Guide for Application of Direct Real-Time Monitoring Systems

Working Group

B2.36

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GLOSSARY OF TERMS.

Emissivity and absorptivity
A perfect black body absorber having the shape of the conductor would have an Absorptivity of 1.0. New aluminium conductors have absorptivity in 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)

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.

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

Continuous or normal thermal rating (so called static 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 actual sensor observation where it is installed, as the actual variable wind.

Electrical clearance
The distance between energized conductors and other conductors, buildings, trees, potential trucks on roads, 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 (and thus sag) but the number of hours per year, during which the higher rating can be used, is limited (e.g. 24 hours per year).

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.

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.

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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 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 levelled 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℃ or more, seasonal ratings, both norm al 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 5oc to 10oc 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 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 (or sag) for a given line current.

1. INTRODUCTION

The purpose of this guide is to familiarize utilities with Real-time Monitoring (RTM) systems for Overhead line thermal ratings (ampacity). RTM systems are valuable tools to overcome operation limitations some of which are described in section 1.5

The Real-time systems referred to in this guide is only relating to thermal rating of lines. That is the current limit the line can transmit which will not exceed the design or templating temperature of the line. The guide does not cover real-time systems to monitor ice or wind loading on lines.

1.1 Objectives of the guide

This guide has following objectives:

- to provide guidance for transmission system operations personnel as to how RTM systems can be used to increase the reliability and the economics of system dispatch;
- to provide guidance for transmission engineers for selection of RTM systems including equipment, communications and software to achieve the desired level of accuracy and reliability;

This document covers only systems that directly measure conductor temperature, tension, sag or clearance from which the thermal rating is determined. It includes the placement of measurement sites, and accuracy and resolution requirements for equipment.

These direct measurement methods use devices that are directly coupled to the line as opposed to indirect methods, such as weather stations, where the device may not be directly linked to line hardware.

Traditionally, many techniques have been developed that measure the sag of overhead conductors indirectly. In these methods, parameters such as conductor temperature and wind velocity are measured then used to calculate sag. One of the biggest disadvantages of these methods is that they only work well if the system behaves exactly in accordance with the mathematical model on which they were developed. However, real world systems are not as ideal as the models used to describe them

Transmission line thermal ratings have traditionally been based on conservative assumptions. CIGRE TB 299 [1] recommends the use of weather conditions so that 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. Conversely, this means that real-time thermal ratings are substantially higher than properly selected fixed ratings at least 90 % of time.

1.2 Derivation of rating

In order to determine the rating of the line the relationship between the position of the conductor in space and the conductor temperature must be known. From this "known state" the current that corresponds to the allowable conductor temperature or maximum allowable sag (worst case)[1], can be determined.

The objectives of determining real-time ratings consist of:

1. determining the actual sag in critical spans and corresponding mean conductor temperature (there are several critical spans in one line).
2. compare the actual sag to maximum allowable sag or maximum permissible temperature (worst case) in each critical of the critical spans. Using this information, determine “safe buffers” for the critical spans.
3. based on known actual load, convert these “safe buffers” into electrical loads (in MVA) for each critical span.
4. Additional information that would be desirable to communicate would include the ampacity variation with time (including prediction) and histograph of occurrences (one day, one month, one year) to give access to the global behaviour of the line.

Some devices directly measure the tension in the conductor (either locally or at a dead end), the conductor temperature (either at points or distributed) or the position of the conductor (either one place or different places). All of these devices need application of well proven models with data (e.g. conductor data, topological data, weather data, line design data, etc) to determine the sag, or temperature, to meet objectives 1 and 2 sited above.

Alternatively, some devices can evaluate sag in the critical spans directly (without any other data needed) and, using TSO maximum allowable sag, meet objectives 1 and 2 easily.

Objectives 3, and 4 may then be addressed with forecasting procedures based on sag-current trends as observed in the recent past of the line or by the following procedure:

- Determining the heat input (ohmic and magnetic losses and solar radiation) and heat output (convection and radiative cooling) variables at a given time for a given line section.
- Applying an algorithm to determine what current can be applied to the line indefinitely, assuming constant weather conditions, without exceeding line design temperature or maximum permissible sag (worst case).[1] This current is the real-time rating of the line section.
- Calculating dynamic or transient ratings which could be caused by significant changes in line current.

1.3 Limitation for real-time ratings

Using real-time rating for a conductor, a very high theoretical value for the ampacity can be calculated at very cold and windy ambient conditions. In most cases this ampacity is practically limited to a far lower value. In particular in EHV grids (TSO) the rapidly increasing need of reactive power on highly loaded monitored lines, the impact on the reactive power balance of adjacent EHV grids as well as weaker system stability due to larger voltage angles must be taken into account. An outage of a highly loaded line leading to an (N-1)

[1] The design temperature is the conductor temperature which the designers assume will result in their specific tension or sag limit. Thus, if the designer expects the maximum sag in a critical span to be e.g. 15 m, and his calculations indicate that 15 m corresponds to 100°C, the rating objective is achieved by reaching the worst case (either 15 m or 100°C) because actual line behaviour may not reach both limits at the same time.

case can cause transient problems on the remaining lines. These transients and the load of the failed line must be properly handled to prevent the overloading and switching-off of additional lines.

1.4 Present major areas of operational applications

1.4.1 Contingency management

Traditionally, when a contingency occurs, the operator must change the system dispatch to return the system to a new (N-0) state. This has an economic cost and may, if not properly handled, jeopardize system reliability. Real-time ratings allow the operator to determine if the limiting line is actually overloaded, and either avoid dispatch changes or limit them to a lesser extent than that indicated by static ratings.

1.4.2 Deferral or elimination of capital expenditures.

Line construction or upgrading can be delayed by permits, lack of material, manpower or funds. Increased capability can also be needed only for a limited period of time, for example, to allow for future generation construction, or reduction of demand may limit the period of needed additional line capacity. In such cases, short-term use of real-time ratings systems can be economically or operationally highly advantageous. Note also that at the end of deferral, the monitoring equipment can be relocated to another line.

1.4.3 Dispatch of generation during capacity deficiency.

There are generation clusters which are in regions connected by lines which have lower capacity than combined generation. Such generation pockets can be better utilized during generation capacity deficiency by use of real-time ratings.

1.4.4 Mitigation of reliability problems

In North America, the reliability rules of system operation have been substantially tightened as a result of the 2003 blackout. In the past, many operators used to ignore minor violations of limits. Because the new NERC standards, the operators now react immediately to any possible violations. On the other hand, NERC rules now specifically allow use of real-time ratings. In case of violations, real-time ratings may offer a fast and the cost effective mitigation solution.

1.4.5 Improving wind power utilization

The best wind power resources are often in areas that are transmission-limited. In many such areas, wind speeds in transmission corridors have a fairly strong correlation with wind generation. Especially with the new “conditionally firm” transmission tariffs, which allow operators to curtail generation for a low percentage of time, real-time ratings can offer the most economical solutions for use of transmission capacity.

1.4.6 Use of higher daytime capability.

In many locations, summer daytime ratings are substantially higher than night time capabilities. This can be utilized in two ways. In areas where air conditioning loads are high, the coincidence of daily load and line capability profiles can be used for improved dispatch through real-time monitoring assuming wind speeds are concurrently high.

Another possible application is for improved dispatch of solar power. Because solar power is located at areas of high solar radiation, the maximum power output may occur at times when wind speeds are higher than assumed in determining the line rating.

1.5 Limitations for operators

Even when networks are heavily loaded, the majority of their transmission lines operate at much lower loads than their thermal limits. This is because the transmission systems must meet all credible contingency events, typically stated as (N-1) or (N-2) states. If a contingency occurs, the operator must then be able to return the system to normal state, typically within 15 to 30 minutes. Thus, the operators cannot usually utilize increased line ratings under normal dispatch conditions to change the economics of the dispatch. Moreover, the operators can use real-time line ratings only with the limits of the available remedial actions which will not interrupt load service.

A second important limitation involves electricity market rules and practices. In open transmission systems the vast majority of energy is sold in day-ahead markets, based on bidding process. With a few exceptions, transmission network owners can only sell firm transmission capability. Capability which is “almost” firm has no value in such markets. Additional real-time capability may have value in the same day balancing markets, if the ratings for the typical 30-60 minute future time can be shown to have a high enough persistence to guarantee, with very high probability, that the capacity will be available for the needed time period.

Another practical limitation relates to the motivation of system operators. Invariably, the primary objectives of the operators are system safety and reliability. Economics of system dispatch are desirable but strictly secondary objectives. The economic objective becomes further clouded by the fact that any change in system constraints creates both gainers and losers under open energy markets. Thus the operators must make sure that their decisions will not favour any parties, which further discourages operator interventions for economic reasons.

2. REVIEW OF PREVIOUS WORK

2.1 STATE OF THE ART DESCRIBED IN 2000.

Stephen, [2] covered the aspect of Real-time monitoring as well as the types of RTM that were current in 2000 worldwide. The purpose of real-time monitoring is to determine, in real-time, the position of the conductor in space.

The real-time rating of the line is a function of position of the conductor in space which in turn, affects safety of the public as well as the integrity of the line. This position is determined by the sag of the conductor, which determines the height above ground. Sag is a function of the conductor temperature (average between core and surface all along a span or section), the conductor construction and the line tension. Sag and tension vary with temperature. The RTM systems therefore consist of devices that measure temperature, sag or tension. From this measured temperature the rating of the line is calculated, preferably using the dynamic formulae to calculate the thermal rating of the conductor, as a function of time.

Sag, tension or temperature measurement systems are either direct or indirect. The paper 22-304 [2] describes direct systems as those which are directly attached to the conductor system. Indirect systems measure other parameters, such as weather conditions, from which temperature and sag are calculated. In order to determine the sag with the minimum amount of calculation steps, tension or direct sag measurements are preferred. These are direct measurement systems and need to be calibrated (tension) or checked (sag) for each line.

Stephen [2] discusses each system and describes their benefits and disadvantages of each. One example is a direct temperature monitor attached to a conductor. The benefit is that the device is attached to the conductor, hence there is a limited error with regard to the measurement of conductor temperature. The disadvantages are that –

- The surface temperature is measured. There is a need to determine the core temperature and then the average temperature from which the sag can be determined. The core temperature is dependent on the radial temperature distribution, which is a function of the thermal input into the conductor from current and solar radiation. As weather parameters are often not measured at the same time as the direct temperature measurement, these parameters are assumed.
- Only one point on the conductor is measured. With line direction being variable the wind angle of attack to the conductor is variable. Thus the cooling effect of the wind will vary from place to place on the line. The measurement at one point is thus not a true representation of the temperature at other points on the line, thus is not representative of the sag and line rating.

In addition to the measurement of the conductor location in space, Stephen, [2] covers the relationship between sag and conductor current rating, which is the aim of RTM. This relationship depends on the ability of the utility meteorologists to predict the weather in the short term. The rating of the line can be presented to the operator in terms of possible load that the line can carry in 15 and 30 minutes under steady state conditions.

2.2 SUMMARY OF CIGRE TECHNICAL BROCHURE 299 [1]

The TB299 [1] is entitled “Guide for selection of weather parameters for bare overhead conductor ratings”. Some of the main features are :

- *The average temperature of a line section will not exceed the maximum design temperature by more than 10 °C, even under exceptio nal 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.*
- *The highest local conductor temperature will not exceed the maximum design temperature by more than 20 °C when the line curren t equals the line rating.*
- *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.*
- *This and other related documents discuss sag and tension calculations only in a general manner. The document 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 is included in the CIGRE Guide on Sag and Tension Calculations (reference)*

- *For ensuring adequate clearances, it is recommended that the transmission owner verifies their actual line clearances at appropriate intervals.*

The document was written as there was apparently a tendency for utilities to increase the wind speed in the current rating determination without a due regard for the implications of the decision with respect to the actual conductor temperature reached. This could result in increased sag and reduced reliability or safety to the public. At the time of the production of the brochure, there was not an internationally recognised document that specified which weather parameters to use as well as the methods by which weather data was to be obtained.

The document reviews many case studies and over 100 references on determination of weather parameters for the deterministic current rating.

It provides weather parameters for the base rating without the need for measurement of weather parameters in a particular geographical location.

It also allows for weather conditions to be determined from studies should the utility feel the necessity to do so. The document also describes the process to follow relating to variable ratings, which are related to specific ambient conditions as well as real-time monitoring systems.

The measurement of weather data is also covered with the emphasis on the errors that may occur by using airport wind data. This data generally has higher wind speeds than that recorded at the site of the transmission line.

The variability of weather conditions such as ambient temperature, wind speed, wind direction and solar radiation is also covered along the span, and line in different terrain conditions. It also covers issues such as wind sheltering and channelling.

This allows the utility to understand the risk of exceeding the the design temperature, determined using a specific set of weather conditions, when considering a change to these weather conditions..

The document provides the industry with a guide whereby the utility can objectively determine the set of weather conditions, as well as understand the risks of not undertaking detailed studies prior to altering or deciding on weather parameters which will be used to determine the current rating.

3. LINE RATING DETERMINATION USING DIRECT RTM MONITORING SYSTEMS

Mechanically, transmission lines are designed and built in “line sections” which consist of multiple suspension spans, generally oriented in the same direction, and terminated at each end by strain structures. Within each line section the conductors are normally supported by horizontally flexible suspension points that allow nearly free movement of the suspension points in the direction of the line section. The intent of this type of construction is to allow tension equalization between “suspension” spans. Tension equalization reduces the longitudinal tension loads on the suspension structures, reduces tension in heavily loaded suspension spans, and reduces the sag in the hottest suspension spans during periods of high power flow.

Electrically, the current in the phase conductors varies very little between suspension spans but variations in wind speed and direction along the line section suspension spans in the same line section is likely to produce relatively large temperature differences between suspension spans and even within long spans. In contrast to their mechanical behaviour, transmission line conductors are very poor temperature equalizers. That is, there is little or no tendency for cool spans to drain heat from adjacent hot spans, therefore the temperature of overhead transmission line conductors at high power flows varies with current and with local weather variables along the line.

While air temperature and solar heating may be fairly uniform along the line, the wind speed and direction can vary from span to span, and, at high conductor current levels (i.e. >1 amp/mm^2), the conductor temperature can vary from span to span along a line section. The strong mechanical coupling between suspension spans, however, keeps the tension in all the suspension spans nearly the same. This is demonstrated in the following table which shows the sag, tension, and span temperature variation in a line section which consists of ten 275 meter suspension spans. Each of the spans experiences the same air temperature (40^{o}C), solar heating (noon), and wind speed (0.61 m/s) but the wind direction varies from parallel to perpendicular.

Span #	Conductor Temp in Span °C	Tension [kN]	Exact* Method Sag[m]	Ideal** Ruling Span Sag[m]**
1	75	16.66	9.02	9.12
2	70	16.67	9.02	9.12
3	75	16.62	9.05	9.12
4	70	16.56	9.09	9.12
5	75	16.41	9.18	9.12
6	100	16.21	9.30	9.12
7	75	16.24	9.27	9.12
8	100	16.17	9.30	9.12
9	75	16.32	9.21	9.12
10	75	16.39	9.18	9.12
Average	80	16.43	9.15	9.12

TABLE I. **Tension equalisation between spans**

Notice that simply varying the wind direction causes the conductor temperature to vary between 70 ^{o}C and 100 ^{o}C but that the tension and sag in each of the spans is nearly equal due to tension equalization between suspension spans. The tension varies with the average line section temperature which is 80 ^{o}C in this case.

It is important to note the difference between span monitoring and section monitoring. Section monitoring inherently supposes that all conductor data are constant along the spans and extrapolates a global section value (e.g.. Tension at anchoring tower or sag in one span) to each of the spans using the ruling span concept and calibration. The span monitoring devices will provide information on the span(s) where it is installed. It can extrapolate its sag (in that case) to other spans of the same section, also using the ruling span concept, but local span data are actual data independent of ruling span concept. Of course, conductor temperature monitored in a span cannot be extrapolated to the section without further measurement, as clearly shown on table I.

The table demonstrates the difference in expected variation between direct in-span line temperature monitors, which measure conductor temperature within a single span, and direct line-section monitors, which measure average sag-tension conditions for the line section.

- If the primary concern in limiting power flow is to maintain clearance at high temperature, then direct monitoring of the average line section temperature or sag-tension allows the use of a single monitor whereas multiple in-span temperature monitors would be needed to determine the average line-section temperature.

- If the primary concern in limiting the power flow on the line is to avoid or limit annealing of aluminium or copper strands or damage to connectors at temperatures above 100 ^{o}C, then the placement of an in-span monitor in the hottest span would be effective. If the hottest span varies with weather conditions, then multiple in-span temperature monitors are required.

The conductor temperature of an overhead line can be determined in one of three ways. In all three, the remote measurements must be communicated in real-time to the utility's power control centre to be useful:

- The weather conditions at multiple points along the line can be monitored with weather instruments (including a high-grade anemometer) and, when combined with the line current, the conductor temperature can be calculated using the transient heat balance formulas of TB207 [3]
- The conductor temperature can be directly measured at multiple spans with conductor temperature sensors.
- The sag or tension can be monitored in critical line sections. The sag-tension data can be converted to an average line-section conductor temperature by applying the state-change equation (see chapter 3.1).

The rate of chronological variation of conductor temperature depends on the conductor thermal time constant, which is typically in the range of 5 to 20 minutes. Therefore, conductor temperature is typically averaged over and reported at a time interval of 5 to 20 minutes. Shorter reporting intervals are unlikely to improve practical accuracy.

The spatial interval of line monitors depends upon the type of monitor and whether the line's temperature limitation is intended to limit degradation of connectors and annealing of aluminium or to maintain adequate electrical clearances (worst case to consider).

Note that all three monitoring methods allow the system operator to track the temperature/sag of the line conductors but that none provides any prediction of temperature/sag or any guidance to the system operator regarding maximum allowable line current during system normal or emergency conditions. This guidance, in the form of real-time thermal ratings, requires additional real-time data and both off-line and on-line, iterative calculations with a heat balance equation such as that of TB 207 [3].

The use of real-time ratings by system operations, under system normal operating conditions has encountered significant resistance. Although thermal limitations of transmission networks are common, very few transmission lines are thermally limited under normal conditions. More typically, the thermal limitations occur after the loss of major generating stations or the highest voltage lines in the system. Only after such contingencies does sufficient power flow shift to lower voltage lines where thermal ratings become an operational constraint. Management of such (N-1) conditions requires both the ability to determine line ratings under relatively low line currents and software to calculate dynamic ratings after significant changes in line current. Typically, actual network in many parts of the world are strongly meshed. "(N-1)" contingency generally leads to an increase of 30% to 40% of the load (and not 100%) in some lines situated near the lost component. The challenge is thus to be informed if the required increase of the load is possible over the initial loading of the line which is typically 50% to 80% of the static rating, in most of the cases.

The implementation of real-time ratings is further limited by the lack of effective load reduction methods to handle occasional unfavourable ratings during periods of high ambient temperature and low wind convection. The operators cannot dispatch the line based on the mostly higher real-time ratings, unless they have available remedial action schemes to lower the line current when real-time ratings occasionally decline. That is why all RTM are taking conservative approaches for line rating.

Real-time line ratings are calculated for a rating period in the immediate future based upon direct monitor data reported for the immediate past. The accuracy of real-time line ratings depends upon the accuracy with which the present thermal state or clearance of the conductor is measured by direct monitors but also upon the accuracy of the weather used in the rating calculation.

3.1 CONDUCTOR TEMPERATURE AND MAXIMUM SAG

As already stated, line rating is linked either to maximum permissible temperature or maximum allowable sag (worst case). RTM systems are first oriented to one of these two values. But all RTM systems used for line rating need to get both values in order to choose the worst case.

3.1.1 Evaluation of conductor temperature by RTM systems.

At high current levels, the temperature of a bare overhead phase conductor varies along each line section primarily due to variation in wind cooling. This can be done by any of the following methods:

Method 1: by monitoring weather conditions along an overhead line, it is possible to calculate the local in-span conductor temperature along the line route by placing weather instruments (measuring air temperature, solar heating and wind speed and direction) along the line route and near to the line.

Method 2: direct in-span temperature monitors can also be placed in multiple spans to directly measure the local conductor temperature and, if multiple monitors are placed within a line section, to determine the average line-section conductor temperature.

Method 3: monitors can be located along the line to measure line parameters such as tension, sag, clearance (directly or indirectly using, for example, conductor inclination or wind induced movements) , which can be converted to the average line-section temperature.

In any of these methods, the measured values must be communicated in real-time to the utility operations centres to allow the calculation of real-time thermal line ratings.

This brochure acknowledges all three line monitoring methods but only considers the latter two direct monitoring methods in detail.

3.1.2 Calculating In-span Conductor Temperature from a weather station.

It is assumed here that the weather monitoring station measures air temperature, solar heating, and both wind speed and direction. It is critical that the anemometer be able to measure wind speeds below 1 m/s accurately. To determine the conductor temperature, it is also necessary that the line current be known.

The method of calculation assumed in this brochure is described in [3]. This brochure provides a general heat balance equation for bare overhead conductor which does not require an assumption that the heat balance is in the steady-state. The general heat balance equation is shown in the following:

$$q_c(T_c - T_A) + q_R(T_C - T_A) + m.C_p\frac{dT_C}{dt} = q_S + I^2.R(T_C) \quad (1)$$

Where:
q_C is the convection heat loss per unit length
q_R is the radiation heat loss per unit length
q_S is the solar heat input per unit length
$m.C_p$ is the heat capacity per unit length
$R(T_C)$ is the conductor electrical resistance "per unit length
I is the line current
q_C depends on the square root of conductor diameter and wind speed
q_R depends on the conductor diameter

This equation can be used to track the conductor temperature near the weather station in the following way:

If the conductor were initially at a temperature T_C(ti), a change in line current or weather conditions (solar heating, wind speed or direction, air temperature) would produce a corresponding change in conductor temperature (ΔT_C) over the next short time interval, Δti, as follows:

$$\Delta T_C = \frac{1}{m.C_p}[R(T_C).I^2 - q_C(T_C - T_A) - q_R(T_C - T_A) + q_S].\Delta t \quad (2)$$

Repeated applications of this equation over time allows the conductor temperature to be tracked over time, as shown in the following flow chart. Here it may be noted that the wind speed, wind direction, air temperature, solar heating, and current vary. Note that even sudden changes in these parameters (e.g. line current at 180 minutes) do not produce an equally sudden change in conductor temperature.

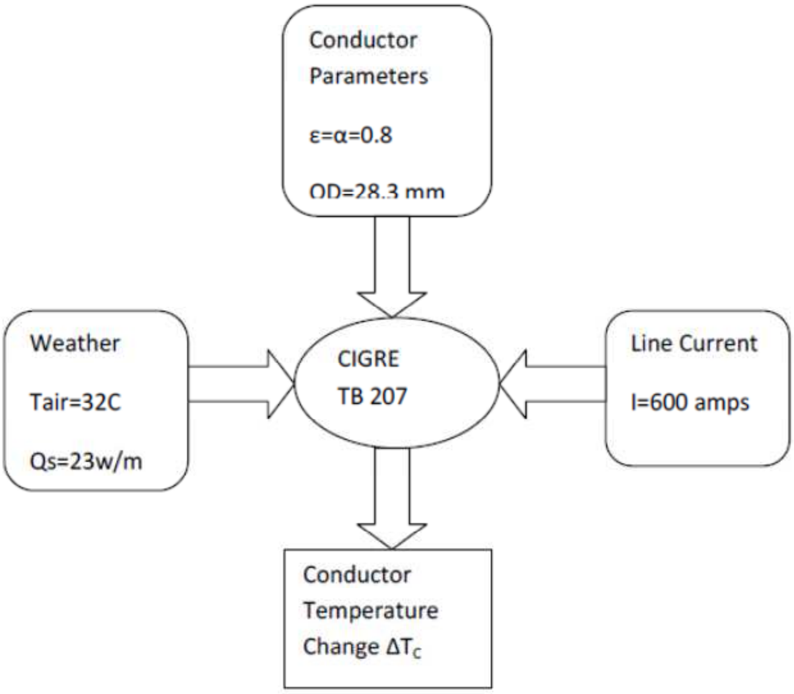


FIGURE I. FLOWCHART ILLUSTRATING THE CALCULATION OF CONDUCTOR TEMPERATURE OVER TIME BY USE OF THE TRANSIENT HEAT BALANCE METHOD OF CIGRE TB 207 [3]

3.1.3 Direct Measurement of In-span Conductor temperature.

The “local” (i.e. in-span) conductor temperature can be measured directly with no need for weather or line current measurement. The average line section temperature can only be estimated if the conductor temperature is measured at a sufficient number of spans within the line section to allow the calculation of average line section conductor temperature.

The placement of a direct conductor temperature monitor within the span may affect the measured temperature. The monitor’s mass and wind disturbance it can cause may also affect the measured temperature.

It should also be noted that the temperature changes along the span. Thus if temperature monitors are to be used, there should be sufficient monitors to account for this variation along the span and along the section.

It must also be noted that the ultimate data to be checked for line rating should be the worst case between maximum temperature and maximum sag, as already stated. Very often actual field conditions are such that the as-design relationship between those two values is no longer valid, thus conductor temperature must be associated with a sag / tension value. That needs to go through state change equation, as detailed in §3.2.

3.1.4 Determining Average Line-section Conductor Temperature

Average line-section conductor temperature cannot be monitored directly. It must be calculated from measurements of tension, sag, or clearance combined with a “state change” or “line calibration” equation, derived from both analytical and experimental data unique to the monitored line section (see §3.2).
The line-section monitors have the advantage that they give a more accurate estimate of sags along the line-section but require field data analysis to determine the experimental relationship between sag-tension and average line-section conductor temperature.

3.2 DETERMINATION OF SAG-AVERAGE TEMPERATURE USING RTM SYSTEMS

Sag is related to clearances, it needs to be less than a maximum value which permits enough clearance at any time between the power line conductor and any potential obstacle below the line.

RTM systems need to measure/evaluate the sag. This is done by direct or indirect ways, as explained in chapter 4. RTM based on temperature needs to use a model to go back to the sag, but temperature here means average line-section temperature as the model is based on the ruling span concept. RTM based on position, tension, clearance or wind induced movement (used to get a direct sag value) can be easily liked with topological and conductor data to determine clearances. The line-section conductor temperature is then obtained by using the sag-temperature relationship. This is done by deriving the “state change” or “line calibration” equation(s)

The state change (line calibration) equation provides a one-to-one mapping of line tension, sag, or clearance into average line-section temperature. The equation may be different for each line section.

3.2.1 Sag-tension Calculations

Sag-tension calculations are described in TB 324 [4] . Typical results include calculation of conductor sag and tension under a wide range of conductor temperatures. This relationship is generally complex and non-linear, particularly with non-homogeneous conductors such as ACSR (Aluminium Conductor Steel Reinforced).

The following sag-tension table is typical of the result that is obtained from numerical calculation. Here the ruling span is assumed to be 300 m and the tension is limited to 25% of the breaking strength of Zebra (33251 N) at -18 ^{O}C unloaded.

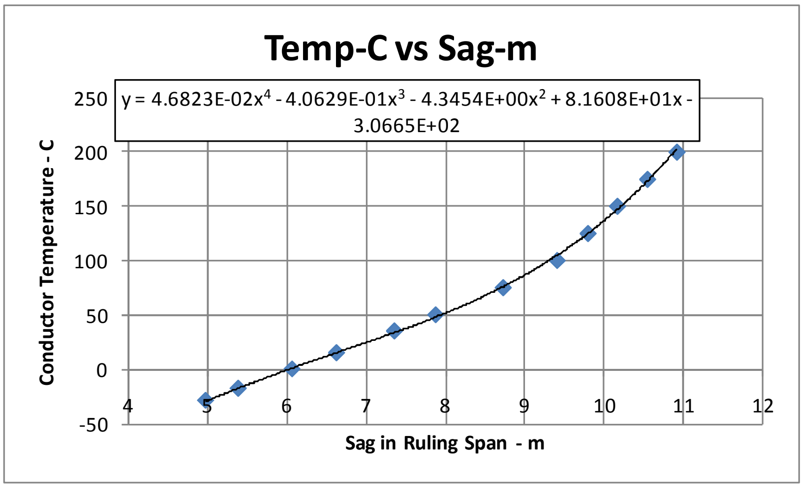
Design Points				Final		Initial	
Temp	Ice	Wind	Weight	Sag	Tension	Sag	Tension
℃	mm	Nt/m	Nt/m	m	Nt	m	Nt
-18.0	12.50	9.0	30.325	6.84	50002	6.60	51822
-29.0	0.00	0.0	15.878	4.97	35987	4.38	40848
-18.0	0.00	0.0	15.878	5.38	33251*	4.67	38304
0.0	0.00	0.0	15.878	6.06	29537	5.19	34485
15.0	0.00	0.0	15.878	6.62	27044	5.65	31669
35.0	0.00	0.0	15.878	7.35	24373	6.29	28441

50.0	0.00	0.0	15.878	7.87	22747	6.78	26389
75.0	0.00	0.0	15.878	8.72	20564	7.60	23568
100.0	0.00	0.0	15.878	9.40	19074	8.40	21344
125.0	0.00	0.0	15.878	9.79	18332	9.16	19567
150.0	0.00	0.0	15.878	10.16	17654	9.90	18122
175.0	0.00	0.0	15.878	10.54	17032	10.44	17196
200.0	0.00	0.0	15.878	10.91	16461	10.81	16617

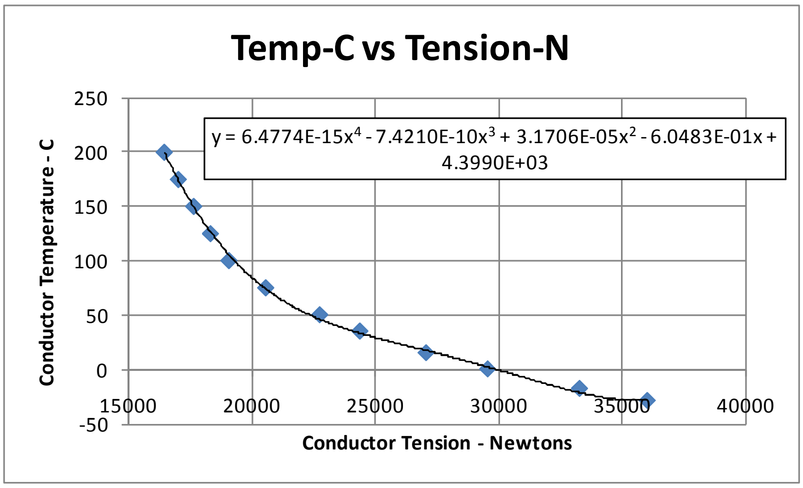
Design points				FINAL		INITIAL	
TEMP	ICE	Wind	Weight	Sag	Tension	Sag	Tension
^{O}C	mm	N/m	N/m	m	N	m	N
-18	0	9	31.325	6.84	50002	6.6	51822
-29	0	0	15.878	4.97	35987	4.38	40848
-18	0	0	15.878	5.38	33251	4.67	38304
0	0	0	15.878	6.06	29537	5.19	34485
15	0	0	15.878	6.62	27044	5.65	31669
35	0	0	15.878	7.35	24373	6.29	28441
50	0	0	15.878	7.87	22747	6.78	26389
75	0	0	15.878	8.72	20564	7.6	23568
100	0	0	15.878	9.4	19074	8.4	21344
125	0	0	15.878	9.79	18332	9.16	19567
150	0	0	15.878	10.16	17654	9.9	18122
175	0	0	15.878	10.54	17032	10.44	17196
200	0	0	15.878	10.91	16641	10.81	16617

TABLE II. SAG TENSION TABLE.

Based on this table, a polynomial equation can be derived which relates either sag or tension to conductor temperature. In this case, since one would normally install such monitors on older lines, the equations should relate final sag and tension to conductor temperature. The following plots show the conductor temperature as a function of the calculated final sag and tension with corresponding 4th order polynomial calibration equations.



Graph I. **Plot of Conductor temperature as a function of sag under final conditions.**



Graph II. Plot of Conductor Temperature as a function of conductor tension under final conditions.

Notice that the sag-tension versus conductor temperature curves show three important characteristics:

- At low conductor temperature, the rate of change of sag with temperature is about 0.36m per 10 ^{O}C.
- At high conductor temperatures, the rate of change of sag with temperature is smaller, about 0.15m per 10 ^{O}C.
- The kneepoint temperature (where the aluminium strand tension goes to zero) is near 100 ^{O}C.

Sag-tension calculations such as the preceding cannot be assumed correct for an existing line without field measurements for two primary reasons:

- The actual measured sag-tension under everyday conditions (e.g. no ice, no wind, at 15 ^{O}C) may not equal the calculated condition for a variety of reasons including, load history and construction errors.
- The conductor behaviour at high temperatures may not be the same as the calculated values for a variety of reasons, as discussed in Technical Brochures 244 [5] and 324 [4]

It is far easier to check the accuracy of everyday unloaded sag-tension than to determine such calculations are correct at high conductor temperature.

3.2.2 Field Measurements

In most cases, setting the state change or line calibration equations solely upon calculated sag-tension data is not recommended. A few of the major objections to this simple process are:

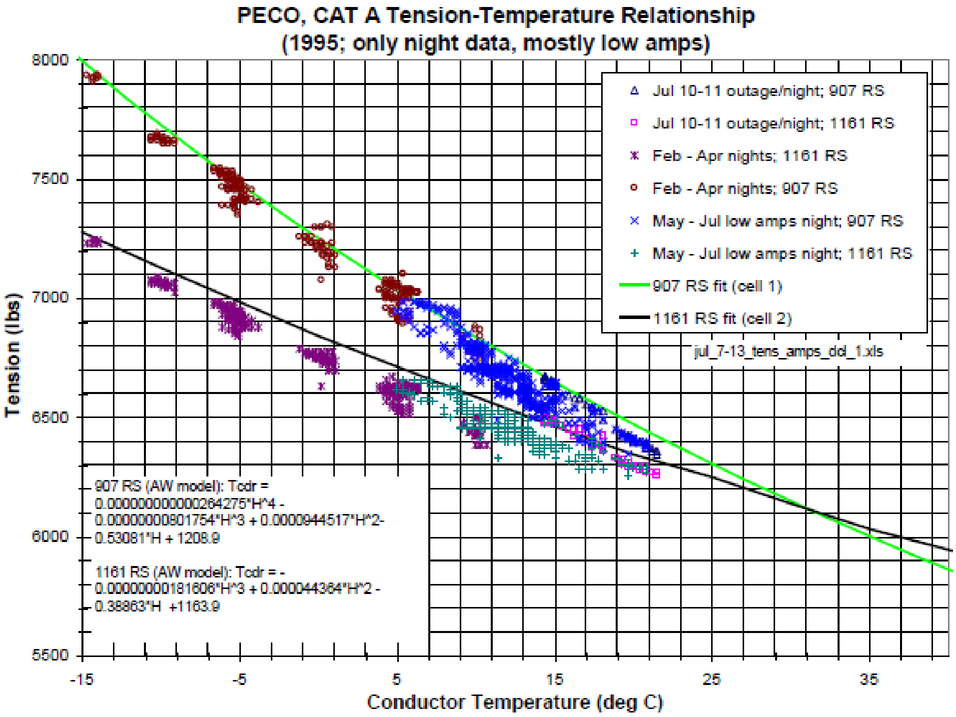
- The final sag-tension values are based upon an arbitrary creep elongation time period (typically 10 years at 15 ^{O}C). The line loading history may be quite different, leading to both errors in the sag magnitude and in the calculated knee-point temperature under final conditions.

- The calculated values depend upon ruling span assumption that there is perfect tension equalization at supports within the line section. Movement of dead-end supports and imperfect tension equalization due to uneven terrain, post insulators or short suspension insulators may make the ruling span assumption incorrect.
- Sag-tension calculations assume that the conductor temperature is constant for all spans in the ruling span line section. In reality, even if tension equalization is perfect, conductor temperature may vary between spans according to terrain and foliage.

Preliminary sag-tension calculations can be refined by making various field measurements. One of the most basic measurements is to check calculated sag and tension for low current, low solar heating conditions where the conductor temperature is nearly equal to the air temperature. For example, tension measurements might be made at night during low wind conditions where the air temperature is above 5 ^{O}C. Under such conditions, one may assume that the conductor temperature equals the air temperature and the preliminary sag-tension calculations can be modified if needed. Ideally, such measurements are made with the line out of service (zero current). A series of such measurements with different air temperatures over months will give a series of calibration points which verify both the intercept and the slope of the state-change, line calibration curve, at least at moderate to low temperatures.

Consider the following field measurements taken in the Eastern United States (40 deg North latitude) over a period of almost a year. These field measurements provide a basis for sag and tension at temperatures between -15 ^{O}C and +22 ^{O}C but give little experimental support for either the slope or offset of the line calibration curve at conductor temperatures above 30 ^{O}C.

The data is taken for two line sections of the same overhead line. The ruling spans (RS) of the two lines sections are 275 m (907 RS) and 350 m (1161 RS). Notice that to get this range of temperatures, data had to be collected over a full year. In equatorial regions, the variation of air temperature would, of course, be less. Notice the 4th order regression polynomials for each of the line sections relating average line-section conductor temperature to line tension.

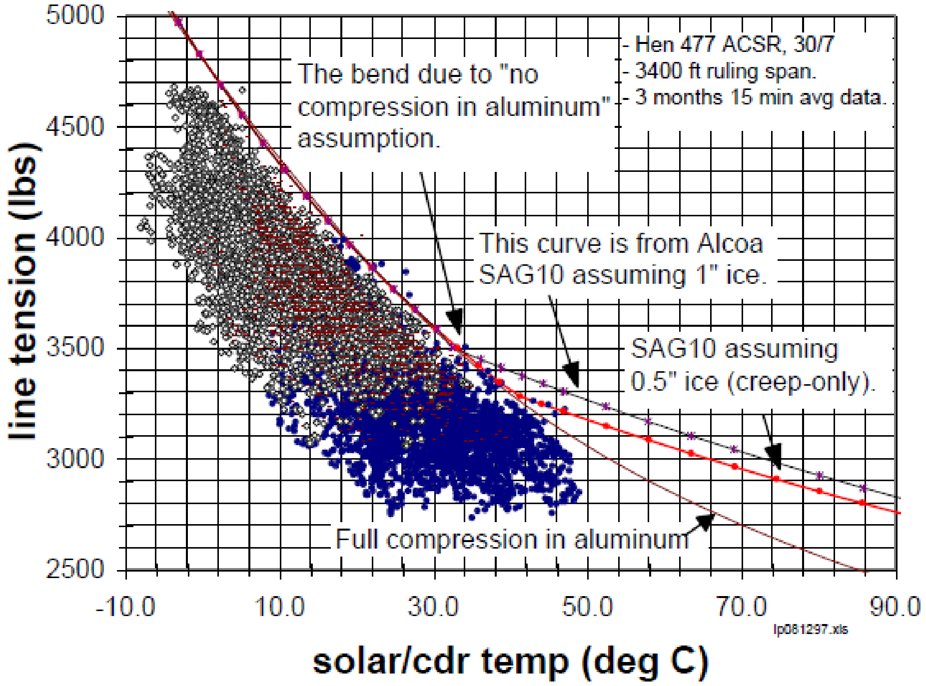


Graph III. **Tension temperature relationships.**

A more elaborate experimental basis for monitor calibration is illustrated in the following figure. Here the conductor tension is plotted against the conductor temperature for zero line current including those times when there is solar heating.

Certain tension monitoring systems measures the conductor tension and Net Radiation Temperature (NRT), also called Solar Temperature. NRT This is measured with a cylindrical sensor, of approximately the same diameter as the conductor and painted to have approximately the same absorptivity as the actual conductor. When this Net Radiation Sensor (NRS) is pointed in the same direction as the line and mounted at approximately the same height, its temperature is equal to that of the conductor without current. Note that NRS senses all radiation received by the conductor, i.e. direct, diffuse and reflected radiation.

The solar temperature (zero current) in this plot is determined by a “net radiation sensor” (a length of aluminium rod having the diameter, emissivity, and orientation of the line section).



Graph IV. Tension VS solar temperature

Note that the inclusion of data points with solar heating raises the upper range of conductor temperatures to near 50 °C. The data points at minimum tension, at each solar temperature, correspond to maximum line currents and worst-case weather conditions. In this field data, the line current approached and occasionally exceeded the line's static thermal rating.

Other checks can be run by comparing conductor temperature based on tension (or sag or clearance) to conductor temperature calculated given weather data (air temp, solar heating, wind speed and wind direction) and line current and by comparing tension-based conductor temperatures for two adjacent line section with comparable sheltering and extent (length?).

Commentaire [MSOffice1]: All text here transferred in the next §3.2 (thus in red)

3.3 Line rating weather data from direct monitors

Conventional **"static" rating** calculations are made with the detailed equations of TB207 [3] for the heat loss and solar gain terms, and the assumption that both line current and weather conditions are constant during the rating period. To be conservative, the weather conditions are assumed to be "worst-case" (low wind speed, high seasonal air temperature). Selection of "worst case" weather conditions suitable for bare overhead conductors in transmission lines is discussed in TB 299 [1]

One common method used in **real-time rating** methods is to assume that the weather conditions will remain the same as measured at present. If the predictive period exceeds one hour, this simple assumption may become quite inaccurate independent of the monitor type employed.

Other, more complex methods of predicting weather conditions a short time into the future (one hour), can be developed, based on analysis of weather data obtained for a historical period immediately preceding the calculation time. Systems normally use a form of regression analysis or neural net techniques to determine the future expected weather conditions based on the previous period of weather data. It is the forecasted weather data that is used to predict the ratings for the periods into the future. Even if the historical weather data and line current is known with great accuracy, the accuracy of the real-time thermal rating is determined primarily by the predicted data.

If weather conditions are monitored at various locations along a transmission line route and the line current is known, the temperature of the line conductor can be calculated ("tracked") at each location by repeatedly applying the preceding transient heat balance equation. For long line sections, the average conductor temperature could be estimated from the average of multiple monitoring locations.

Any line rating is predictive. For example, a 15 minute line rating is the maximum line current which the conductors in the line can carry for 15 minutes without exceeding a specified maximum allowable conductor temperature (e.g. 100 ^{o}C) or a specified maximum permissible sag (worst case) under weather conditions predicted for the next 15 minutes. If the actual weather conditions which occur during this 15 minute time period are worse (lower wind speed, etc.) than predicted, then the line rating will be too high and the maximum conductor temperature may be exceeded if indeed the load current would reach the predicted ampacity, but RTM will inform about that continuously, so that actions could be taken in case of risky situations.

Monitoring conductor temperature or maximum sags is useful but not sufficient to determine line rating which system operations needs to avoid overheating lines or oversagging spans.

Former section 3.1 describes three methods for determining "present" conductor temperature in an overhead line and actual sags.

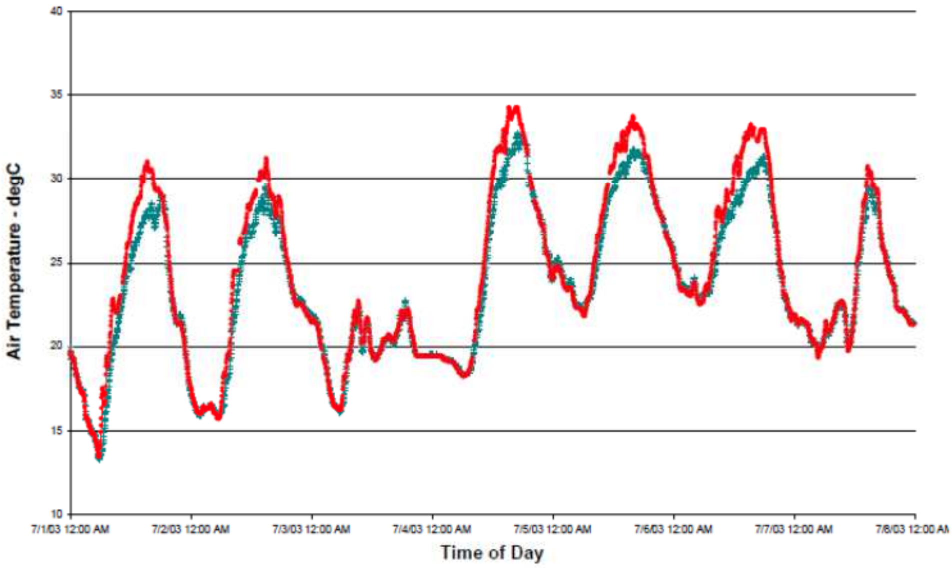
The advantages and disadvantages of each method of these various monitors are discussed in [2], however, it is very important to note that, regardless of the method used to determine the "present" conductor temperature and actual sags, the monitor data alone does not allow "per se" to estimate the maximum line current (real-time thermal rating) which corresponds to a maximum allowable conductor temperature or maximum permissible sag. These calculations require predicted weather in combination with the general heat balance equations using the TB207 [3]. The next paragraphs explain how direct RTM system are doing that in a safe and conservative way.

3.3.1 Non-wind Weather Parameters

Air temperature and solar heating can be measured in the vicinity of a transmission line. These parameters do not need to be measured along the right-of-way since their variation along the line is minimal – good for local span and line section calculations.

These rating factors are also reasonably predictable. Thus having measured air temperature and solar heat intensity over the last hour, it is likely that the air temperature will be similar over the next hour and that the solar heat intensity will follow the normal diurnal cycle. For example, if the air temperature is 15 ^{o}C at 10AM, it is likely to be 16 ^{o}C to 18 ^{o}C between 11AM and noon.

Similarly, the variation with distance is modest as shown in the following field data which compares the air temperature at two locations approximately 2 km apart over a period of a week.

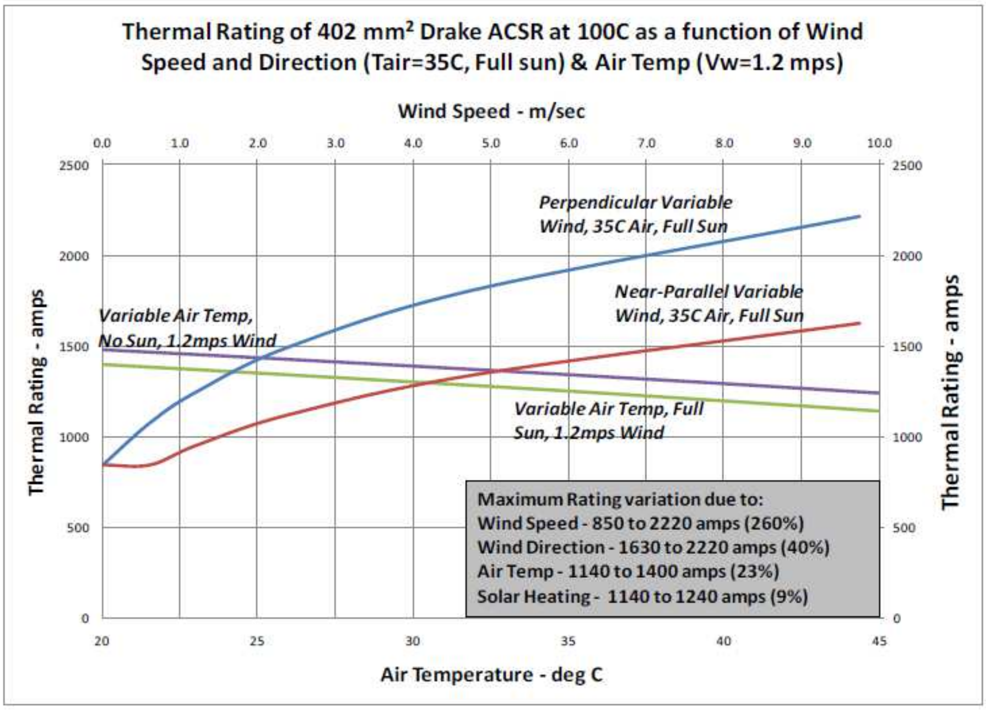


Graph V. **Variation of temperature with distance**

3.3.2 Local In-span wind speed

Wind speed and direction exhibit much greater variation over time and distance. It may be reasonable to say that the wind speed and direction over the next 15 minutes is likely to be similar to that seen for the last hour but it is not valid to assume that the wind speed and direction will be similar to the last hour beyond one hour into the future nor that that these weather parameters are likely to be consistent along the whole transmission line route at any time.

In addition being more variable and less predictable, line ratings are also more affected by the normal variation in wind speed and direction than by normal variation in solar heating or air temperature. This can be seen from the following figure:



Graph VI. Thermal rating as a function of wind speed and direction

The combination of sensitivity to wind speed and direction and the variability of wind speed and direction leads to the conclusion that real-time ratings are driven primarily by short-term wind predictions.

Local In-span wind speed and direction can be monitored with an anemometer or calculated from direct temperature monitor and line current data using TB207 [3].

Nowadays, with a direct monitoring system, the effective wind speed can be deduced from the actual observation of sag/tension/conductor temperature, knowing all other data (like ambient temperature, solar heating and Joule losses), which are, as stated above, more easy to measure. Such wind speed is then called “effective perpendicular wind speed”.

The user-defined thermal rating is then calculated based on the weather station values (or other ways to catch them) of air temperature, solar heating. It also needs actual current flow in the conductor which can be easily obtained by different ways.

TABLE III is showing for some cases the wind speed and direction and their corresponding “effective perpendicular wind speed”.

Wind speed - mps	Wind Direction relative to the conductor axis - deg	Effective Perpendicular Wind Speed - mps	Tair - C
0.61	90	0.61	20
0.87	45	0.61	20
1.60	20	0.61	20
3.15	0	0.61	20
0.77	45	0.61	40
1.40	20	0.61	40
2.95	0	0.61	40
0.91	90	0.91	20
1.30	45	0.91	20
2.23	20	0.91	20

TABLE III. Effective perpendicular wind speed

It should be clear that the use of actual wind speed and direction yields the same convection cooling as the use of the effective perpendicular wind speed.

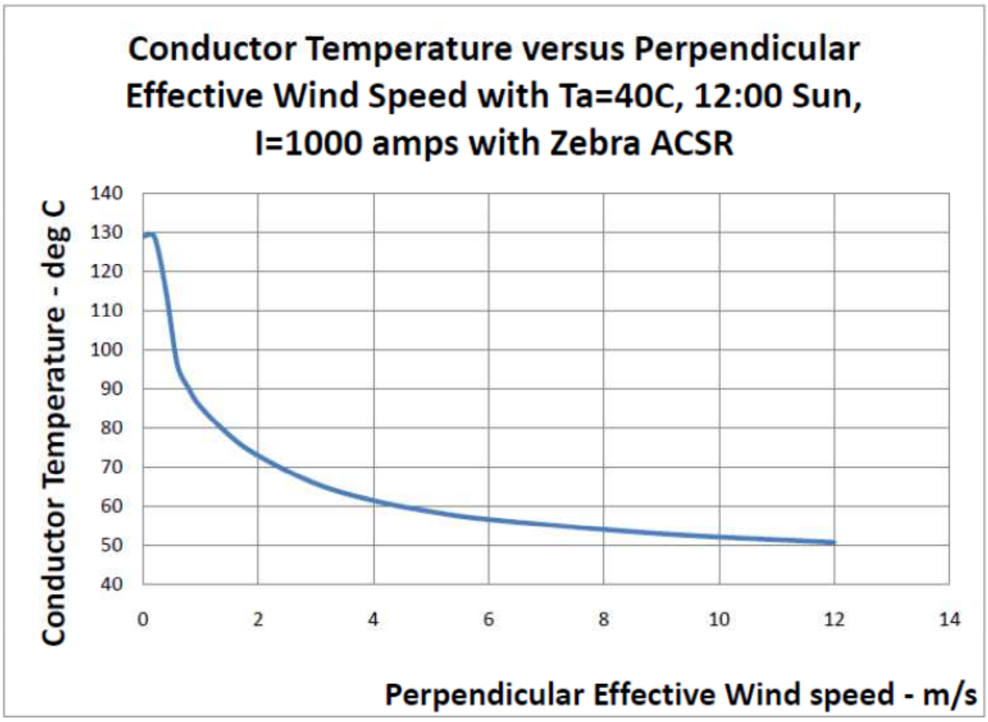
When using line monitors, the wind calculation of real-time thermal ratings follows the same process:

- Unless measured directly with a conductor temperature monitor, the monitored parameter (tension, sag, clearance, wind vibration, or angle of inclination), must be converted to conductor temperature by means of a “change of state equation” which relates the parameter measured to the conductor temperature.

- The calculated or measured real-time conductor temperature is then combined with the air temperature, solar heat input, and line current in TB 207 to calculate an effective perpendicular wind speed.

- The measured weather conditions and calculated effective perpendicular wind speed are then predicted for the next 10 to 60 minutes based on the most recent real-time measurements.

- One or more thermal ratings are calculated for the predicted weather conditions using a thermal calculation method such as that in TB 207. Going back to the relationship sag-temperature, the corresponding sags are evaluated. At this stage the worst rating condition (either maximum temperature or maximum sag/minimum clearance) has to be taken into account if they give different answers (which is generally the case after some years of line operation).



Graph VII. **Conductor temperature vs perpendicular eff. Wind speed**

3.3.3 Average Line-section wind speed

The relationship of average line-section conductor temperature to effective perpendicular wind speed for the line section may be the same as for in-span conductor temperature and local effective perpendicular wind speed. But this is not true in general as we have seen on TABLE III of this brochure. That is because the air temperature and solar heating over the line section is essentially the same, so different effective perpendicular wind speed may be found for different spans inside the same section.

Averaging of these wind speeds may be done to get a line section value (thus for both perpendicular wind speed and conductor temperature) or, better, considering all different cases to keep, at the end, the most conservative value of ampacity of the line.

3.3.4 Example of calculating ampacity in the case of an averaging wind speed and conductor temperature.

Consider a line whose phase conductors are Zebra ACSR (emissivity = absorptivity = 0.8) limited to a maximum conductor temperature of 75 ^{o}C (note that maximum conductor temperatures are a function of the line loading requirements and can vary from around 50^{o-}C to over 100^{o}C). In order to keep things simple, assume that the line current and weather conditions are constant over the last hour or so, and the line is equipped with a monitor that reports (or can evaluate) a mean conductor temperature of 45 ^{o}C given the line current of 500 amperes, air temperature of 32 ^{o}C, and full noontime solar heat input of 23.4 Watts/m. In this case, the heat balance model of TB 207 [3] allows the user to calculate that the wind speed perpendicular to the line at the corresponding span is 1.15 m/s. If we suppose here that we may consider 1.15 m/s as average line-section perpendicular wind speed and 45℃ as average line-section temperature, the thermal rating of the line can then be calculated by repeating the preceding heat balance calculation with the same air temperature, solar heat input, but using the effective wind speed and setting the conductor temperature equal to 75 ^{o}C (= the maximum conductor temperature as stated above). The line current required to produce the maximum allowable conductor temperature of 75 ^{o}C is 1120 amperes. This is the real-time line thermal rating (= ampacity) as long as the weather conditions remain the same.

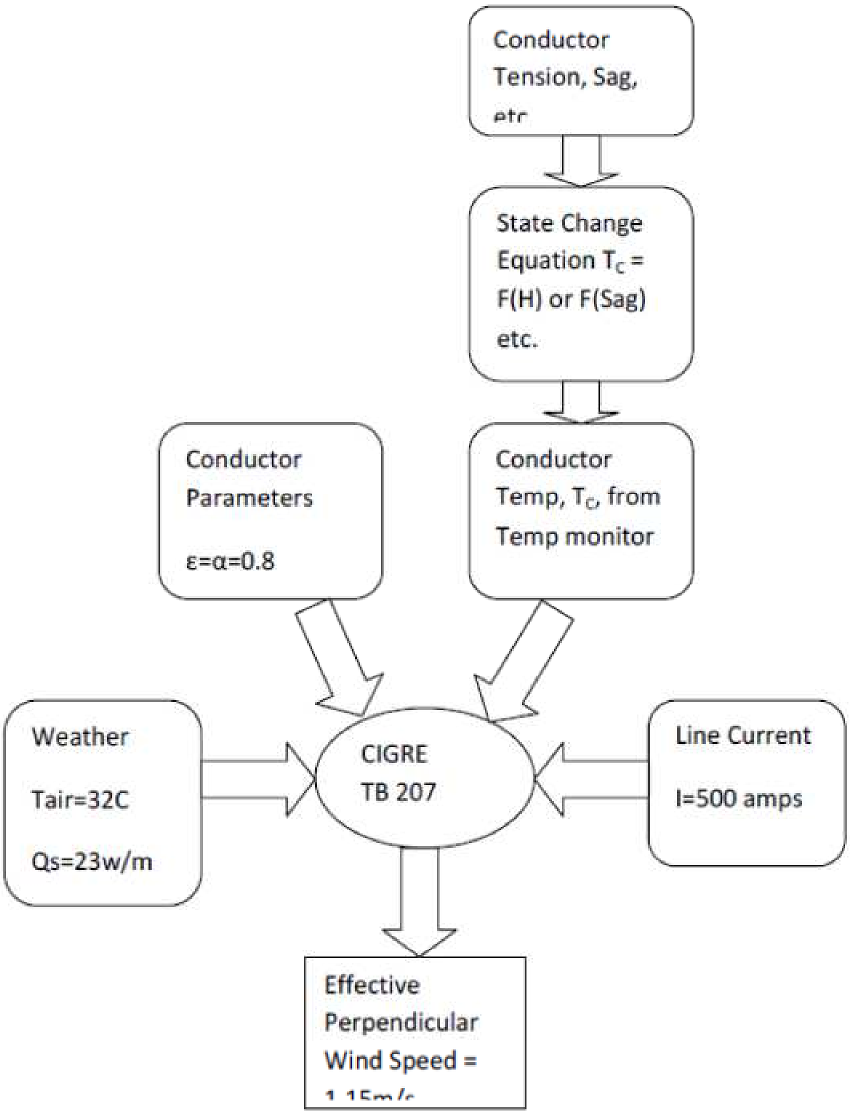


FIGURE II. FLOWCHART FOR CALCULATION OF EFFECTIVE WIND SPEED

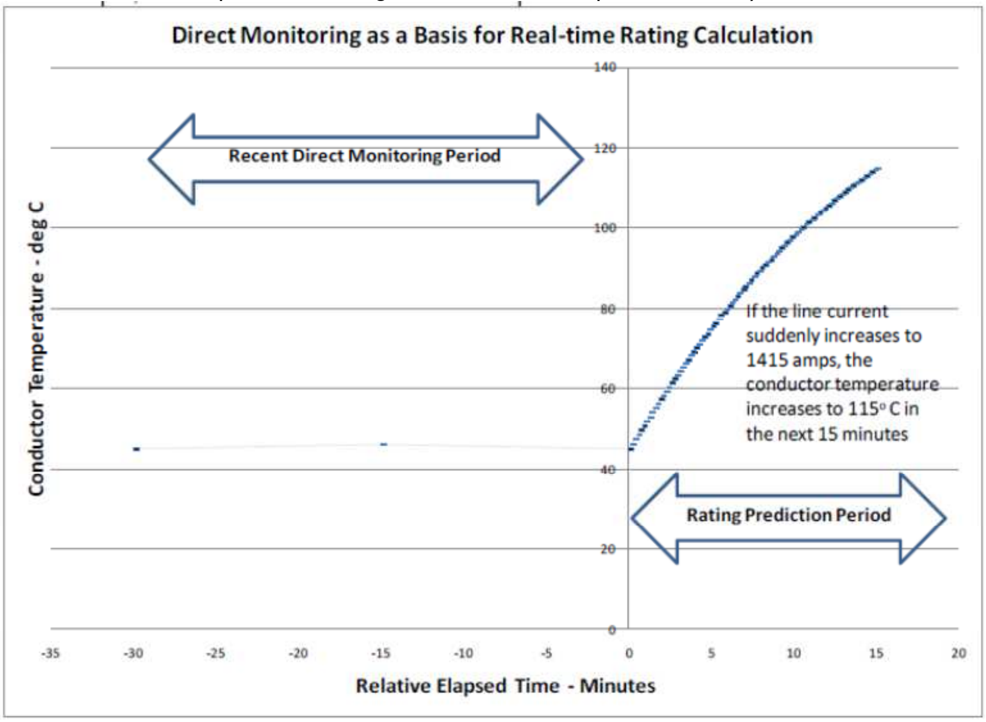
3.3.5 Weather data consistency and short term forecasted line rating

Real-time ratings are predicted for a specific period of time which may range from 5 minutes to several hours. At the beginning of this prediction period, the conductor temperature is known from direct monitor measurements and the weather conditions and line current are available for the last several hours, the direct monitoring period.

The weather conditions for the rating prediction period can be calculated using a variety of methods including simple averaging, trending, regression analysis, Box-Jenkins equations, and more sophisticated methods such as neural net calculations. The prediction of weather conditions is discussed in the following sections.

The magnitude of the ampacity (= maximum line current) is tested until the conductor temperature or the sag (worst case) just reaches the maximum allowable value at the end of the rating period. First, infinite time is considered to evaluate ampacity (means a line current that would be acceptable for any duration if weather conditions are as predicted). In addition, transient states are calculated taking into consideration the thermal inertia of the conductor in case of potential rapid change of line current.

For example, assume that the line conductor temperature was measured to be 45 ^{o}C as shown below. (A similar curve could be obtained for the sag evolution with time until it would reach the maximum permissible sag in the most critical part of the line).



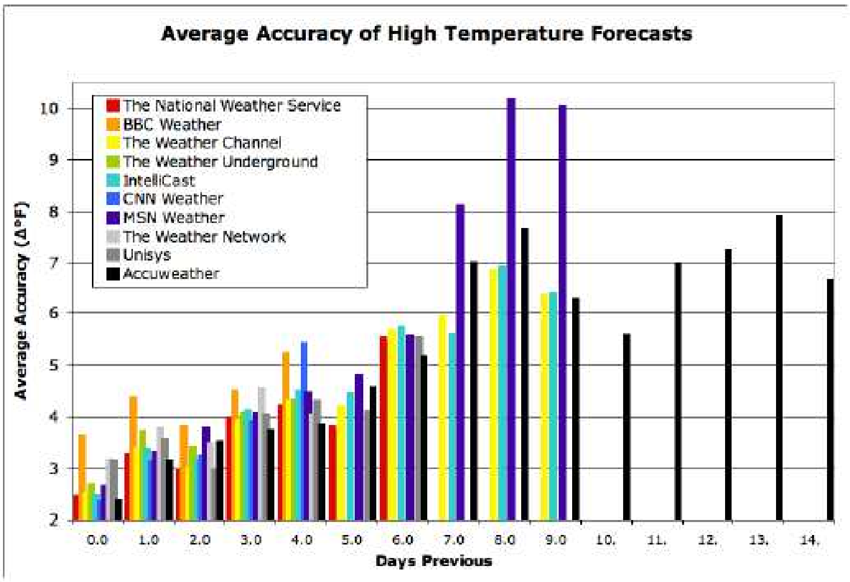
Graph VIII. Chronological diagram showing both the recent direct monitoring period and the rating prediction period

Generally, the rating accuracy is inversely proportional to the duration of the rating period. As time progresses, the predictions must be continually updated as new direct monitor data becomes available.

Prediction of air temperature

Air temperature usually changes slowly throughout the day and follows the diurnal cycle. With maximum allowable conductor temperatures above 75 ^{o}C, real-time thermal ratings of up to one hour duration are not sensitive to small errors in predicted air temperature. The predicted air temperature for a rating prediction period of up to an hour can be taken as the average air temperature reported by direct monitors over the last hour.

Air temperature can also be predicted, as part of commercial meteorological analysis, for hours and even days into the future. Consider for example the following plot showing the accuracy of various commercial weather services in predicting air temperature up to a week in advance.



Graph IX. Average accuracy of predicted air temperature from various commercial sources.

The combination of predictability and relatively low sensitivity of line rating to air temperature means that the impact of predicted air temperature on the accuracy of real-time ratings is slight.

Solar heating (worst-case) prediction

Solar heating of a bare overhead conductor can be calculated quite accurately for clear sky conditions. Given the sometimes scattered cloud cover along transmission lines, it may be sensible to calculate the solar heat input for the rating period. This yields a conservative estimate of line rating. The solar heat input during the rating prediction period can be calculated using TB 207 [3]

It should be noted, however, that the use of calculated solar heating for the rating prediction period does not mean that solar heating should not be measured during the direct monitoring period. If it is assumed that the conductor experiences full solar heating during the direct monitoring period, the average line-section effective wind speed will be overestimated and the real-time rating will be too high. Conservative approaches are needed and developed by each RTM system, for example based on different ways to get actual meteorological data.

Wind cooling prediction

Forced convection has a large impact on line rating and is difficult to predict more than an hour in advance. Several attempts have been made to predict low speed winds for line rating use. The conclusion is that such predictions of effective wind cooling cannot be made for predictive rating periods more than 1 to 4 hours.

For real-time rating durations less than 60 minutes, the effective wind speed may be taken as the minimum 10-minute average wind for the preceding hour. For rating durations of one to four hours, the effective wind cooling speed needs to be calculated by a sophisticated regression method or taken as a minimum time-of-day value based on field studies.

3.3.6 Example Real-time Line Rating Calculation

The following example problem demonstrates the process of line real-time line rating calculation with TB207 based upon direct monitor data. This calculation is very similar, regardless of the type of direct monitor, employed. Accuracy of the calculated real-time thermal rating will depend on the following issues:

- The accuracy of the direct monitor.
- The accuracy of the equation of state (line calibration equations) which are used to estimate conductor temperature.
- Errors in Predicted rating conditions.

Consider the following simplified real-time direct monitor data for a direct monitoring period of only 30 minutes (it would normally be for at least one hours) where the reported line current, air temperature, etc. are 15-minute averages (they would more commonly be 5 or 10 minute averages).

The predictions of air temp for the rating period are taken simply as the 15 minute averages reported by the direct monitoring system (it could also be obtained from meteorological station in the vicinity).

The real-time thermal ratings are calculated for Zebra ACSR conductor where the maximum allowable conductor temperature is 125 °C for 5 and 10 minute rating periods and 115 °C for 15 and 30 minute rating periods. Longer rating periods would likely want to use lower maximum conductor temperatures.

Recent Monitoring Period				Prediction Period			
Time	-30	-15	Present Time	5	10	15	30
Tension/Temp	8.4/45	8.3/46	8.4/45	-	-	-	-
Line current	450	460	470	480	480	480	480
Air Temp	23	23	23	23	23	23	23
Solar %Peak	60	50	50	100	100	100	100
Eff Wind Spd	2.3	2.1	2.5	2.0	2.0	2.0	2.0
Tmax	-	-	-	125	125	115	115
Rating-amps	-	-	-	2400	1900	1610	1450

TABLE IV. Typical data for a direct monitored line showing 4 different rating prediction period times – 5 through 30 minutes

Using the default weather conditions recommended in TB 299 [1] (40 ^{o}C air, full sun, 0.61 m/s perpendicular wind), and a continuous rating maximum conductor temperature of 95 ^{o}C, the continuous static thermal rating is 1050 amperes. The higher real-time ratings are due to a combination of heat storage effects and less conservative wind and air temperature conditions.

It is possible to predict the rating for a few hours or days into the future. In this case it is advisable to follow methods detailed in (reference dynamic weather rating). Prediction methods will not be covered in this document.

4. DIRECT REAL-TIME MONITORING METHODS

In this section, the direct methods are examples of some of the methods used currently. There are other methods such as use of power line carrier which are not covered here. It should be noted that these devices are being developed all the time thus this is a snapshot at the time of writing.

Electric utilities are always under pressure to make optimum use of their existing facilities. An overhead high voltage transmission system is an integral part of this effort. In any interconnected HV transmission system, there is a need to define in quantitative terms the maximum amount of power that may be transferred without violating the system safety, reliability and security criteria that are in place. Real-time ratings of transmission line circuits are critical to system capacity utilization. In most cases, the real limit due to physical sag is well below the thermal limit. For this reason, real-time conductor sag measurement and real-time current rating hold promise for the improvement of system transfer capability

Traditionally, many techniques have been developed for the determination of overhead conductor parameters (sag, temperature, or tension) using both direct and indirect measurement methods, the distinction being that direct methods involve measuring at least one physical parameter of the line, such as tension, temperature, vibration frequency, or ground clearance, which is then used to derive parameters such as sag, temperature and tension where not directly measured. With indirect methods, it is typically weather parameters that are first measured and then used in conjunction with conductor electrical load to calculate the temperature (and subsequently the sag and/or tension) of the conductor. It is worth noting that direct monitoring systems typically use additional inputs from indirect measurements in order to further calculate circuit rating (ampacity).

It is also worth noting that wherever a measurement (whether direct or indirect) is used to derive a secondary parameter, that assumptions must be made as to the behaviour of the overhead line as a system. However, the “real world” rarely behaves exactly according to the mathematical models developed for design purposes, so to improve accuracy systems must undergo a calibration process as described in section 3.2.

In this section direct monitoring systems will be described; they include clamp-on devices to measure the temperature of the conductor as well as methods to measure the conductor tensile force, ground clearance, or fundamental vibration frequency (a direct function of sag) of the conductor.

4.1 CONDUCTOR TEMPERATURE MEASUREMENT

Direct temperature measurements are performed generally by clamp-on thermal couples that transmit the temperature via radio communication to a central station or need to be locally downloaded; the recorded temperature is then compared to the design temperature and the readings can be used for thermal limit determination. The sensors are usually located at few positions only, however the temperature varies along the span as well as between spans due to different wind velocities or angle of wind attack. Nevertheless, the temperature measured is the conductor surface temperature and not the average conductor temperature that affects sag. The conversion from the conductor surface temperature to a sag dimension is still required in order to determine the position of the conductor in real-time. The accuracy of the thermal rating will depend on how precisely the relationship between the measured temperature and sags can be established.

As mentioned previously, it is possible to determine the conductor temperature with temperature monitors as long as there are sufficient numbers to cater for the variation along the span and the section. Distributed fiber optic with Bragg grading may also be used to get a full profile of temperature along the conductor, as regularly done in underground cable.

4.2 ANGLE MEASUREMENT.

It (angle measurement devices) uses the conductor angle to estimate the actual conductor sag. Indeed a parabola (or even better a cosh) shape can be rebuild based on the knowledge of the slope of the parabola at a given point of the curve (to be known), if the span length, unlevelling and some conductor data are known.(see FIGURE IV).

FIGURE III. DONUT DEVICE CLAMPED ON A HV TRANSMISSION LINE.

The donut is capable of simultaneously monitoring parameters including:
•Current (Amps)
• Line to ground voltage (kV)
•local Conductor Temperature –

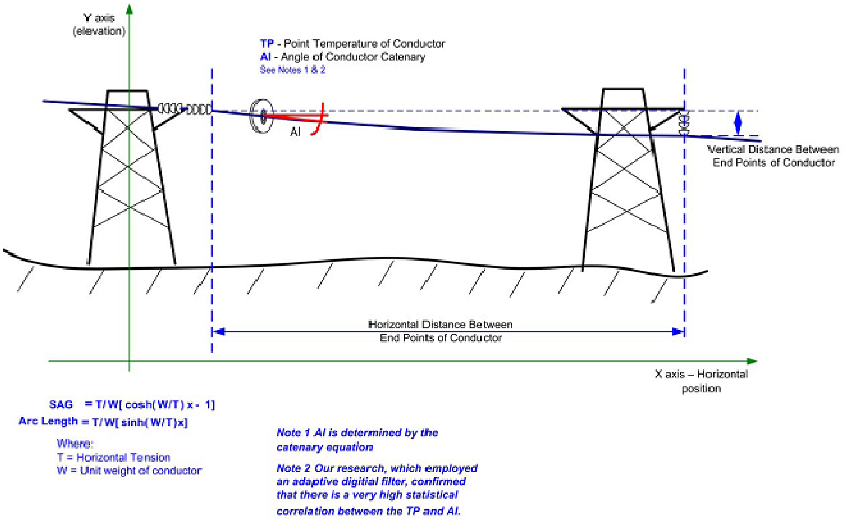


FIGURE IV. DONUT - CLEARANCE MONITORING

Conductor temperature given by this method receives similar comment as for direct temperature sensor because of the heat sink effect of the device.

4.3 MONITORING OF POINT ON CONDUCTOR IN SPAN

This device uses a sophisticated camera (generally installed on the tower) and a target (on the conductor) placed at the critical span of the line. The camera is used to capture the position of the target and using advanced image processing techniques, the position of the target is used to evaluate the conductor sag. Regular maintenance required. This device can be installed on any kind of structure by simply bolting or banding the different housings directly to the structure. All of the components, with exception of the target, are mounted a safe distance away from the conductors. Only the target is installed on the conductor itself. The target is typically installed about 150 feet from the camera using a hot-stick while the line is energized. The camera is mounted at approximately the same elevation as the target. The electronics and power supply boxes can be located anywhere on the structure that is safe and convenient. The only measurement needed for calibration is the conductor-to-ground clearance at the target location. However, as part of the installation routine, other survey measurements are taken to define the span geometry and wire catenary and to establish ground clearance measurements at other critical points along the span. These measurements can then be used to calibrate the monitored span for use with a stand-alone monitoring routine.

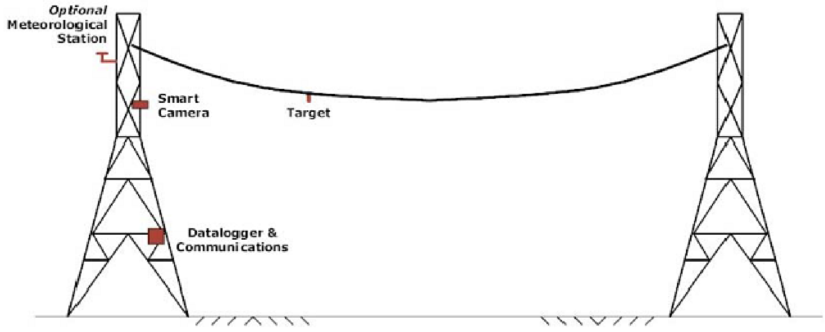


FIGURE V. SAG MONITOR DEVICE

FIGURE VI. SAG MONITOR DEVICE – CAMERA(LEFT); TARGET (RIGHT)

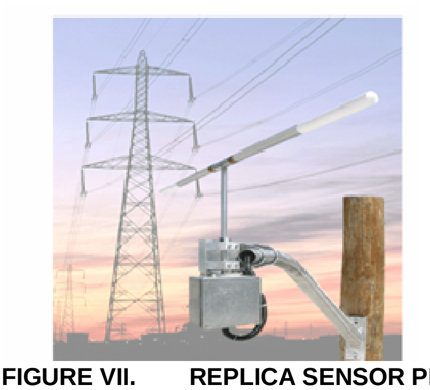


FIGURE VII. REPLICA SENSOR PLACED NEAR THE LINE

4.4 SAG MONITOR BASED ON WIND INDUCED CONDUCTOR MOVEMENT

Power line conductors always move due to wind conditions.. Indeed wind turbulence as well as wind spatial coherence along the span easily generate small (or large) movements that include the intrinsic mechanical oscillation frequencies of the span. These frequencies are the signature of the span for a given sag, just like a musical instrument e.g. a violin for which the chord is the conductor and the bow moving is the wind. The characteristic sound of the instrument is determined by the mix of harmonics. A power line span length will develop harmonics of its fundamental frequency which is a function solely of the sag and nothing else.

A smart monitor has been developed that attaches directly to the overhead power line conductor, and is able to evaluate the sag of a span without knowing any data (no need of sagging data, no need of topological data, no need of conductor data, no need of weather data) in real-time.

This device can accurately measure a particular sag in a span.

FIGURE VIII. 400 KV INSTALLATION OF VIBRATION SENSOR ON ELIA NETWORK.

The device and method is based on conductor vibration analysis to detect the fundamental frequency of the span. This is the exact signature of the span's sag. Larger sag means lower frequency and vice versa. The external conditions (load, weather, topology, suspension movement, creep, presence of snow/ice, …) all influence sag and thus the measured frequencies. Therefore the frequency based measurement makes this device a direct sag evaluator and this for all causes of sag. Because the whole conductor vibrates the monitor can be installed anywhere in the span significantly simplifying the installation.

Differences were less than 20 cm range for all observed sags (sag range from 6 to 25 m), a precision that is fairly good for ampacity prediction. More details can be found in (CIGRE 2010, paper C2-106 [7] and in the case study (chapter 8.2).

From sag to line rating, the method is explained in other parts of this document. But with the noticeable difference measurement of sag is a valuable back up to certify that maximum sag is never violated and to "calibrate" the thermal model and state equations with "real life" data instead of relying on design stage data and sometimes misleading local weather sensors .

4.5 DIRECT CLEARANCE MONITORING

Overhead line clearance measuring equipment using acoustic wave technology is feasible to measure the clearance of conductor above ground. The clearance monitor reported values at 10 minute interval with standard deviation of less than 1 cm. The device launches a series of high-amplitude sound pulses with narrow spectral content. The reflections of these sound pulses from nearby objects are recorded as a function of time. The device with proper programming and alignment has a practical range up to 40 m. The echo processing algorithms extract the time flight, which is related to the distance by the speed of sound.

FIGURE IX. CLEARANCE MONITORING STATION – HYDRO ONE 230KV LINES (SONAR DEVICE IN BLUE) PHOTO BY: KINECTRICS INC. TORONTO, CANADA

4.6 TENSION MONITORING SYSTEMS

The tension monitors device uses a line tension monitoring system that is installed in series with a dead end insulator on a power line conductor; this device gives an accurate measure of tension. Knowing tension, net radiation temperature, clearance and conductor temperature, it's possible to obtain real-time rating for the line.

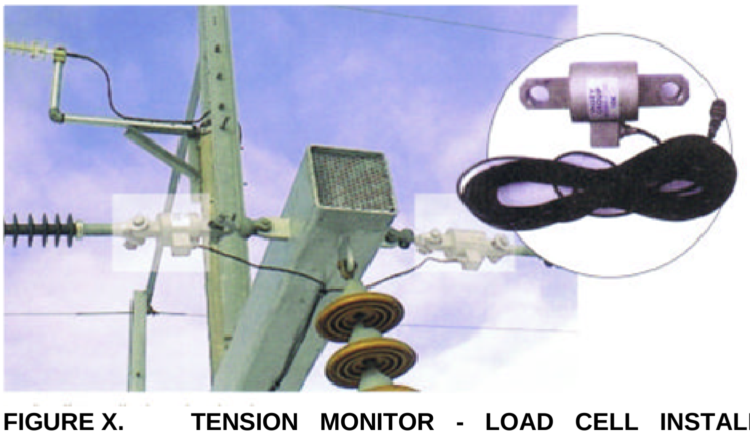


FIGURE X. TENSION MONITOR - LOAD CELL INSTALLED AT DEAD-END STRUCTURE

Real-time tension monitoring systems measure the tension of the conductor with an accuracy of 0.25% of full scale and a resolution of 0.06% of full scale. Because most monitoring systems operate at about 50% of full scale, the practical accuracy is about 0.5% and the resolution about 0.2% of the measured value.

Because the thermal rating of the line must be derived from conductor heat balance equation [3] the derivation of the rating requires accurate knowledge of conductor's temperature. As shown by the CIGRE brochure of Sag –Tension Calculation Methods [Brochure 324 [4] the design calculations cannot be trusted to represent the dependence of tension from conductor temperature[2]. Thus, independent of the sag or tension measurement method, the line sections must be calibrated. Note that this is not a calibration of equipment; it is a calibration of line parameters.

Certain tension monitoring systems measures the conductor tension and Net Radiation Temperature (NRT), also called Solar Temperature. NRT   This is measured with a cylindrical sensor, of approximately the same diameter as the conductor and painted to have approximately the same absorptivity as the actual conductor. When this Net Radiation Sensor (NRS) is pointed in the same direction as the line and mounted at approximately the same height, its temperature is equal to that of the conductor without current. Note that NRS senses all radiation received by the conductor, i.e. direct, diffuse and reflected radiation.

The calibration procedure consists of recording tension data and NRS data from the tension monitors. The data when conductor current is low is used for calibration. The calibration curve is the record of measured tension vs. NRT values at low currents[3].
The shape of calibration curve will allow accurate determination of the actual ruling span (equivalent span) compared to the ruling span assumed in design calculations. Frequently, the difference is significant. The actual ruling span is then used to derive a correct relationship between measured tension and conductor's actual temperature.

While the above procedure is quite adequate for single material conductors (AAC, AAAC, ACAR etc) and low % steel ACSR conductors, it may require further corrections for ACSR conductors with high steel %. Such ACSR conductors have kneepoint temperatures[4] at temperatures which can be significantly lower than the maximum operating temperatures of the conductor. The kneepoint temperature can be determined by iterative calculations, if the conductor is operated above the kneepoint temperature. Until such operational temperatures are reached, the temperature estimates must be based on worst rational assumptions of high kneepoint temperatures.

4.6.1 Conductor Rating

[2] Actual sag and tension of the line depends, among other things from conductor's installation practices, mechanical loading history, uncertainty of actual thermal elongation coefficient, uncertainty of elastic modulus, stiffness of deadends, effect of angle structures and several other variables described in TB 324 [4]

[3] For example, it the conductor's static rating is based on a 50^{o}C temperature rise, line current of 10% of rated current will cause a maximum of 0.5^{o}C error in the calibration curve.

[4] At and above the kneepoint temperature all tension of the conductor is carried by the core and aluminum wires are slack (or may carry some compressive stress). The kneepoint temperature depends on the manufacturing temperature of the conductor which is generally unknown and the stress history of the conductor. The variation compared to design assumptions is generally +/-20^{o}C.

From the computed conductor temperature, the rating can be determined in the following method:

1. The measurement of NRT provides data from both ambient temperature and actual solar radiation input to the conductor. The Joule input is known from the current data of the SCADA system. The calculated conductor temperature determines the outgoing thermal radiation.
2. The only unknown, the effective wind speed[5], can be solved from the data.
3. The effective wind speed is then used to calculate the line rating.

<u>Comments:</u>

1. Because the line current is not constant, calculations must include methods of monitoring line current for at least three time-constants of the conductor. The energy of "past" Joule losses is not dissipated instantaneously! One of the methods is to use quasi-static rating by determining the conductor's time constant[6] and "aging" the energy of past Joule losses with this method.

   Even this method will provide only quasi-static ratings. If the line current is increasing before observation, the computed ratings will be higher than true ones. Conversely, if the current is decreasing, the ratings will be depressed. After a few observation intervals, the ratings will track actual conditions more accurately.

2. A more accurate calculation method, which should be used when line current and/or wind conditions are highly variable, is a true dynamic rating algorithm. In such algorithm, the energy storage of the conductor is taken into account.

4.7 DEVICE UNDER DEVELOPMENT : DGPS MONITOR

A recently developed 'direct' method to measure sag incorporates a differential Global positioning system mounted at the mid-span. The method relies on information received from the GPS satellites and is capable of measuring sag to an accuracy announced of approximately 25mm using a commercially available carrier based GPS System. The biggest advantage of this method is that it measures conductor sag directly by measuring the conductor to ground clearance based on altitude information obtained from the GPS device. Accuracy of GPS can be affected by a number of factors, including satellite positions, noise in the radio signal, atmospheric conditions, and natural barriers to the signal. Noise can create an error between 1 to 10 meters that result from static or interference from something near the receiver or something on the same frequency. Clouds and other atmospheric phenomena, and objects such a mountains or buildings between the satellite and the receiver can also produce error, sometimes up to 30 meters. The presence of bad GPS measurement data could be attributed to a variety of sources, some of which are not fully understood. The momentary loss of some GPS satellites from view will negatively impact the measurement accuracy. One way to reduce these errors involves the comparison of a GPS position calculation with that at a known surveyed position. In this way, an error or a difference is generated which is then used as a correction. The concept is called differential GPS and the technology is further denominated depending on the collection of the final position result at the surveyed base station (*direct DGPS*) or the 'rover' remote station (*inverse DGPS*). More recently, there have been recommendations to add an additional

[5] Effective wind speed is the perpendicular wind speed which has the same convective cooling effect as the actual spatially variable wind speed and direction along the ruling span.
[6] Time constant is a function of conductor size and effective wind speed.

frequency to the system. This is intended to improve the accuracy of civilian GPS applications. The DGPS operation offers significant position accuracy improvement over standard GPS. DGPS compensation greatly attenuates errors common to all local receivers in use. The following accounts for the increased use of DGPS: nanosecond-order precise time tagging capability (accuracy), compactness, portability, low cost and, around the clock operation in all weather conditions anywhere on Earth. The outputs obtained from the bad data rejection and Kalman filtration. have an announced error less than ±5%.
Orientation of the antenna is important, which may be sensitive on single conductor.

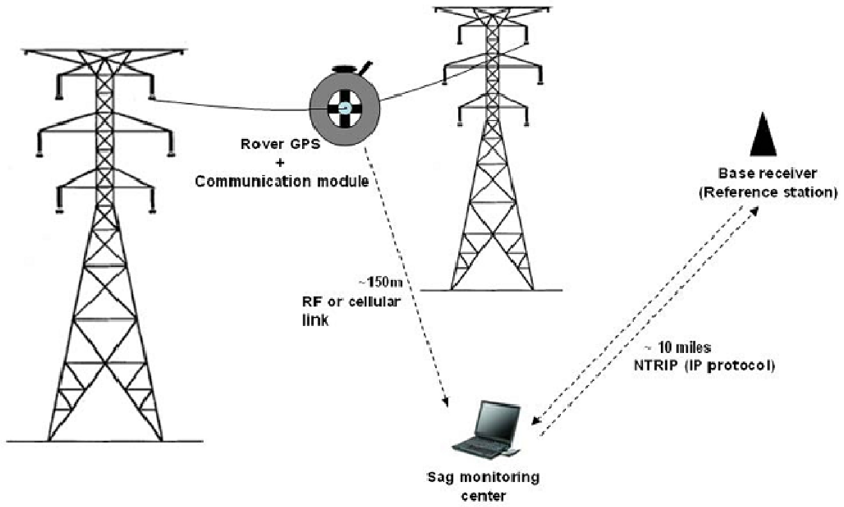


FIGURE XI. DGPS BASED SAG MEASUREMENT SYSTEM

5. ACCEPTABLE ERROR MARGINS

5.1 TYPICAL TSO'S SPECIFICATIONS

For TSOs, the clearance or distance between conductor and obstacles is the fundamental data to be checked. These clearances have to respect the country's legislation.

Unless direct measurement of clearance, it is necessary to determine the sag to check the clearance. One of the aim of an OHL monitoring system is to deliver the sag of the line spans.

A direct measurement of clearance can be obtained with an accuracy of +/- 20cm.

Moreover, the design of an OHL generally takes into account a distance margin to cover initial measurement error at the installation and long term creeping. Typically this margin distance is + 50 cm or more, depending TSO's specifications.

Due to previous values, **the sag has to be determined with an accuracy of +/- 20 cm.**

For each different monitoring system, the algorithm will be described and the measuring error will be determined to prove that the required accuracy required is met.

From the sag given by the monitoring system, the following step is to determine the real-time rating with the actual meteorological conditions..

For instance for a 570.mm2 AAAC conductor, at 45℃ reference temperature, a 20 cm sag variation which is the minimum accuracy, represents about 5℃ conductor temperature change. This 5℃ change which represent s a 10% temperature variation, induces a 10% ampacity change.

Taking into account the error of the equation between conductor temperature and ampacity, and the previous uncertainties, **the global error margin on real-time rating acceptable for operators should be around +/- 10%.**

5.2 ERRORS IN RATING CALCULATION

After direct monitoring systems are calibrated, they can be used to determine the temperature of the conductor.

The effects of various error sources are described below.

5.2.1 Ambient temperature

Ambient temperature is fairly consistent and would generally vary less than +/- 1^{o}C within a ruling span section and no more than +/- 3^{o}C over a 30 km line, unless there are substantial elevation differences. These would affect the line rating by 1% and 3% respectively.

It is recommended that ambient temperature be monitored as similar altitude as the power lines and not too far (a few km is clearly possible) from it.

5.2.2 Line Current

Line current is generally available from EMS/SCADA systems with accuracy of 0.3% (based on CT ratios, note that the current varies along the line due to capacitive current and could vary more than 2-3% from beginning to end.). On the other hand, on certain lines, the line current can vary rapidly. To avoid sampling errors in such cases, the line current should be monitored at intervals that are in the order of 10% of time constant of the conductor, and the Joule losses should be averaged over a period that corresponds to the time constant (typically 10 to 20 minutes).. The alternative is to use a fully dynamic algorithm, which accounts for change of the change in thermal energy stored in the conductor between observations. Line current may also be measured inside the sensor if it is mounted on the conductor itself.

5.2.3 Outgoing radiation

The radiation loss depends on the conductor and ambient temperatures and the emissivity of the conductor. If the conductor emissivity were estimated with an error of +/- 0.1, it would typically change the rating calculation in the above example by -/+ 2%.

Note that real-time rating calculations should always be made using an estimated value of emissivity. Guidance on this subject is available in TB 299 [1] which shows that the emissivity of weathered transmission conductors is typically 0.8-0.9.

5.2.4 Solar radiation

Mistaken estimates of solar radiation are one error source in rating calculations. They affect rating calculation in two ways. Under most rating conditions the line current is low or moderate and the solar radiation has a significant effect on calculated components of heat balance calculations. Secondly, but to a lesser effect, they affect the heat balance calculations under the assumed rating conditions.

Typically, ratings need to be calculated when line current is relatively low. In our example case, the solar radiation energy amounts to 10.7 W/m of conductor. If the calculations were made assuming full solar radiation, the energy would be 21.3 W/m and if the solar radiation were omitted the value would be zero. If the line had no current, the solar radiation of 550 W/m^2 would increase its temperature by 4.7^{o}C, while full sun would increase it by 9.4^{o}C.

Assume now that the current of the line is 300 A. This would cause the conductor temperature to rise to 40.2^{o}C. Using the correct value of solar radiation the energy balance components for solar energy, convection and radiation would be 10.7, 18.2 and 4.8 W/m. If full solar radiation were assumed, the values would be 21.3, 28.8 and 4.8 W/m. Essentially; the too high estimate of incoming solar radiation would be attributed to higher wind speed than actual.

Using correct value of solar radiation the calculated effective wind speed is 1.0 m/s. If full solar radiation is assumed, the calculated effective wind speed is 2.3 m/s. If no solar radiation is the assumption, the resulting effective wind speed is 0.2 m/s. By using the different solar radiation assumptions we can derive the following ratings for 85^{o}C:

Solar radiation 550 W/m^2:	1106 A	
Solar radiation 1100 W/m^2:	1288 A	(+16%)
Solar radiation 0 W/m^2:	855 A	(-23%)

As it can be seen the rating is very much wind speed and current flow dependant.
There are several ways to solve this problem:

1) Use pyranometers. However pyranometers are not fully accurate, because they do not measure accurately diffuse sky radiation and do not account for reflected radiation, caused by ground albedo.
2) Use conductor replica to obtain a “solar temperature” which would be the conductor temperature without the Joule effect, but with all other effects, including solar heat. It needs to have similar size of the conductor and similar emissivity/absorptivity and placed in similar arrangement (orientation, height above the ground) to receive similar wind , solar radiation as the power line conductor.
3) Deduce a mix of solar heat and effective wind speed in a conservative way based on the actual observation of conductor temperature and ambient temperature (measured as explained in §5.2.1), and taking into account the observed solar heat at a weather station in proximity.

5.3 ERROR SOURCES

Potential errors for RTM systems may be as detailed in this chapter. Some devices are more sensitive to some of them and others are more insensitive. The list here is given for the final user to be able to discuss about that with potential RTM system.
Mitigation techniques exist for most of the errors.

Errors may come from:

- Errors in conductor data (including external added material like Aircraft Warning Markers (AWM)),
- Errors in section topological data
- Errors on ruling span concept: hypothesis behind ruling span are numerous and includes constant data (weather, conductor temperature and conductor data).
- Varying weather data along span/section
- Nonlinear behavior of conductor

Mitigation techniques

- redundancies in measurement
- repeated calibrations
- weather data measured at conductor level
- use conductor replica
- learning process based on observations, experience
- Apply different sag-tension relationship methods, like detailed in CIGRE brochure N° 324. [4]
- Apply safe buffer estimation
- Back up observations which certify ampacity when it comes close to zero

What has been observed in practice?

- Sagging conditions are no more valid at observation time (step 1 important if no backup solution available), that is due to creep, thermal elongation, rare events inducing permanent elongation or slipping in clamps, etc…
  The consequences are that devices using "as design" values cannot be robust and absolutely need updated data.
- Topological data (span length, span unleveled) often known with bad precision (several % error) which very much influence the extrapolation of clearances from/to span to/from ruling span data.
  The consequences are that errors on span lengths induce doubling error effect (a 1% error on span length induce 2% error on sag) on sag evaluation in a given span.
- Temperature changes quite a lot in the same section from span to span depending on local vegetation, orientation to the winds, etc… and even between points in the same span. High temperature low sag conductor has definitely not the same behavior as classical ones and for example have large gradient inside their core which can be constituted of different material.
- Low wind speed (the most important weather data for ampacity) is difficult to estimate at conductor level in both value and direction. Such low wind speed values may vary quite a lot from span to span.
-
  The consequences are that evaluating rating with a measured wind speed without correction to effective wind speed deduced from actual measurement on the line is not ideal.
- Ruling span concept has many uncertainties compared to actual power lines behavior, as actual data (mass of conductor and hardware, temperature, weather) are rarely constant along the section. Alignment may also influence that concept.

General remark about thermodynamics of conductors

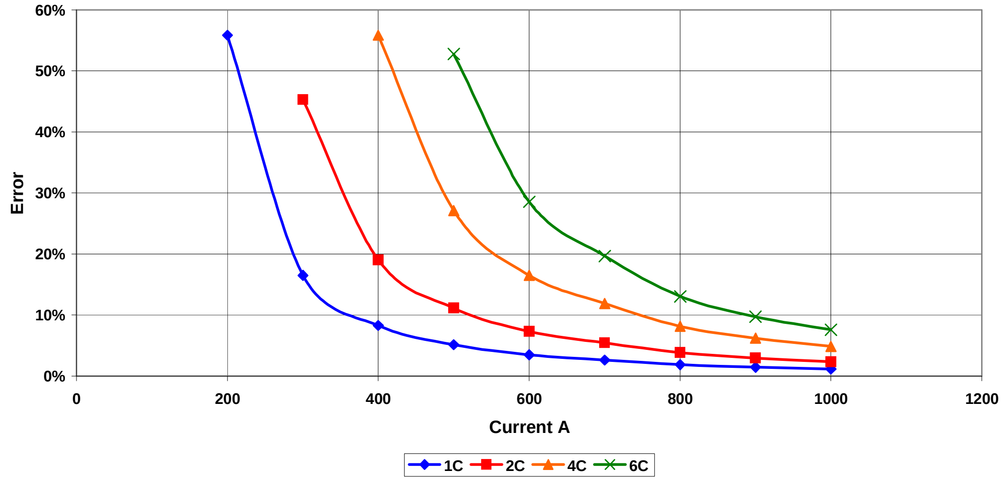
Note that determination of even static rating is a dynamic or quasi-static process. The conductor's thermal state is, because of its heat storage capabilities, a dynamic process. For example, the thermal time constant of ACSR "Drake" is about 12 minutes (note that this time constant is not constant but varies based on wind and current). This means that at a given time, 45% of the combined heat energy content (ohmic losses and solar radiation) is more than 10 minutes "old" and 20% more than 20 minutes "old". Whichever method is used to determine the conductor thermal state, it must consider the heat input history and age the heat input with appropriate algorithms, because the line current and solar radiation are generally quite variable.

The fundamental principles of thermal rating calculation with the different methods are rather similar. The conductor's temperature is determined by either direct measurement or by using the calibrated dependence of tension, sag or clearance from conductor temperature to calculate the average temperature of the line section.

Ambient temperature and solar radiation (or alternatively the combined solar temperature) are measured. Algorithms based on CIGRE or IEEE standards are then used solve the effective wind speed of the line section.[7]. This effective wind speed and the measured ambient temperature and solar radiation are then used to calculate the rating of the line section.

Independent of the method of temperature measurement, reasonably accurate calculation of the line rating requires sufficient current to achieve a sufficient temperature rise of the line. We can investigate the required current by considering the base case of TB 299 [1], namely rating a Drake conductor for 100^{o}C, under conditions which would give it a static rating of 1047 A[8]. Because the most dangerous condition is a too high rating, Graph X depicts the maximum positive error as a function of line current, the combined error of the temperature rise measurement as a parameter.

Figure 1. Maximum positive error for rating ACSR "Drake, temperature resolution as a parameter



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[7] Effective wind speed is the speed of the perpendicular wind which has the same net cooling effect as the varying wind speed and direction along the line section. See Figure 2 in TB 299[1].

[8] See TB 299 [1], section 4.3.

Graph X. Maximum positive error for rating acsr drake temperature resolution as a parameter

In practice, the best possible resolution from existing devices is about 1.0-1.5^{o}C,. Note that even relatively poor resolution provides reasonably accurate ratings at high line currents, when accuracy is most important.

By the way the recommended 10% error on rating cannot be achieved for very low current flow but this has no impact on line operation as precision is not requested in such situation. In case of a sudden increase of line current from very low to very high value, real-time monitoring will progressively detect and change their rating as temperature is increasing gradually with its time constant (about three times the time constant is needed to reach the final situation), which is generally above some tens of minutes for low wind speed, the critical case.

5.3.1 Accuracy of sag/clearance measurement

The following is pertinent:

- Operators need to be informed on rating. Thermal rating is based on either minimum clearances (for the whole line) or maximum temperature (mean value for the worst span into the whole line)
- The design stage defines a maximum sag (or minimum tensile load) for all spans and there are few of them called critical spans for which there is a significant risk of clearance violation. At design stage that maximum sag is reached for the maximum allowable temperature of the conductor (and fittings). Maximum sag (minimum tensile load) is obviously the image of minimum required clearance.
- Actual conditions after some years may lead to mismatch between maximum sag (minimum tensile load) and maximum temperature. Of course the worst case has to be used for rating. Generally it is a sag issue (which can be converted into a tensile load problem).
- Thus it is imperative to check the actual sag (to be compared to maximum sag) or actual tensile load for dynamic line rating. That value has then to be transformed in available rating for operators.
- RTM are using different method to go to clearances and that needs some clarifications.

It should be first noted that sag is not a physically determinable quantity; it is a parameter describing the shape of a catenary curve.

Even in the most trivial case, that of a level span, direct measurement of sag is not possible (length of conductor, tension, height above ground etc is determined by direct measurements and the sag deduced). In that case it would represent the largest vertical distance between the catenary and its (imaginary) cord.

Because each of these measurements and the method of the conversion of their result into “sag” depend on the applied measurement methods and mathematical approximations, it should be the task of the equipment manufacturer to provide the users necessary information and proof of their assumptions and methods.

5.4 EXAMPLE OF POTENTIAL ERRORS

5.4.1 Accuracy of frequency measures

In the case of frequency measurement there is no need of weather data, topological data, conductor data or sagging conditions.

Errors may thus only occur in the precision of fundamental frequency evaluation.
A basic error analysis on the sag-frequency relationship is giving a ratio between the precision on sag and the precision on frequency (sag error being twice as much as frequency error).

The precision on frequency is thus depending on sampling rate. The sampling rate is depending of needed precision. If we need a 20 cm precision (to agree with section 5) on a sag near 10 m, means 2%, frequency value must then be obtained with a precision of 1 % (the half of the sag precision needed).Basic frequency being near 0,15 Hz , Thus it would need on that frequency a precision near 2 MHz. Such a precision is easily obtained with appropriate value of sampling frequency and number of data.

Former discussion needs to detect movements and being able to extract a frequency spectrum. On that point, sensor sensibility must be chosen appropriately.

5.4.2 Accuracy of temperature measurements

Temperature measuring devices and their measuring capability have already been discussed in other parts of this brochure, the problems being the heat sink effect from the sensor itself, the difference between local spot temperature and mean value for a whole span, the circumferential as well as longitudinal temperature effect due to sunshine and clouds, due to conductor constitution, particularly with high temperature conductor. It should also be noticed that adjacent spans may have different angle of attack of wind, thus conductor temperature may be different and a whole section approach for line rating needs an average line section temperature which may be far from a local value.

5.4.3 Direct measurement of conductor tension, sag or clearance

While all such measurements are functionally equivalent (they all give access to the sags in critical spans as well as corresponding conductor temperature), individual solutions have different resolutions depending on instrumentation, applications and software. A general description of anticipated accuracies is provided in Seppa [1] Section 5.3.3[9]. Mitigation techniques used as well as back up information may be extremely different. For example the basic data captured by the sensors may or may not need a model to be converted into sags and temperatures. If you measure the mean span temperature for example, you need a model to go back to the sag and the reverse is true.

While properly calibrated tension, sag or clearance monitors provide accurate measures of average conductor temperature, determination of temperature rise above ambient conditions requires substantial accuracy of measurement of ambient temperature and solar radiation heating. Ambient temperature variation and solar heating (see §3.3.2) along the line is generally rather small, unless the line is in mountainous terrain[10].

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[9] See especially Footnote 19. Note that in the example case the anticipated temperature resolution for sag measurement is about 0.5°C and tension measurement about 0.25 °C, thus substantially better than for direct conductor temperature measurement.
[10] See references [24], [47] and [56] of Seppa [1] TB 299.

Backup of direct systems are based on the fact that actual measurement is what is occurring on the line at the instant of observation and weather conditions or external action must fit with the observation, that is called the effective weather data .

For example discordance between measured weather data and actual observation may be due to rain (which may be local), consequences of short-circuit heating up, snow accretion, etc…. Moreover critical cases at low wind speed may be considerably affected by the turbulence of the wind which may be very high in such a situation, intermittent higher winds may change drastically the convection. Some systems can follow these events.

5.5 RATING OF A COMPLETE LINE WITH MULTIPLE LINE SECTIONS

Some systems are supervising a full section by dead end installations, some other are supervising critical spans.

The line section, and even inside them, the spans with the lowest rating determines the rating of a complete line. Because the monitoring of every line section/spans is impractical and often not cost effective, it is important to monitor a sufficient number of the line sections/spans which are likely to be most limiting. As ambient and solar temperatures do not generally vary much along a transmission line, the monitored sections/spans should be selected among those being most sheltered by trees or terrain or sites where terrain forces the wind to be parallel to the conductor. .

When line sections/spans are in generally uniform terrain, it appears that conductor temperature distribution between different line sections is close to normally distributed. Certain reports show that within similar terrain, the occurrence of highest average conductor temperatures of the line sections/spans can be determined with a relatively small error (3-6^{o}C) based on a limited number of line sections.[11]

In most cases, thermally limited transmission lines are relatively short, i.e. 20-50 km in length. If 4-6 line sections (or about 10-15 spans) are monitored, the recorded rating or temperature data provides an excellent basis to determine the standard deviation of ratings based on different line sections. Based on engineering analysis of the clearance buffers of the line it is then possible to determine operationally “safe” ratings for the line, e.g. based on two or three sigma probability limits.

The numerous references of Seppa [1] section 4.3.4.6.3 provide important background of the typical variability of ratings along transmission lines. Of especial interest are the findings which show that the occurrence of a given risk for a given limiting rating based on 4-6 line sections is 2-3 times higher than a risk of single limiting line section[12]. Also, two references indicate that on larger scale, wind speed and effective wind speed appear approximately normally distributed.[13]

It is a good practice to distribute the monitored line sections/spans along the line to avoid conditions caused by sudden weather changes. Records from many lines indicate that the distribution of the ratings of line sections show frequent cases where weather fronts have reached one end of the line and sudden wind or rain causes a rapid temperature drop of affected line sections, while other sections still operate at high temperatures.

[11] See references [88] and [105] of TB 299 [1].
[12] See the cases discussed in reference [29]
[13] References [9] and [14] of TB299 [1], discussed in TB 4.3.4.6.3.

6. NUMBER OF REQUIRED MONITORING UNITS FOR A LINE

Direct monitoring systems can be based either on measurement of tension, sag or clearance, in which case the measured quantity will track the average clearance/ temperature over multiple span sections of the line, or alternatively using multiple temperature sensors to estimate the average temperatures of ruling spans. In each case, the number of monitoring systems must be statistically sufficient to meet the criteria of [1] namely to ensure the worst case between (1) the highest of the average temperatures of the ruling span sections determined with an accuracy of about $10^{o}C$ or (2) the worst critical clearance (in critical spans) or the maximum sag in all spans of the sections of the line, with a precision of 20cm . If these criteria cannot be met with reasonable certainty, either (i) the maximum rating temperature should be reduced, or (ii) it must be ascertained that all the line sections have sufficient clearance to operate at the temperature which equals the original rating temperature plus the identified potential temperature error.

Seppa [1], Section 4 shows that ambient temperature, solar radiation and Net Radiation Temperature are consistent and vary little along ruling span line sections. It also shows that wind speed and direction vary substantially and rapidly along even a single span, albeit the average effective wind speed over several spans has significantly lower variation. Thus the number of monitors needs to be selected to cover the expected variability of the wind.

For economical reasons it is not always practical to install a very sophisticated RTM system with sensors on all spans. It is, however, recommended to determine the necessary number of sensors to be installed to get confident in the results delivered by the RTM system.

Prior determining the number of monitoring units to reach the expected sag accuracy, the knowledge of the profile and environmental aspect of the line is fundamental.

The answer to how many sensors must be installed is dependent on many criteria:

- The line length. The number of sensors will not be the same for a 50 km line and for a 5 km line, but the number of the long line will not be 10 times the number of the short one.
- The number of surroundings: urban or rural areas, crossings with main roads, commercial areas….
- The homogeneity or not of the climatic environment:
  - line orientation with predominating wind,
  - existing of wind corridors,
  - forest crossings,
  - difference of altitude

The above list of criteria is not exhaustive.

All these criteria will allow to determine “critical spans” to be instrumented. These critical spans will represent the spans for which, if the clearances are respected, the clearances will be respected on the rest of the line.

So a global answer on the number of critical spans and consequently the number of sensors to be installed is difficult. The answer need to be adapted to each line.

Section 4.3.4.6.2 of [1] and its references deal with local temperature measurements along a line. Of special interest is reference [54] of Seppa [1] which deals with high temperature tests of a special conductor in a heavily instrumented two span line section of 360 m length.

The data indicates that local temperatures could vary as much as 40-50°C, when the conductor was operated at an average temperature of 180°C. Further analysis in reference [74] of Seppa [1] indicates that standard deviations between temperature rises were about +/-15%.

Furthermore, the readings showed both a random variation and a systematic variation. The systematic variation was indicated by predominantly higher temperature rises being recorded by the thermocouples near the centres of the spans.

Other field reports using line mounted temperature sensors references [6] and [16] of Seppa Seppa 2006] indicate temperature differences between 10% and 50-80%, when measured with sensors located between 1–6 km from each other.

This statistical variability leads us to recommend that:

- Determination of the average temperature of a ruling span section requires at least four temperature monitors.
- Unless the statistical variability between the readings is evaluated, the conservative approach would be to use the highest of the four readings as the temperature of the conductor. Alternatively, the temperature should be assumed to be the average of the readings, plus two-sigma level of the temperature distribution.
- Monitors should be mounted at such locations of the span which are closest to ground.

After the temperatures of the ruling span sections are determined with the above method, the rating of the complete line can proceed..

As a first step, more sensors than needed may be installed with a period of observation that would cover most of meteorological conditions. And that would be followed by optimal number of sensors to remain in specific places.

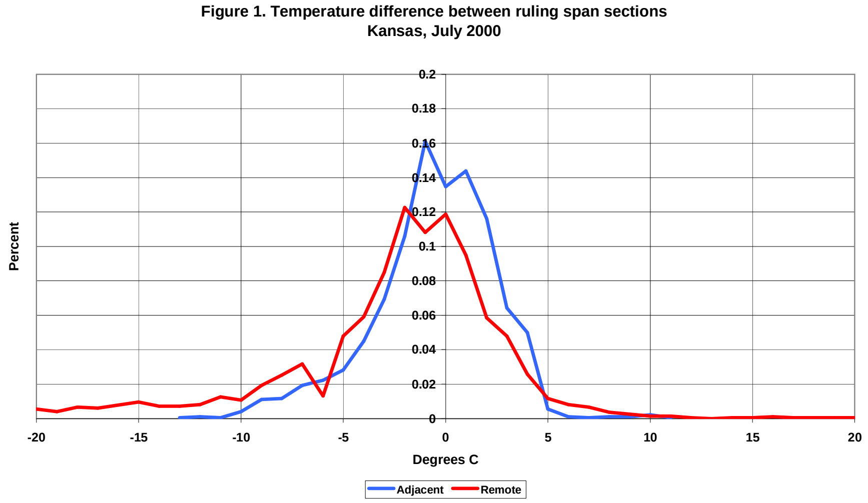
Also the ruling span concept may be tested and better tuned with available redundancies based on spans measured on different span of the same section so that only one sensor per critical section would be needed.

6.1 PRACTICAL EXAMPLES BASED ON TENSION MONITORS REQUIRED

There is a large number of transmission lines with multiple tension monitoring sites in several countries. Four such lines have been selected for analysis. All these lines operate at currents of at least 40% of rated current a substantial part of the selected time period. This is important, as the accuracy of ratings calculation from tension or sag measurements depends on having a reasonable temperature rise. The selected sites are:

1. Kansas, USA, July 2000. 115 kV, 20 km, ACSR “Partridge” 135/22 mm^2. Two monitoring systems, located 10 km apart. One monitors two adjacent spans, the other one a single section adjacent to a substation. Detailed data in [references 105 and 110 of TB 299, [1]]

   The data shows that the standard deviation of the temperature difference of the “adjacent” line sections was 2.8°C and between the “remote” sections 4.5°C. Actually if we eliminate the cases when temperature of one of the line sections was depressed by rain or high wind (approximately 10% of observations), the two-

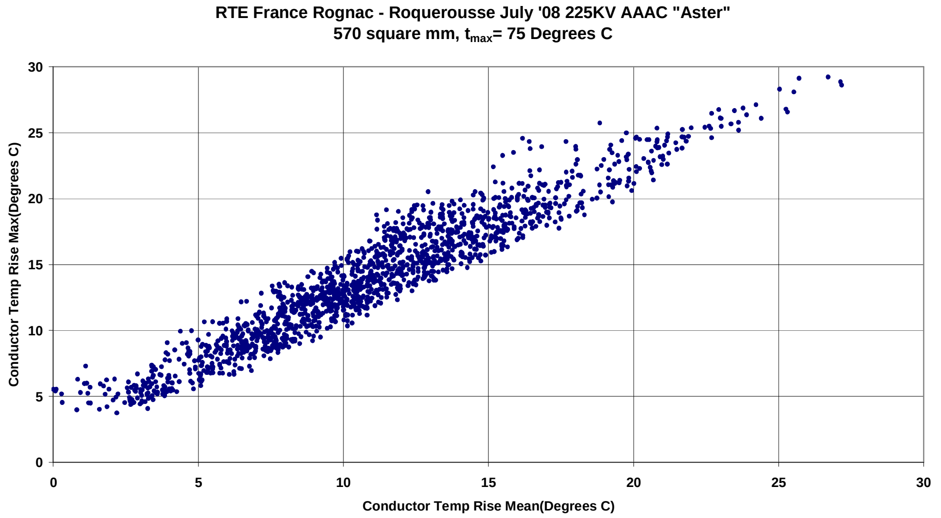


sigma limit is less than 5°C. It appears that the temperature differences are approximately normally distributed as describes in Seppa [1], except under conditions where strictly local events depress the temperature.

Graph XI. Temperature Difference Between Ruling Span Sections In Kansas July 2000

2. Southern France, July 2008, 230 kV line, 30 km. AAAC “Aster”, 570 mm^2, Three monitoring systems of which one monitors two line sections and two monitor one line section each. In this case, as in the two following ones, data is presented as x-y plots, with average temperature rise over Net Radiation Temperature of all sections at y-axis and the highest of all four temperatures at y-axis.

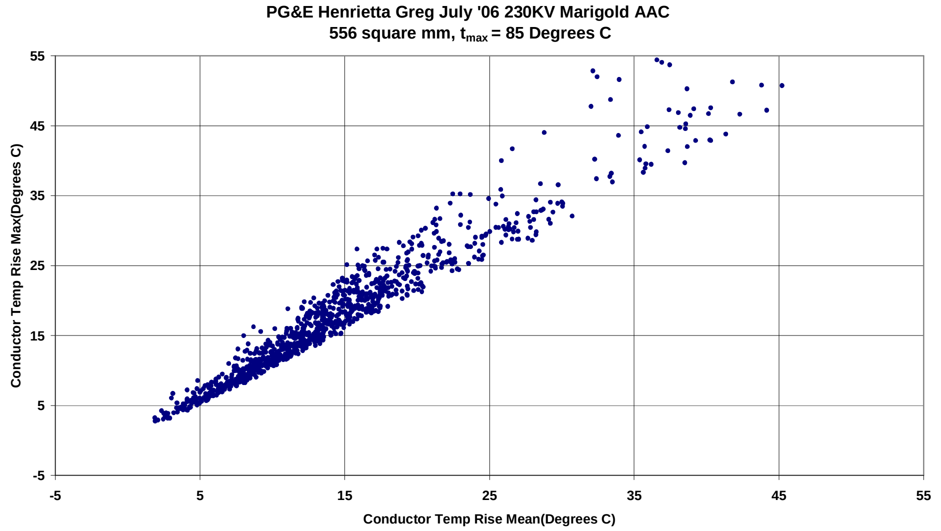
   The data indicates a tight correlation, with a standard deviation of only 2.1°C. Note also that the temperature variation narrows towards highest temperature rises. Temperature rises are fairly well balanced. The four line sections are thermally critical 20%, 17%, 37% and 25% of time, respectively.



Graph XII. **RTE example**

3. PG&E, California, USA. July 2006. 230 kV, 35 km, AAC “Marigold, 565 mm^2. Two monitoring systems, each monitoring two line sections, 16 km apart.

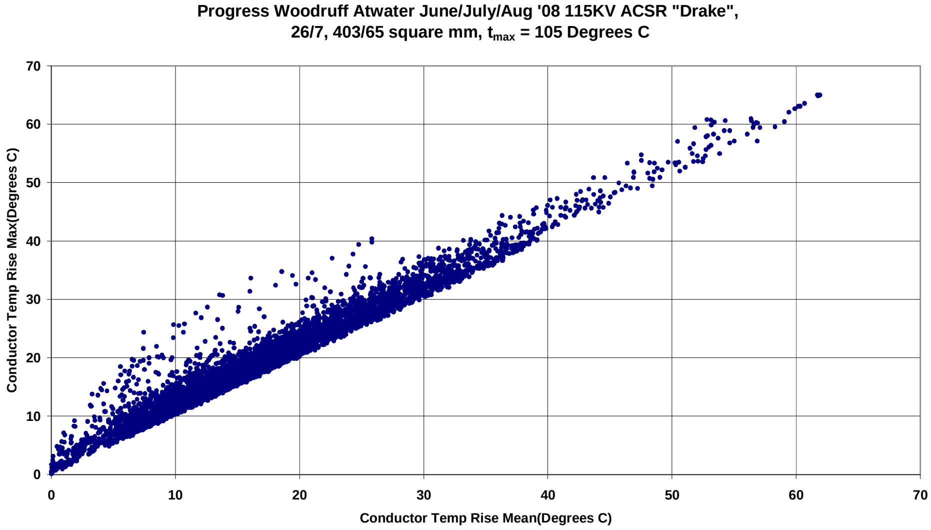
   The data shows good correlation with the standard deviation of 2.9^{o}C, with the exception of a series of 12 observations (average temperature 25-37^{o}C, max. temperature 37-55^{o}C). These observations happened during one night, between 1 am and 3 am). Such events are known to occur occasionally in California’s Central Valley during summer nights. Otherwise, temperature rises are fairly well balanced. The four line section are thermally critical 27%, 17%, 13% and 43% of time, respectively.



Graph XIII. **PG&E example**

4. Florida Progress, USA, 115 kV, 21 km, ACSR “Drake” 26/7, 403/65 mm^2. Three monitoring systems, each monitoring one line section, roughly at 1/3 points along the line. This line was monitored three months, June-August 2008.

   The standard deviation is tight, averaging 2.1°C. Also, the differences between highest and median readings narrow at high temperature rises. The temperature rises are well balanced. The three line sections are thermally critical 43%, 23% and 34% of time, respectively.



Graph XIV. Progress woodruff example

In addition to the above four examples, there are a significant number of other lines monitored with transmission line tension monitors. As long as the terrain is roughly similar along the line and the line length is less than 30 km, the typical finding when monitoring of four line sections of such lines indicates that:

a. Data on temperature rise differences tends to be close to normally distributed, with a typical standard deviation of 2-4°C.
b. Largest individual variations occur during scattered rain events, when some monitored sections are cooled by rain. These events generally happen under weather conditions, which do not represent critical cooling conditions and high temperatures anywhere in the line.
c. If the rating is based on the highest temperature reading of four line sections, the average value of the difference between the highest simultaneous temperature observation and the average of temperature observation represents approximately the standard deviation of temperature differences between line sections.
d. The general finding is that to achieve a 3-sigma certainty towards the objectives as stated in TB 299 [1], i.e. a maximum of 10°C error in any ruling span of the line, monitoring four line sections is sufficient.
e. Exceptions to this rule are:
   - Lines longer than 30 km. Monitored sections need to be increased to account for different weather events along the line. A statistical analysis such as shown above needs to be conducted after the monitor installation to verify that the monitoring installations are sufficient.

- Lines crossing multiple weather zones. In such cases limiting calm conditions may occur at different times and be independent of each other. Examples of such cases are shown in [Reference 29 of TB 299 [1]].

6.2 NUMBER OF SAG MONITORS REQUIRED

This is covering all monitors dealing with the measurement of conductor position including the sag monitor based on wind induced movements.

As already stated these sensors have to be installed in critical spans, means where potential violation of clearances may occur. Clearance violation may be due to different causes which are very similar as the ones explained for tension monitor.

Despite the fact that the measurement of the sag in one span can be used to go back to all other spans of the same section using ruling span concept (simply using the ratio of the square of span length), it is strongly recommended to use these sensors in each critical spans, even if several of them are located in the same section. The information could be redundant but sometimes also it is not the case as ruling span concept may deviate from actual situation on the field (due to local effect or local creep, local clamp slip, etc).

The experience with these devices shows typically that a device every 3 km is generally a good value that has to be adapted depending on terrain condition.

7. ESTABLISHING THE OPERATOR DISPLAY

This section covers the display methods for operators. It is possible that in future the RTM rating feedback will not be displayed to operators but will be linked directly to the EMS system for either automatic operation or linking to the alarms in SCADA.

The man-machine interface required by different operators varies, not only depending the type of application, as described above, but also on the system economics, operating practices and the relevant regulations governing system operation. It is quite common that systems operate only on the background, providing information to the operators only on as-needed base.

Nevertheless, a common requirement is extremely high reliability. Any unusual data or lack of data transmission must lead into operator alarms. In general, this requires the use of same communications paths, methods and error checking as the other elements of the transmission system. When data is needed, it must be displayed on operator’s normal display consoles.

Data displays vary widely from user to user, because of the different vendors of central energy management (EMS) systems and their different ages. It should also be noted that even similar EMS systems have, as a rule, different communications protocols at different utilities.

Another complication is that data needs to be shared between different utilities and between utilities and regional transmission organizations. This can cause complexities that can be seemingly trivial (e.g. the utility rates the lines by MVA and the System operator by amperes!) or complicated because network models may not be similar. Cyber-security rules may complicate data transmission and disallow e.g. use of common carriers. Market-sensitive information may not be allowed outside control room firewalls. For example, actual current of a line is market-sensitive information and is not generally provided for non-operating personnel or entities.

The dated operating rules in some entities also cause complications in advanced applications. For example, accurate transient temperature calculations based on real-time ratings can provide very different results than the traditional rules based on assumed preload and fixed time constants. Similarly, the use of fixed emergency time limits are often not technically justifiable but hard-coded in utility operations. An example of those is a utility system which sets three emergency limits for fixed time intervals (drastic action = 5 min; Short term emergency (STE) = 15 min, Long term emergency (LTE) = 4 hours) for all conductors in their system

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Nevertheless, a common requirement is extremely high reliability. Any unusual data or lack of data transmission must lead into operator alarms. In general, this requires the use of same communications paths, methods and error checking as the other elements of the transmission system. When data is needed, it must be displayed on operator's normal display consoles.

Whatever is the measured physical value in RTM systems to determine the location of the conductor in space (tension, temperature, distance, vibration,..), the sag value or the conductor temperature value are not usable values for the control centre operator. The operator cannot operate the grid with the information that the conductor temperature is actually 38℃ for a reference temperature of 65℃ f or that line. He cannot extrapolate the permissible load increasing for the conductor temperature margin.

For the operator, the essential parameter is the real-time rating of the line which varies during the day in particular with climatic conditions. The operator can compare permanently the real-time rating to the actual load of the line, to appreciate the margin ampacity in case of contingency and load shift.

In case of load shift over the real-time rating, the second essential parameter is the permissible time to maintain the final load after shift, before exceeding the safety distances. This time is necessary for the operator to decide the strategy to adopt to sort out the load constraint of the line and to come back to a permissible value. How many switch operations can be carried out by the operator during this time. If no action is carried out before the end of the remaining time, the operator has to trip the line. The time is displayed when the line load overpasses the real-time rating.

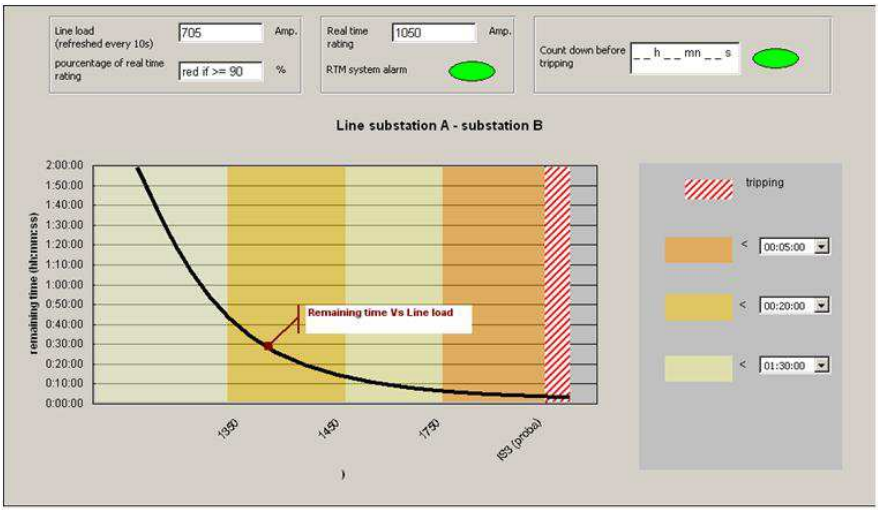
So the parameters which have to be displayed to the operator are:

- line load (MVA or Amp). The line load has to be refreshed very regularly, typically every 10 s
- real-time rating (MVA or Amp.)
- count down or remaining time (min.). This value is displayed if the time is less than 1 or 2 hours per example. Otherwise the time can be considered as infinite. A curve giving remaining time vs line load can be displayed to help the operator to verify that the prepared strategies in (N-1) contingengy are appropriate.

The real-time rating and the countdown have to be refreshed regularly to maximize the time for the operator to choose the best strategy. The refreshment can typically be every 1 min. In operation, the operator has to be alarmed in the following situations:

- the line load is close to the real-time rating (i.e. 90% of real-time rating)
- the countdown is activated due to load increasing over real-time rating
- the failure of RTM system: sensor, controller unit, data transmission ,…

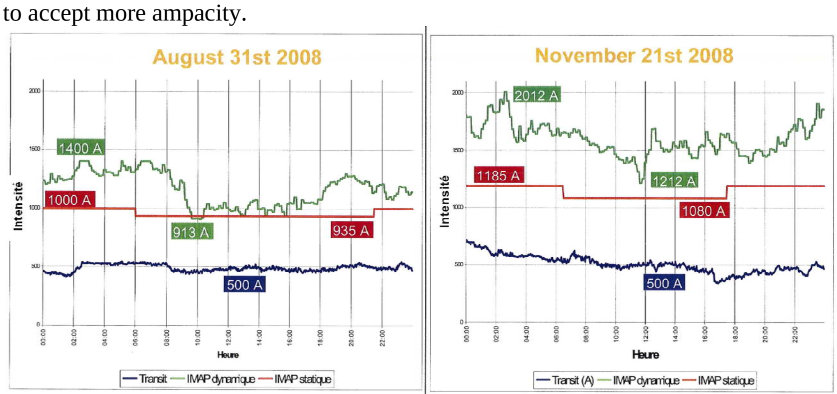
In case of RTM system failure, the operator must be able to come back to line static rating, instead of real-time rating. So the static rating is displayed in case of RTM system failure in the real-time rating window.



Graph XV. **Example of HMI display**

7.1 TYPICAL OUTPUTS OF AMPACITY

Moreover to real-time analysis statistical outputs may be obtained for a global view of the line and its ability to accept more ampacity.



Temperature : from 21 to 29°C

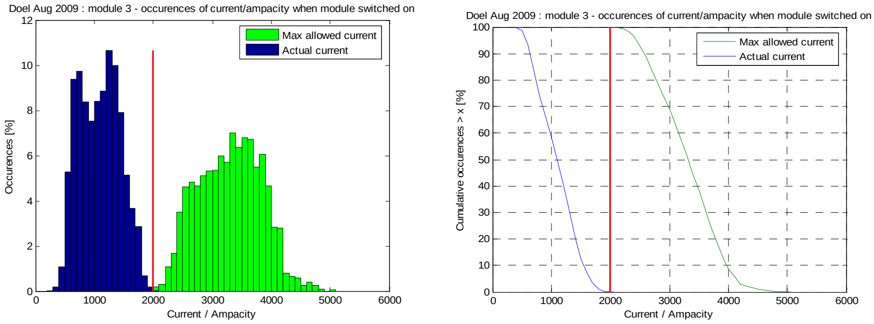
Wind speed : from 4 to 18 km/h

Temperature : from 10 to 21°C

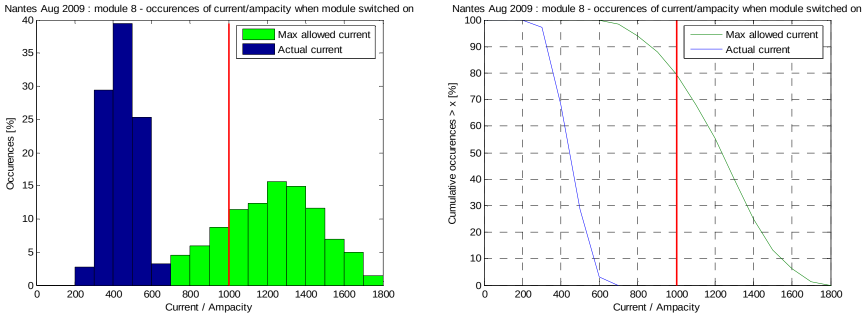
Wind speed : from 26 to 42 km/h

Graph XVI. **Typical real-time outputs (courtesy RTE,)**

The next and Graph XVII and Graph XVIII show an ampacity histogram for some practical cases.



Graph XVII. Typical 400 kv ampacity during august 2009 (twin bundle). Static rating at 2000 a. Occurrences and cumulative occurrences of actual current and available capacity (courtesy elia)



Graph XVIII. Typical 225 kv ampacity during august 2009 (single conductor). Static rating at 1000 a.

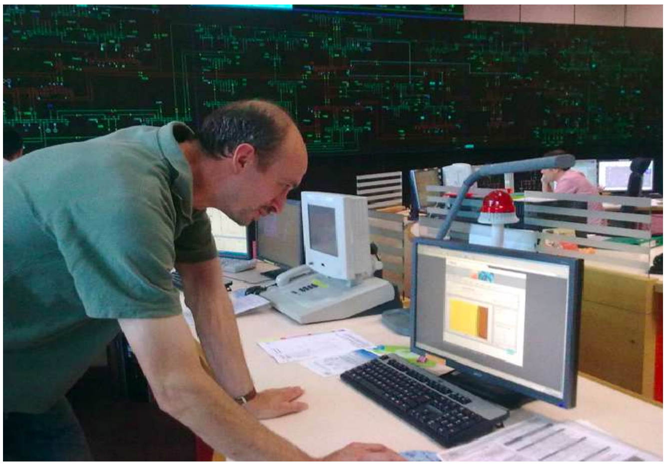
Of course, HV lines must be able to cope with a contingency situation ((N-1)). As can be seen the contingency limit (which would typically exceed actual load by about 40% on these lines) would not cause major problems in the case of Graph XVII but will need appropriate decision in the case of Graph XVIII.

7.2 EXAMPLE OF OPERATOR DISPLAY

RTMs are integrated with control centre consoles and the examples of operator display are shown below. The display generally shows,

- Real-time capability of the line
- Line current
- Additional capability remains
- Current state versus real-time capability
- Comparison to the allowable sag limit
- Duration to clearance violation.

Example 1: Ampacity layout at the control centre level is reproduced



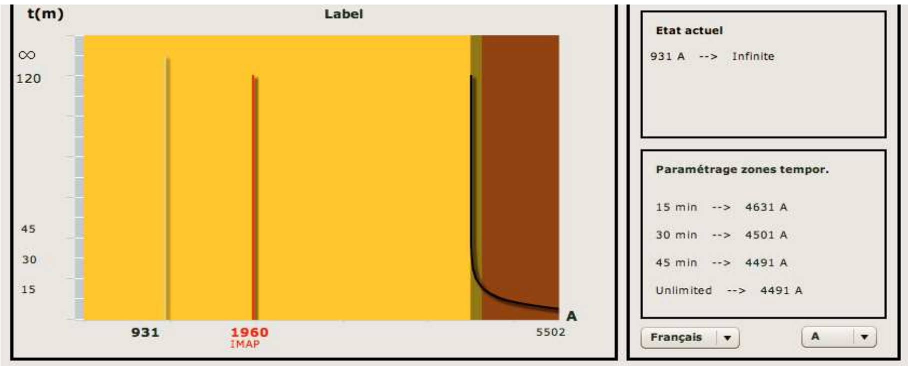


FIGURE XII. EXAMPLE OF DISPATCHER LAYOUT (UPDATED ANY 5 MINUTES) SHOWING ACTUAL CURRENT (931 A), STATIC RATING (1960 A) AND AMPACITY AVAILABLE (BLACK CURVE) (COURTESY ELIA AND RTE)

Example 2

Interface A

Present: 1105 Amps
Maximum: 1456 Amps

Interface A
Clearance Warning

14 Minutes to Violation
Present: 1565A
Maximum: 1565

Example 2 is a simple example of the display to operators indicating the two levels of possible current limits.

Example 3.

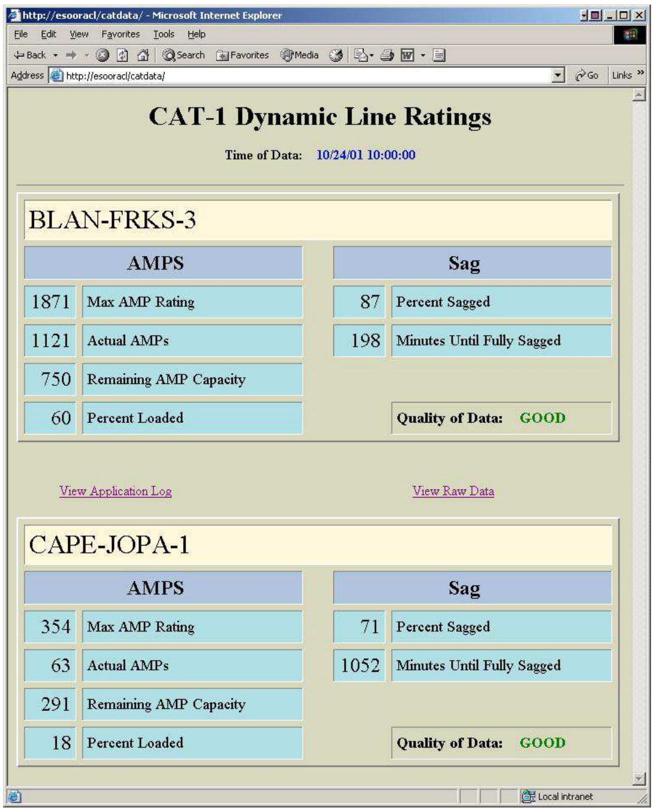


FIGURE XIII. EXAMPLE OF OUTPUT FOR OPERATORS SHOWING MORE DETAIL FOR PARTICULAR LINES.

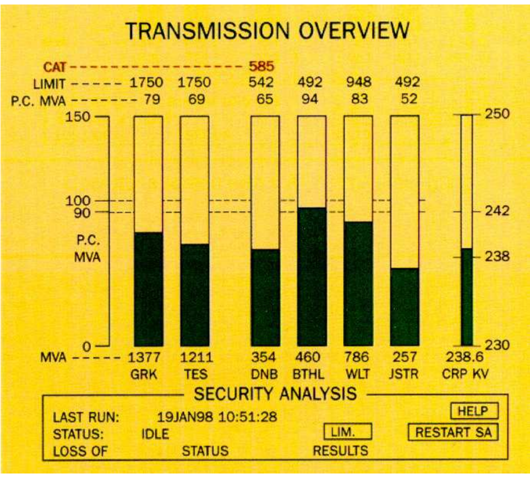


FIGURE XIV. OPERATOR OUTPUT SHOWING THE ACTUAL AND PERMISSIBLE LOADS FROM A THERMAL VIEWPOINT

Example 4.

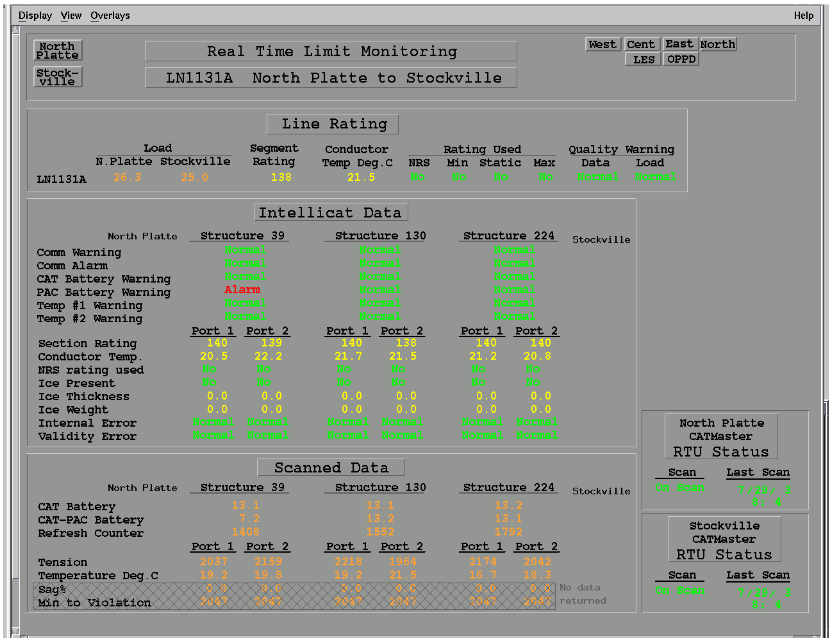


FIGURE XV. SHOWING THE RATING, DATA AND CONDITION OF THE EQUIPMENT.

Example 5.

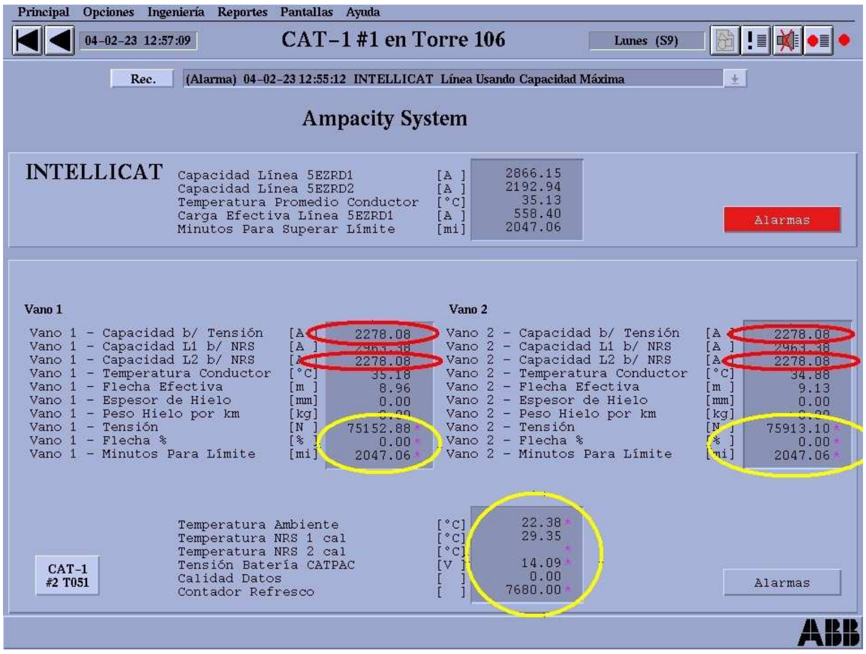


FIGURE XVI. GIVING TENSION AND AMBIENT DATA AS WELL AS RATINGS AND TIME TO REACH THE LIMIT WITH CURRENT LOADING.

The operator displays shown in this section indicate the various items of information which can be displayed to operators. Each operator may have their own preferences with regard to the information required. It is necessary for the suppliers to determine the requirements and screen layout per application.

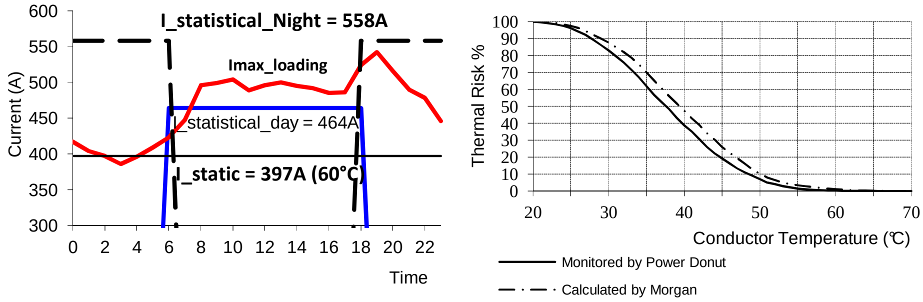
8. APPLICATIONS OF REAL-TIME MONITORING (CASE STUDY)

8.1 CEMIG´S CASE STUDIES

8.1.1 Delay in Construction of New Substation

The Arcos-Divinópolis2 138 kV OHTL is located in a rural area on undulating terrain at altitudes ranging from 700 to 900 meters above sea level was selected for this research because its overload based on construction new substation delay. The conductor monitoring system was comprised of 6 Power Donut sensors were installed along the line for monitoring current and conductor temperature for one year data. The assembly also includes two weathers stations installed at substation and two critical spans 112-113 and 176-177 with only wind speed and direction.

The Graph XIX “left” shows current curves and it is possible to see that this line was on emergency operation “Imax_Loading” almost of the time based in static ampacity. So this line was a very good site for research in ampacity. The Graph XIX“right” shows “1-cdf” Linnet conductor temperature curves integrated at 1 hour during one year intervals as follows: “Tm” = temperatures recorded by the Power Donuts and “Tc” = temperatures calculated using the set of weather data and current values monitored simultaneously.



Graph XIX. Accumulated Distribution of the Calculated and Monitored Temperatures "LINNET Conductor" and Ampacity Profile of Normal and Emergency Conditions.

As final result of this research, based on the real temperature of conductor rarely exceeded template design temperature (60℃) as shown in the Graph XIX "right", even so, by negligible quantities that such fact was an indication that the high loading and worst weather conditions for ampacity (low wind) are very unlikely to occur simultaneously and reinforces the interesting of using monitoring system in the RTM.

8.1.2 Testing Temperature, Tension and Sag systems in the same OHTL

This research has shown the operating principle of some monitoring systems in order to find their advantages and disadvantages. The main applications by comparing them with the three distinct real-time monitoring systems were done in 2003, which were applied on the Neves 1-2, 138 kV transmission line of 12 km long. The FIGURE XVII shows the three sensors researched and the geography its locations at Line.

As final result of this research, based on the three monitoring systems applied in two different spans was found: (i) Both tension and Donut systems as shown in the Graph XIX"left" had a strong correlation when they are applied in the same span. (ii) Sonar system had a good correlation with that of tension and Donut systems in spite of located in different spans as shown in the FIGURE XVIII"right", such facts were an indication that the three different systems can be select to use in a short transmission lines. This research reinforces the interesting of using the monitoring system in the RTM.

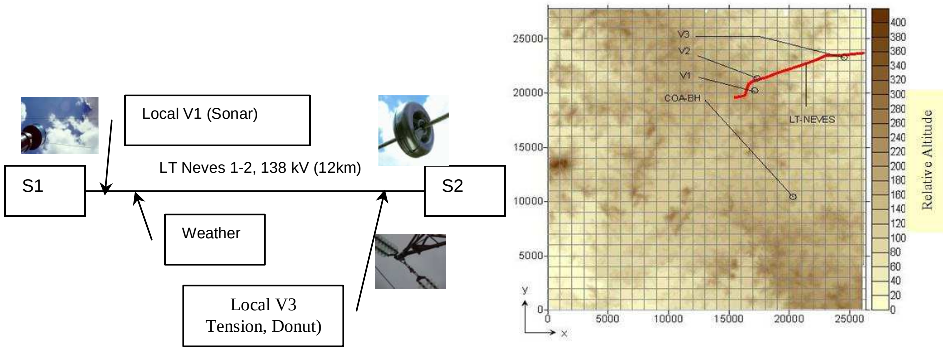


FIGURE XVII. LOCATION OF SENSORS AT OHTL AND GEOGRAPHY LOCATIONS OF RESEARCH POINTS AT LINE.

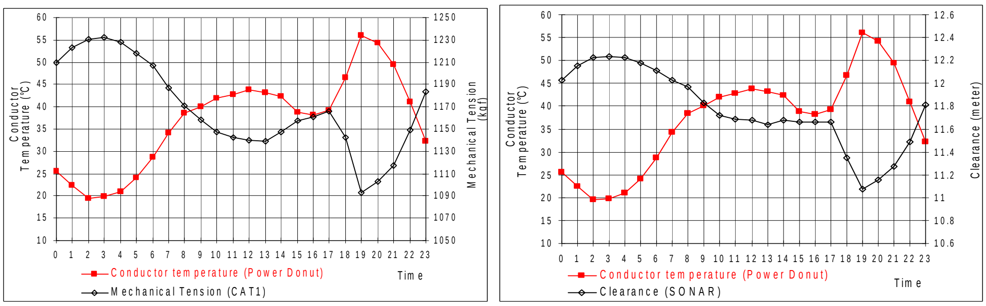


FIGURE XVIII. CLEARANCE (SPAN 4-5) AND CONDUCTOR TEMPERATURE AND TENSION (SPAN 33-34) AVERAGES AT OVERHEAD LINE AS FUNCTION OF HOUR.

8.1.3 Delay in Reinforcements of 138 kV OHTLs

The Cemig´s Planner experienced delay in implementation of the reinforcements to the OHTL in the region named Sete Lagoas in Brazil as shown in TABLE V. To avoid constraints the actual load for Nova Granja – Vespasiano 2 OHTL (calculated 106% based on static rating) in order to support load before the completion of reinforcements OHTL, which effectively ended in May 2010.

OHTL	*(kV)*	*(MVA)*	*Load Calculated (Based on Average Load)*					
			2008		*2009*		*2010*	
			(MVA)	*(%)*	*(MVA)*	*(%)*	*(MVA)*	*(%)*
Nova Granja – Vespasiano 2	*138*	*150*	***155***	***104***	***159***	***106***	***157***	***105***
Nova Granja – Vespasiano 1	*138*	*96*	*78*	*81*	*89*	*92*	*89*	*92*
P. Leopoldo – Vespasiano 1	*138*	*96*	*49*	*51*	*59*	*61*	*59*	*61*
Neves 1 – P. Leopoldo 3	*138*	*147*	*107*	*73*	*108*	*74*	*111*	*76*
Matozinhos – Neves 1	*138*	*146*	*100*	*69*	*107*	*73*	*110*	*75*

TABLE V. Sete Lagoas 138 kV transmission lines system.

TABLE VI presents the numbers analysed during the data collection of one-year study. The first analysis that naturally arises from these data is that the OHTL exceeded of its electric capacity "static rating" as anticipated in the planning study shown in TABLE V, and also overcoming his physical ability in design temperature but even then, only two records into the population of 73,654 monitored and no register exceeded the emergency design of temperature as shown in the FIGURE XIX in more details.

Period of time		*Total of registers (10 min)*	*No. of Registers Exceeded OHTL Vespasiano 2 – Nova Granja, 138 kV*	
from:	*9/nov/2009*	*73654 registers*	*Static rating (625A)*	*56 registers*
to:	*6/nov/2010*		*Normal Design Temperature (93℃)*	*2 registers*
			Emergency Design Temperature (100℃)	*0 registers*

TABLE VI. Resume of analyse data.

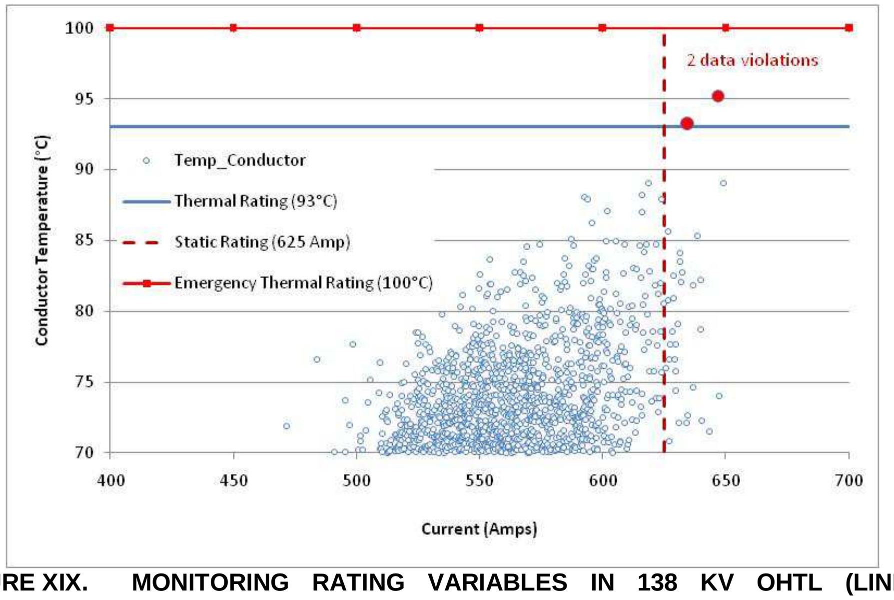


FIGURE XIX. MONITORING RATING VARIABLES IN 138 KV OHTL (LINNET CONDUCTOR).

This should include actual case studies of RTM applications with lessons learnt of failed systems where relevant and success stories with savings.

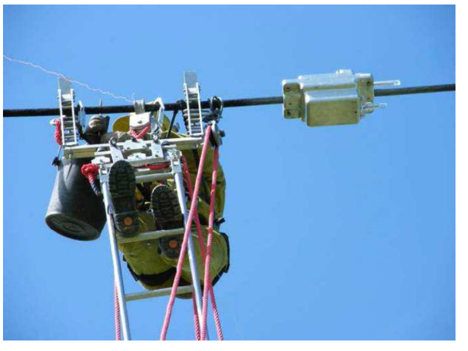
8.2 ELIA (BELGIUM) & RTE (FRANCE) CASE STUDIES

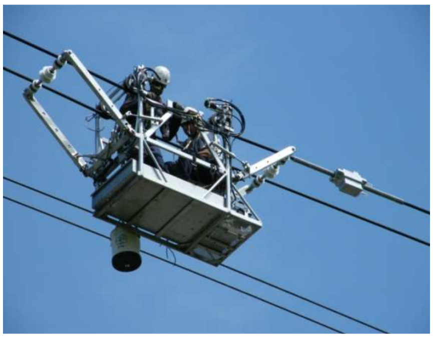
8.2.1 Need for increased capacity due to the connection of new RES production in coastal regions

The growing demand for power is a major challenge for grid operators. The massive implementation of renewable energy sources, especially large costal and off-shore wind farms have triggered the need for additional transmission capacity. All grid operators worldwide face the same problem: it is nearly impossible to build new overhead power lines. In such an environment, transmission system operators must explore the idea of increasing the capacity of transmission lines by maximizing the use of the existing conductors on towers.

Against this backdrop, Elia (the Belgian system operator) and RTE (the French system operator) decided to participate in a project launched by the University of Liège (Belgium) using a vibration monitoring system that converts conductor motion to sag. The pilot experiments lasted for about two years and were successfully completed in 2010.

Phase 1: Measuring sag accurately and reliably

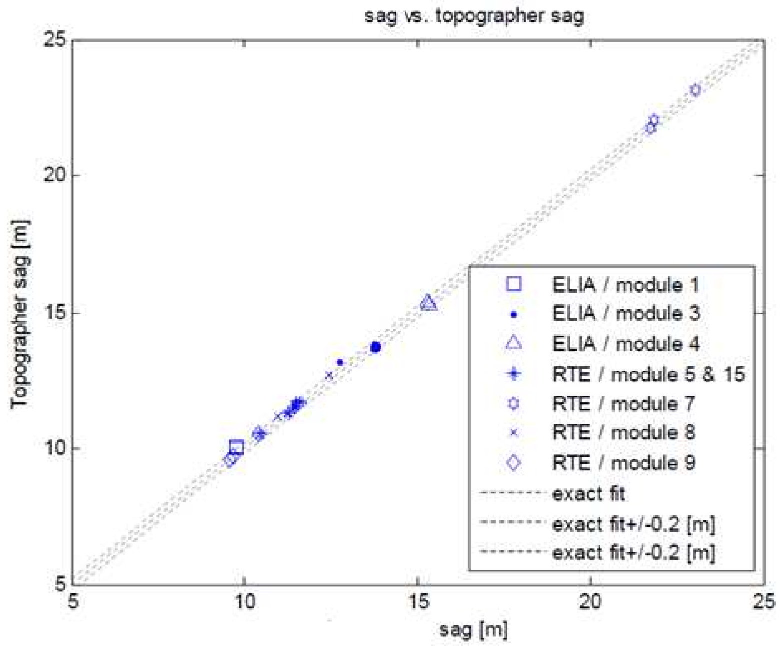




A number of frequency based modules have been fitted to Elia's and RTE's HV grid and connected with the national control centre using the TASE2 protocol.

Romain and Didier, from Fabricom GTI (Belgium) during off line installation of the sensor on a 400 kV line.

Jean-Claude, line man during its live line installation of the sensor on a 245 kV line (RTE-France staff)



Graph XX. sag measured via vibration monitor versus topographer sag

To certify the system, independent land surveyors measured the sag at a given point over a period of several days and on many different spans (different conductors, different span length, suspension span, dead-end span, etc.). Measurements showed a margin of error of around 20 cm, which is accurate enough to predict ampacity.

Phase 2: Determining Real-time ampacity accurately and reliably

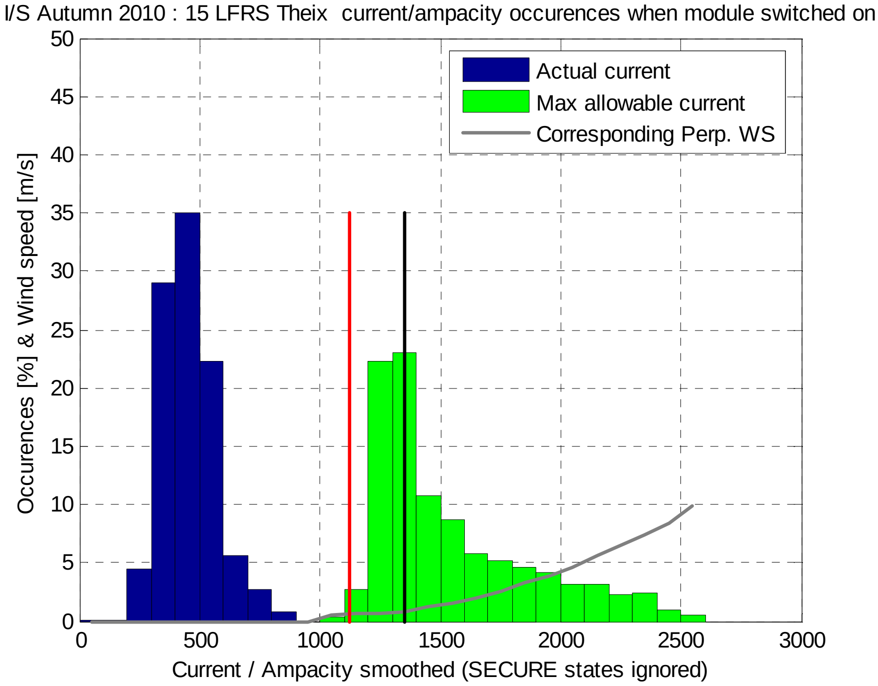
Once the sag measurement was validated the next step consisted in validating the real-time ampacity calculations based on the sag measurement and ambient temperature obtained via existing weather stations in the proximity of the line in question. Wind and solar radiation are not measured but deducted for the sag measurement and current using the state equation to determine the conductor mean-temperature from sag and then using the thermal model with this conductor temperature to determine the experienced weather conditions[14]. The results where validated by the R&D lab of RTE (REX) that confirmed the values based on independent calculations.

The figure below shows an ampacity histogram for a HV lines of RTE in Bretagne (coastal region in the west of France).

Based on observations we can say that the permissible ampacity was far higher than static ampacity, in most cases by at least 20% even using the conservative approach described above. The target in this case was to be able to load the line up to the material limit of 1400

[14] A conservative approach is taken when matching sun radiation and perpendicular wind speed to the obtained conductor temperature that will underestimate the wind most of the time to make sure the calculated dynamic line rating is conservative and never overestimated

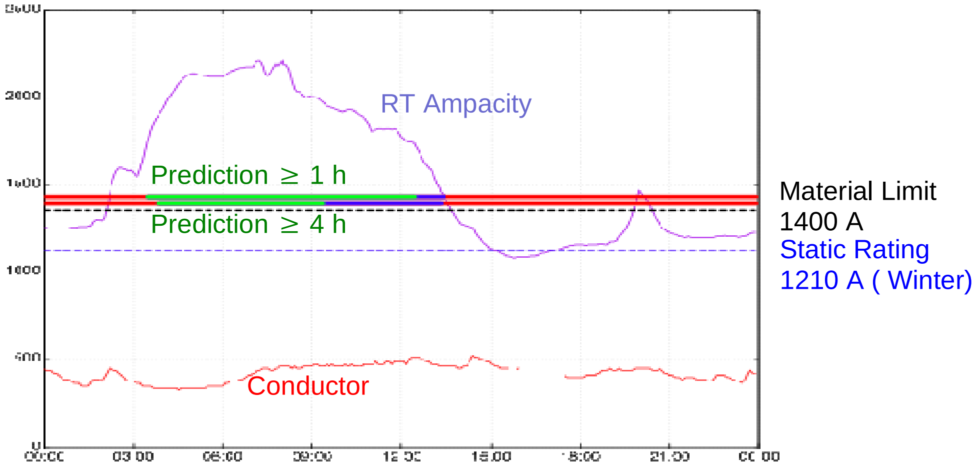
A and this was possible 70% of the time.



Graph XXI. Histograms of occurrences for actual load flow (left part), seasonal static rating (vertical line at 1200 A) and dynamic rating (right part). The vertical line at 1400 A is the target for operators.

Phase 3: Four hours prediction of ampacity

The next logical development step was to predict ampacity for the imminent future. The chosen approach was to predict if the line could be loaded up to its material limit of 1400 A for the coming hour(s) or not as illustrated in the graph below.



Graph XXII. showing the 1 hour and 4 hour predictions for the use of 1400 A(green means yes more than 1 or 4 hours, red means no and blue means yes but less than 1 or 4 hours) and purple the real-time ampacity as was actually measured.

season	dates	duration (days)	prediction 1h	reliability 1h	prediction 4h	reliability 4h
winter 2009	10/11/2009-20/04/2010	160	58%	99,62%	54%	98,5%
summer 2010	10/5/2010-20/9/2010	129	39%	99,60%	39%	94,8%

TABLE VII. showing the occurrences and reliability of the 1 and 4 hour forecasts. The occurrences is the percentage of time that the 1400 A was available during the period, i.e. both the green and blue periods (see graph above).

The predictions where compared with the actual ampacity calculated and proved to be very reliable as can be seen in the table above. The 4 hour predictions where correct nearly 95% of the time even in summer (the figure increasing to 98,5% in winter) and the 1 hour predictions where correct 99,6 % of the time.

It is very important to stress that at no time the secure operation of the line is put at risk: Even if a non expected change in the weather occurs the operator is given enough prior warning to act before the clearance limit is violated; All calculations err on the conservative side.

Phase 4: Next steps

Currently the output of the frequency based system is being integrated in RTE's energy management system where the appropriate alarms are being defined to allow a seamless integration into the working environment of the dispatcher.

At Elia the RT ampacity calculations will be used shortly as input for optimum powerflow calculations to drive the output from connected Windfarms and maximise the amount of energy being injected into the network.

The final phase is to achieve reliable day-ahead ampacity forecasts. This functionality is still under development in the context of the European Union funded Twenties project and should be tested both in France and Belgium before the end of 2011. To achieve reliable forecasts we will combine a locally optimised weather model with the historical data of the vibration system. The forecast will be provided to Coreso, a regional coordination service center owned by several European TSOs coupled with the installation of PMUs (phase monitoring units) and Phase Shift Transformers to demonstrate a new smarter way to operate the pan-European Network and deal with the congestion issues brought along by the integration of large quantities of RES.

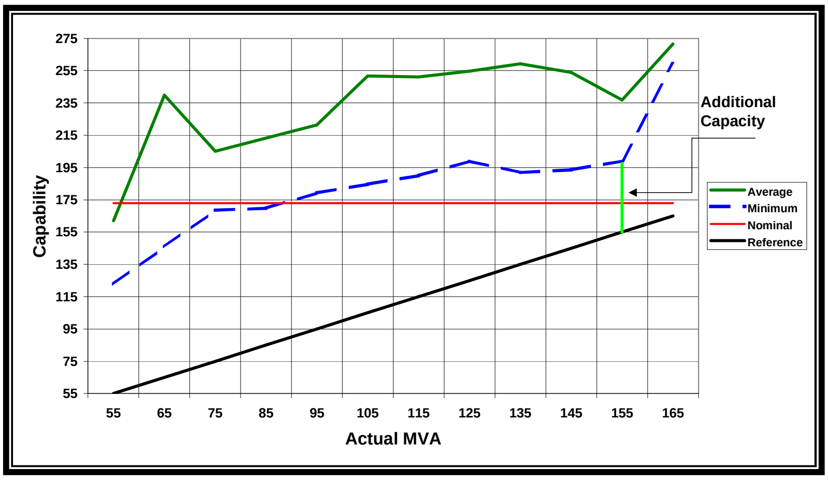
8.3 CASE STUDY: AEP WEST

AEP-West was looking to maximize the output of several wind farms in west Texas. As is often the case, the wind farms were built in a remote location ideal for wind power, but with less-than-ideal transmission access. Additional transmission capacity was needed, but only when the wind farms were operating. AEP-West was quick to recognize the synergy between dynamic thermal line rating and wind generation!

In June 2002, they re-deployed several tension systems from a line that was now being re-conductored. These systems enabled AEP-West to maximize wind generation, ensure transmission reliability, and avoid nearly $20 million worth of line construction and upgrades that would otherwise have been needed.

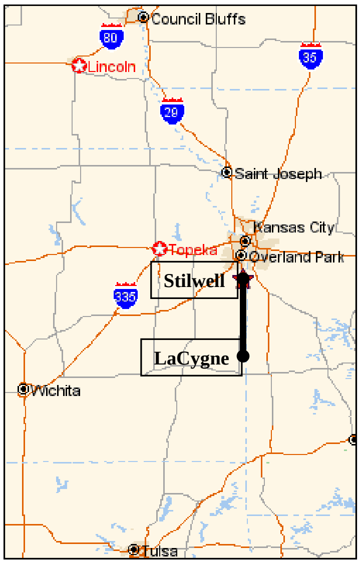
The graph below shows the results of this tension based system application. The wind farm output was previously constrained to the 173 MVA static rating. The reference line shows the actual power flows (i.e. generation output) recorded over the sample period. The top curve is the average real-time line rating, and the middle curve shows the lowest observed rating. Note how line capacity and generation output increase together. When the generation output was 155 MVA, the average real-time capability of the line was typically 235 MVA, and the lowest capability recorded was 197 MVA. The result: This transmission line can be safely uprated by at least 24% (42 MVA) without any chance for generation curtailment. If up to 2% curtailment is allowed, the line rating could be increased by over 60 MVA (35%) without any additional transmission line construction.

It does not take the high wind speeds needed for wind generation to significantly increase transmission capacity. Similar benefits can be found in traditional generation applications as well. More often than not, additional capacity already exists on a typical transmission line, and real-time rating is a proven means of capitalizing on that opportunity while, ensuring system reliability at all times.



Graph XXIII. ACTUAL MVA VS CAPABILITY

8.4 CASE STUDY: KCPL



In February 2002, KCPL began making plans to equip their 32-mile long 345KV Stilwell-LaCygne line with a tension monitoring system Transmission Line Monitoring System. The line had a summer static rating of 1251 MVA.
By June, the system was purchased, delivered, installed, calibrated, and field measurements were taken to assure operations that the data being displayed on their EMS screen was accurate. Over the course of that summer, KCPL was able to safely and reliably operate this line up to 16% above its static rating for 167 hours, recovering the cost of the entire tension monitoring system project in a matter of days!

Since that time, the Stilwell-LaCygne line has been re-conductored, and the tension monitoring system relocated to another line, ready to help KCPL continue to economically provide reliable energy to its customers. This also demonstrates that the tension monitoring Transmission Line Monitoring System is never a stranded investment - it is fully portable, and will repeatedly pay for itself time and time again.

8.5 CASE STUDY TENNET GERMANY

In order to evaluate the sensitivity of direct conductor temperature measurement TenneT TSO compared the results of two different measurement systems: A CAT-1 and a fibre optical cable system of nkt. Additionally the ambient conditions were recorded to investigate the influence. The measuring arrangement is shown in FIGURE XX

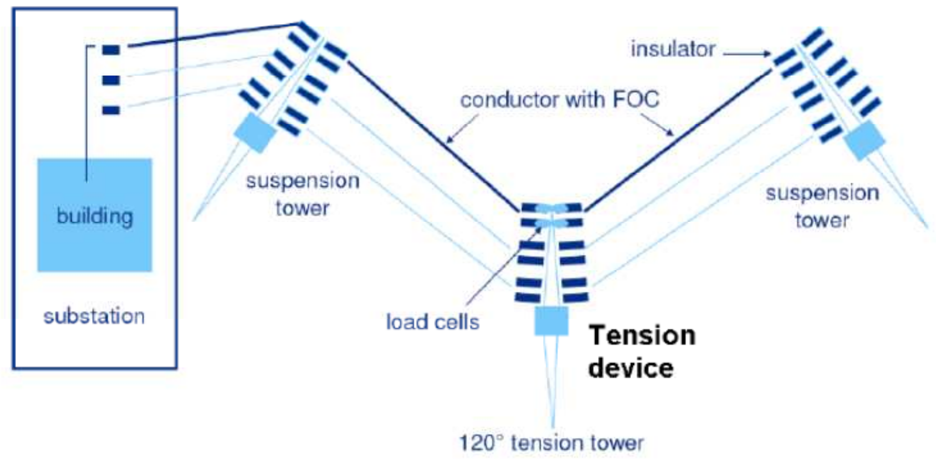
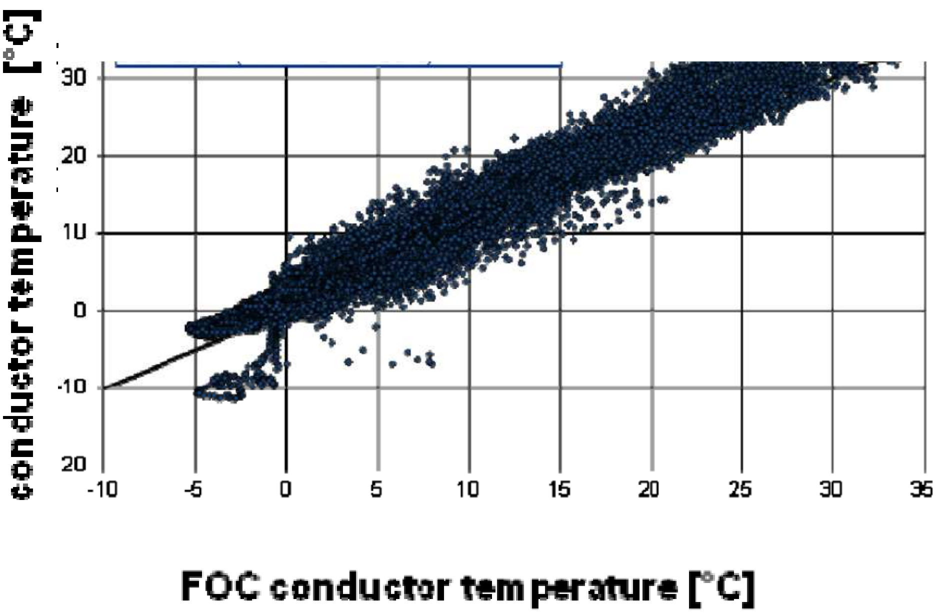


FIGURE XX. MEASURING ARRANGEMENT

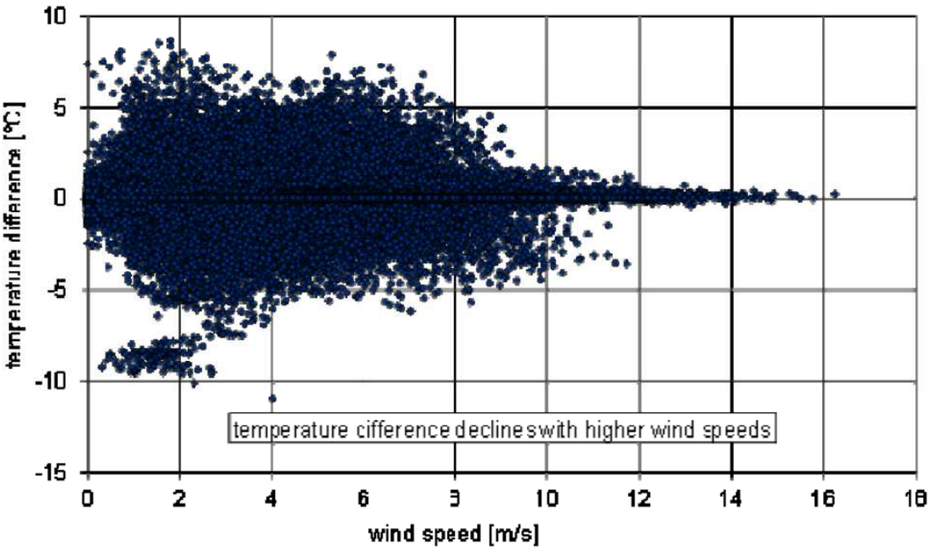
As test track 2 km line section of a110-kV-overhead line in Northern Germany were chosen. A conductor with a FOC was stringed to use the nkt-measuring system for space-resolved measurement of the conductor temperature. The CAT-1 measuring system to detect the mean conductor temperature for a section by tension measurement was installed at the tension tower in the middle of the arrangement.

As shown in the conductor temperature measured by the two systems differs. In 90% of the results the difference is between -3 K and 7 K. With respect to maximum allowed conductor temperature (ACSR 230/30) of 80℃ the deviation is quite high.



Graph XXIV. tension vs FOC temperature

Another observed effect is the dependence of the conductor temperature from wind angle and speed. Regarding the conductor temperature before and after the tension tower, the difference declines with rising wind speeds.



Graph XXV. Temperature difference before and after 120° angle tension tower depending on wind speed

9. LIMITS OF ACTUAL RTM SYSTEMS

In real-time, faced with a contingency, the operator is limited to simple and short term operations to rapidly relieve constraints. To be able to react rapidly and safely to a contingency, the operator needs to have prepared curative remedial action(s) to sort out the problem. The efficiency of a remedial action must be checked in advance, and sometimes must be coordinated with TSO neighbours. When curative actions are not sufficiently rapid, preventive remedial actions need to be implemented before the occurrence of the related contingency.

The use of data coming from RTM system in real-time helps the operator to decide the use or not of the prepared solution(s). If the RTM system indicates that there is a margin on the real-time rating compared to the present load or to the expected load within the next period, the operator decides not to make any modification to the grid structure or to ask for the start of fast generation resources.

Typical solutions available to solve contingencies are:

- Change of network configuration
- TSO to TSO counter-trading (without impacting the market) or Reduction of capacities, (impacting the market)
- Connection of a customer on a single line with the risk of customer cutting in case of grid failure,

- Disconnection of customers (consumers or producers according to the contingency to be fixed). This can be applied to wind farms for which the increasing of line rating is linked to better line cooling in case of wind
- Redispatching of fast generation such as hydro power or gas turbine.

A short term predictive line rating model associated with the RTM system should allow the dispatcher to check that prepared remedial actions are still appropriate or necessary in case a contingency occurs (peak load period or risk of overload in (N-1) contingency). The predictive line rating model should include historical data on the behaviour of the instrumented line given by the RTM system and weather forecasts. Typically a rating prediction of 30 min. or 1 hour should be sufficient to limit the number of curative remedial actions required to manage grid parameters (line load, voltage level) and/or to limit the effect of generation tripping by asking the producer to reduce the generation power and not to trip directly generators.

A longer prediction horizon of line rating of a few hours or even better day ahead is required for an economical optimization of grid use and generation plans. Such a prediction can allow:

- to adapt grid structure to limit grid losses
- to minimize power dispatch by limiting requested generators to minimum power, the necessary power being adjusted few hours ahead to cover peak load periods or by not requesting power dispatch generators if the prediction can be done one day ahead.

It should also be noted that the critical span, i.e. that span upon which the rating of the line is based, will vary from time to time depending on the wind speed and direction or other local phenomena. . All potential critical spans must be supervised. This could be done by different ways, depending on the chosen RTM system.

To conclude the RTM systems allow real-time operations by control centre operators, in case of contingency. An optimization of grid operation with substantial economical savings will be reached with the addition of a predictive line rating model to the RTM systems.

10. CONCLUSION

The RTM systems are designed to ensure that the line conductor is not contravening regulation, safety or operation criteria by monitoring the current situation and calculating the allowable current that can be safely transmitted without such contraventions.

The RTM system does not permit the line to run “hotter” than it is designed for. With RTM systems, the average conductor temperature may be higher than without RTM systems due to the ability to safety determine allowable current for the present weather parameters. But with direct RTM system there will be no violation of maximum temperature or maximum sag (the worst case), which is not warranted using static rating.

Moreover, with direct RTM system, you may be forced to use the line at a lower temperature than the templating temperature, in case of larger actual sag than expected following as-design situation.

10.1 BENEFITS AND APPLICATIONS OF REAL-TIME MONITORING.

10.1.1 Application of RTM

The application of the RTM system will depend on the type of constraint the utility or system operator is facing. It may not always be the solution for uprating of a line; however, it can assist in delaying new construction or accommodating new build delays as shown in the case studies. A particularly interesting and more and more frequent application of a direct RTM system is on lines that are congested due to the integration of renewable production. Currently this production is often curtailed to remain below the static limits of the adjacent network. With a direct RTM system in place it is possible to limit this curtailment to the strict minimum and because increased ampacity due to the wind and volume of renewable (wind) energy go hand in hand (depending on the topology of course) the gains in injected energy can be substantial. Last but not least, direct RTM system may also be used to facilitate cross-border trading.

10.1.2 Contingency management

Traditionally, when a contingency occurs, the operator must change the system dispatch to return the system to a new (N-0) state. This has an economic cost and may, if not properly handled, jeopardize system reliability. Real-time ratings allow the operator to determine if the limiting line is actually overloaded, and either avoid dispatch changes or limit them to a lesser extent than that indicated by static ratings.

10.1.3 Deferral or elimination of capital expenditures.

Line construction or upgrading can be delayed by permits, lack of material, manpower or funds. Increased capability can also be needed only for a limited period of time, for example, to allow for future generation construction, or reduction of demand may limit the period of needed additional line capacity. In such cases, short-term use of real-time ratings systems can be economically or operationally highly advantageous. Note also that at the end of deferral, the monitoring equipment can be relocated to another line.

10.1.4 Dispatch of generation during capacity deficiency.

If there are generation clusters which are in regions connected by lines which have lower capacity than combined generation. Such generation pockets can be better utilized during generation capacity deficiency by use of real-time ratings.

10.1.5 Mitigation of reliability problems

In North America, the reliability rules of system operation have been substantially tightened as a result of the 2003 blackout. Because of the revised, more stringent, NERC standards, the operators now react immediately to any possible violations. On the other hand, NERC rules now specifically allow use of real-time ratings. In case of violations, real-time ratings may offer a fast and the cost effective mitigation solution.

10.1.6 Improving wind power utilization

The best wind power resources are often in areas that are transmission-limited. In many such areas, wind speeds in transmission corridors have a fairly strong correlation with wind generation. Especially with the new “conditionally firm” transmission tariffs, which allow operators to curtail generation for a low percentage of time, real-time ratings can offer the most economical solutions for use of transmission capacity.

10.1.7 Use of higher daytime capability.

In many locations, summer daytime ratings are substantially higher than night time capabilities. This can be utilized in two ways. In areas where air conditioning loads are high, the coincidence of daily load and line capability profiles can be used for improved dispatch through real-time monitoring assuming wind speeds are concurrently high.

Another possible application is for improved dispatch of solar power. Because solar power is located at areas of high solar radiation, the maximum power output may occur at times when wind speeds are higher than assumed in determining the line rating.

10.2 Limitations for operators

Even when networks are heavily loaded, the majority of their transmission lines operate at much lower loads than their thermal limits. This is because the transmission systems must meet all credible contingency events, typically stated as (N-1) or (N-2) states. If a contingency occurs, the operator must then be able to return the system to normal state, typically within 15 to 30 minutes.

A second important limitation involves electricity market rules and practices. In open transmission systems the vast majority of energy is sold in day-ahead markets, based on bidding process. With a few exceptions, transmission network owners can only sell firm transmission capability. Capability which is “almost” firm has no value in such markets. Additional real-time capability may have value in the same day balancing markets, if the ratings for the typical 30-60 minute future time can be shown to have a high enough persistence to guarantee, with very high probability, that the capacity will be available for the needed time period.

The further evolution of direct RTM systems and there combination with reliable ampacity prediction models will open-up further untapped business value in the coming years.

10.3 DIRECT VERSUS INDIRECT SYSTEMS

This document covers direct monitoring systems for RTM. There are other indirect systems such as weather stations used for calculating the allowable current without actually measuring the conductor parameters. This will have additional risk which must be taken into account.

Direct RTM system are also the first step in smart grid sensor applications, other targets than dynamic line rating could be treated with similar systems. Also the combination of direct RTM systems with other “smart grid” technologies like for example WAMS and power control devices make a lot of sense to manage the transmission networks in a more efficient way and substantially enhance the capacity of the total system.

RTM is thus a tool to maximise the use of assets by taking into account the prevailing weather conditions and monitoring the effects on the overhead lines to guarantee safe operations at all times and in all circumstances.

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