High Temperature Overhead Conductor Rating Considerations

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***Abstract*— Transmission utilities are deploying an increasing amount of high temperature conductors such as ACSS, ACCR and ACCC® relative to traditional ACSR. The higher capacities offered by these conductors helps utilities meet an ever growing list of commercial and design constraints such as providing for future load growth, upgrading existing corridors, and accommodating high levels of contingency loading. While these high temperature conductors are well suited for use in many scenarios, care should be taken to ensure that line rating assumptions that have been suitable for lower temperature lines do not introduce unexpected risk of overheated conductors when used at high temperatures. This paper reviews the variables that are used to calculate the current-temperature relationship in bare overhead conductors and examines the line rating sensitivity to these variables at conductor temperatures of 90°C versus the 200°C commonly used for high temperature conductors.**

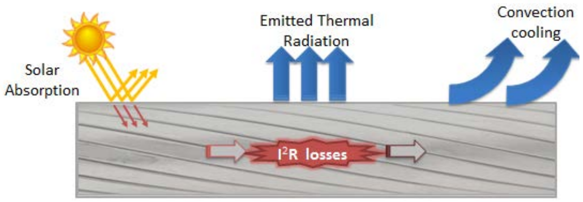
I. INTRODUCTION

Once reserved for limited deployments such as reconductoring applications, the use of high temperature conductors has expanded and has become commonplace for new line builds as well. With the high costs of project planning and permitting, utilities are leveraging high capacity conductors to maximize capacity on projects. The primary driver for this market shift toward higher temperature lines is clear: more available capacity. What may not be clear is that at high temperatures, the magnitude and the relative impact of the different heat transfer mechanisms that are applicable to line rating calculations change as well. Not considering these changes can expose the conductor to a large amount of thermal risk in the event that the line is ever called upon to carry its full rated capacity. Factors that are major contributors to line ratings at lower temperatures have diminished impact when conductor temperatures rise and factors that are minor at traditional operating temperatures can have much larger impacts. Line rating methodologies considered to be conservative for 90°C conductor operation can lead to large temperature errors capable of producing four or more feet of excess sag on a 1000 foot span when used for rating high temperature conductors such as ACSS.

II. CURRENT-TEMPERATURE RELATIONSHIP

The primary driver for deployment of high temperature conductors is the increase of current carrying capacity. As current increases, the heat generated within the conductor increases exponentially. These electrical losses are known as “I^2R losses” where “I” is the electrical current and “R” is the electrical resistance of the conductor. Additionally, conductors are heated during the day by absorbed solar radiation. As the amount of heating increases, care must be taken to ensure that conductor temperature does not rise beyond the chosen maximum operating temperature for the line. The risks from overheating a line include excessive sag that can result in electrical clearance violations and damage to the conductor and/or line hardware. The heat generated in the conductor must be dissipated into the environment to avoid this overheating. The mechanisms for heat transfer out of a conductor are convective cooling (wind) and radiative cooling (energy radiating from the surface). The most common method in the US for establishing the relationship between electrical current and conductor temperature is detailed Iq 1n IEEE Standard 738. At the core of this standard is a heat balance equation that states that at steady-state, the heat coming into the conductor must equal the heat flowing out of the conductor. If the heat can’t diffuse fast enough the temperature will rise. This rise in temperature will increase the amount of heat flowing out of the conductor until equilibrium is established.

$$q_{con} + q_{rad} = q_{solar} + I^2\mathrm{R}$$



On the left side of the equation above is heat energy flowing out of the conductor from both convective and radiative cooling. On the right hand side is the heat generated in the conductor by electrical current and resistance plus the solar heat gain.

q_{con} = convective cooling
q_{rad} = radiative cooling
q_{solar} = solar heating
I= electrical current
R=electrical resistance

For a full description of the methods and equations see IEEE 738. [1]

III. LINE RATINGS

The North American Electric Reliability Corporation (NERC) requires that each Transmission Owner develop "facility ratings used in the reliable planning and operation of the Bulk Electric System (BES) … based on an established methodology". These methodologies can be based on industry standards organizations (IEEE, CIGRE), ratings provided by equipment manufacturers, or by "practice that has been verified by testing, performance history, or engineering analysis".[2] Most US utilities use the calculations outlined in IEEE 738. The intent of the standard is to provide a method for calculating the relationship; however, "the standard does not recommend suitable weather conditions or conductor parameters". Thus the selection of the values of the input variables to these calculations is up to the user of the standard. For many utilities, the values used in their rating methodologies were established before the use of high temperature conductors became widespread. Utilities have many decades of operational experience to validate their rating methodologies for ACSR; however, wide scale use of higher temperature conductors is relatively new. For utilities using these higher temperature lines it is worth reevaluating assumptions to see how they may influence higher operating temperature line ratings.

IV. LINE RATING VARIABLES

A list of the major variables in IEEE 738 is below:

Conductor Maximum Operating Temperature: typically based on utility engineering judgment and manufacture recommendations

Conductor material properties: primarily electrical conductivity

Conductor Geometry: primarily conductor diameter

Convective Cooling: dependent on wind velocity, angle, ambient temperature, and air density

Incident Solar Radiation: dependent on atmospheric conditions, elevation, azimuth of line, northern latitude, time of day, date

Conductor surface properties: coefficients of emissivity and absorptivity

Ambient Temperature: temperature of air and surroundings

Heat transfer into and out of a conductor is driven by the difference in temperature between the conductor and the environment. Since the conductor is hotter than the surrounding environment, heat will flow out. The rate of this heat exchange is dependent on this difference in temperature. As the temperature difference gets larger the rate of heat transfer increases but not necessarily in a linear fashion. To evaluate the risk inherent in a line rating methodology it is prudent to evaluate not only a range of environmental parameters, but also of conductor operating temperatures, to understand the differences in behavior as operating temperatures increase.

V. LINE RATING SCENARIOS

The simplest way to evaluate sensitivity to changing inputs in a multivariable calculation is to establish a baseline set of values and then change input variables one at a time to see how the output changes. To illustrate this process for line rating a common conductor has been selected along with a "middle of the road" set of input values. The output from this will establish the baseline. The conductor selected for this study was a 1590 kcmil Falcon ACSS conductor. While some utilities may rate ACSS to operate at up to 250 °C, a lower 200°C is a more common maximum operating temperature and will be used in this analysis. To keep from introducing new variables into the comparison the same ACSS conductor will also be evaluated at 90°C instead of the ACSR that would likely be used. Ambient temperature, crosswind velocity, emissivity, and absorptivity will then be varied over a range of values. The baseline assumptions and range for each variable is summarized in the table below.

Conductor	**1590.0 kcmil 54/19 Falcon ACSS**				
Base line assumptions			**Vary between**		
Conductor Max Temperature			90	200	°C
Ambient Temperature:	**35**	**°C**	20	49	°C
Crosswind (90°) Velocity:	**2**	**ft/s**	0	6	ft/s
Emissivity:	**0.5**		0.24	0.9	
Absorptivity:	**0.5**		0	1	
Total Solar Radiated Heat:	**98.4**	**W/ft²**			
Azimuth of Line:	*90*	*° (E-W)*			
Atmosphere:	*Clear*				
Northern Latitude:	*32*				
Time of Day:	*12:00 PM*				
Month and Day of Year:	*1-Jul*				
Elevation:	**774**	**ft**			

A few notes of explanation for the values selected: For ambient temperature, the baseline of 35°C was selected as it is commonly used. The high ambient temperature was chosen as it is the hottest day ever recorded in the state of Texas. The low of 20° C was chosen as a value often used for seasonally adjusted wintertime ratings. For absorptivity, the low value of 0.0 would represent a methodology excluding solar gain entirely. The high value of 1.0 was chosen as the highest possible value. For emissivity, 0.24 represents a new conductor and 0.9 is a value used by several US utilities. For wind speed, 0 ft/s is the most conservative and 6 ft/s is the highest value believed to be used by a utility in Texas and the surrounding states.

The initial analysis ignores any correlation between variables and only changes one at a time to show the individual impact. Secondary analysis will then evaluate the "matched" emissivity and absorptivity values commonly used in the industry.

VI. ANALYSIS

Results from the calculations for the Falcon ACSS conductor at 90° C are below.

	Ampacity ratings for 1590 Falcon ACSS @ 90°C			
	Absorptivity: vary from 1 to 0	Emissivity: vary from 0.24 to 0.9	Ambient Temp: Vary from 49°C to 20°C	Wind Speed: Vary from 0 ft/s to 6 ft/s
Amp Rating	1300	1311	1200	**1102**
	1366	1427	1351	1427
	1428	1510	1498	1698
	1504	1588	1629	**1901**
Range	204	277	429	799

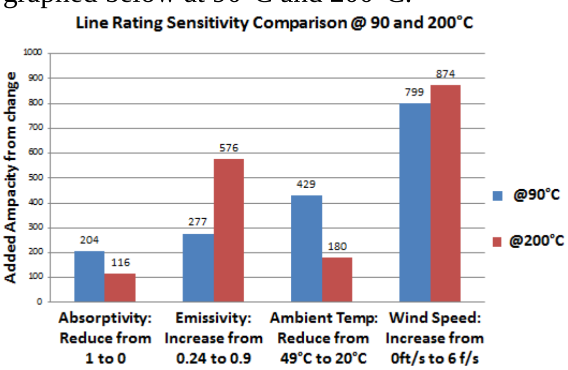
Wind speed is the dominant driver of line ratings when varied from 0 to 6 ft/s. Most utilities in Texas use the more conservative 2ft/sec wind speed which lessens the impact if the wind stops blowing for a period of time. Ambient temperature is the second most impactful variable. Ambient temperature is seasonal and is used by many utilities to adjust line ratings to increase winter ratings when the air is cooler. Impacts to ratings from emissivity and absorptivity show similar magnitude, although their impacts are inversely correlated. When emissivity increases, ratings increase. When absorptivity increases, ratings decrease. Since the magnitude of the change is roughly equal, this supports a philosophy that as long as emissivity and absorptivity values are close, they will not have a major impact on line ratings at lower temperatures.

Results from the calculations for the Falcon ACSS conductor at 200° C are below.

	Ampacity ratings for 1590 Falcon ACSS @ 200°C			
	Absorptivity: vary from 1 to 0	Emissivity: vary from 0.24 to 0.9	Ambient Temp: Vary from 49°C to 20°C	Wind Speed: Vary from 0 ft/s to 6 ft/s
Amp Rating	2397	2205	2359	**2169**
	2423	2449	2418	2449
	2449	2621	2480	2776
	2513	2781	2539	**3043**
Range	116	576	180	874

At 200°C, the impact of wind speed is still the largest, and similar in magnitude to results at 90°C. The sensitivities to the other variables change significantly. The impact of emissivity has been magnified while the impacts of ambient temperature and absorptivity are diminished.

The relative impacts of each of the variables are graphed below at 90°C and 200°C.



Note how at 90°C the difference between the impact of emissivity and absorptivity is 73 amps, while at 200°C, the difference is five times greater at 460 amps. The changing magnitude of these impacts has considerable implications for line rating risk and will be explored in more detail.

VII. Emissivity

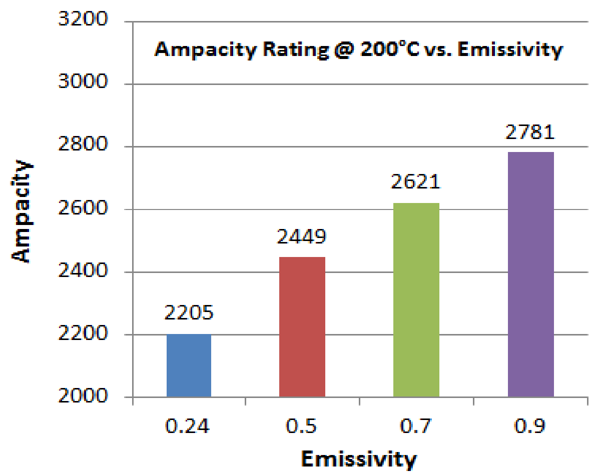
Hot surfaces lose energy (cool down) in part by radiating heat. A perfect "black body" surface radiates the theoretical maximum amount of energy from this heat transfer mechanism. Emissivity is a ratio of the amount of energy that a material radiates compared to a perfect "black body". [3] Emissivity of metals starts out low and increases with weather and pollution and is highly dependent both on the age and the atmospheric conditions where it has been used. Two older studies from 1958 and 1963 suggested that after only a few years, the emissivity of an overhead conductor would increase to high values [4, 5]. More recently, EPRI has done emissivity testing for General Cable on conductor samples including three samples collected from Texas utilities. The Texas samples show relatively low emissivity values even after several decades of use. Lower atmospheric pollution levels are one possible explanation for the difference between the old and new emissivity measurements.

EPRI Test results from Texas Conductors

Age (Years)	Measured Emissivity	Location	Conductor
0	0.24	-	ACSR-Drake
3	0.25	Amarillo	ACSS-Falcon
32	0.32	DFW	ACSR-Bittern
32	0.45	Austin	ACSR-Drake

Some US utilities use emissivity values of 0.8, 0.9 and even higher. While this may be accurate for very old lines that experienced high levels of industrial pollution and acid rain, conductor emissivity of more recent lines and of those deployed today is unlikely to reach that level based on the limited samples from Texas. These three data points suggest a more accurate value would be to use an emissivity value in the 0.3 to 0.4 range.

The chart below shows the impact of changing emissivity from 0.24 for a new conductor to 0.9 for the same 1590 Falcon ACSS.

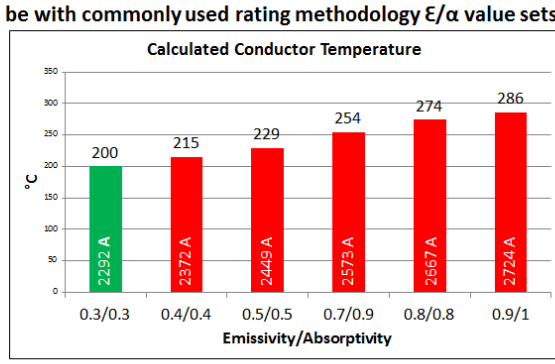


As the conductor ages and weathers, ampacity will increase. The question is how fast will emissivity increase and how high will it get before the conductor sees full loading? The question can also be asked, “If a line rated with an emissivity value of 0.9 is called upon to carry its full rated capacity while still new and shiny, what temperature would the conductor be?” The answer to this second question is that instead of operating at 200°C, the 1590 Falcon ACSS conductor in this scenario would operate at 326°C. This unexpected temperature rise would add approximately 6 feet of sag to a 1000 foot span and would possibly result in damage to the conductor and hardware. Clearly this is an undesirable situation.

VIII. CORRELATED VARIABLES

The flip side of the coin from emissivity is the variable called absorptivity. Absorptivity is the ratio of how much of the incident solar radiation hitting a conductor will be absorbed versus reflected. As a conductor ages and its surface darkens from pollution and oxidation, both the emissivity and the absorptivity will increase. [6] Increased emissivity can increase line ratings. Increased absorptivity will lower line ratings. In practice, most utilities have a closely matched set of emissivity and absorptivity values in their line rating methodology. Emissivity/Absorptivity value sets of 0.4/0.4, 0.5/0.5, 0.7/0.9 and 0.8/0.8 are all used to rate lines in ERCOT. [7] Values of 0.9/1.0 are used in adjacent states. For conductors operating at 90°C, the absorptivity values counteract the increase in emissivity and ratings stay relatively stable regardless of which set is used. At higher temperatures where the emissivity dominates the influence, the ratings diverge. The following chart shows the impact of using different common sets of emissivity/absorptivity values and the temperature risk if these values are used to rate a 1590 Falcon ACSS line at 200°C where the actual emissivity is a relatively low 0.3/0.3.

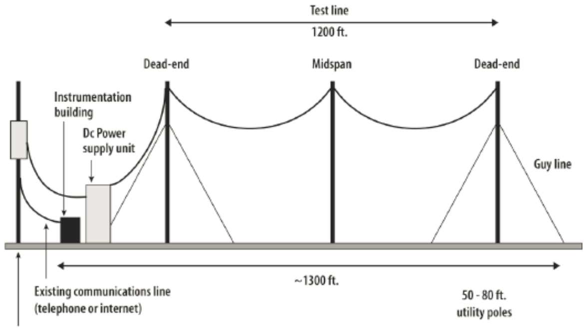
If actual Ɛ =0.3/α =0.3, what would conductor temp be with commonly used rating methodology Ɛ/α value sets?



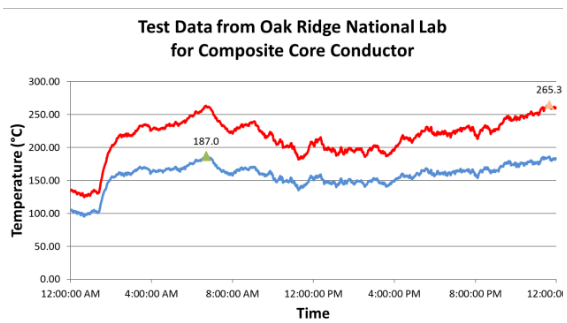
This chart is meant to shows the realistic scenario in which the conductor emissivity is in line with the EPRI test results from the DFW area, but lines are rated with higher values. This demonstrates how important it is to know actual emissivity values. Even the most common emissivity/absorptivity values of 0.5/0.5 would result in temperature errors of 29°C which would result in an additional one to two feet of sag depending on the span length. The highest emissivity values would result in 86°C of temperature error, which could not only result in over four feet of sag on a 1000 foot span but could damage the conductor and the hardware leading to premature failure.

IX. EMISSIVITY MATTERS

While emissivity may be the most difficult line rating variable to understand conceptually, for high temperature conductors it has a very real, and potentially unaccounted, for impact. To demonstrate the impact of emissivity, General Cable worked with the US Department of Energy’s Oak Ridge National Laboratory (ORNL). ORNL developed the Powerline Conductor Accelerated Test (PCAT) facility to test high performance conductors. The lab consists of two 600 foot aerial spans where conductors can be subjected to a variety of situations while the performance is closely monitored. [8]



The illustration above shows the basic test setup. For this testing, a high temperature conductor with a new specular surface was installed for the 1200 feet on one side of the pole and the exact same type of conductor with a known high emissivity of 0.9 was installed on the other side. The two were then connected electrically in series so both would see the same electrical loading. Temperature was measured with thermocouples spaced periodically along the conductor. A dramatic difference of operating temperatures was seen. [9]



These results validate what the IEEE 738 equations tell us: selecting the correct emissivity for a conductor matters a great deal for high temperature line ratings. If a selected emissivity is too low, then line ratings will not take advantage of a conductor's actual capacity. If the selected emissivity is too high, the temperature at full electrical load will be much higher than anticipated, causing excessive sag and potential damage to the line. Since lines are only typically loaded to their maximum rating during a contingency event this excess sag and potential damage could have very major impacts.

X. Conclusions/Recommendations

When determining the ampacity of high temperature conductors it is important to understand the impact of changes to the various line rating parameters and specifically the assumed conductor emissivity value. Line rating methodologies which have proven reliable for traditional ACSR operating temperatures may need to be reevaluated for use with conductors such as ACSS, ACCC, or ACCR. Emissivity errors can lead to very large temperature errors, which in turn can lead to excessive sag and conductor and hardware damage. Commonly assumed values for emissivity can lead to 20-90°C temperature errors. Emissivity values in use by some utilities can have an equivalent impact on conductor temperatures to a 4 ft/s wind speed error that exists not just when the wind stops blowing intermittently but for the many decades of conductor use. Recent EPRI testing done on conductors from Texas shows lower than expected emissivity values of 0.32 and 0.45 for 32 year-old conductor samples. Levels of airborne pollutants such as fine particulates and the chemicals causing acid rain are much lower than they were in the mid-1980's when these conductor samples were first deployed. [10] Understanding emissivity values is important. The good news is that emissivity is measureable in a laboratory environment. [11] For any utility operating high temperature lines it would be prudent to have lines of different ages analyzed to see if the value being used in line ratings is appropriate or if it could lead to excess sag or conductor damage, possibly during an emergency event.

Acknowledgment

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