wind day, with a 15-minute moving average applied to the ampacity calculations. This shows that the assumptions made can have low impact – about a 200 A difference on a 796.0 kcmil Drake conductor for low temperature transmission lines. However, the impact on calculations for a high temperature line increase drastically to about a 500 A difference for an ACSS 796.0 kcmil Drake. Similarly, on a 336.4 kcmil Linnet line, the increase in ampacity from these values changes from 100 A on low temperature to 300 A on a high temperature conductor, and for a 2156.0 kcmil Bluebird line this change is 400 A at low temperature to over 1000 A at high temperature.



(a) (b) (c)

Figure 6. DLR Ampacity over 48 hours for (a) Linnet, (b) Drake and (c) Bluebird transmission lines for different RTO/ISO emissivity/absorptivity assumptions.

The impact of the emissivity and absorptivity the on transient temperature of a line can also be calculated. In Figure 7, the transient temperature for the same transmission lines are plotted with the same set of emissivity/absorptivity assumptions. The line load is assumed to be a constant at about 90% of the average static rating among the different RTO/ISOs – this rounds out to 580 A for 336.4 kcmil Linnet ACSR, 1000 A for 336.4 kcmil Linnet ACSS, 1000 A for ACSR 796.0 kcmil Drake conductor, 1760 A for 796.0 kcmil ACSS Drake conductor, 1850 A for ACSR 2156.0 kcmil Bluebird, and 3400 A for ACSS 2156.0 kcmil Bluebird. The dashed black lines show the maximum conductor temperature of 100° C for ACSR and 250° C for ACSS for reference. While at lower temperatures, the spread given these assumptions is about 30-40° C, for a high temperature conductor there is a drastic difference of 200, 175 and 150° C for Linnet, Drake and Bluebird conductors, respectively. Thus, if an RTO/ISO assumes high emissivity values for high temperature transmission lines which actually have a much lower emissivity, there is potential to exceed the maximum conductor temperature for a given transmission line. This spread of the calculated temperatures under real weather conditions increases with smaller conductors due to higher resistances and lower cooling rates. In addition, the increase in the conductor temperature variability as a function of time for smaller sizes is highlighted in the difference between the plots.



(a) (b) (c)

Figure 7. Transient temperature over 48 hours for (a) Linnet, (b) Drake and (c) Bluebird transmission lines for different RTO/ISO emissivity/absorptivity assumptions.

4. CONCLUSION

It was shown that at higher temperatures, the importance of different variables in the calculation of static ratings for overhead conductors can shift significantly. The wind speed has a very large effect across any conductor maximum temperature, but the conductor emissivity can become rather important at higher conductor temperatures. An interesting result is that the ambient temperature is less sensitive with higher maximum conductor temperatures. For RTO/ISOs utilizing AARs this means that for the high temperature conductors, that type of methodology becomes less effective than methods which utilize the full set of weather conditions. Transmission owners should not assume that line rating methodologies that have been suitable for traditional lower temperature lines are equally suitable for higher temperature lines, and the assumed values for emissivity, wind speed, and wind direction should be evaluated. It was shown for calculated transient temperature values that incorrect assumptions on conductor emissivity can cause large overshoots in maximum conductor temperatures.

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