299

GUIDE FOR SELECTION OF WEATHER PARAMETERS FOR BARE OVERHEAD CONDUCTOR RATINGS

Working Group
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1. EXECUTIVE SUMMARY

1.1 Objective

Following discussions at CIGRE SC B2 meeting in Edinburgh, U.K. September 8, 2003, a task force with the following Terms of Reference was established:

Identify and describe a logical process whereby suitably conservative weather conditions can be selected for use in conventional static thermal line rating methods based on limited field data collection. The methods (for selecting the weather parameters) may include probabilistic or those based on engineering judgment.

Deliverable: A brochure that clearly describes a conservative process whereby weather conditions may be selected for overhead line rating calculations.

In January 2004, IEEE's Towers, Poles & Conductors Subcommittee established a parallel activity within IEEE. The two Task Forces have since cooperated closely and shared all documents, essentially working as a Joint Task Force (JTF). The recommendations reflect the views of all eighteen members of the Task Forces.

1.2 Technical background

Transmission lines are designed to carry electrical power between locations which may be hundreds of kilometers apart. Their energized conductors must maintain minimum electric clearances to all anticipated activities and objects, including buildings, people, vehicles and other lines even at high conductor temperatures generated by occasional high current, emergency operating events. In its considerations regarding electrical clearance, the JTF recognizes that there are practical limits on the engineer's ability to accurately calculate the position of the line's energized conductors under all conditions over the entire service life of the line and that appropriate buffers may be required to assure minimum clearances.

The following recommendations represent a practical guide for developing conservative thermal rating estimates for overhead lines assuming the engineer will recognize the need for usual clearance buffers and safety margins employed in the design and operation of overhead transmission lines.

The JTF considers that the methods for calculation of line ratings by CIGRE [1] and IEEE [2] provide very similar results and are both fully appropriate for engineering calculations. The objective of this report is to provide guidance for the selection of input parameters for either of these line rating calculation methods.

The JTF has set the following general qualifying objectives for the determination of the weather parameters:

a. The average temperature of a line section will not exceed the maximum design temperature by more than 10^{o}C even under exceptional situations and will provide a confidence level of at least 99% that the conductor temperature will be less than the design temperature when the line current equals the line rating.

b. The highest local conductor temperature will not exceed the maximum design temperature by more than 20 ^{o}C when the line current equals the line rating.
c. Because ratings based on probabilistic clearances require consideration of other criteria than weather parameters (load probabilities, traffic under the lines etc.) their application is not included in this document but can be found in [3].
d. This and other related documents discuss sag and tension calculations only in a general manner. JTF recognizes that maintaining adequate clearances is usually the primary objective of line ratings and that conservatism in sag calculations can mitigate the consequences of too optimistic rating assumptions. Yet, such combination may not be applicable in all circumstances. More detailed discussion on the subject will be included in the forthcoming CIGRE Guide on Sag and Tension Calculations.
e. For ensuring adequate clearances, it is recommended that the transmission owner verifies their actual line clearances at appropriate intervals.

1.3 History and current practices

Until the advent of deregulation, most transmission utilities based their deterministic ratings on the assumptions of 0.5-0.6 m/s perpendicular wind, a high seasonal or annual temperature and full solar radiation. Most lines were also designed with relatively generous clearance buffers, typically 0.8-1.5 m above statutory clearance requirements. The beginning years of deregulation, together with increased difficulties in transmission construction or funding, caused many utilities to increase the maximum operating temperatures of their lines by taking advantage of the existing buffers or applying less restrictive rating criteria.

If lines are designed for low maximum operating temperatures, adjusting the ratings depending on ambient temperature was accepted as a practice in certain utilities. As described later in the report, this practice became increasingly dangerous when utilities started accepting high maximum conductor temperatures. When conductor temperature rise above ambient is high, forced convection (i.e. wind speed and direction) is the dominant rating factor. It was not realized that at lower temperatures and especially at night, prolonged periods of essentially zero wind are frequent, as ambient temperature and wind were considered independent variables.

Furthermore, it was often not realized that conventional sag calculation methods at high conductor temperatures contain a number of error sources which can lead to substantial underestimates of sags [4].

In 1998 CIGRE TF 12-1 of SC 22 conducted a survey of line rating practices [5], receiving responses from 71 utilities in 15 countries. Some of the key findings of the survey were:

- About 70% of the responders assumed perpendicular wind speeds of 0.5-0.61 m/s. The next most common assumption was 0.9 m/s. There were exceptions, including wind speeds as high as 1.55-2.0 m/s and as low as zero.
- Vast majority of utilities use deterministic ratings. The major exceptions were U.K. and South Africa who use probabilistic ratings as described in [3].

- Most utilities use an ambient temperature that is close to the highest expected annual summer temperature. Over one half adjust their ratings seasonally.
- Almost all utilities take solar radiation into account. Typical assumed solar radiation intensities were 1000-1150 W/m^2. A slight majority of the utilities used a relatively low conductor absorptivity of 0.5-0.6. Most of the rest used absorptivities of 0.7-0.9.
- 79% of the responders cited clearances as the main reason for ratings, while annealing was cited as the main reason by 9%.
- Importantly, during the prior 5 years, 51% of the utilities had increased the maximum operating temperature of their transmission lines. 30% had increased their ratings by changing their other rating assumptions.

1.4 Organization of the project

Early in the project, the JTF realized that there are large numbers of published and unpublished studies on the subject. Initially, over 200 studies were identified. These reports were then reviewed and finally 119 of them were qualified as data sources. The qualification was based on the following criteria:

- Did the report clearly deal with line rating information; e.g. is it based on observations in actual transmission line environment? A large number of studies were removed from the data base because they did not meet these criteria. Examples are reports which were based on airport data. As explained in Section 4 of the brochure, airport wind observations are generally very different from those at transmission line corridors.
- Did the used instrumentation and experimental planning meet minimum acceptable criteria? This is discussed in Section 5 of the brochure.
- Was the data collected for sufficient time period and were the analysis methods technically sound to draw clear conclusions?

Additionally, several of the JTF members produced special summaries and reports based on their own previously unpublished data. Such reports became valuable in judging several key topics, which are generally poorly understood and can cause judgment errors in rating evaluation. These topics include:

- Correlation between wind speed, ambient temperature and solar radiation. Considering these variables independent or mutually exclusive without proper analysis is a common mistake.
- Effect of terrain and sheltering on wind speed. Wind speed at most transmission corridors is much lower than at open locations, e.g. airports.
- Variability of wind speed and wind direction along a span or a series of spans forming a ruling span line section. Sags of a line section depend on the average conductor temperature, which has a very different probability distribution than conductor temperature or weather observations made at a single point.
- Variability of rating conditions along a transmission line. Because the rating of the line is that of the lowest rated line section, the likelihood that limiting conditions occurring somewhere along the line is substantially higher than that at a single observation point.

These findings form the basis of Section 4 of the report, *Condensed Findings Based on Literature Review*. This section includes not only consensus conclusions; it also identifies areas where future research may be helpful for explaining the dispersion in the findings.

After finishing the work on section 4, the JTF could quite clearly see the direction in which its work on the remaining sections 3 (*Recommendations*) and 5 (*Recommendations regarding weather and rating measurements*) would proceed. As detailed below, the JTF recommends that the selection of weather parameters be a three-tiered process. The lowest, Base ratings, can be applied in essentially all circumstances without further studies. Study-based ratings can be used to justify higher ratings for a line or an area. Finally, Variable ratings, including real time ratings, can be used for further gains. This is discussed in 1.5.3 below.

1.5 Selection of weather parameters

In the absence of data from field rating studies according to Section 4 of the Brochure, the JTF recommends the use of Base ratings, described below, as default ratings.

1.5.1 Base ratings

Base ratings may be applied for any transmission line and should be used unless the utility adopts practices according to 1.5.2. or 1.5.3. below.

1.5.1.1 For sag-limited lines, the JTF recommends that base ratings be calculated for an effective wind speed of 0.6 m/s, an ambient temperature close to the annual maximum of ambient temperature along the line route and a solar radiation of 1000 W/m^2. When combined with an assumed conductor absorptivity of no less than 0.8 and emissivity of no more than 0.1 below absorptivity, this combination can be considered safe for thermal rating calculations without field measurements.

1.5.1.2 For those lines, where annealing of conductors is the primary concern, having narrow, sheltered corridors, with energized conductors either below tree canopy height or between buildings, the Base rating should be estimated based on either a 0.4 m/s effective wind speed or by reducing the maximum conductor design temperature by 10^oC. Although the average conductor temperature, which determines the line sag, is not likely to be higher than that based on 0.6 m/s wind speed, the local effective wind speed in sheltered locations may be significantly lower.

1.5.1.3 Seasonal ratings should be based on an ambient temperature close to the maximum value of the season along the line and other criteria in 1.5.1.1 and 1.5.1.2. above, although the precautions discussed in Section 4 of the Brochure should be exercised.

1.5.2 Study-based ratings

The transmission line owner/operator may base the rating assumptions of selected lines or regions on actual weather or rating studies, provided that:

1.5.2.1 Rating weather studies are conducted in the actual transmission line environment, using the methods recommended in Section 5 of this Brochure. If seasonal ratings are applied, such studies must include the respective seasons.

1.5.2.2 Alternatively, rating studies can be conducted with devices which monitor line tension, sag, clearance or conductor temperature. The methods are specified in Section 5 of this Brochure.

1.5.3 Variable ratings

1.5.3.1 Continually ambient-adjusted ratings.

Ratings can be adjusted based on varying ambient temperatures measures at the time. These are termed continually ambient-adjusted ratings. In this case, unless real time rating systems are used, the wind speed should be based on the assumption of a more conservative effective wind speed than Base ratings. The extensive literature review by the JTF clearly indicates that ambient temperature and wind speed are not independent parameters, higher wind speeds being associated with high ambient temperatures.

If the Base Rating is to be adjusted for daytime conditions, the JTF recommends the following: If the ambient temperature adjustment is less than 8^{o}C compared to the temperature selected for Base Rating conditions (for example, if the base ambient temperature is 35^{o}C and the actual ambient temperature is between 35^{o}C and 27^{o}C), the effective wind speed should be selected as no higher than 0.5 m/s. If the temperature adjustment is more than 8^{o}C, the effective wind speed should be selected as no more than 0.4 m/s. For nighttime ambient-adjusted ratings (between sunset and sunrise when solar radiation is zero), wind speed should be selected as zero (natural convection only), and solar radiation can also be considered nil. Continually ambient-adjusted ratings can provide technically justified ampacity increases for lines which are designed for low maximum conductor temperatures, e.g. below 60-70^{o}C. On the other hand, they will generally not provide technically justified benefits for lines designed for 100 ^{o}C or higher temperatures [6] and their use is not recommended.

If a study-based line rating is to be adjusted for ambient temperature, the engineer must be careful to reduce the assumed wind speed to account for correlation with ambient temperature. As with ambient adjustment of Base ratings, the wind speed at night should be much lower.

1.5.3.2 Real time ratings.

Rather than using “worst-case” weather assumptions, the transmission line owner/operator may elect to use real time monitoring equipment for determining the line rating, provided:

- Monitoring equipment meets the sensitivity, accuracy and calibration requirements specified in Section 5 of the Brochure.

- It has been verified that the lines which are to be monitored meet the design clearance requirements.

- Monitors are installed in sufficient quantity to provide statistically valid information of the sag or temperature of the monitored circuit. See sections 4.5 and 5.6 of the Brochure for additional guidance.

- The operator has the capability of adjusting the line current to the level of standard or enhanced ratings in emergency conditions.

1.6 Reasons for recommendations and recommended further work

For more detailed explanations, the reader should refer to Section 3 of the brochure and its footnotes, and "Condensed Findings Based on Literature Review", section 4 of the Brochure.
The literature review and recent work, such as the *Guide on sag-ten calculations* and the Brochure on *Conductors for uprating of overhead lines* [7] have brought out the need for revisions in the CIGRE Model for evaluation of conductor temperature in the steady state. The recommended revisions include taking into account wind turbulence; including the improved AC resistance model and calculation of the effects of radial temperature gradients.

References (Executive Summary and Electra Report only)

[1] CIGRE WG12.12; The Thermal Behaviour of Overhead Conductors Section 1 & 2: Mathematical Model for Evaluation of Conductor Temperature in the Steady State and Application Thereof, Electra No.144, pp.107-125, October 1992.
[2] Working Group on the Calculation of Bare Overhead Conductor Temperatures; Draft Standard for Calculating the Current-Temperature of Bare Overhead Conductors, IEEE 738 Standard, 2003.
[3] CIGRE WG 22-12: Probabilistic determination of conductor current ratings. CIGRE Electra, February 1996, No. 163, pp. 103-119.
[4] D. A. Douglass, T.O. Seppa, Y. Motlis; IEEE's Approach for Increasing Transmission Line Ratings in North America, CIGRE 2000 Session 22-302, 2000
[5] CIGRE SC22 TF 12-1, Survey on Future Use of Conductors, France, 1998.
[6] T. O. Seppa: Benefits of continually ambient-adjusted ratings. CIGRE TF B2.12.6, Rio De Janeiro, Brazil, September 9, 2005.
[7] Conductors for uprating of overhead lines, Electra- April 2004, No. 213 pp:30-39, Technical Brochure #244, 2004.

2. ASSUMPTIONS AND DEFINITIONS

2.1. Underlying Assumptions

1. Thermal ratings must be calculated such that electrical clearances will be maintained so long as the line current does not exceed the rating under stated conditions. This is the primary assumption since violation of minimum clearances may compromise the public safety, launch costly litigation, and possibly result in unexpected line outages that may affect system reliability.
2. A conductor heat balance calculation can serve as the basis for thermal rating calculations, relating the line current to the conductor temperature.
3. Conservative weather conditions can be chosen such that the calculated thermal rating is safe.

2.2. Common Terminology

Some terms and ideas are in wide use. Their definition here, greatly simplifies the writing of the technical brochure on "Selection of Rating Assumptions for Line Ratings". A glossary is included in this document.

Thermal ratings are determined according to the practices of transmission line engineers but ratings are applied in an operational environment in order to maintain safe operation. The system operator, therefore, greatly influences the sort of ratings that are to be calculated.

Absorptivity of conductor

A perfect black body absorber having the shape of the conductor would have an absorptivity of 1.0. New aluminum conductors have absorptivity on the order of 0.2 to 0.3. Old aluminum and copper conductors have an absorptivity which approaches 0.9 depending on the environment. Absorptivity and emissivity are correlated and it is likely that both are high (near 1.0) or low (near 0.2)

Ambient adjusted thermal ratings

One of the weather assumptions necessary to the calculation of overhead line ratings is the ambient air temperature. Ambient-adjusted line ratings are calculated based on a real-time estimate of real-time maximum air temperature along the line. Other weather conditions are normally held constant.

Ampacity

The ampacity of a conductor is that maximum constant current which will meet the design, security and safety criteria of a particular line on which the conductor is used. In this brochure, ampacity has the same meaning as "steady-state thermal rating." The preferred term in this document is "steady-state thermal rating".

Annealing

The process wherein the tensile strength of copper or aluminum wires is reduced at sustained high temperatures.

Continuous or Normal Thermal Rating

In the simplest thermal rating system, a single thermal rating is specified. For example, the rating of an overhead line can be specified on the basis of "ampacity tables" provided by the conductor manufacturer. Based on such tables, the "normal" or "continuous" thermal rating of each conductor (e.g. Drake ACSR) is specified for

certain weather conditions and conductor parameters. This rating is used by operations personnel as a current limit for all lines that use this conductor, under all system conditions.

Dynamic Thermal Ratings

In this case, the line rating is calculated for real-time weather conditions. Since they are based on varying weather conditions, dynamic thermal ratings are valid for a rather short period of time (e.g. 15 minutes) unless "predicted" ratings are derived from field studies.

Effective Wind Speed

Most transmission lines consist of multiple line sections, each line section being terminated by strain structures. Wind speed and direction (and thus conductor temperature) may vary along each line section but the sags depend on the average conductor temperature in the line section. The effective wind speed is that perpendicular wind speed which yields the same average conductor temperature along the line section as the actual variable wind.

Electrical Clearance

The distance between energized conductors and other conductors, buildings, and earth. Minimum clearances are usually specified by regulations.

Emergency Thermal Rating

In most power systems, a second thermal rating, called an "emergency" thermal rating, is defined. The emergency rating of an overhead line is normally higher than the continuous rating since the conductor is usually allowed to reach a higher temperature but the number of hours per year, during which the higher rating can be used, is limited (e.g. 24 hours per year).

Emissivity of conductor

See Absorptivity. Note also that emissivity is generally considered to be slightly higher than absorptivity.

Line Design or Maximum Allowable Conductor Temperature

The temperature of the current carrying conductor in an overhead power line is typically limited in order to limit the sag of the line and to avoid annealing of the aluminum or copper strands. This temperature is defined in this document as the maximum allowable conductor temperature. The choice of temperature may vary with the type of conductor and with the type of thermal rating but a single temperature is usually designated for the entire line. Maximum allowable conductor temperature is sometimes called templating temperature.

Long-time emergency rating (LTE)

During a limited period of time after the loss of a major component of the power system (generator, EHV line, etc.), remaining circuits may experience higher than normal loads. During such infrequent emergencies, higher operating temperatures and/or accelerated aging of equipment may be allowed for limited periods of time (4 to 24 hours). These higher than normal line ratings are called long-time emergency ratings.

Net radiation temperature

See solar temperature. Measured with Net Radiation Sensor.

Nusselt number

The Nusselt number is a dimensionless measure of heat transfer rate by convection. Given a convection heat transfer coefficient, h, measured in the units of [watts/m^2-^oC], the Nusselt number for a conductor of outside diameter, OD [meters], is defined as h*OD/k where k is the thermal conductivity of air in [watts/m-^oC].

Probabilistic clearance

Weather conditions along a transmission line may be measured over an extended period of time and the corresponding line clearances calculated. In choosing an acceptable probabilistic line rating, the line rating distribution is calculated and an acceptable probability of meeting clearance limits is chosen.

Probabilistic rating

Weather conditions along a transmission line may be measured over an extended period of time and the corresponding line rating distribution calculated. In choosing a probabilistic line rating, the line rating distribution is calculated and an acceptable probability of meeting clearance limits is chosen.

Rated Breaking Strength ("RBS") of conductor

A calculated value of composite tensile strength, which indicates the minimum test value for stranded bare conductor. Similar terms include Ultimate Tensile Strength (UTS) and Calculated Breaking Load (CBL).

Real-time thermal rating

This is the thermal rating calculated based on real-time weather data.

Ruling (Effective) Span

This is a hypothetical level span length wherein the variation of tension with conductor temperature is the same as in a series of suspension spans. It is also called equivalent span.

Seasonal Thermal Ratings

In regions where the difference between average daily air temperature in summer and winter varies by $10^{o}C$ or more, seasonal ratings, both normal and emergency can be defined. Since the winter ratings are based on a lower air temperature, they are typically higher than summer ratings.

Short-time emergency rating (STE)

A thermal rating calculated for a short period of time

Solar temperature

The solar temperature of an overhead conductor is the temperature of the conductor when it carries no electrical current. During the summer, the solar temperature of an overhead conductor may exceed the air temperature by $5^{o}C$ to $10^{o}C$ depending on the wind conditions and the conductor emissivity and absorptivity. Also called net radiation temperature.

Static Thermal Rating

A static thermal rating is normally based upon "worst-case" weather assumptions, and specified conductor parameter.

Steady-state thermal rating

A steady-state thermal rating is calculated based upon constant values of line current and weather conditions.

Templating conductor temperature

In order to select and locate structures (i.e. tower spotting) for a new line, the conductor in all spans is assumed to be at the same temperature and to experience the same ice and wind loading. To assure that minimum electrical clearances to ground and other conductors are met under maximum electrical loading, the sag is calculated for a maximum "templating" temperature and that same temperature is used in rating calculations.

Thermal Rating

The maximum electrical current which can be carried in an overhead transmission line under specified weather conditions (same meaning as ampacity).

Thermal time constant

Given an abrupt change in weather conditions or electrical current, from one steady value to a new steady value, the conductor temperature changes in an approximately exponential fashion. The thermal time constant is the time period during which 63% of the ultimate change in temperature occurs. The thermal time constant of a bare overhead conductor (typically ranging between 5 and 20 minutes) depends primarily on the size of the conductor and the forced convection cooling.

Transient thermal rating

A transient thermal rating, valid for a short period of time (e.g. 15 minutes), is calculated for a step increase in line current. The calculation considers heat storage in the conductor and the resulting rating is a function of the pre-step line current.

Uprating

The process by which the thermal rating of an overhead power line is increased.

"Worst-case" weather conditions

Weather conditions which yield the maximum or near maximum value of conductor temperature for a given line current.

3. RECOMMENDATIONS REGARDING WEATHER PARAMETER SELECTION FOR RATING CALCULATIONS

Objective

Following discussions at CIGRE SC B2 meeting in Edinburgh, U.K. September 8, 2003, CIGRE WG B2.12 established a Task Force with the following Terms of Reference:

Identify and describe a logical process whereby suitably conservative weather conditions can be selected for use in conventional static thermal line rating methods based on limited field data collection. The methods may include probabilistic or those based on engineering judgment.

Deliverable: A brochure that clearly describes a conservative process whereby weather conditions may be selected for overhead line rating calculations.

In January 2004, IEEE's T,P&C subcommittee established a parallel activity within IEEE. The two Task Forces have since cooperated closely and shared all documents, essentially working as a Joint Task Force (JTF). The recommendations reflect the consensus views of all eighteen individual members of the combined Task Forces.

3.1. Technical background

Transmission lines are designed to carry electrical power between locations which may be hundreds of kilometers apart. Their energized conductors must maintain minimum electric clearances to all anticipated activities and objects, including buildings, people, vehicles and other lines even at high conductor temperatures generated by occasional high current, emergency operating events. In its considerations regarding electrical clearance, the JTF recognizes that there are practical limits on the engineer's ability to accurately calculate the position of the line's energized conductors under all conditions over the entire service life of the line and that appropriate buffers may be required to assure minimum clearances.

The following recommendations represent a practical guide for developing conservative thermal rating estimates for overhead lines assuming the engineer will recognize the need for usual clearance buffers and safety margins employed in the design and operation of overhead transmission lines.

The JTF considers that the methods for calculation of line ratings by CIGRE [95] and IEEE [51] provide very similar results and are both fully appropriate for engineering calculations. The objective of this report is to provide guidance for the selection of input parameters for either of these line rating calculation methods.

The JTF has set the following general qualifying objectives for recommendations:

a. The average temperature of a line section will not exceed the maximum design temperature by more than 10^{o}C even under exceptional situations and will

provide a confidence level of at least 99%[1] that the conductor temperature will be less than the design temperature when the line current equals the line rating[2].

b. The highest local conductor temperature will not exceed the maximum design temperature by more than 20°C when the line current equals the line rating [3].
c. Because ratings based on probabilistic clearances require consideration of other criteria than weather parameters (load probabilities, traffic under the lines etc.) their application is not included in this document[4].
d. This and other related documents discuss sag and tension calculations only in a general manner. JTF recognizes that maintaining adequate clearances is usually the primary objective of line ratings and that conservatism in sag calculations can mitigate the consequences of too optimistic rating assumptions. Yet, such combination may not be applicable in all circumstances. More detailed discussion on the subject will be included in the forthcoming CIGRE Technical Brochure on Sag and Tension Calculations.
e. For ensuring adequate clearances, it is recommended that the transmission owner verifies their actual line clearances at appropriate intervals.

3.2. Selection of weather parameters

In the absence of data from field rating studies according to Section 4 of the Brochure, the JTF recommends the use of Base ratings, described below, as default ratings.

3.2.1. Base ratings

Base ratings may be applied for any transmission line and should be used unless the utility adopts practices according to 3.2.2. or 3.2.3. below.

3.2.1.1. For sag-limited lines, the JTF recommends that base ratings be calculated for an effective wind speed[5] of 0.6 m/s, an ambient temperature close to

[1] See 4.3.4.6.2and 4.3.4.6.3 as well as Appendixes A and B. Extended discussion is also in reference [29]. For additional guidance on the subject, see also 5.6.

[2] The main objective of thermal limitations is to ensure that the clearances of the lines are not violated. The literature review and the Cigre Technical Brochure on Sag and Tension Calculations show that the uncertainties of the high temperature sag calculations even in single spans typically exceed 30 cm. In multiple span line sections designed by ruling span method, the additional uncertainty can exceed +/- 1 m, at conductor temperatures above 100 °C. Because a 1°C uncertainty in conductor temperature is typically equivalent to a sag change of 1.2 to 2.5 cm, the JTF considers 10 °C as an appropriate objective for rating temperature uncertainty of sag-limited lines.

[3] This topic relates to annealing considerations. Variation in temperature rise within a span or a series of spans can typically amount to +/-10 % and can be even larger if parts of the line section are sheltered by trees or buildings. See discussion under Condensed Findings, Sections 4.6.1 and 4.6.2

[4] Probabilistic ratings are calculated based on known or assumed combined statistics of weather conditions, activity (typically vehicular traffic) under the line and load variation and are more properly considered as probabilistic clearances. They are applied in some countries (e.g. South Africa and U.K., in latter case for N-2 conditions only) but are not allowed in others (e.g. USA, Germany).

[5] Effective wind speed is the perpendicular wind speed which results in the same forced convection as a wind of a given angle and speed or which has the same forced convection effect at the average wind conditions along a line section. For example, a steady 1.17 m/s wind at a constant angle of 30 degree to the conductor axis has an effective wind speed of 0.6 m/s. See Figure 2 in Condensed Findings section of the Brochure.

the maximum annual value[6] along the line route and a solar radiation of 1000 W/m^2. When combined with an assumed conductor absorptivity of no less than 0.8 [7], this combination can be considered safe for thermal rating calculations without field measurements[8].

3.2.1.2. For those lines, where annealing of conductors is the primary concern, having narrow, sheltered corridors, with energized conductors either below tree canopy height or between buildings, the Base rating should be estimated based on either a 0.4 m/s effective wind speed or by reducing the maximum conductor design temperature by 10^{o}C [9]. Although the average conductor temperature, which determines the line sag, is not likely to be higher than that based on 0.6 m/s wind speed, the local effective wind speed in sheltered locations may be significantly lower.

3.2.1.3. Seasonal ratings should be based on an ambient temperature close to the maximum value of the season along the line and other criteria in 3.2.1.1 and 3.2.1.2. above, although the precautions discussed in Section 4 of the Brochure should be exercised [10].

3.2.2. Study-based ratings

The transmission line owner/operator may base the rating assumptions of selected lines or regions on actual weather or rating studies, provided that:

3.2.2.1. Rating weather studies are conducted in the actual transmission line environment, using the methods recommended in Section 5 of this Brochure[11]. If seasonal ratings are applied, such studies must include the respective seasons.

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[6] A recommended solution is to select an ambient temperature which is exceeded only 1-2 days in an average year.

[7] Conductor emissivity should be chosen to be 0.1 less than absorptivity.

[8] Based on extensive literature survey, the combination of standard rating assumptions appears to represent a risk level of less than 1%, meaning that if the line were operated 100% of time at rated current, it would exceed design temperature less than 1% of time but by no more than 10 ^{o}C. Data sources in the literature survey cover essentially all weather regimes except tropical forests. Section 4 of the Guide shows some conditions where reduction of solar radiation or conductor absorptivity can be considered justified.

[9] Effective wind speed is usually the most important rating variable, especially for lines with design temperatures over 75 ^{o}C. Data shows clearly that the effective wind speeds in sheltered corridors can be much lower than in open areas. This is caused partly by the sheltering effect and partly because narrow corridors tend to direct the wind along the line corridor, thus reducing its cooling effect.

[10] Ambient temperature has a large annual variation in cold climates and a moderate annual variation in temperate climates. Especially in cold climates where the electric loads peak during cold weather, use of seasonal variation is attractive and generally justified. Condensed Findings section of the Brochure includes precautions, namely such conditions where low and laminar winds coincide with low temperatures.

[11] Because most National Weather Service stations are deliberately located at open sites, data for such sources is not suitable for line rating studies. Furthermore, such stations typically provide only single hourly observation of instantaneous wind speeds, which are poorly related to line rating requirement of average wind speeds, e.g. at 10 minute intervals. Also, most such weather sites are equipped with anemometers with very high start/stall thresholds.

3.2.2.2. Alternatively, rating studies can be conducted with devices which monitor line tension, sag, clearance or conductor temperature[12]. The methods are specified in Section 5 of this Brochure.

3.2.3. Variable ratings.

3.2.3.1.Continually ambient-adjusted ratings.

Ratings can be adjusted based on varying ambient temperatures measures at the time. These are termed continually ambient-adjusted ratings. In this case, unless real time rating systems are used, the wind speed should be based on the assumption of a more conservative effective wind speed than base ratings. The extensive literature review by the JTF clearly indicates that ambient temperature and wind speed are not independent parameters, higher wind speeds being associated with high ambient temperatures.

If the Base Rating is to be adjusted for daytime conditions, the JTF recommends the following: If the ambient temperature adjustment is less than 8^{o}C compared to the temperature selected for Base Rating conditions (for example, if the base ambient temperature is 35^{o}C and the actual ambient temperature is between 35^{o}C and 27^{o}C, the effective wind speed should be selected as no higher than 0.5 m/s. If the temperature adjustment is more than 8^{o}C, the effective wind speed should be selected as no more than 0.4 m/s. For nighttime ambient-adjusted ratings (between sunset and sunrise when solar radiation is zero), wind speed should be selected as zero (natural convection only), and solar radiation can also be considered nil. Continually ambient-adjusted ratings can provide technically justified ampacity increases for lines which are designed for low maximum conductor temperatures, e.g. below 60-70^{o}C. On the other hand, they will generally not provide technically justified benefits for lines designed for 100 ^{o}C or higher temperatures [118].

If a study-based line rating is to be adjusted for ambient temperature, the engineer must be careful to reduce the assumed wind speed to account for correlation with ambient temperature. As with ambient adjustment of Base ratings, the wind speed at night should be much lower.

3.2.3.2 Real time ratings.

Rather than using “worst-case” weather assumptions, the transmission line owner/operator may elect to use real time monitoring equipment for determining the line rating, provided:

- Monitoring equipment meets the sensitivity, accuracy and calibration requirements specified in Section 5 of the Brochure.

- It has been verified that the lines which are to be monitored meet the design clearance requirements.

- Monitors are installed in sufficient quantity to provide statistically valid information of the sag or temperature of the monitored circuit[13].

[12] Tension, sag and clearance monitors essentially use the conductor as a “hot wire anemometer”. Rating studies require that the instrumented lines are at least moderately loaded.

- The operator has the capability of adjusting the line current to the level of standard or enhanced ratings in emergency conditions[14].

3.3. Reasons for recommendations

The footnotes summarize briefly the main reasons for each of the above recommendations. For more detailed explanations, the reader should refer to "Condensed Findings Based on Literature Review", Section 4 of the Brochure.

[13] See Condensed Findings and Recommendations Regarding Weather and Ratings Measurements.
[14] Generally, real time ratings are applied most effectively for mitigation of transmission line load relief under N-1 conditions, allowing the system operators to either avoid or minimize the required corrective actions. Nevertheless, the operator must have sufficient ability to reduce the line current to that equivalent to the worst-case scenarios.

4. CONDENSED FINDINGS BASED ON LITERATURE REVIEW

4.1. Overview:

The literature review conducted by the Task Force [112] summarized 119 reports, from 15 countries, 88 transmission lines or tests spans, including data from 164 observation sites, spans or line sections. The task force believes that this represents a comprehensive survey which can be used for guidance in selection of weather parameters for overhead bare conductor ratings.

The report discusses a substantial number of findings which are surprisingly uniform and site-independent. Examples of such general findings include low probability of low wind speeds at high ambient temperatures, uniformity of ambient temperature along a line route and reduction of solar radiation effect at high ambient temperatures. The report also discusses such cases where the variability of weather conditions and line ratings along the line routes, variations caused by seasons and time of day and other factors that limit the applicability of common rules and require site specific information. Thus some of the findings may appear contradictory. Before applying any of the findings in this report, the reader should carefully consult the specific referenced documents to verify that local conditions are comparable to those of the reference.

The objective of the following evaluation is to provide guidance for technically justifiable selection of weather parameters for line ratings. It is up to each of the transmission line owner or operator to decide, which combination of the parameters, combined with their designs, safety regulations and operating practices assures a safe operation of their transmission lines when applying the observations of this guide.

Specifically, each transmission owner/operator should consider not only the findings of this report but also such factors as:

- Does the national code allow any infringements of clearances? If the national code is deterministic, some of the probabilistic considerations of the following discussions (generally based on 99-95% probability) may need to be modified or applied only with adequate clearance buffers.
- What are the consequences of a higher conductor temperature than anticipated? For example, if the worst-case temperature reaches a level where the conductor integrity is endangered at a single point of the line, should this be a limiting factor, instead of line clearances which depend on the average temperature of a line section?
- What is the probability of the contingency overloads and how quickly can the control system react to them?
- Are there isolated locations in the system where the transmission line rating conditions can be substantially less favorable than in the locations where data has been collected?
- Is the modeling of transmission line sags and temperatures acceptably accurate and does it incorporate the most recent findings regarding possible errors?

Thus, the following treatment should be considered as a **guide**, modified by best practices analysis and engineering judgment. The references provided in this document are only partial. More detailed directory of references can be found in Literature Review [112].

4.2. General principles of ratings

1. The objectives of transmission line thermal ratings are to ensure safe operation of the line above all anticipated activities by maintaining national code clearances [5], and that the integrity of the conductor is not endangered because of local annealing or other degradation.

The first objective is generally met if the average conductor temperature in a ruling span section does not exceed the maximum design temperature of the line section [5],[22],[88]. The second requirement is met if the highest local temperature does not cause excessive annealing of the copper or aluminum strands of the conductor or cause other degradation, e.g. loss of protective grease in the steel core.

There is a significant difference between the above requirements. Survey of literature has indicated that the local temperature rise somewhere in a given line section can exceed the average temperature rise of the conductor by 10-25% [6],[74],[97]. This can be significant when lines are operated in the temperature ranges where high local temperatures can cause annealing, degradation of the steel core galvanizing, or connector damage. See 4.3.4.6.2.

2. Transmission lines are seldom operated at full design ratings, but they should be able to endure occasional high loads due to the loss of major generation or transmission components.

Emergency line ratings typically apply for limited time periods. Ratings which apply for emergency loadings that endure 5-30 minutes are typically referred to as Short Term Emergency (STE) ratings. Ratings which apply for longer periods (up to 24 hours) are typically referred to as Long Term Emergency (LTE) ratings.

Long time emergency events are uncommon and limited in duration. Therefore, the conductor may be allowed to reach higher than normal temperatures, accepting the limited risk of annealing. Even higher temperatures can be tolerated during STE events, because most system operators can reduce line loads by remedial actions within 10-15 minutes. Since typical transmission conductors have time constants of 10-15 minutes, most conductors will reach only 60-70% of their final temperature rise within such time periods [19]. Thus the allowable conductor current for STE ratings is usually higher than for LTE ratings.

STE ratings for more than 20 minutes for small/medium conductors should be used with caution. Given the short thermal time constant of small/medium conductors, high emergency loads can cause quite high temperatures, especially if the preload is high. From a technical point-of-view, STE limits should be related to the conductor size with smaller conductors having shorter time limits. While this may present practical

problems for system planning functions, the principle should be recognized in system operations.

In most cases, electric regulations require that minimum safety clearances are met even during emergency operating conditions. The major exception to the above is in such cases where regulations allow probabilistic clearances, based on rigorous analysis of combined probabilities of activities under line, load patterns and weather conditions.

3. Circuit ratings should consider temperature limits on conductors, connectors and substation terminal equipment.

Many components of the circuit other than the conductor may be thermally limiting. Well made connectors, deadends or splices do not limit the line's thermal capability, as they operate at lower temperatures than the conductor. However, marginal connectors and other line accessories may limit line ratings. Substation elements (transformers, disconnects, line traps etc.) may also be more limiting to the circuit capabilities than line ratings[17].

4. Methods used in the design of older lines may not be technically appropriate for high temperature clearance calculations.

Many old lines were designed for low temperature operation (e.g. 49^{o}C in North America), using design methods and assumptions which can not be accurately extrapolated for higher temperature operation [38],[41],[71],[109]. Even if the lines were designed with significant buffers at low temperatures, reduction of the assumed "excess" buffer to allow high temperature operation may not ensure safe operating conditions. Any line contemplated for substantial increase in operating temperature should be carefully studied and analyzed using modern evaluation tools and analytical methods.

The following discussion analyzes findings in the technical literature regarding conductor temperature and rating observations in actual transmission line environments. The reader will note that certain conventional assumptions are questioned and critiqued. For a more detailed list of the specific findings within the reference documents, see Review of Literature [112].

4.3. Impact of major variables on ratings calculations

Line ratings are generally calculated using either IEEE-738 [51] or CIGRE rating method [95]. These two methods give very similar results under most common rating conditions [4]. Some utilities employ their own modified methods, e.g. EPRI Dynamp [18], [40] in the U.S. Any variations of ratings between these different sources are strictly secondary compared to the impact of variations in the input parameters [4],[17].

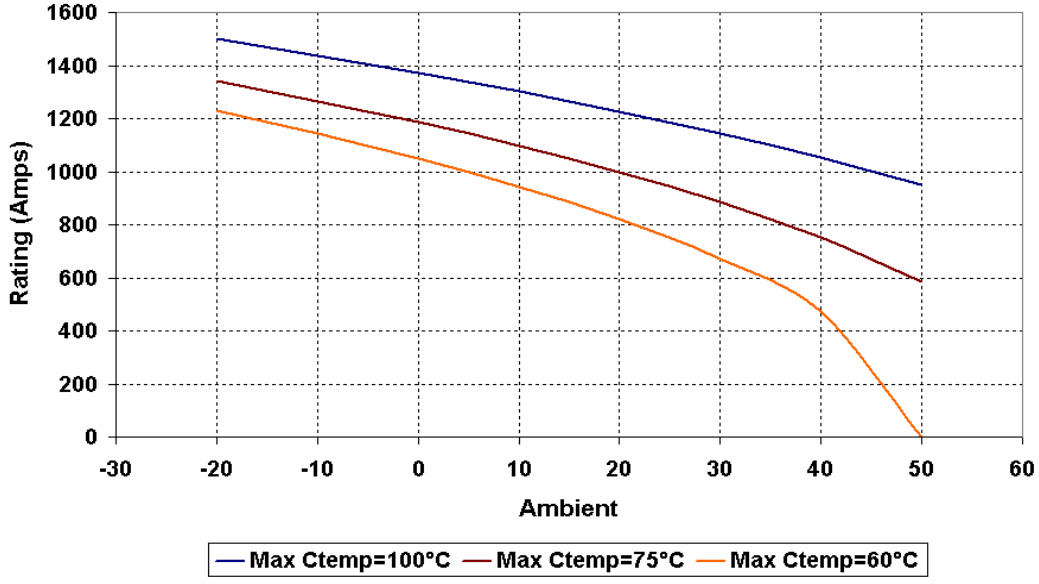
The basic reference case in this document uses 405/65 mm^2 ACSR 26/7 "Drake" as the reference conductor and a maximum operating temperature of 100^{o}C. In the base case the conductor is assumed to have an absorptivity and emissivity of 0.8, an ambient temperature of 40^{o}C, a wind speed of 0.6 m/s perpendicular to the line, to be

at latitude of 40 degrees North, and the time is assumed to be 12 noon on July 1. The direction of the line is East-West, it is at sea level and the sky is clear. The static rating is then 1047 A (CIGRE). The IEEE calculation gives a slightly lower value, 1023 A. The main cause for the difference is slightly higher convective cooling in the CIGRE formula [4].

4.3.1. Ambient temperature

Ambient temperature affects the conductor temperature in a one-to-one relationship. If, under given conditions, ambient temperature increases by 10 ^{o}C, conductor temperature increases essentially by the same amount. (Note, though, that in actuality wind speed is statistically dependent on ambient temperature as discussed in 4.5.1 and Appendixes B and C). Selection of ambient temperature has relatively little effect if conductors are rated for high operating temperatures but can have a significant effect for lines thermally rated at lower temperatures [21],[34]. For example, static rating for ACSR Drake is 1047A for the base case at 40^{o}C ambient. It increases to 1139 A if the ambient temperature is changed to 30^{o}C (+8.8%). If, on the other hand, the line were thermally rated to 60 ^{o}C, the base case would show a rating of only 458 A for 40^{o}C ambient temperature but 662 A for ambient temperature of 30^{o}C, i.e. a 44.5% increase. See Figure 1 below.

Fig 1. Rating vs. Ambient Temperature
ACSR Drake, Base Case



Ambient temperature variation along the transmission corridor is usually rather small, unless the line is a mountainous terrain [24],[47],[56].

4.3.2. Solar radiation

Most rating calculations assume midday, clear sky, perpendicular solar radiation and some calculations even include additional diffuse and reflected solar radiation [42],[67] [95]. The commonly used radiation intensities vary between 1000 and 1280 W/m^2. In the base case at latitude of 40 degrees, full solar radiation causes a

conductor temperature rise from 40 to 51.2°C in the absence of any current. Note that this temperature rise is roughly proportional to the absorptivity of the conductor. If the absorptivity were 1.0 and emissivity 0.8, the temperature rise would be 15.3°C while for absorptivity of 0.5 the temperature rise would be 7.7°C.

In the absence of any current, the conductor temperature is equal to air temperature plus a temperature rise due to solar radiation. The combined effect of ambient temperature and solar radiation is called Net Radiation Temperature (Solar temperature)[18]. For example, in the above case the solar temperature is 51.2°C. The difference between Net Radiation Temperature and ambient temperature is called Net Radiation Gain (NRG) [23],[62]. NRG is proportional to the absorbed solar radiation, i.e. the absorptivity of the conductor and solar radiation intensity. Because NRG is inversely proportional to convection, high wind speeds reduce NRG.

Literature references indicate that NRG's over 10°C are rare and do not happen when the ambient temperature is high [13],[23],[62]. This is caused both because high solar radiation rarely coincides with low wind speeds and because in most locations the sky clarity decreases when ambient temperatures are high. Thus the impact of solar radiation may be overestimated in rating calculations, especially when lines are thermally rated for high temperatures [1]. As a practical guide, rating calculations can be made assuming a solar temperature about 7-9°C higher than ambient [62]. Alternatively, the solar radiation can be assumed to be no more than 800 W/m^2 when ambient temperature is high [1].

Special conditions exist at high latitudes when the ground is covered by snow [23], [62]. At certain times, reflected solar radiation can increase the total radiation received by the conductor more than 50 %. Highest observed NRGs are then as high as 16-17°C under low wind speed conditions.

Another effect to be recognized, though minor, is that during clear nights the solar temperature can be 1-2°C lower than ambient, because of radiation to deep space [10], [23] [62].

4.3.3. Emissivity and absorptivity

Emissivity and absorptivity of energized conductors are highly correlated, increasing rapidly from initial values of about 0.2-0.3 after conductor installation to values higher than 0.8 within two years of high voltage operation in industrial or heavy agricultural environments [30],[31],[38],[42],[62]. This increase has a beneficial effect when the lines are operated at temperatures over 70-80°C, because outgoing radiation then exceeds the solar heating. Some utilities use lower ratings for lines during the first year after conductor installation, because of reduced radiation losses caused by initially low emissivity.

Conductor emissivity and absorptivity may stay moderately low in certain desert-type or high rain rate areas. Data from certain U.S. western states indicates that absorptivity may stay as low as 0.6 even after 10 years of operation.

Excluding the above, it is generally recommended that both values should be set at 0.8 –0.9, or, for the sake of conservativeness, absorptivity be set at 0.9 and emissivity at

0.7 [30]. There is also technical justification for use of slightly higher absorptivity than emissivity [19],[38]. At present, a substantial number of utilities use values of 0.5-0.6, which are moderately conservative for lines thermally rated over 70-80°C. Conversely, such values may entail a 3-5°C temperature risk, if lines are thermally rated for e.g. 50°C maximum temperature.

4.3.4. Wind speed and direction

Wind speed and wind direction are the most important variables in determining the line rating. They are also the most difficult weather variables to assess, unless special studies are made. The following table shows the relative impact of changes in these variables, when compared to the base case rating of 1047 A for 100°C maximum temperature. During a period of calm (instead of the base case 0.6 m/s wind) line current equal to the 1047 A rating would yield a conductor temperature of 127°C. The temperature risk associated with this rating is thus 27°C.

Note that an assumption of 1.2 m/s perpendicular wind yields a higher rating of 1203 A for 100°C maximum operating temperature but also increases the temperature risk to 48°C. On the other hand, if the 1.2 m/s assumption is justified, the transmission line could be operated at 15% higher current than using the more common 0.6 m/s assumption.

TABLE I

Assumed Wind speed m/s	Assumed Wind angle degrees	100°C max . temperature rating (A)	Temperature at wind speed = 0	Temperature at wind speed = 0.6
0		803	100 °C	79 °C
0.3	90	861	106 °C	98 °C
0.6	90	1047	127 °C	100 °C
0.6	45	977	119 °C	93 °C
0.6	20	874	107 °C	84 °C
0.9	90	1135	139 °C	109 °C
1.2	90	1203	148 °C	117 °C

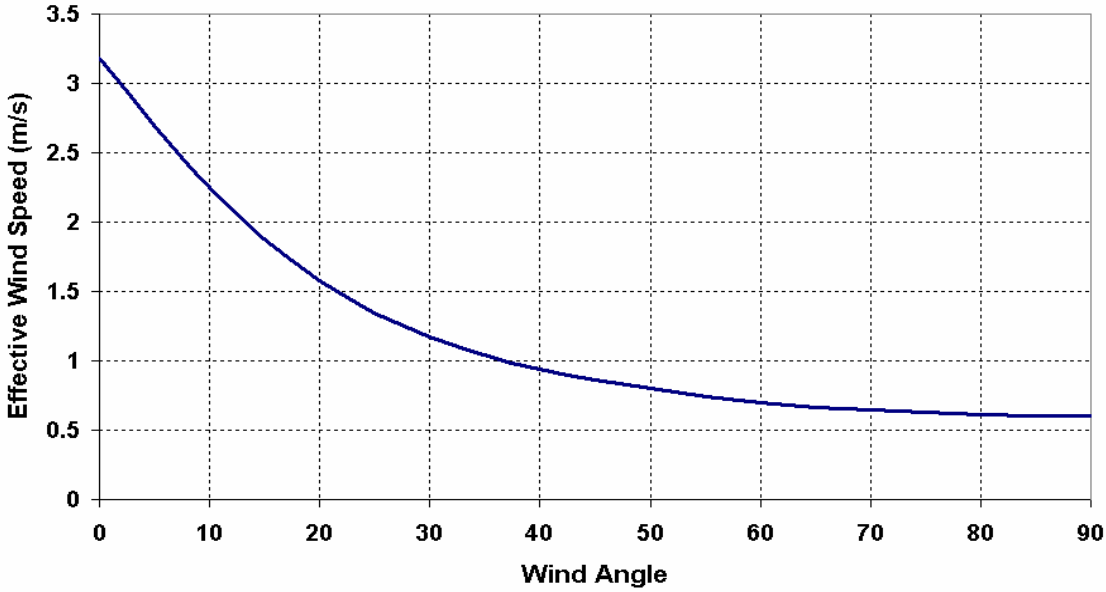
The consequences of too optimistic rating assumptions are discussed in [24],[72], [75].

4.3.4.1 Wind structure

Compared to wind tunnels, where the air flow can be characterized by two variables, air flow under natural wind conditions is more complex. The wind exhibits medium-scale turbulence, meaning that wind speed and direction vary in time and in space. Pure parallel and perpendicular winds do not exist in actual transmission line environment even at a single location, and even less along a span or a multi-span line section. Moreover, natural winds exhibit, especially during daytime conditions, varying degrees of wind pitch. This results in a small vertical wind component which is normally negligible in rating calculations.

Natural winds can be characterized for line ratings purposes by their "effective wind speed". This is the perpendicular wind speed which has the same convective cooling effect as natural winds to which the line is subject. For example, a steady wind at 45^o angle has 85% and wind at 30^o angle has 74% of the cooling effect of a perpendicular wind. This means that to have an "effective" wind speed of 0.6 m/s, wind with a 45^o angle must have a speed of 0.86 m/s and wind with a 30^o angle a speed of 1.17 m/s. See Figure 2 below.

Fig 2. Actual wind speed required for different wind angles to equal an effective wind speed of 0.6m/s



Wind speed varies with height above ground [7],[31],[39]. Wind speed generally increases with increasing height according to an exponential law, the exponent depending on the surface roughness. For rating purposes, wind measurements should be conducted at approximately the height of minimum clearance above ground [74]. Note that for lower voltage transmission lines this is less than the standard height for meteorological observations (10 m). For example, if wind speed is measured at 7.5 m elevation, the correction for a conductor at 6 m elevation is indicated as 0.95 and for 21 m elevation as 1.15 to 1.3 in a partly treed rolling terrain [7]. Also, if the conductors are above a solid canopy, wind speed will be substantially lower than at the same elevation above open ground.

4.3.4.2 Wind turbulence

Wind turbulence causes variations of wind speed and direction [12]. Most of the wind turbulence spectrum occurs in the time range of 20 seconds to 5 minutes [111]. In distance scale, this means that the typical turbulence dimension is between 10-300 meters [22]. Thus, the majority of the temperature variation caused by turbulence occurs within the confines of a single span. The magnitude of turbulence is strongly dependent on ambient temperature and solar radiation, as well as wind speed [22],[114]. During warm summer days, standard deviation of wind direction is typically 45 degrees or more for low wind speeds, meaning that daytime low speed

winds are quite non-directional [6],[66] The change of wind direction between 10 minute average measurements typically exceeds 60 degrees [24]. Nighttime winds can be more laminar, and standard deviation of wind direction can be 20 degrees or even less [6],[66]. If standard deviation of wind angle is larger than 50 degrees, the effective yaw angle of the wind is between 35 and 45 degrees, irrespective of the average wind direction [38]. When wind speeds were less than 1.5 m/s, during summer conditions in California, the standard deviation of wind direction averaged 48 degrees during daytime and 20 degrees at night [6],9116]. Reports discussing large variability of wind direction include [6], [7],[20],[38],[56],[66], [73].

These findings have important impacts on line ratings, namely:

a. Temperature of a conductor in a transmission span or a series of spans varies both in time and along the span [6]. The average temperature of a span or of multiple spans consisting of a ruling span section varies substantially less [18], [74].
b. Use of averaged wind direction has very little meaning for rating calculations, unless it is combined with information about wind turbulence. For example, if the average wind is parallel to the line, but the standard deviation of wind direction is +/- 45 degrees, the effective wind angle is about 30-35 degrees [39].
c. In many locations, wind speed has a strong diurnal variation and daytime average and minimum wind speeds can be more than twice nighttime wind speeds.
d. Wind data should be averaged with a time interval which is related to the conductor's time constant [9],[51],[56]. Using short time intervals tends to give high cumulative probabilities for low wind speeds [31]. For most cases, 10-minute averaging time appears appropriate.

4.3.4.3 Wind direction

Irrespective of the effect of wind turbulence which mitigates the effects of wind direction, it is a serious error to assume that the observed wind is consistently perpendicular to the line [24]. Consider the case of a 90-degree line angle. If wind were perpendicular to the conductor at one side of the angle, it would be parallel at the other side. Theoretically, the best possible net effect would be incidence at 45 degrees to each line section. In practice, the turbulence effects make the variation of conductor temperature and line ratings caused by wind direction to be substantially less than assumed based on theoretical calculations [7],[14]. Certain authors recommend rating calculations or real time ratings to be based on observed wind speeds but a small fixed angle (12-25 degrees) for conservatism [18],[38],[39],[66], [73].

4.3.4.4. Effects of sheltering

Frequently, substantial parts of a transmission line can be sheltered by trees, buildings or terrain. Because the rating of a transmission line should be based on the line section which operates at the highest temperatures, it is essential to base the estimate of the wind conditions on the most sheltered line sections [28],[39],[47]. Numerous reports show that wind speeds at such locations are often only one half or less of those

recorded at nearby open terrain sites, such as airports, national weather stations or substations [11],[16], [54], [56]. Moreover, in forested areas wind direction tends to be more parallel than perpendicular to the conductor [54], [62].

4.3.4.5. Vertical component of wind

Vertical component of wind is caused by two different mechanisms. One is wind pitch, caused by ground elevation variations or by frictional effects when surface roughness is significant. Except at steep slopes, these effects are small.

The second cause is thermal turbulence, which is generally only significant during hot and sunny conditions and usually minimal at night [6]. The median values of such turbulence-caused wind speeds appear to be between 0.2 and 0.5 m/s during hot summer days. Their effect on convective cooling is relatively small, except at sites where lines are substantially sheltered and horizontal wind speeds are low [6], [55]. It should also be noted, that the vector-average value of thermal turbulence derived winds is zero, downward flow having an equal probability as upward flow. Thus, if the rating calculations are based on mixed convection at low wind speeds, e.g. using the CIGRE method, the net effect of vertical wind is actually insignificant.

4.3.4.6. Spatial variability of wind

The most confounding problem in the weather parameter selection is how to account for the large variability of wind speed and direction along the transmission line and even along single spans [40], [74]. This was originally considered the “critical span problem”, i.e. identifying the span which was operating at the highest temperature at any given time [9]. Later, it has been realized that within a ruling span (dead-ended section) of the line, tensions equalize because of insulator swings, and that the conductor tension and the line sags closely follow the average temperature of the conductor in the line section [15],[18], [22]. Thus the concept of “critical span” has been replaced by the question of identifying the thermally critical line section or clearance critical line section and estimating the variation of average temperatures between such line sections.

4.3.4.6.1 Spatial variability of wind within a span

There are no available studies about variability of wind speed along a span in actual transmission line environments, although [26] indicates that short term comparisons of two nearby anemometers can show large differences. The best indirect evidence of large variation of effective wind speed comes from conductor temperature measurements in test spans [22 note 1],[9],[15], [40], [54], [74], [97] or on a transmission line [47]. The data indicates that such variations can cause up to 10-25% differences in the local temperature rises within a single span. Observed local temperature rises appear to be normally distributed with a standard deviation of about 10% [6],[88],[97].

Because of this variability, ratings studies conducted using temperature measurements at single point locations on transmission conductors are subject to most of the same interpretation deficiencies as single point weather –based rating calculations. On the other hand, if the line currents are high, ratings analysis using conductor temperature

measurements is more likely to provide accurate data about the most critical rating observations under low wind speed conditions [28].

4.3.4.6.2. Spatial variability of wind within a ruling span section

There are no substantial studies of wind speed variation along a ruling span section of a transmission line. There are some reports which identify poor correlations between nearby weather stations. For example, reports [18], [56] shows essentially no correlation between simultaneous recordings at two sites about 2.5 km apart in a line corridor, and [9] indicates that conductor temperatures calculated based on wind speed data 1.6 km distance from test span had average errors of 10^{o}C and that errors over 20^{o}C occurred more than 10% of time.

There is more information based on conductor temperature measurements. Report [54] shows that within a narrow corridor, temperatures of two adjacent spans (when average temperature of the conductor was 180 ^{o}C) could differ as much as 50^{o}C. This is a 20-25% difference in temperature rise, although this can be considered an extreme case because of the narrow line corridor [74]. Report [6] describes observations of 10% differences in temperature rises a few spans apart. Implied local wind speeds based on local temperature sensors show that effective wind speeds are typically in a range from 2:1 to as high as 5:1 along a short 6 km line [16].

When line ratings are determined by tension, sag or clearance measurements, they depend on the average rating conditions along the ruling span section, and especially on the average effective wind speed over a substantial distance. These methods can be also used to calculate the average effective wind speed, provided the line current is sufficient. Such measurements [29] indicate that the risk of low wind speed at a single point of a line is substantially higher than existence of a low average effective wind speed all along the line section. For example, the assumption of 0.5 m/s effective wind speed combined with high ambient temperature and full solar radiation, appears to have a risk of 1-4%, when calculations are made based on weather sensors at single locations [29 F1]. On the other hand, if the rating is based on the average temperature of a line section, the equivalent risk appears to be lower than 1% [29 F10,13,14,15]. This implies that occurrence of calm over a significant length of line has a significantly lower probability than the occurrence of a calm at a single point of line.

4.3.4.6.3. Spatial variability between ruling span sections of a transmission line.

Spatial variability can best be studied from measurements of line tensions or line sags, which follow the average temperature of a line section [5],[18],[74]. Because ambient temperature and solar radiation vary relatively little along the line, the variability of tension-derived conductor temperatures is primarily caused by differences in average effective wind speeds between the different line sections. There is substantial data available about the variability, mainly based on tension monitoring installations on a large number of lines. The data highlights the need to consider the different aspects of spatial variability, namely:

a. Some transmission lines are in terrains which are quite uniform and where vegetation along the line is rather similar. In such lines, it appears that conductor temperature variation between different line sections is close to normally distributed. Report [110] shows that there was relatively little

difference in comparison between adjacent line sections vs. another one 10 km distant. Reports [88] and [105] show that within similar terrain, the occurrence of highest average conductor temperatures of the ruling spans can be determined with a relatively small error (3-6^{o}C) based on limited number of line sections.

b. In other cases, some line sections are more sheltered and experience lower effective wind speeds than other line sections [18],[28], [47]. These cases can usually be identified by a careful study of the line topography. Meteorological rating studies should be concentrated on those line sections, where wind speeds can be expected to be low. Similarly, line monitoring should focus on the anticipated limiting line sections.

c. Cases were also reported where different line sections are limiting at different times of day because of varying diurnal wind conditions along the line [17], [29 F11, F12]. Such conditions often occur near major bodies of water. Also, especially at night, relatively subtle terrain variations can cause substantial differences in the occurrence of calm [29].

Spatial variability of ratings along transmission lines is discussed in several reports, including [15],[17],[18],[26],[29],[47],[52],[75],[29].

On a larger geographical scale, some data appears to support the assumption that spatial variation of wind speed is normally distributed. Studies in Belgium [14] between 18 National Weather stations indicate that the standard deviation of wind speed in the country is about 1 m/s. In Georgia, U.S., conductor temperature prediction errors were found to be statistically equal if based on weather data sources 12, 29 or 41 km away from test span [9].

Winds of medium and high speeds seem to have a better spatial correlation, because such winds are generally influenced by macro- or meso-scale meteorological events. If high wind speed (5 m/s+) is observed along the line, the likelihood that wind speeds are at least moderate (1-2 m/s) elsewhere is reasonably high [113]. On the other hand, a moderate wind speed at one observation site gives no assurance that wind speeds at other nearby sites are also moderate [18],[27],[38],[47].

4.3.4.6.4. Special cases of wind directionality

There are special cases in which wind can be highly directional. A common one occurs when transmission lines are in tree-sheltered corridors and the conductors are below canopy height [54], [56]. In such cases the effective wind speeds should be modified to account for the lowered cooling effect of the close-to parallel wind direction. Other cases of directional winds occur near bodies of water or along sloping terrain [106]. At such sites, line ratings may vary substantially depending on the line angle, especially under laminar nighttime wind flows.

4.3.4.7. Coincident most critical rating conditions

Zero wind speeds (or low speed winds with small angles of incidence); high ambient temperatures and high solar radiation intensities can occur in transmission line environments. However, meteorological cross-relations show that high solar radiation

induces local winds and that, in many locations, during high ambient temperatures the opacity of the sky is significant, reducing solar radiation [25],[107]. Because of this, most thermal rating criteria are based on a low but non-zero perpendicular wind speed assumption (0.5-0.6 m/s) and coincidence of high temperature and full solar radiation. An alternative method is to assume a zero wind speed and a lower temperature (or to use zero wind speed and actual temperature, as assumed by PJM power pool in the U.S.) Note that assuming a non-zero wind and a lower temperature than near maximum for the area is most likely to be non-conservative [26].

At many sites, low convective cooling conditions are most likely during morning hours or around sunset [22],[[29 F11/F12],[47],[60],[62],[92]. In such areas where line loads are high around sunset, the resulting low ratings may lead to the most limiting conditions for the line.

Observations of most critical rating conditions at different locations are shown in Appendix B.

4.3.4.8. Occurrence of prolonged calm periods

Prolonged periods of wind speeds less than 0.5 m/s are quite dangerous, especially for small conductors. Such situations have a low probability during daytime, but may be quite prevalent during nighttime and may persist several hours [6],[20],[22],[28],[47], [54],[70].

4.3.4.9. General spatial considerations

Utilities which serve large areas with significant variation in weather conditions may consider different ratings in different areas, e.g. coastal, with lower temperatures and higher wind speeds compared to interior regions [55],[60]. Similarly, it should be noted that long lines may have lower limiting rating conditions than short lines, because the probability that low rating conditions exist at some section of the line can be proportional to the line length [29].

4.4. Impact of variables other than weather in rating calculations

4.4.1. Joule losses

For most practical purposes, use of manufacturer's catalogue values provides a safe basis for resistive loss calculations. Because the conductivity values and the conductor's cross section are based on minimum guaranteed values, they include a small safety margin for rating purposes.

An exception to the above are conductors with a steel core and odd numbers of aluminum layers, where magnetic core effects increase the Joule losses at high current densities [75],[91]. This effect is generally recognized in the application of single aluminum layer ACSR conductors. It is less commonly recognized regarding three aluminum layer ACSR conductors (e.g. 54/7, 45/7). If such conductors are operated at high current densities (over 3 A/mm^2), the Joule losses can exceed those calculated based low current density resistance values by up to 5% [91]. The effects of single and three layer ACSR conductors can be modeled and included in rating calculations.

For example, if 383/63 mm^2 ACSR 54/7 "Cardinal" conductor is rated based on its low current density resistance for 100^oC operation under the "base case" conditions, its rated current would be 1172 A. At that current, the conductor will actually operate at 103^oC, when high current magnetic effects are accounted for. The correct rating, taking into account magnetic losses, should be 1144 A, i.e. 2.4% lower.

4.4.2. Radial temperature gradients

Both CIGRE and IEEE thermal rating calculations determine the thermal balance at the surface of the conductor. Because thermal energy must be removed from the inside of the conductor to the surface, the conductors have radial temperature gradients which are proportional to the line current and to the conductor diameter [75],[78]. Because a part of the conduction occurs through metallic contact between wire layers, the thermal gradient is also affected by conductor tension. Conductor sags, caused by material elongation, are either approximately proportional to the average temperature of the cross section, or in case of high temperature operation of steel-cored conductors, to the temperature of the core material.

In normal operation of small and medium conductors, such gradients are relatively small. The situation is quite different in large conductors, especially if operated under emergency ratings.

Consider the base case of ACSR "Drake", operated at 100^oC surface temperature with a current of 1047 A. The core temperature would be 102^oC. The line sag will increase by 2-3 cm. This can be compared to a 130^oC emergency operation of ACSR "Bluebird", at 2420 A. The core temperature would actually reach 136^oC. The incremental sag increase is about 6 cm.

It should be realized that the radial temperature gradient effect and the magnetic loss effect are mutually independent. Thus, the two sag increases are additive to each other.

4.4.2.1 Radial temperature effects in high-temperature conductors

High-temperature operation of composite conductors (ACSR, ACSS, ACCR etc) generally means that the stress of the outer aluminum layers is zero or negative at high temperatures. As stated above, this means that radial thermal conductivity will be reduced and core temperatures will increase proportionately [45],[115]. Some unpublished data seems to indicate that the radial temperature gradients of e.g. large ACSS conductors under high currents could exceed 30^oC. This will have an effect of increased high temperature sags and should be taken into account. A 30^oC thermal gradient could increase the sag by 20-30 cm.

4.4.3. Effect of conductor size

Small conductors react more rapidly to current and other rating variable changes than large conductors. If we compare 26/7 ACSR Partridge (135 mm^2), 54/7 ACSR Cardinal (483 mm^2) and 84/19 ACSR Bluebird (1092 mm^2), we find that their thermal time constants are 6.5, 14 and 21.5 minutes, respectively, assuming 100^oC rating conditions and a 0.6 m/s perpendicular wind [19], [51],[96]. This means that during a 15-minute emergency load or a 15-minute low wind period, these conductors reach

92%, 65% and 52% of their respective final equilibrium temperatures. Thus, based on the above discussion, emergency ratings for longer than 15 minutes are not advisable for small conductors [22].

4.4.4. Sag uncertainties

While technically outside the scope of this report, a cautionary note is included regarding the uncertainties of high temperature sags of lines. A growing body of evidence shows that there are substantial errors in line sag estimates based on calculated or measured conductor temperatures. [19],[41],[74],[87]. Some of the error sources relate to imperfect modeling of strand interaction in composite conductors [5],[18],[41][45],[74],[75],[115]. Other error sources relate to conductor manufacturing practices [41],[48],[50],[75]. A further error source is caused by ruling span (equivalent span) methodology [26],[38],[41],[47], [53],[71],[75].

4.5. Special rating methods

4.5.1. Ambient-adjusted ratings

There are two separate practices of adjusting the ratings based on ambient temperature. The first deals with seasonal ratings and the second with real-time adjustment of ratings depending on ambient temperature.

As discussed above in section 4.3.1, ambient temperature change affects conductor temperature in a one-to-one relationship, as long as all other variables remain well behaved. In reality, as discussed in section 4.3.4, solar radiation and wind speed are statistically dependent upon ambient temperature. Particularly, wind speed and wind turbulence increase with increasing temperature. A summary of the correlations between the observations is given in Appendix B.

In general, ambient –adjusted ratings have the largest effect for lines which are thermally rated for low maximum operating temperatures as discussed in section 4.3.1.

4.5.2. Seasonal ratings

In areas where seasonal temperature changes are large, it is a relatively common practice to adjust ratings seasonally, e.g. using different ratings for summer and winter conditions or sometimes using a third rating for spring and fall. Often the rating adjusts are limited to seasonal air temperatures employing conservative wind speed independent of season. However, if wind speed is less than conservative, such ratings can be justified, provided that the following conditions apply:

- Seasonal wind conditions do not differ substantially, which is not always true [23],[28]. In some areas winter wind speeds are substantially lower and do not exhibit the same diurnal patterns as summer winds [1],[76]. At other locations, especially near shorelines, periods of low wind speed may occur during shoulder seasons or in the winter [92].

- Contrary to high temperature summer conditions when wind direction is generally highly variable, cold winter temperatures are often associated with laminar and directional winds.
- In areas of significant snow cover, increased solar radiation because of reflection from snow may need to be considered [62].

Depending on the nature of the line corridors, wind conditions may differ substantially between winter and summer. An important consideration is summer foliage, which may cause a substantial reduction in wind speeds [23],[28]. Such effects cannot be detected from open terrain meteorological observations, which often indicate higher wind average speed for summer months [76].

4.5.3. Continually ambient-adjusted ratings

Certain utilities and transmission system operators adjust their line ratings either continually or in steps depending on the ambient temperature [92]. Such adjustments can be considered justified if based on an adequately conservative wind speed, e.g. zero wind. Use of conservative wind speeds is necessary because of the previously discussed correlation between ambient temperature, solar radiation and wind speed. Appendix B provides further information about this subject.

Special caution should be directed towards the application of real-time ambient adjusted ratings for low winter temperatures. Under such conditions, lowest winter temperatures can be associated with extremely low wind speeds [76].

4.5.4. Real time ratings based on line monitors

CIGRE WG B2-12 defines real time ratings as follows [5] :

- Real time monitoring is the monitoring of parameters enabling the conductor position above ground to be determined in real time. The permissible thermal limits are then calculated to enable the operators to optimise the power flow along the line(s). This is achieved by informing the operators of the present conductor temperature as well as the available capacity on the line as a function of time. For example the operator will be informed that on a particular line the power can be increased by 400 MVA for 10 minutes, 200 MVA for 20 minutes and 50 MVA for 60 minutes. The operator can also be informed of how long he can continue operating the line at the present load before the ground clearance or annealing criteria is exceeded.

It should be noted that with real time systems the line is not operated at temperatures higher than designed but running at its design temperature for a longer period of time. Thus the line is better utilized.

There are several methods for determining real time ratings. The basic methods are described in [5]. Specific methods and applications are discussed in [7],[16],[17], [22], [28],[36],[64],[68],[74],[80],[81],[88],[89],[93][99],[105].

When lines are monitored in real time the operators have accurate information on the sags, clearances and conductor temperatures, as long as the monitoring equipment is

accurate, reliable and applied in appropriate locations. Transmission owners and operators can then adjust their line rating criteria commensurate with the monitoring equipment capabilities to provide the operators advance warnings of impending rating violations. Thus, transmission planning may be based on probabilistic criteria as long as the monitors ensure deterministic operational reliability and safety.

Application of real time monitors can be especially attractive for lines which have heavy loads only infrequently, e.g. in emergency situations. If low rating conditions are infrequent and/or if line loads are high at the same time when rating conditions are generally favorable, the transmission owners may benefit from increased line capabilities and reducing the amount of operating interventions.

Real time ratings should only be applied if the operator has a line load intervention scheme readily available, e.g. through remedial actions.

Archived data from real time monitoring systems is also widely used in ratings studies by a large number of utilities [5],[7],[16],[18],[22],[28],[29],[47][52],[53],[64],[66], [80],[88],[92],[105]. The additional advantage of such measurements is that they are more directly related to the main objectives of ratings, namely conductor sags and temperatures [5].

4.6. Consequences of too optimistic rating assumptions

4.6.1. Clearance violations

The most common consequence of too optimistic rating assumptions is a clearance violation, which can occur if the design clearance buffers are inadequate compared to the risk of high sags in most critical operating conditions [24],[49],[71],[72]. Typically a 10^{o}C increase causes, depending on span length and conductor type, a 15-25 cm increase in line sag [108]. Most transmission line designers used to incorporate a 50 to 120 cm safety buffer in line profiles[61],[65]. Evaluation of transmission lines have indicated that buffers less than 100 cm may not be adequate because of normal variation in line construction [82],[83],[84] and accuracy of sag calculation methods [39],[41],[71],[87], [98],[109]. In addition to being a reliability problem, clearance violations may also pose substantial safety risks to the public [72],[108].

4.6.2. Annealing

Annealing of aluminum or copper causes loss of conductor strength [101],[103]. Annealing is one of the main reasons for limiting the long term emergency ratings of transmission line conductors to a few hours. While the behavior of aluminum materials is well researched, there is substantial uncertainty with copper annealing rates [8],[50].

ACSR conductors with more than 7% steel by area are much more tolerant of annealing effects than conductors with less or no steel.

4.6.3. Elevated temperature creep

In normal operation, aluminum materials in conductors undergo permanent elongation, dependent on wire stress and temperature, as well as the occurrence of high wind and/or ice loads. Under normal operating conditions, this process reaches a terminal value in 10-20 years, after which the conductor is assumed to be at its "final" sag. Conversely, if the conductor is operated at temperatures above 70^{o}C for prolonged periods, the creep may restart or accelerate [102]. Creep elongation is permanent and since it is dependent on local temperature and aluminum stress, different spans in a ruling span section may have different elongation rates, making correction of sag imbalances difficult [104].

Note that most ACSR conductors are relatively immune to high temperature creep, because aluminum stresses at high temperatures are either low or zero [104].

4.7. Specific rating observations in literature

Appendix A contains an abbreviated directory of references to a specific set of reports which include direct recommendations or observations about ratings in different locations, terrains and seasons. Before using the observations in this appendix as guidance or comparison to a utility's practice, it is strongly recommended that each reader familiarizes himself with the referenced document.

Appendix B is a directory to the observed coincidences between ambient temperature, solar radiation and wind speed which is intended to assist the readers in selecting the likely coincidence of the most critical conditions. As above, study of each of these documents is recommended before applying discussed techniques or processes.

Appendix C contains observations of line ratings based on multiple sites or ruling span tension or sag measurements. As explained in 4.6, these observations tend to be more closely related to actual line ratings than single point measurements.

5. RECOMMENDATIONS REGARDING WEATHER AND RATING MEASUREMENTS

Overview and objective:

The Task Force has recommended that bare overhead conductor standard ratings should be calculated based on CIGRE or IEEE standards [51],[95] and based on the default assumptions of:

…an effective wind speed[15] of 0.6 m/s, an assumption of ambient temperature equal to the maximum annual value along the line route and a solar radiation of 1000 W/m with an assumed conductor absorptivity of no less than 0.8. This combination can be considered safe for thermal rating of sag-limited lines.

Recognizing that rating conditions in certain areas or locations can be more favorable, the JTF has considered the minimum level of monitoring equipment and data analysis which should be used to verify that such more favorable conditions exist. While the following recommendation falls short of a full scientific study of rating conditions, it is considered to be appropriate for practical and reasonably inexpensive engineering analysis for establishing conductor rating conditions for a given line or area. The resulting ratings are called "Study-based ratings" in Recommendations, Section 3 of the Guide.

Such studies can be conducted using either weather instrumentation or, in case of lines with at least moderate electrical loads, using tension, sag or clearance monitors.

5.1. Common requirements

Choose a site with vegetation and corridor width which are representative of the greater part of the line, avoid unusually open areas. Several sites will be needed if different typical wind conditions occur in different areas (i.e. one section close to the sea and another inland), and if large differences in line direction occur. If only one measurement can be made, the most sheltered part of the line should be chosen to be conservative.

For several practical considerations, such as access to the equipment, proper mounting height, avoidance of vandalism and interference of other activities in the line corridor, the monitoring equipment is generally mounted on transmission structures, which, as stated above, should be selected based on the objectives of weather measurements and not on their ease of access. This typically prevents power supply from service network and requires either solar or battery powered equipment as well as wireless communications. Considerations of power consumption are very important, as well as providing enough backup battery capacity for prolonged inclement periods. This

[15] Effective wind speed is the perpendicular wind speed which results in the same forced convection as a wind of a given angle and speed or which has the same forced convection effect as the average wind conditions along a line section. For example, a steady 1.17 m/s wind at a constant angle of 30 degree angle to the conductor axis has an effective wind speed of 0.6 m/s. See Figure 2 in Section 4 of the Brochure.

precludes some generally used meteorological equipment and methods, such as deicing of anemometers. It also means that the equipment must have a high reliability.

Any monitoring equipment within transmission corridors is subject to high electric and magnetic fields as well as strong electric transients caused by switching surges and lightning. Such effects may either damage the equipment or degrade data quality[16].

Under worst-case weather conditions, with low speed winds that change direction rapidly, measurement of wind (or conductor temperature) at a point can be a poor indicator of the average convection cooling (and average conductor temperature) along an entire line section. Therefore, in lines where the conductor temperature is limited in order to maintain adequate clearances, the measurement of sag or tension, in order to determine the average conductor temperature in a multi-span line section, is preferable to measuring the conductor temperature or wind speed at a single location. The variation in air temperature and solar heating along the line is much less, so these weather parameters can be measured at a single point.

5.2. Meteorological measurements and equipment

Because the objective is to determine line rating conditions at conductor height within line corridor, several details of the following recommendations differ from generally recommended WMO practices.

The minimum requirement for weather instrumentation for a rating study consists of measurement of ambient temperature, wind speed, wind direction and solar radiation.

5.2.1. Ambient temperature

Ambient temperature can be measured with any suitable temperature sensor, with an accuracy of at least 1.0^{o}C. The ambient sensor should be in an aspirated shield. Because in some conditions substantial temperature differences can exist between ground and conductor elevations, the sensor should be mounted at approximately the same elevation as the conductor average in the line section [99].

5.2.2. Wind speed and direction

Wind speed measurement should be done with an anemometer with a start and stall speed of no more than 0.5 m/s. More sensitive equipment is desirable, but may lead to more frequent and expensive maintenance. Wind speed should be measured as scalar average at 10-minute time intervals. Wind direction should be measured as vector average over the same time period.
The anemometers may be of propeller type or cup type with a separate wind vane. Ultrasonic anemometers may also be used. If wind measurements are made triaxially,

[16] Tower-mounted instrumentation will be affected by lightning flashes, with peak tower currents that exceed 100 kA and current steepness (dI/dt) in excess of 100 kA per microsecond. All instrumentation cables should be suitably routed and shielded for this environment. Equipotential bonding is required at instrumentation height. Surge arresters may also be needed on instrument terminals and across line insulators. Certain types of anemometers are sensitive to power frequency interference that can require filtering in addition to equipotential bonding.

the recorded quantity should be the 10-minute scalar average of the vector sum of the three components. Triaxial measurements may improve the results slightly in locations where ambient temperature is high.

Wind direction can be measured with either an integral wind vane in case of propeller anemometers, or a separate wind vane. For use of wind direction data, see 5.4.1. below.

Additionally, and useful for quality control purposes, the monitoring site may record the standard deviation of wind speed and wind direction. Although these values cannot be easily used as inputs in the CIGRE and IEEE rating calculations, they can be useful in more detailed studies and clarify discrepancies between meteorological and rating monitor based ratings [116].

For practical reasons, anemometers are usually mounted on transmission structures. Especially at tubular structures and wood or concrete poles, anemometers should be mounted as far from the structure as practical to avoid wind shielding by the structure[17]. The anemometers should be mounted at an elevation close to the level of maximum sag of the line. If the measurement elevation is substantially different, e.g. because the vicinity of energized conductor, the wind speed readings should be corrected using approximate formulas for wind speed variation vs. height above ground[18]. Should no suitable structures exist, anemometers should be erected on a pole at the vicinity of the proposed line route.

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[17] Anemometers are affected by shadowing and upwind stagnation of the structures. If anemometers are used for real time rating comparison, they should be mounted from the side of the structure so that the least frequent flow direction passes through the tower. For anemometers used on poles for real time rating purposes, the distance from the pole should be at least ten pole diameters.
On the other hand, if the anemometers are used for statistical purposes only and the distribution of wind direction at low speeds is reasonably random, shielding effects will tend to average out, because wind speed stagnation from some directions will be balanced by wind speed augmentation from other directions. See discussion of directional effects under Data Collection and Analysis and footnote 19.

[18] Surface friction reduces the wind speed at different transmission conductor elevations. The wind profile is approximately logarithmic and is described by the following equation:

$U = (u^*/K) \ln (z/z_0)$
where
U = mean wind speed.
u^* = friction velocity (representing surface stress).
K = von Karman constant (normally set at 0.4)
z = height
z_0 = aerodynamic roughness length.

The aerodynamic roughness length varies with the terrain, and is a measure of how the surface features interfere with the surface airflow. The magnitude of the roughness length is smaller than the physical size of surface obstructions.

At a conductor height of 10 m, wind speed over dense forest (z_o=1 m) would be 33% of the wind speed over a grass plain (z_o=0.01 m) under the same overall weather conditions.

The correction for anemometer height, often taken as the 1/7 power, is as follows:

Height	1/7 Power	ln (Z/1 m)	ln(Z/0.01m)
7 m	0.950	0.845	0.948
10 m	1	1	1
13 m	1.038	1.114	1.038

The anemometers require periodic maintenance which should be conducted according to the maintenance intervals and methods recommended by the manufacturers.

5.2.3.Solar radiation

Accurate measurement of the solar heating of the conductor is difficult. Theoretically, it would require measurement of "total radiation", i.e. the combination of direct, diffuse and reflected radiation. Total radiation is measured using net radiometers or pyrgeometers, which are very expensive and need constant maintenance. Because of this, CIGRE standard recommends calculation using less expensive and less maintenance-intensive global radiation meters (pyranometers).

IEEE only considers direct radiation in its solar intensity calculations, and thus understates the solar heating. The task force recommends that, for practical reasons, total solar radiation is used even if the calculations are made using IEEE Standard.

To calculate the solar heat gain, the absorptivity of the conductor has to be estimated with reasonable accuracy. There is no easy way to measure this quantity accurately. The task force recommends either determining the emissivity of the conductor and estimating absorptivity to be 0.1 higher than this value, or using a default absorptivity of no less than 0.8.

5.3. Using tension/sag monitors to determine ratings

5.3.1. Rating principle

Use of tension or sag monitors is based on the fact that conductor tension depends on the average temperature of a span or a line section [5],[29]. Properly calibrated sag or tension monitors provide quite accurate information of conductor temperature. If the line current is sufficiently high, the resulting conductor temperature rise can be used to determine the line rating, based on known formulae which relate temperature rise to line current. Furthermore, if ambient temperature and solar radiation energy input to the conductor are known, the effective wind cooling and thus the average effective wind speed along the line section can be calculated using CIGRE or IEEE rating formulas. Essentially, the conductor is used like a long hot-wire anemometer.

In the most common technology, a load cell in a strain structure is used to measure the conductor tension [23],[88]. The tension measurements are then either transmitted in real time to the utility's SCADA system or collected in a data logger and downloaded remotely via cellular telephone. Tension monitors can be mounted on selected dead-end structures along a transmission line. When two load cells are used at a deadend structure, the tension of the line sections can be monitored in two directions and the temperature rises of both line sections can be determined. If the deadend is an angle structure, the data from the two line sections can be compared to each other to provide information on the wind turbulence. Alternatively, such measurements can be conducted with sag or clearance monitors along the two line sections.

This correction is also seen to depend on surface roughness, meaning that the anemometer needs to be placed in an exposure similar to the overhead conductors. See also [7].

In addition to tension or sag, the monitoring equipment must also include ambient temperature and solar radiation sensors, or alternatively, net radiation sensors which measure the combined effect of ambient temperature and solar radiation (Net radiation temperature or solar temperature). Net radiation sensor is a solid cylinder of approximately the same diameter, same colour and the same heat capacity as the conductor. When located at the same height as the average height of the conductor, its temperature is the same as that of the conductor without current [23],[80],[88].

For rating analysis purposes, the current of the line must be known. If the data is communicated directly to the SCADA system, the line ratings are calculated in real time and logged. The real time line rating is determined using an algorithm which compares the conductor temperature to the temperature which represents the design temperature of the line section. The rating is that current which will result in maximum design temperature. Alternatively, line current can be logged and the rating analysis conducted off-line.

5.3.2. System calibration

In order to determine the thermal rating the relationship between the solar temperature and sag needs to be established. This requires a careful calibration to determine the characteristics of a line (tension or sag vs. the net radiation temperature based on recorded data). The relationship between the sags and net radiation temperature is then established. In the case of ACSR, the sag-temperature algorithms incorporating the compression of aluminum need to be taken into account. The resulting calibration curve represents the conductor tension or sag as a function of conductor temperature and is equivalent to an empirically determined final unloaded tension or sag as a function of conductor temperature [5].

An accurate calibration procedure is an essential part of ratings determination with tension or sag monitors. Usually, calibration curves can be generated with an accuracy of +/-1^{o}C, when net radiation sensors are used. If net radiation temperatures are generated using separate ambient and solar radiation sensors, the calibration accuracy is typically +/-2-4^{o}C.

Because calibration methods vary from equipment to equipment, manufacturers of such equipment should provide clear instructions about required calibration procedures, their accuracy and resulting uncertainties in rating determination. Because the tensions and sags can change due to structural movements, conductor creep and exceptional loads, periodic calibration should be conducted according to equipment suppliers instructions.

5.3.3. Resolution and stability requirements

Tension and sag monitoring systems provide most accurate rating data when line currents are high and wind speeds are low, i.e. under the conditions which are most critical for transmission line operation. Before considering their application, the users

should carefully consider if the types of equipment and application are well suited for their purposes[19].

Sag and tension monitoring systems determine the ratings of the lines based on sag or tension variation due to change of environmental conditions. For accurate rating calculations, it is paramount that the equipment itself is not affected by environmental variations, such as temperature, wind, rain or solar radiation. Note that for accuracy of rating determination, it is more important to have a high resolution and high environmental stability than a high absolute accuracy.

1. Resolution of sag measurement should better than 20 mm or equivalent to a sag change caused by 1 ^{o}C temperature change.
2. Combined error caused be environmental variation, aging, creep etc. should be less than 0.5% of the measurement full scale and less than 1% of the measured sag or tension value.
3. Accuracy of the net radiation temperature (conductor temperature in the absence of current) should be better than 1^{o}C. If net radiation temperature is not measured directly, the absorbed solar radiation by the conductor should be determined with an error less than 10%[20].

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[19] The resolution requirements are best illustrated by the following example. Consider line section of 403/66 mm^2 ACSR 26/7 "Drake", designed for 100 ^{o}C maximum operating temperature and having an emissivity and absorptivity of 0.8, and with a ruling span of 300 m. The line has a final tension of 28 000 N and a final sag of 6.6 m. Under standard rating conditions of 0.6 m/s effective wind, 40 ^{o}C ambient and full sun, the conductor can carry 1047 A. If aluminum wires remain in full compression, its tension would be 19 714 N and its sag 9.15 m at that temperature.

Now assume that the ambient temperature is 20^{o}C and that the sky is partly cloudy, resulting in a net radiation temperature of 29^{o}C at 0.6 m/s effective wind speed. If the line current is 0.5 A/mm^2 (202 A), the conductor temperature is 31^{o}C, i.e. the Joule heating causes only 2^{o}C temperature rise. A 1.0 A/mm^2 (403 A), current under similar conditions would cause a temperature rise of 7^{o}C and a 1.2 A/mm^2 (484 A) a temperature rise of 10^{o}C. In this temperature range the sag changes are about 30-35 mm/ ^{o}C and the tension changes about 120-140 N/ ^{o}C.

A sag measurement with a resolution of 1.5 cm would represent a 0.5^{o}C error and a tension measurement with a resolution of 30 N an error of 0.25^{o}C. These are within the capabilities of modern systems. Obviously neither of these errors is a limiting factor for rating accuracy.

The limiting factors are the combined accuracy of the calibration curve and the determination of net radiation temperature. With accurate net radiation sensors, this can be as good as 1-1.5 ^{o}C, but if separate ambient and solar radiation sensors are used, the error can amount to 2-4 ^{o}C.

The above analysis shows that depending on the resolution of the systems and the type of instruments applied, reasonably accurate rating studies can be conducted with high resolution equipment and accurate calibration at about 0.7-0.8 A/mm^2 current density and with lower quality equipment at a current density of 1.0-1.2 A/mm^2.

[20] Solar radiation can increase the conductor temperature by as much as 10-12^{o}C under ideal conditions and under typical daytime conditions by 4-6 ^{o}C. This temperature increase is proportional to the perpendicular solar radiation to the conductor and to the absorptivity of the conductor. Thus, a 10% error in absorbed solar radiation can introduce a 0.5-1.2 ^{o}C error in net radiation temperature. The calculation of net radiation temperature or the absorbed solar radiation in the absence of net radiation sensor requires:

- Determination of conductor absorptivity with an accuracy of 0.1.
- Calculating the absorbed radiation depending on angle of line and sun's angle
- Measuring the total radiation and estimating the reflected radiation due to ground albedo.

4. Maximum error of the current measurement should be less than 2%.

5.3.4. Installation of equipment

Because sag and tension monitors provide data on the average conditions of a line section, the resulting data varies less spatially than data from weather-based rating systems which are affected by variations of local wind speed. To provide information of ratings variability along a transmission line, a single site with two load cells or two sites with sag monitors should be considered the minimum requirement. For long lines in varying environment, application of two tension or four sag monitors may be required for high quality information. For more detailed explanations, the reader should refer to the Part 4 of the Guide, "Condensed Findings Based on Literature Review".

Net radiation sensors and solar radiation sensors should be mounted on heights and locations where their shadowing by nearby objects, is similar to that of the transmission conductor itself. If shadowing occurs at certain times of day or season, the resulting data may cause rating errors.

5.4. Data collection and analysis

5.4.1. Data collection and analysis for meteorological systems

The objectives of the data analysis are:

a. To identify the most critical cooling conditions for a line or an area. This means calculating the line ratings based on the measured data, and tabulating them in ascending order.
b. To identify daily rating patterns, which indicate what times of day the rating conditions can be most limiting. For example, it is not atypical to find that lowest ratings occur after sunrise and around sunset.

Data should be collected at 10-minute intervals and analyzed at least monthly. This will allow early detection and correction of possible instrumentation problems. While a full 12-month period is recommended for a study, at least one month of data during representative seasonal conditions should be analyzed for each seasonal rating period[21] In selecting such monthly periods, the selected month should represent the time of highest ambient temperature of the season.

The collected data is used as an input to calculations made according to CIGRE or IEEE standards [51],[95] with the following modifications:

[21] If the lines are designed for high operating temperatures, the most critical rating conditions are determined by the prevalence of low wind speeds, which typically have a repeatable pattern with a short return period. In such cases, weather studies can be conducted over relatively short time periods. If the lines are designed for low maximum temperatures, the ambient temperature and solar radiation – with much longer return periods- are more important. In the latter case it should be ascertained that the study period includes temperatures close to such extremes.

- Because of high directional variability of low wind speeds and variability in line directions, it is recommended that for wind speeds lower than 2 m/s, the yaw angle respective to the line is assumed to be 25 degrees[22].
- Instead of fixed solar intensity in the standards, actual measured global radiation is used.
- Unless the study relates to a single line in one direction only, ratings should be calculated for the least two principal line directions, e.g. E-W and N-S.

It is important to realize that all monitoring equipment, especially the anemometers, should be periodically maintained and calibrated according to manufacturer's instructions. The maintenance is required at least annually.

5.4.2. Data collection and analysis for tension and sag based rating systems

In addition to the recommendations of data collection periods, recording intervals and general procedures explained under meteorological measurements, the following considerations apply:

1. Tension and sag based measuring systems provide valid data only under conditions of sufficient line current. The equipment supplier should provide information of this threshold, and data related to currents below threshold should be excluded from data analysis.
2. The conductor temperature is affected by the current variation during the prior 2-3 time constants of the conductor. The line rating should be calculated using a dynamic algorithm which takes this into account.
3. The equipment supplier should provide to the user either:
    - An algorithm, which calculates the real time line rating based on the measured data, or
    - An algorithm, which calculates the effective wind speed based on measurements. This effective wind speed can then be combined with measures ambient temperatures and solar radiation to calculate the line rating based on either CIGRE or IEEE standard.

4. When monitoring is conducted on multiple line sections along a line, the rating of the line should be based on the lowest of the simultaneous ratings. When multiple line sections are monitored, the variation between simultaneous ratings will also provide valuable information of the dispersion of ratings along the line.

5.5. Combination of weather and line monitor ratings

Tension or sag-based monitors provide the most accurate rating information when line current is high and when the wind speeds are low, i.e. during the most critical conditions. On the other hand, they become inaccurate when line loads are low and wind speeds are high, because of insufficient temperature rise of the conductor [18].

[22] In this case, expert opinions differ. Some experts recommend wind angles as low as 15 degrees. On the other hand, others recommend for daytime wind speeds less than 1.0 m/s a value of 45 degrees. Measurement of standard deviation of wind direction can be helpful in determining the effective angle of the wind. See discussion in Section 4 of the Brochure under 4.2 and recommended references.

Weather-based instrumentation is least accurate when wind speeds are low, due to the anemometer stall and also due to the large spatial and temporal variation of wind direction. Under such conditions, wind direction information is essentially useless for rating calculations.

Quality of rating analysis can be significantly enhanced by using monitoring equipment which combines tension or sag monitoring with weather monitoring, albeit with increased cost of equipment and data analysis.

5.6. Establishing Study-based ratings based on the studies

Establishing Study-based ratings requires engineering judgment. For example, if a line is designed for low maximum temperature the line owner/operator may elect to use higher ratings at night and at low ambient temperatures, based on the analysis of collected data. Conversely, if the line is designed for high operating temperatures, data analysis often indicates that the combination of moderate temperatures (especially in the morning and evening) coincide with the lowest wind conditions, allowing higher ratings for the daytime when the loads may be higher. The task force offers the following general guidance for rating selection[23]:

a. If rating study is based on two weather stations, the Study-based rating for the line should be set at a risk level equal to the lowest 3% of the combined ratings statistics.
b. If the rating study is based on a single weather station, the Study-based should be based at a risk level equal to the lowest 1% of the ratings.
c. If rating study is based on two line monitors monitoring four line sections, the Study-based rating for the line should be set at a risk level equal to the lowest 5% of the combined ratings statistics.
d. If rating study is based on one line monitor monitoring two line sections, the Study-based rating for the line should be set at a risk level equal to the lowest 2% of the combined ratings statistics.

The above guidelines are only approximate. A careful engineering analysis is also recommended for considering the consequences of extreme conditions, as well as the knowledge of the accuracy of the sag conditions of the specific transmission lines for which the ratings are applied.

[23] Different risk levels are based on the observations that:
- Although solar temperatures do not vary much along a line during most critical rating conditions, low wind speed conditions seem may occur at different sites at different times.
- Tension, sag or clearance monitors provide information on the average conductor temperature of a line section and thus represent more accurately the primary ratings objective, that of maintenance of safe clearances.

See also Section 4 of the Brochure for additional guidance.

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