

# IEEE'S APPROACH FOR INCREASING TRANSMISSION LINE RATINGS IN NORTH AMERICA

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## ABSTRACT

Open transmission access and economic uncertainties are the reasons why many North American utilities are operating their lines at much higher loads than they were initially designed for. Because of this, IEEE's WG on Thermal Aspects of Conductors and Accessories has been actively engaged in studying the effects of higher operating temperatures on the safety and reliability of overhead lines. The work has identified significant areas where improved analytical methods are necessary. Several such methods have already been created and their impact is discussed in the following report.

**KEY WORDS:** Overhead line, ratings, sags, conductor design, safety, reliability, high temperature operation.

## 1. INTRODUCTION

North America's electric utilities are undergoing a major transformation, which is redefining the utilization of the electric transmission network. While mandated open transmission access is causing heavier and heavier loads on transmission lines, economic uncertainties have made most transmission owners very reluctant to expend capital resources on network reinforcement and the construction of new lines. In turn, this has resulted in a greater need to operate transmission lines at higher currents and at higher temperatures than initially designed. Thus, the assessment of the impact of these desired increases in power transfer capabilities on reliability and safety are of increased and vital importance.

Further, the increasing frequency of higher temperature operation has brought with it the realization that some of the theoretical methods used to evaluate conductor performance are not sufficiently accurate at these higher temperatures. In an effort to analyze these effects, IEEE's Working Group on Thermal Aspects of Conductors and Accessories has been dealing with the problem areas in a systematic manner. The following describes the ongoing program and its results.

## 2. PRESENT NORTH AMERICAN PRACTICE

All lines in North America are governed by either the National Electric Safety Code (NESC) in the United States or the CSA standard in Canada, and sometimes by more restrictive local codes. All of these codes include deterministic, voltage-specific limits on line clearances. Individual existing lines have widely different "templating" temperatures, some as low as 50°C or as high as 150°C. The recent IEEE/CIGRE survey [1] showed that with a few rare exceptions, actual line-specific thermal limits are caused by clearance limits and not by annealing.

Rating practices and assumptions vary from utility to utility. The most common practice is to calculate line ratings based on coincident high ambient temperature, full solar radiation, and an effective wind speed of 0.61 m/s. Nevertheless, the IEEE/CIGRE survey shows that over the past decade, a number of utilities have incrementally increased their line ratings by relaxing some of the rating assumptions. Some utilities now assume an effective wind speed of 0.91 m/s, or even higher.

Another important traditional practice has been the use of clearance buffers in addition to the NESC or CSA clearances. These buffers have allowed for inaccuracies in design and construction of lines, as well as for uncertainties in conductor properties. According to the survey, these buffers vary from 0.15 to 2.1 meters, with the most common being on the order of 1 m. Some utilities have been reducing these buffers to accommodate operating temperatures above the original design limits, without adequately addressing their impact.

Three other important features characterize North American transmission line design. They are:

- More than 80% of all lines [1] and over 90% of highly loaded lines use ACSR conductors, and the most common conductors have a high content (>13%) of steel by area.
- Sags have been calculated using computer programs which are based on the "Alcoa graphic method" [2].
- Typical line sections between deadended structures average 10-20 spans, rising on occasion to as many as 100 spans or more.

Field measurements of line sags and tensions at high operating temperatures have shown that there can be major discrepancies between calculated and measured sags. These discrepancies have indicated that there is a need to review design methods. Consequently, this has been the major reason for the work undertaken by IEEE's WG on Thermal Aspects of Conductors to develop improved analytical methods for analysis of lines at high temperatures.

### 3. IEEE's APPROACH

IEEE's approach to the need to increase thermal line ratings encompasses work within several active task forces, which have divided the investigation into the following elements:

- Development of thermal rating standards.
- Identifying the sources and magnitudes of errors in as-built sags at everyday temperatures, to define recommended safety buffers for clearances.
- Accurate calculation of high-temperature sags.
- Probabilistic aspects of line rating and of the buffer component of the vertical clearance.
- Evaluation of real-time line rating methods.

### 4. CALCULATION OF THERMAL RATINGS

IEEE Standard 738-1993 "IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors" [3] is widely used by utilities in North America. It has recently been revised to improve the solar heating calculation and to provide SI units throughout.

A recent publication by Schmidt [4] demonstrates that the IEEE standard gives results similar but not identical to those obtained with the CIGRE method, as described in reference [5]. For a typical rating calculation with a 400 mm<sup>2</sup> ACSR conductor, Schmidt finds a difference of less than 2% in the rating when calculated by the IEEE and CIGRE methods. The DYNAMP [6] method, which is also widely used in North America, also produces similar results.

Neither IEEE's nor CIGRE's calculation methods offer a suitable AC resistance calculation method. The CIGRE method lumps "skin effect" and magnetic core losses into an approximate correction equation. The IEEE standard ignores magnetic core losses but allows the user to enter two values of resistance at different temperatures.

CIGRE's method does mention factors such as radial temperature differences although it does not provide explicit guidance for calculation of the effects, while the IEEE standard omits them. With highly loaded lines increasingly commonplace, such effects are becoming more significant. At high currents, the core temperature of a large conductor may be 10-15°C hotter than its surface. Thus, proper sag calculations should use an effective average temperature of the cross section, instead of the conventionally used surface temperature. There is a close cooperation between IEEE and CIGRE's TF12-1 towards quantification of these effects and the development of appropriate calculation methods.

### 5. EFFECT OF RULING SPAN ERRORS ON THERMAL RATING

Historically, the industry practice and objectives were to predict conductor behaviour for normal operating temperatures in the range of up to 70°C with sufficient accuracy. However, for higher operating temperatures, those predictions are more complicated. It is of extreme importance to be able to accurately predict line sags at high temperatures, to meet minimum safety clearance requirements.

The following section addresses the effect of the Ruling Span (RS) approximation on sags at high temperature, which studied in detail in [7].

The RS method is a commonly used method to string conductors in a multispans deadended overhead line section. The definition of a ruling span is a level

deadend span that gives the same change in tension from changes in loading, creep, and/or temperature as a series of suspension spans between two deadend structures. The ruling span method permits correct sagging of conductors and provides prediction of conductor behaviour with creep, loads and temperatures within the traditional operating ranges of 50°C and 70°C.

However, the RS approximation may not be accurate enough to analyze the operation of a line, although it was used for the design of the line. This is especially true if there is a need to operate the line significantly above its original design temperature.

Transmission lines are usually sagged to maintain the insulators plumb. With temperature rise, creep, and permanent strain from weather loads, the conductor elongates. When a line section has spans of differing lengths, the conductor elongation causes the insulators to depart from their vertical position. As the conductor temperature increases, the suspension points move toward the long spans and away from the short spans to equalize the horizontal tension.

This longitudinal swing of line insulators may cause unexpected errors when calculating sags at high operating temperatures. RS inaccuracies are largest for lines with short insulator strings since the RS approximation assumes an infinite string length. The shorter the insulator string's length, the greater the restriction is on its movement. High operating temperatures (over 100°C) further degrade the accuracy of the RS approximation. Thus, the complete analysis of a multispans line section should take into account conductor properties, spans, line profile, line angles, insulator string properties, support stiffness, original sagging and clamping-in procedures, weather loading history, creep, and a reasonably good knowledge of the existing condition of the line section under study.

IEEE's WG on Thermal Aspects of Conductors has spearheaded the investigation of these effects, including encouraging development of several computer programs which can be used to evaluate sag errors. The results of these programs were compared in [7]. The results showed that all programs predict the same magnitude of errors, which can be up to +/-1 meter when compared to the classical RS calculation.

## 6. IDENTIFIED ERROR SOURCES FOR HIGH TEMPERATURE SAGS

Some of the other factors which have already been studied at IEEE, that can affect the accuracy of sag/tension calculations for high temperature operation, include:

### 6.1 "Kneepoint Temperature" of ACSR

Many older lines in North America utilize ACSR conductors with a relatively high steel content. Typical strandings of 30/19, 30/7, and 26/7 are found. With 30/7 and 30/19 strandings, the steel area is 23% of the aluminum, while for 26/7 it is 16%. As these conductors age under tension, the aluminum strands elongate non-elastically, which transfers load to the steel core until, at some point, the aluminum strands are no longer in tension at all. During high current loadings, the aluminum strands elongate twice as much as the steel and the tension transfer to the steel core is even greater.

This "kneepoint temperature" is quite low for older, high steel content conductors, as shown in the following table:

ACSR Type	% Steel by Area	Typical Kneepoint Temp [°C]
30/7, 30/19	23	30
26/7	16	65
54/7	13	95
45/7	7	150

At the "kneepoint temperature", the load in the aluminum strands goes to zero and all the tension is in the steel core. Traditionally, in North America, at temperatures above the "kneepoint", the conductor was assumed to expand according to the thermal coefficient of expansion of steel. However, research programs and field measurements indicate that this expansion above the "kneepoint" is greater than that predicted under this assumption, indicating that the aluminum strands can support some compression loads.

Two different methods have been proposed for calculating the increase in sag above the "kneepoint temperature" [8,9]. While the theoretical explanations differ, both result in compressive stresses of aluminum which can increase the "kneepoint temperature" by up to 20-30°C and increase the calculated high temperature sag by as much as one meter. The IEEE work on this problem continues in cooperation with CIGRE's TF12-1.

### 6.2. Conductor's radial temperature gradient

The inner layer(s) of stranded conductors are hotter than the outer layer, causing a radial thermal gradient. The inner layers elongate more than the outer layer. Thus, tension transfer from aluminum strands into the steel core happens sooner in the inner than in the outer layer. If the conductor temperature continues to increase, compression in the inner layers increases faster than in

the outer layer. On the other hand, the radial temperature gradient results in a higher tension in the outer aluminum wires because they are at a lower temperature than the inner layer, thus increasing their ability to restrain the radial forces in the inner layer. This enables the aluminum to support a greater compressive axial load, thereby increasing the birdcaging temperature and the high temperature sag. The radial thermal gradient in the stranded conductor can increase the limiting compressive stress up to 18 MPa or higher. This latter value of stress can account for excess high-temperature sags of up to 1 m in a 300 m span. The higher the limiting compressive stresses in the aluminum strands, the larger the high-temperature sag is.

## 7. ERROR SOURCES UNDER STUDY

IEEE's Task Force on High Temperature Sags plans to study the following effects which may further affect clearances:

- Conductor design (number of layers, lay factor, shape of strands)
- Manufacturing practices
- History and sequence of loading experienced by the line conductor during its life

### 7.1. Conductor design

The amount of compressive load the aluminum strands can support depends on the aluminum area and the conductor structure. In general, a single layer ACSR conductor supports the lowest compressive load. The outer layer of aluminum strands restrains the free expansion of inner layers and as a consequence, multilayer aluminum conductors support higher compressive loads. In addition to the compressive load in the aluminum, the extra sag also depends on the ratio of aluminum to steel area. It is obvious that for large aluminum to steel ratios even a low compressive stress in the aluminum can produce a large increase in the sag.

### 7.2. Manufacturing practices

The following manufacturing practices may result in the aluminum wires having initial slack:

- Hot aluminum wires wound around cold steel core wires
- Aluminum strands not wound onto the steel core at very high tension during manufacturing
- Variation of lay lengths and other mill practices

The initial slack contributes to the total permanent elongation of the aluminum, which determines the stress

distribution in the conductor and thereby the birdcaging temperature. Thus, the initial slack in aluminum is important for the calculation of stresses and high-temperature sags.

## 8. RATINGS AND PROBABILITY

The main objective of the aforementioned IEEE activities has been to ascertain whether traditional, low temperature operating environment calculation and rating methods can be validated or modified for use in today's higher temperature operating environments. The main direct economic benefit from these activities is that they may allow reduced clearance buffers as long as the lines are operated in a similar fashion to the past, in such a way that high line currents are very infrequent. Unfortunately, this is rarely true. More and more lines are frequently operated near their static rating limits.

As older transmission lines are operated close to their thermal capacity, the probability of clearance infraction occurrences increase. This problem is compounded when utilities accept line ratings based on less conservative weather assumptions for rating calculations. This is illustrated in Figure 1.

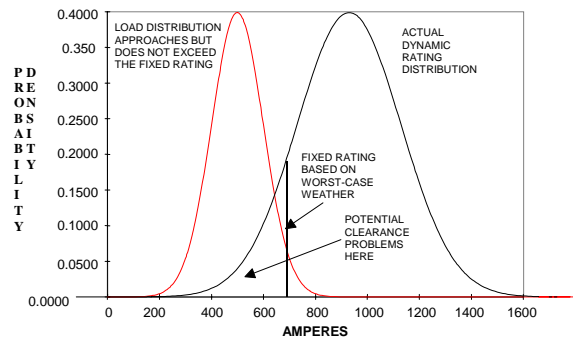


Figure 1 - Comparison of Loading and Rating Distributions for an Overhead Line

Figure 1 shows a probability density plot for both line ratings and line loading. Note that a static rating is indicated in the left-most tail of the rating distribution and that the static rating may occasionally be higher than the actual ratings. The loading is allowed to occasionally approach the static rating but never to exceed it. In spite of this, there are times at which the load exceeds the rating and when clearance infractions may occur.

If less conservative rating assumptions are used, the static rating would be increased (moved to the right in Figure 1). The operator would increase line loadings, still not exceeding the static rating but increasing the area of overlap between the rating and loading plots, increasing the risk level.

Some of the impetus to use less conservative rating assumptions is based on a misunderstanding of the wind assumptions typically used in rating calculations. In normal rating calculations, the rating is calculated for a single set of weather conditions including a high air temperature, low wind speed, and full solar heating, but the very non-conservative assumption that the wind is blowing perpendicular to the line.

The difference between the wind blowing perpendicular or parallel to the conductor is dramatic. A 0.6 m/sec wind blowing perpendicular yields the same convection cooling rate as a 1.2 m/sec wind blowing at 20 degrees, or a 1.8 m/sec wind blowing at 10 degrees from the conductor axis. Clearance-based line ratings depend on the average temperature of a line section, i.e. the average effective wind along the line section. The average wind speed can be quite different from the value determined by a point measurement or multiple-point measurements. These two effects combine to yield "equivalent" wind speeds which can be lower than single point anemometer measurements by a factor of 3 or 4.

To study these effects, a new IEEE Task Force on Probabilistic Rating of Transmission Lines has been formed:

- To develop methods to apply probabilistic clearances to design of new overhead lines, and
- To develop probabilistic methods for analysis of vertical clearances of the existing lines.

The general treatment of probabilistic clearances for overhead lines will include such topics as code requirements, clearance buffers, deterministic clearances, probabilistic clearances, a statistical field clearance model, and calculation of probabilistic clearances. The work is expected to result in two IEEE reports in 2000 and 2001.

## 9. REAL TIME RATINGS

The objective of real time ratings of transmission lines is not to operate lines at higher temperatures or lesser clearances than what the line was originally designed for. The objective of real time ratings of transmission lines is to be able to operate the line closer to these limits more often. Real time rating methods allow system operators to generate economic benefits utilizing those frequent occasions when weather conditions provide higher ratings than those assumed by the necessarily conservative static rating calculations. Furthermore, they allow line operation close to their design limits with a higher confidence, permitting the use of reduced clearance buffers for real time monitored lines.

In the past, the most common real time rating approach was to use either weather-based real time ratings or to determine the local conductor temperature with instruments. Three recent IEEE panel sessions have explored these approaches and have pointed out the significant uncertainties of these methods. Thus, modern real-time rating methods concentrate on determining line clearances based on either tension or sag measurements, and on deriving real time capability calculations from such measurements. The end result is real time thermal rating data which is displayed to the energy management system (EMS) operators.

Tension-based real time line rating systems [10] are presently being used by 15 of the 60 largest North American utilities. A variation of the same method is EPRI's DTCR system [11], which provides ratings based on the identical tension measuring technology, backed up by weather-based ratings. Additionally, some utilities are experimenting with optical, ultrasonic, radar and laser-based sag measurement methods, none of which has yet progressed to operational use.

While the technology of providing real time line ratings to operators seems to have progressed to the point where accurate and reliable data can be made available, the larger question relates to the use of this information by the system operators. To this end, IEEE has created a Real Time Ratings Joint Task Force, between the WG on Thermal Aspects of Conductors and Accessories and the Transmission Operations Subcommittee.

The goal of this new Task Force is the writing a technical paper, reflecting both operational and engineering design viewpoints on dynamic thermal rating of overhead lines. The paper will include a brief historical review, a discussion of present methods of monitoring and rating calculations, a description of the major issues in effectively integrating such methods into system operations, and a recommended bibliography. Specific technical issues include communication and storage of real time data, calculation of ratings during normal and emergency operating conditions, predictability of ratings, and the maintainability and reliability of monitors.

## 10. CONCLUSIONS

1. In the past five years, line loadings in North America have increased significantly. Lines are now frequently operated at temperatures significantly above their original design temperatures.

2. While physical uprating of lines has been used to accommodate some of these capability increases, a large part of the capability increase has been accomplished by

relaxing of rating assumptions and reducing the design safety buffers. IEEE's work on the development of more accurate analytical tools for thermal and mechanical analysis has been a direct result of this challenge.

3. IEEE's work has found several different factors which affect high temperature conductor sags. While these factors are mostly independent, they all generally contribute towards increasing high temperature sags.

4. Unless new and more accurate analytical tools are used, the sags in the temperatures above 100°C can be as much as 1 m to 2 m larger than anticipated. While some of the needed tools have been developed, IEEE's continuing work is expected to result in the remaining analytical tools being in place by 2003.

5. IEEE's Real Time Rating TF will be actively engaged in defining the operational methods and opportunities in the use of variable line ratings. Full implementation of such methods will also require development of financial tools and operational methods.

#### REFERENCES

[1] CIGRE TF12-1 of SC22: "Survey of Properties and Uses of Novel Conductors". SC 22 Meeting, Paris, France, Sept. 1998.

[2] T. Varney: "ACSR Graphic Method for SAG-TENSION Computations". Aluminum Company of America, Pittsburgh, PA 1927.

[3] IEEE Standard 738-93, "IEEE Standard for Calculation of Bare Overhead Conductor Temperatures", 1993.

[4] N. Schmidt: "Comparison between IEEE and CIGRE Ampacity Standards", IEEE PE-749-PWRD-0-06-1997, Berlin, Germany, July 1997.

[5] CIGRE WG12-22: "Thermal State of Overhead Line Conductors", Electra, No. 121, pp.51-67, 1997.

[6] W.Z. Black and W.R. Byrd: "Real Time Ampacity Model for Overhead Lines", IEEE Transact., Vol. PAS-102, No. 7, July 1983, pp. 2289-2293.

[7] Y. Motlis et al (IEEE WG on Thermal Aspects of Conductors): "Limitations of the Ruling Span Method for Overhead Line Conductors at High Operating Temperatures", IEEE Paper PE-197-PWRD-0-12-1997, 1998 WPM, Tampa, Florida.

[8] O. Nigol and J.S. Barrett: "Characteristics of ACSR Conductors at High Temperatures and Stresses", IEEE Transact. Vol. PAS 10, No. 2, February 1981, pp. 485-493.

[9] C.B. Rawlins: "Some Effects on Mill Practice on the Stress-Strain Behavior of ACSR", IEEE WPM 1998, Tampa, FL, February 1998.

[10] T.O. Seppa et al: "Use of On-Line Tension Monitoring Systems for Real Time Ratings, Ice Loads and Other Environmental Effects", CIGRE Report 102-22, Sept. 1998, Paris, France.

[11] D.A. Douglass and A-E. Edris: "Field Studies of Dynamic Thermal Rating Methods for Overhead Lines", IEEE T&D Conference Report, New Orleans, April 7, 1999, New Orleans, LA.