Guidelines for Determining Conductor Temperatures During Measurement of Sag Along Overhead Transmission Lines

1. Introduction

Proper determination of conductor temperature is critical when evaluating the thermal rating (ampacity) of an existing overhead transmission line based on measurements of actual field conditions, such as sag and ground clearance. Inaccurate assumptions, estimates and/or measurements of temperature will likely lead to erroneous conclusions.

The significance of this issue has been highlighted by the North American Electric Reliability Corporation’s (NERC) recent publication entitled “NERC Alert: Recommendation to Industry – Consideration of Actual Field Conditions in Determination of Facility Ratings”. Issuance of this recommendation was prompted by a conductor-to-ground fault that resulted in a lockout of a bulk power system transmission line. Investigation of the cause revealed that the conductor-to-ground clearance was less than expected. The deficient clearance was a result of substantial inconsistencies between the actual topographic characteristics of the corridor and those assumed during design of the line. In response, NERC has recommended that all transmission owners with lines under NERC’s jurisdiction review their current facility ratings methodologies to ensure they are based on actual field conditions versus design assumptions and that any differences found are within the limits allowed by their respective methodologies. NERC also recommends that transmission owners perform their assessments based on actual field conditions using methods and/or technologies with sufficient accuracy to identify whether the ratings are appropriate.

Several approaches are now being used to ascertain actual field conditions for line rating assessments. The need to establish an accurate conductor temperature during the field measurement processes used to obtain other physical data, such as sag and structure heights for example, is fundamental to all of the approaches currently being utilized. Determining an accurate representative temperature can be challenging due to the effects of fluctuating operating and meteorological conditions. (Note: Representative
temperature as used herein means the average temperature of the conductor along a ruling span section. Failure to establish an appropriate value of conductor temperature at the time the physical measurements are obtained can introduce significant errors into the determination of a line’s rating. This paper provides guidance to assist transmission owners in determining conductor temperatures with the goal of minimizing potential inaccuracies in line ratings.

2. Scope of Guidelines

These guidelines focus on providing direction on methods for determining conductor temperatures representative of those occurring when conductor sags are measured for the purpose of assessing/verifying line ratings based on actual conditions.

While the guidance provided herein is limited to the scope described above it is important to note that conductor temperatures and contemporaneous sags are only two of several variables that need to be considered to reliably assess/verify the ratings of existing overhead lines. Other variables that should be considered to determine whether they will significantly impact the ratings of a specific line include:

- Deviations of as-built conditions/configuration from the assumed design conditions/configuration
- Actual available clearance buffers
- Potential changes in ROW conditions including changes in surface profile, vegetation, land use, and sheltering
- Potential additions of new circuits, underbuilds and crossings
- Differences in the temperature versus tension versus sag behavior of bimetallic and bi-material conductors in different temperature ranges
- Changing conditions of aging aluminum strands (e.g., annealing and fatigue) and core wire (e.g., corrosion) and the integrity of compression connectors
- Actual meteorological conditions including changes in climatology/meteorology along the line versus assumed conditions
- Line amperage data, before and during survey data collection

Of these variables, two that can have a significant impact and are often improperly or only partially accounted for are the actual meteorological conditions along the line, and the knee-point/zone tension/sag behavior of bimetallic and bi-material conductors.

It is not uncommon for wind speeds used in rating calculations to be overestimated and the effect of the wind angle to the line to be ignored. Collectively, these factors can result in overestimation of forced convective cooling, and underestimation of conductor temperature. Similarly, improper assumptions regarding the characteristics of winds occurring coincident with sag measurements can lead to unreliable estimates of the concurrent conductor temperature. This, in turn, can lead to calculation of inaccurate line ratings. A brief overview of proper use of meteorological conditions for determining...
3. Impact of Line Current on Conductor Temperature Error

When an overhead line is out of service or carrying less than 0.25 amps/kcmil, the temperature of the conductor is usually only 5°C to 10°C above the air temperature, even on a sunny day. Therefore, the potential error in calculating the temperature and the variation from span to span along the line is typically less than 5°C.

Figure 1—Conductor Temperature versus Line Current at 25°C Ambient Temperature, Full Sun and Wind Speeds of 2fps and 16fps

At higher line currents, however, as shown in Figure 1, the conductor temperature rise above the 25°C air temperature increases. At a current density of 0.75 amps/kcmil the
conductors. The temperature rise is about 4 times as large and the potential calculation error increases similarly. Also, at higher line currents the wind speed has a more significant impact on the conductor temperature as illustrated by the differences in the curves for 2 fps and 16 fps wind speeds, respectively. Hence spatial variation in wind speed along the length of a line operating at a high current density can introduce significant errors in conductor temperature estimates.

4. Effects of Conductor Temperature Inaccuracies on Ratings

The consequences of using inaccurate temperatures vary with each situation and the degree of inaccuracy. Substantial inaccuracies in determination of conductor temperatures can lead to risky and/or costly decisions regarding how to operate transmission lines.

4.1 Consequences of Underestimating Conductor Temperature

Calculating line ratings using conductor temperatures lower than actual when sag measurements are performed should lead to conservative estimates of ratings and safe operations except perhaps in the case when the rating is governed by the clearance between the conductor and another line or obstacle under which the conductor is crossing. However, this may also lead to overly conservative operating decisions and/or costly line modifications.

To illustrate this problem let’s assume we are interested in verifying the adequacy of clearances in a given span at a conductor maximum operating temperature of 95°C using calculations based on actual field measurement of sags. To enable the necessary calculations a survey crew is deployed to measure the actual sag of the conductor. The crew does not know the temperature of the conductor, but let’s assume for the purposes of this example that the actual temperature of the conductor at the time the sag is measured is 30°C and that the person who performs the rating calculations makes a best guess based on the ambient air temperature recorded in the survey notes that the conductor temperature was 20°C when the survey measurements were performed. Using this input the conductor sag is overestimated at the maximum operating temperature as shown in Figure 2. Such excessive estimates may lead to an unnecessary reduction in ampacity ratings or unnecessary line modifications to increase clearances.
4.2 Consequences of Overestimating Conductor Temperature

Calculating line ratings using conductor temperatures higher than actual when sag measurements are performed can lead to underestimation of sags at maximum operating temperature and therefore overestimations of ratings and potentially risky operations except perhaps in the case when the rating is governed by the clearance between the conductor and another line or obstacle under which the conductor is crossing.

To illustrate this problem let’s reuse the example above and assume that all the conditions are the same except that this time the person who performs the rating calculations makes a best guess based on ambient air temperature that the conductor temperature was 40°C when the survey measurements were performed. Using this input the conductor sag is underestimated at the maximum operating temperature as shown in Figure 3 resulting in an overestimation of thermal capacity and the potential for operating the line so that minimum clearance requirements are compromised.
The preceding examples illustrate the importance of using reliable estimates of conductor temperatures when performing line rating calculations based on field measured sags.

5. Methods for Estimating Conductor Temperature

The temperature of a conductor at a specific location is a function of several variables. The variables noted below have different levels of impact on conductor temperature depending on the situation:

- Weather conditions and their spatial and temporal variation
- Solar flux
- Orientation of conductor with respect to sun
- Orientation of conductor with respect to the wind
- Topography and sheltering effects
- Number and location of line taps
- Cross sectional area and percent aluminium
- Material properties of all strands including core
- Geometry of strands and air gaps
- Current
- Attachment hardware
- Air density and viscosity
- Surface condition
  - Emissivity and absorptivity
  - Roughness
— Corrosion
— Internal condition
— Strand breakage
— Corrosion

The extensive list of variables and their interrelationships and interdependencies combine to make the determination of a location-specific temperature of an energized conductor a very complex problem. Care must be taken to account for the impact of these variables on conductor temperature. For the purposes of these guidelines we are not concerned with determining temperature at a discrete point along the length of a conductor, rather we are concerned with establishing a reliable estimate of a representative temperature of a ruling span section of line coincident with sag measurements. With a bit of due diligence conductor temperature can be reliably estimated in a variety of ways without having to quantitatively define the specific effects of each of these variables.

Our ability to reliably estimate temperature while mitigating the risk of large error can be significantly enhanced by monitoring line and environmental conditions locally and by imposing limits on operating conditions when sags are measured. The most important limit/control that should be exercised is to measure sags when lines are operating under normal electrical loads. In general, the reliability of temperature estimates is inversely proportional to the current density on the conductors, and, for a given current density the possible variation in temperature resulting from a given change in wind speed reduces as the average wind speed increases. Measuring sags when wind speeds are above 1m (3.2’) per second and current density is less than 0.5 amps/kcmil will limit errors in estimates of conductor temperature to +/-5°C. Temperature estimates made with little to no electrical load flowing on the conductors will be the most reliable. This control will virtually eliminate the potential for significant error due to spatial variation in wind speed and direction, differences between conductor surface and core temperature, and transient electrical effects as described more fully below.

The temperature of an energized conductor is transient in nature. This is due to temporal changes in weather and electrical current. The term “transient” is used herein in the context of sudden and significant shifts in electrical current such as those associated with a change in state from normal to short-term emergency operating conditions. We will assume for the purpose of these guidelines that when conductors are carrying low electrical loads that they are in a near-steady state condition. This condition is characterized by thermal equilibrium with an isothermal conductor temperature approximately equal to ambient air temperature plus any temperature gain attributable to solar flux; at low electrical loads any ohmic heating will be approximately balanced by convective heat loss.

— Potential Errors Caused by Spatial/Temporal Variation in Wind Speed/Direction: Of all the inputs to estimating conductor temperature, none are as unstable as effective wind speed; and unfortunately, none have more potential to result in error. Effective wind speed is that wind speed perpendicular to the ROW that when used to calculate conductor temperature results in an accurate estimate; it is a function of wind speed and wind direction relative to the line. High in the
atmosphere, wind flow is relatively laminar, but near the ground, surface
rroughness caused by everything from grass to mountains, and thermal effects,
causes turbulence. This results in significant spatial and temporal variation in wind
speed and direction. At high operating temperatures, the effect of convective
cooling due to this variation can not be accurately predicted. Under normal
operating conditions, however, where the conductor is operating at temperatures
10 to 20\(^\circ\)C above ambient air temperature, this effect—and the spatial variability
in conductor temperature that results—is minimized. Normal operating conditions
reduce the uncertainty in conductor temperature during sag measurements.
Calculations to determine ratings at maximum sag under normal operating
conditions are kept within tolerable limits.

— Potential Errors Caused by Conductor Radial Temperature Gradients: Conductor
temperature varies radially, with the highest temperatures generally occurring at
the core and lowest temperatures at the surface. The impact of the temperature
gradients can be ignored in line rating calculations performed starting with sags
measured during normal operating conditions, i.e., a reliable estimate of a
representative surface temperature is sufficiently accurate. The impact of radial
temperature gradient on ratings calculations can be ignored except in the case
where actual sags are measured under emergency operating conditions in which
the conductor was carrying a very high electrical loads (current densities of 1.5-2
amps/kcmil). This should not be an issue because attempting to base rating
calculations on sags measured during emergency operating conditions is not
considered good practice.

— Potential Errors Caused by Transient Electrical Effects: When conductor current
changes suddenly such as may occur during a shift from normal to short-term
emergency operating conditions, a contemporaneous change in conductor
temperature will occur. This conductor temperature change will not be
instantaneous. In this situation, conductor temperature will ramp up in an
approximately exponential manner to a new quasi-steady state temperature
assuming that all other variables are constant, which they are not. If this change in
state occurs during the period when conductor temperature is being estimated
and/or sags measured it can introduce significant errors in ensuing rating
calculations. Measurements should not be performed during such transient
operating conditions. If emergency operating conditions arise in the midst of
taking measurements their validity should be carefully scrutinized; re-
measurement during normal operating conditions may be warranted to replace data
that could compromise the validity of rating calculations.

The following subsections of these guidelines discuss the various methods for estimating
conductor temperature coincident with sag measurements. This is followed by a
summary of key considerations regarding best practices for each method.

All of the methods discussed below assume that reliable electric current information is
available for the period when representative temperatures are being assessed and sag
measurements made.
5.1 Estimating Representative Conductor Temperature Based on Weather Conditions

Calculating conductor temperature based on line current and local weather parameters is an established and proven methodology used for thermal rating studies and the accuracy of computed line sag has been extensively verified experimentally when used in conjunction with weather conditions measured in the vicinity of the line. The accuracy of such measurements is, however, potentially subject to significant error if weather observations are from remote sites or if careful consideration is not given to the actual line load and potential variations in meteorological conditions along the line at the time field survey measurements are made.

Weather conditions can, and often do, vary significantly along the line, particularly when the line traverses varying terrain and sheltering conditions, and, in certain situations, line current can also vary. Likewise, conductor temperatures typically vary along the line. To ensure that these variations are correctly modeled during use of the IEEE 738 [7] methodology, the effects of local environmental conditions within each line section (dead end to dead end) should be estimated. This can be achieved either by deploying multiple weather stations along the line or by using a mobile airborne meteorological probe that estimates the wind speed and direction, air temperature, and other environmental factors in close proximity to each line segment at the time of survey (see Section 5.2).

A number of parameters need to be defined before a conductor temperature can be calculated, including: line current, ambient temperature, solar flux, effective wind speed and conductor absorbtivity and emissivity. It is important that these variables be defined as accurately as possible, while always erring on the side of conservatism and/or accounting for these variables by adding appropriate design/analysis buffers. For the purposes of this document, conservatism means using values that will not lead to overestimating the conductor temperature. The following provides some general guidance in selecting appropriate values for each of these variables:

— In most cases, line current can safely be assumed to be constant for the length of the line. Exceptions are when line current changes as the result of a line tap or when it changes radically (either upwards or downwards) in the 5 to 20 minute period immediately prior to the time in question. For tapped lines each section needs to be evaluated individually and for lines with significant current changes, they need to be evaluated using a transient temperature calculation that profiles the actual current change. If there is any question about the appropriate current value to use, the conservative approach is to use the lowest value in the estimated range.

— Ambient temperature seldom varies more than 1-2°C within the area surrounding a line, thus the ambient air temperature measurement of a nearby weather station is generally appropriate for use. In this context, it has been found experimentally [1] that correlation between local weather stations at distances separated up to 15-20 miles is good and errors vary from 0.4°C rms to 3°C rms over 10 miles. Based on these data, weather stations should be no more than 15 miles from the line segment being surveyed if temperature errors are to be kept to less than 3°C. However, if the line varies in elevation from one point to another by more than 300m (1000′),
or if the weather station is at a similarly disparate elevation from the line, then the ambient temperature value needs to be adjusted to account for the probable temperature differential between the different elevations. If the closest weather station is sufficiently distant so as not to have similar meteorology to the line then at least one temperature sensor should be deployed somewhere along the line prior to survey. A common approach is to adjust the ambient temperature using a lapse rate of -7°C per 1000m (3280') of elevation increase, however a measured vertical temperature profile is preferred if available. When in doubt over the ambient temperature value to use, the conservative approach is to use the lowest estimated temperature value.

— Solar radiation is similar to ambient temperature in that it seldom varies significantly within the geographic area encompassing the line. As such, the measurements taken at a nearby weather station are generally appropriate for use. However, if there are one or more sections of line that are shaded from direct sun, such as by large buildings, towering forests, or ridgelines, then consideration should be given to reducing the solar input for temperature calculation of these line sections to zero. When in doubt about the solar input value to use, the conservative approach is to use the lowest estimated value.

— The effective wind speed value is the single most influential input parameter used for calculating conductor temperature. It is also often the most difficult value to estimate. For example, low wind speeds have little directionality; wind direction is very random. As such, the effective wind speed could conservatively be approximated as the average wind speed acting at 45 degrees to the line. Generally speaking, wind speed measurements from weather stations apart from the line should not be used; only high quality anemometers located within the line corridor at regular intervals (on long lines) and positioned at the average conductor height of the lowest conductor will yield appropriate values for these calculations. Additionally, wind speeds need to be measured at multiple points along the line to effectively account for the effects of terrain and sheltering changes. This is particularly important when there is high current density (>0.5amps/kcmil). For current densities less than 1.0 amps/kcmil, a wind speed value somewhat higher than the average normal wind speed for the section in question should be used. And, the taking of field measurements when the current density is above 1.0 amps/kcmil should be avoided where possible as the error in calculating conductor temperature can become excessive in this range.

— While high values for conductor emissivity and absorptivity (e.g. $\varepsilon = 0.9$ and $\alpha = 0.9$) are commonly used for calculating conductor temperature when rating older lines with aged conductor, such values will not yield the conservative results desired for the purposes herein. For newer conductors, 0.5 is recommended for both emissivity and absorptivity. The same value could also conservatively be used for aged conductor, but in an effort to achieve greater accuracy higher values might also be justified where there is research to support such values. The lower the values assumed, the more conservative will be the results.
5.2 Estimating Conductor Temperature Based on Local Wind Speed Measurements Made Using Ground Based or Airborne Wind Speed Sensors

To eliminate the measurement error introduced by the remote observation of wind speed several LiDAR service providers are using helicopter mounted air data probes that measure wind speed and direction on a span by span basis during the LiDAR survey. The technology used compensates for the motion of the aircraft and downwash of the helicopter blades and has been demonstrated to accurately estimate wind speed and direction at the flying height which ranges typically from 50-100m above the wire height. This technique allows the measurement of wind speed and direction to an accuracy of typically better than +/- 0.5m (+/-1.6”) per second and +/-20 degrees orientation. When compensated for the flying height versus wire height by use of a suitable power law established by measurement of the vertical wind profile the resulting wind speed at wire height has been shown to be accurate to within 0.5-1.0m/second (1.6-3.3’/sec) of the true value with data being available on a span by span basis.

Trials of such an air data probe conducted during 2011 demonstrated that during a series of measurements representative of typical survey conditions an air data probe operated on a LiDAR equipped helicopter was able to accurately measure the average wind speed and predict conductors temperatures to less than 2°C at one sigma, using the IEEE 738 [7] methodology as shown in Figure 4. This resulted in sag prediction errors using line modeling software of less than 5cm (2”). Full details of the trial and results will be made available as a research report in 2012. Trials are continuing to establish the limitations of this methodology under more extreme operating and environmental conditions.

![Figure 4—Comparison of Conductor Temperatures Measured Utilizing Wired Thermocouples and Calculated from Air Data Probe Measurements.](image-url)
5.3 Estimating Representative Temperature Based on Sag and/or Tension Measurements Made Using Line Segment Monitors/Sensors

Conductor temperature calculations that are based on a known line current and the measurements of line segment monitors can yield accurate estimates of average conductor temperature, provided the line monitors have been accurately calibrated. While solar influx and ambient temperature are fairly consistent along any given line section, wind speed will often vary significantly. The cooling effect of wind is a primary contributor to conductor temperature. As such, wide variations in conductor temperature can occur among the spans in most line sections especially when the line is operating with relatively high current density (>0.5 A/kcmil). However, while each line should be considered individually, in most cases, due to the mechanical coupling between suspension spans, the wire behavior in a short to moderately long ruling span section of a line on level terrain, is such that the tension in all the spans will be approximately the same. This makes line segment monitors good tools for establishing average conductor temperature in most situations.

There are a variety of ways in which the different types of line segment monitors make measurements, including the direct measurement of tension, sag or clearance, or indirectly through the measurement of inclination or vibration frequency. Regardless of the type of measurement made by a line monitor, it is necessary to convert the measurement to an average conductor temperature using a relationship between the measured parameter and average conductor temperature established through a “field-calibration” process.

Field calibration of a line segment monitor begins with the correlation of a “known” conductor temperature with a specific monitor measurement value. The monitor measurement value is commonly converted to a conductor tension to facilitate use of readily available software for analyzing the relationship between tension/sag and temperature. This “known” conductor temperature can most easily be established during a period when the line is carrying no load (i.e., during a line outage) and the solar influx is negligible (e.g., during periods of heavy cloud cover or at night). At such times the conductor can safely be assumed to be at ambient temperature. Ambient temperature can also be assumed if the conductor is operating at very low current, providing there are negligible solar influx and a moderate wind. Then, by pairing this “known” temperature with a line segment monitor-generated measurement value, the relationship between the measured value and temperature can be established using a program that can accurately model the thermal behavior of the conductor for the monitored line section. Because most lines in question will have been in service for a while, the conductor temperature should generally be based on final tensions of the conductor (i.e. after initial creep).

To validate the relationship between the value measured by the monitor and temperature, the field-calibration process should ideally involve capturing a series of pairings of “known” conductor temperature and monitor measurement values that cover a range of ambient temperature conditions in low- or no-load situations. Having several calibration points will allow for a part of the lower temperature portion of the line calibration curve to be generated. This curve can then be compared to the line calibration curve generated
by an analysis program to ensure that a proper conductor tension (or other measured parameter)-temperature relationship is being used.

Caution must be exercised in extrapolating the conductor temperature generated by a line segment monitor for one line section to other un-monitored sections of the same line. Where adjacent sections of the line traverse similar terrain and all have reasonably open exposure, the average conductor temperature in each section can be expected to be approximately the same, provided the conductor current is not above ~0.5 amp/kcmil. However, if the geometry, terrain and/or sheltering conditions between the monitored and un-monitored line sections are different, then some differences in average conductor temperatures can be expected. Higher line current densities generally result in larger conductor temperature differences.

5.4 Estimating Representative Temperature Based on Temperature Measurements at Discrete Points Using Contact Sensors

Because transmission line sags are a function of the representative temperature (i.e., average temperature) of the conductor along a ruling span section, use of discrete temperature sensors mounted on the conductor can introduce two distinct uncertainties which affect sag determination. These include: (1) the heat sink effects and (2) the variability of temperature along a line section. Care must be exercised in selecting the type and number of sensors to be used and the locations where they are to be installed in order to ensure reliable results.

— **Heat sink effects:** Any instrument installed on the conductor has the potential to cause two different types of disturbances. The added surface area of the sensor increases the convection and radiation losses which tend to reduce the measured temperature compared to undisturbed conductor. Also, in case of small wind yaw angles the sensors may shield the wind, which in extreme cases may result in too high measured values. It is difficult to provide universal guidance on heat sink effects, although it is known that some early temperature sensors showed temperature rise errors of 12-23%. Moreover, as shown by [9], the heat sink effects are a function of wind angle. The designs of some more recently developed sensors purportedly account for these limitations. Figure 5 is an example of accuracy tests performed on a recent design of conductor temperature sensor over a range of conductor diameters, windspeeds and conductor temperatures resulting in 276 measurement points. A mean difference of less than 1.6°C was found between the sensors and high accuracy wired thermocouples. It should be noted that the sensors were evaluated at temperatures as high as 120°C which are unrealistic for most survey conditions where the rise above ambient is more likely to be less than 30°C. When acquiring sensors, users should request test results (e.g., wind tunnel test results) and other information from the sensor manufacturer that demonstrate that their sensor design mitigates the potential effects of these variables.
Variability of temperature along spans and ruling span sections: CIGRE TB 299 [1] discusses extensively the variation of temperature along spans and ruling span sections, caused by variability of wind. In general, it concludes that variations of temperature rise often exceed +/-10% and can in some cases exceed +/-20%. This temperature variation is caused by variations in wind speed and direction between different locations along a span or different spans in the ruling span section. A study at Oak Ridge National Laboratory (ORNL) has identified three main reasons for the variability. They are:

a. Variation caused by varying sheltering of line by neighboring trees or terrain.

b. Variability of wind speed depending on elevation above ground. Typically, temperatures near the support points of the conductor run significantly cooler than the locations of minimum elevation.

c. Natural variability of wind speed and direction, which is generally largest when wind speeds are moderate or low. [10]

At the ORNL test site each of the above three factors contributed roughly one third each to the observed +/- 25% variability in the temperature rise along the 360 m long two-span test line.

The risks of inaccuracies arising from these aforementioned limitations can be mitigated by applying a sufficient number of well-designed temperature sensors at appropriate locations. It should also be noted that these differences are more pronounced when the conductor temperature is significantly higher than the ambient temperature.
5.5 Estimating Representative Temperature Based on Temperature Measurements Made Using Noncontact Sensors

5.5.1 Airborne Infrared (IR) Detection of Conductor Temperatures

Airborne IR has been applied on transmission line conductors and connectors by electric utilities for over two decades with some success. In general, IR has been used to check connectors/conductors for hot spots which could indicate a high risk component. However, it is also feasible to use IR to measure conductor temperature for purposes such as those addressed by these guidelines as long as care is taken to ensure that the measurements are reliable.

There are two primary types of thermal imaging cameras, uncalibrated cameras and calibrated cameras. Uncalibrated cameras are good for detecting irregularities in a thermal scene, like a component that is warmer or colder than other similar components in the same scene. Calibrated cameras are designed to measure absolute temperatures. For conductor temperature measurements, calibrated cameras must be used.

IR cameras detect three types of thermal radiation emitted by objects and the environment around them:

1) Radiation emitted from the target object
2) Radiation reflected off of the target object from surroundings
3) Radiation emitted by the atmosphere

Factors that have an impact on thermographic conductor temperature measurements include:

4) Camera resolution
5) Emissivity/Reflectivity
6) Atmospheric influence
7) Reflected radiation
8) Background (sky, ground, foliage, etc)

— Resolution [11]: The spatial resolution of an IR camera is a function of the detector size and lens used. The measurement resolution of the camera is typically less than the spatial resolution. Temperature measurements made outside the resolution range will have noise caused by the object background (as a result of temperature averaging with the pixels around the object).

— Emissivity: The emissivity of conductors and connectors differ, even though they are made out of the same alloy. An aged connector may have an emissivity of 0.25 while a stranded aged ACSR conductor may have an emissivity in the region of 0.6 (based on EPRI measurements) after being in the air for 20 plus years. Factors which affect emissivity are as follows [6]:

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1) Temperature
2) Geometry
3) Wavelength
4) Surface condition

In addition to this the emissivity along the conductor could vary between 10 and 25% [3]. The closer the emissivity is to 1, the more accurate the IR measurement will be.

— Reflected radiation: Surface reflectivity can affect the apparent temperature measured by an IR camera. The reflection from an object’s surface can be a significant contributor to the thermal radiation from the object. For accurate temperature measurements, the reflected temperature has to be known. An example of this is as follows. If a shiny piece of aluminum foil is placed on the ground and then inspected with an IR camera from above, the aluminum foil will reflect the sky above. Hence, the IR measurement will include this reflected temperature thereby reducing the accuracy of the measurement of the object’s temperature. If the piece of foil is scrunched up, the reflective effects will be reduced.

— Object background: IR inspection of an elevated object from a vantage point on the ground will generally have the sky as the object’s background. Often, IR systems sense the sky as being much colder than the conductor. This results in the measured temperature being lower than what it actually is. IR inspections from the air generally have the ground/fields/trees as a backdrop. While these objects are also cooler than the conductor the temperature differential is not as great as with ground based IR. If the camera resolution is not high enough, these measurements can be also impacted by the object background resulting in lower temperatures being measured, although not as low as with the sky as a backdrop.

Test Measurements

Tests were done by EPRI in 2007 [5] and 2011[4] to determine the precision of IR camera measurements, as well as distance limits from the target. During the 2011 tests a small section of the conductor was painted which high emissivity paint and the temperature of the painted section measured using infrared cameras at three different distances from the conductors over a range of conductor temperatures. Six different conductor diameters were evaluated varying from 0.78” in diameter to 1.45”. Inspection distances varied from 32 to 75’ and a 7° telephoto lens was utilized on two different camera models. It should be noted that the results from one model were found to be inaccurate due to the inherent design of the camera and telephoto lens; this was verified by the camera vendor. The measurements were all made from the ground on a sunny day (no cloud cover). Figure 6 shows a comparison of the conductor temperatures predicted utilizing the infrared camera and wired high accuracy thermocouples.
The inspection distance was within the range recommended for the camera /telephoto lens combination. No correlation was found between inspection distance and error. It should be noted that the results in Figure 6 are for the temperature of a conductor section which has been painted with high emissivity paint; the results are not indicative of measurements on an untreated section of conductor.

**Guidance for IR Inspections**

Based on the preceding discussion the following points should be noted:

1) Use a thermal imaging device that can lay several pixels of resolution over the target conductor at the appropriate measurement distance.
2) Ensure the emissivity level of the conductor is known and properly entered into the analysis.
3) Measure the reflected radiation.
4) Correct properly for atmospheric attenuation.
5) Calibrate the camera with a black body and check the calibration frequently.


The temperatures of energized bare overhead transmission line conductors are constantly changing due to variations in weather conditions and/or electrical current. Even de-
energized conductors can experience significant changes in temperature due to varying weather conditions and solar flux. Therefore, care must be taken in estimating a conductor temperature that is representative of the temperature coincident with sag measurements in order to mitigate the effects of potential inaccuracies that can be introduced by these changes. A summary of key considerations regarding best practices for conductor temperature assessment are tabulated below to help utility personnel avert problems that can be introduced by improper methods. The specific methods addressed are grouped into the following four categories, as described in the previous section.

Methods for Measuring Variables used to Estimate Conductor Temperature

I. Weather condition measurements
II. Sag and/or tension measurements using sensors for monitoring line segments
III. Temperature measurements at discrete points using contact sensors
IV. Temperatures measurements made using noncontact sensors

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<th>Key Considerations Regarding Best Practices</th>
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<td>Ambient Temperature and Solar Flux Measurements: Generally speaking, the use of ambient temperature and solar flux can be adequately determined by using remote weather stations located within 15-20 miles of the spans of interest provided there is no significant change in elevation.</td>
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<td>I</td>
<td>Wind Speed Measurements:</td>
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<td>- Remote wind speed measurements (e.g., measurements made at airport weather stations distant from the line) should not be used unless a significant buffer is included to compensate for the potential errors due to local terrain. Local weather measurements are recommended.</td>
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<td>3) High values for conductor emissivity and absorptivity should be used for calculating conductor temperature. For newer conductors, 0.5 is recommended for both emissivity and absorptivity. The same value could also conservatively be used for aged conductor, but in an effort to achieve greater accuracy higher values might also be justified where there is research to support such values.</td>
</tr>
<tr>
<td></td>
<td>4) If ground based weather sensors are used for measurements –</td>
</tr>
<tr>
<td></td>
<td>a. The sensors should include high quality wind anemometers.</td>
</tr>
<tr>
<td></td>
<td>b. Wind speeds should be measured at multiple points along the line to effectively account for the effects of terrain and sheltering changes. This is particularly important when there is high current density (&gt;0.5 amps/kcmil).</td>
</tr>
<tr>
<td></td>
<td>c. The sensors should be placed in close proximity to the line. If a more remote sensor is used, the wind speed error will be greater and a more conservative input should be used in the IEEE 738 [7] analysis.</td>
</tr>
<tr>
<td></td>
<td>d. The sensors should be located in areas representative of the sheltering</td>
</tr>
</tbody>
</table>
conditions along the line. If it is not feasible to deploy enough sensors to adequately represent the sheltering conditions along the length of the line then the sensors should be placed in open areas. To ensure conservatism the objective should be to ensure that there is less shielding at the sensor than existing at the line and it should be assumed that the wind speed estimate is thus higher than that likely existing at the line.

e. The sensors should be located near conductor height. If measurements are not made at the average conductor height, the average wind speed should be adjusted to account for the increase in wind speed with height due to surface drag by using a vertical wind speed profile or appropriate Power Law.

5) If an airborne sensor is used it should be appropriately calibrated for use on the specific helicopter and vertical profiles flown during each survey relative to established ground based weather stations.

Summary of Measurement Errors for Weather Sensors:
The most significant contributors to line temperature error resulting from the use of weather sensors are ambient temperature and local wind speed and direction. Reported measurement errors are typically less than +/-0.5°C and 0.5 m (+/-1.6') per second for local in span sensors and properly calibrated air data probes. While errors for more remote weather sensors may be 2-3 times greater. During normal operating conditions typically encountered during line surveys, conductor temperature errors can be limited to +/-5°C (one sigma) when using a sufficient number of appropriately spaced in span weather sensors; to less than +/-2°C when using an appropriately calibrated and processed air data probe and to less than +/-1.0°C if high accuracy meteorological sensors are mounted at conductor height in a sufficient number of representative spans.

Assessment of Potential Errors in Weather-Based Conductor Temperature Estimates:
Regardless of the absolute accuracy of the weather sensors used it is recommended that the current line load, ambient temperature, wind speed, solar flux and the possible errors in such measurements be used to predict the likely error in conductor temperature that can result. In most cases this error will be small and provides confidence in the base result. In the cases where larger potential errors could exist due to higher current loads or excess measurement uncertainty consideration can be given to re-measurement or more careful evaluation of the resulting clearances.

II

Accurate estimates of average conductor temperature within a ruling span section can be established based on a known line current and line monitor measurements by using correlations between the measured variable (e.g., conductor sag or clearance, tension, inclination or vibration frequency) and temperature established through a “field-calibration” process. (While wide variations in conductor temperature can occur among the spans in most line, in most cases, due to the mechanical coupling between suspension spans, the wire behavior in a short to moderately long ruling span section of a line on level terrain, is such that the tension in all the spans will be approximately the same.) Important steps in the “field-calibration” process include:

- Establish “known” conductor temperature: Field calibration begins with the correlation of a “known” conductor temperature with a specific monitor measurement value. This “known” conductor temperature can most easily be established during a period when the line is carrying no, or very low current and the solar influx is negligible; hence, the conductor can safely be assumed to be at ambient temperature.

- Correlate line monitor measurements with conductor temperature: The next step in the calibration process includes pairing “known” temperatures with a line segment monitor-generated measurements value and establishing the relationship between the measured value and temperature using a program that can accurately model the thermal behavior of the conductor for the monitored line section. Because most lines in question will have been in service for a while, conductor temperature
should be based on final tensions of the conductor (i.e. after initial creep).

- **Validate the correlation:** To validate the relationship between the value measured by the monitor and temperature, the field-calibration process should ideally involve capturing a series of pairings of “known” conductor temperature and monitor measurement values that cover a range of ambient temperature conditions in low- or no-current situations.

Caution must be exercised in extrapolating the conductor temperature generated by a line segment monitor for one ruling span section to other un-monitored sections of the same line. This should be avoided if the current is above ~0.5 amp/kcmil, and/or the geometry, terrain and/or sheltering conditions between the monitored and un-monitored line sections are different.

**Summary of Measurement Errors for Line Segment Monitors/Sensors:**

Conductor temperature calculations based on measurements of line segment monitors coupled with known line current can yield accurate estimates of average conductor temperature, provided the line monitors have been accurately calibrated. During normal operating conditions typically encountered during line surveys, conductor temperature errors based on measurements made by commonly used sag and tension monitors can be limited to less than +/-1°C. A variety of monitors are available and the measurement accuracy of each should be verified with the manufacturers.

Temperature measurements made using contact sensors installed at discrete points can be used as the basis for estimating representative conductor temperature provided that key measurement and environmental factors that can introduce uncertainties are properly addressed. In particular, the heat sink effects of the sensor design and the variability of conductor temperature along a line section must be carefully considered.

- **Heat sink effects:** When acquiring temperature measurement sensors, users should request the manufacturer to provide information on their accuracy. This information should include test data demonstrating that the sensor design mitigates: 1) heat sink effects caused by the surface area of the sensor increasing the convection and radiation losses thereby potentially lowering the localized temperature of the conductor, and 2) wind shielding effects created by the sensor profile that may raise the localized temperature of the conductor.

- **Spatial variability of conductor temperature:** Significant differences in conductor temperatures can occur along spans and ruling span sections. These differences are more pronounced when the conductor temperature is significantly higher than the ambient temperature. Variation in wind speed and direction between locations is the primary cause. These variation may be caused by factors including:
  - Varying sheltering conditions caused by neighboring trees, buildings or terrain.
  - Elevation above ground. Wind speeds tend to be higher at higher elevations therefore, temperatures measured near conductor support points may be cooler than temperatures measured at points of minimum elevation.
  - Natural variability of wind speed and direction, which is generally largest when wind speeds are moderate or low.

The risks of inaccuracies arising from these aforementioned limitations can be mitigated by applying a sufficient number of well-designed temperature sensors at appropriate locations.

**Summary of Measurement Errors for Line Mounted Temperature Sensors:**

Recent test results for a new line mounted contact temperature sensor show its measurement accuracy to be +/-1.6°C when compared to an embedded thermocouple while other commercial devices have been reported to have higher measurement errors of a few degrees C.

**IV**

It is feasible to use IR to measure conductor temperature provided that key measurement and environmental factors are addressed.
- **Resolution:** Temperature measurements made outside the resolution range of an IR camera will appear cooler than the actual temperature. Therefore, measurements should be made within the spatial and measurement resolution of the camera. Measurement resolution is typically less than the spatial resolution of a camera; using a telephoto lense may improve resolution. A thermal imaging device that can lay several pixels of resolution over the target conductor at the appropriate measurement distance should be used. When using a ground-based thermal imager the camera must remain steady so as to avoid introducing random background energy into the measurement and the position of the camera relative to the conductor must remain fixed for the duration of the measurement period.

- **Emissivity:** Emissivity along a conductor can vary. The closer the emissivity is to 1, the more accurate the IR measurement. Therefore, it is important to ensure the emissivity of the conductor is known and entered into the camera. Use of a high emissivity paint applied to the conductor can improve measurement accuracy.

- **Reflectivity/Reflected radiation:** Precautions are necessary when attempting to measure conductor temperature from the air. A reflective material will reflect the sky above. An IR camera will detect the reflected temperature. This effect can introduce errors (which may or may not be significant) in the apparent temperature measured. Reflected radiation should be measured.

- **Background:** IR inspections from the air will generally have the ground/fields/trees as a backdrop and will be more accurate than those made from the ground and having the sky as the backdrop unless the ground-based measurements are properly adjusted to account for the effects of the sky.

It is also important to correct properly for atmospheric attenuation, and to calibrate the camera with a black body and check the calibration frequently.

**Summary of Measurement Errors for Thermal Imaging Sensors:**

Recent testing shows that measurement accuracies of +/-3.5°C (one sigma) can be achieved with a fixed, ground-based thermal imager making observations at ranges of up to 75’ from the conductor when a high emissivity paint is applied to the conductor prior to making measurements.

More detailed information to support these guidelines can be found in the references provided below.

### 7. References


5. EPRI et al. Improved thermal modeling tools for substation equipment. EPRI, Palo Alto, CA; CenterPoint Energy, Houston, TX; KeySpan Energy, Hicksville, NY; PSE&G, Newark, NJ; PNM, Albuquerque, NM; Georgia Power, Forest Park, GA; and American Transmission Company, Waukesha, WI. 2007. 1014789.


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