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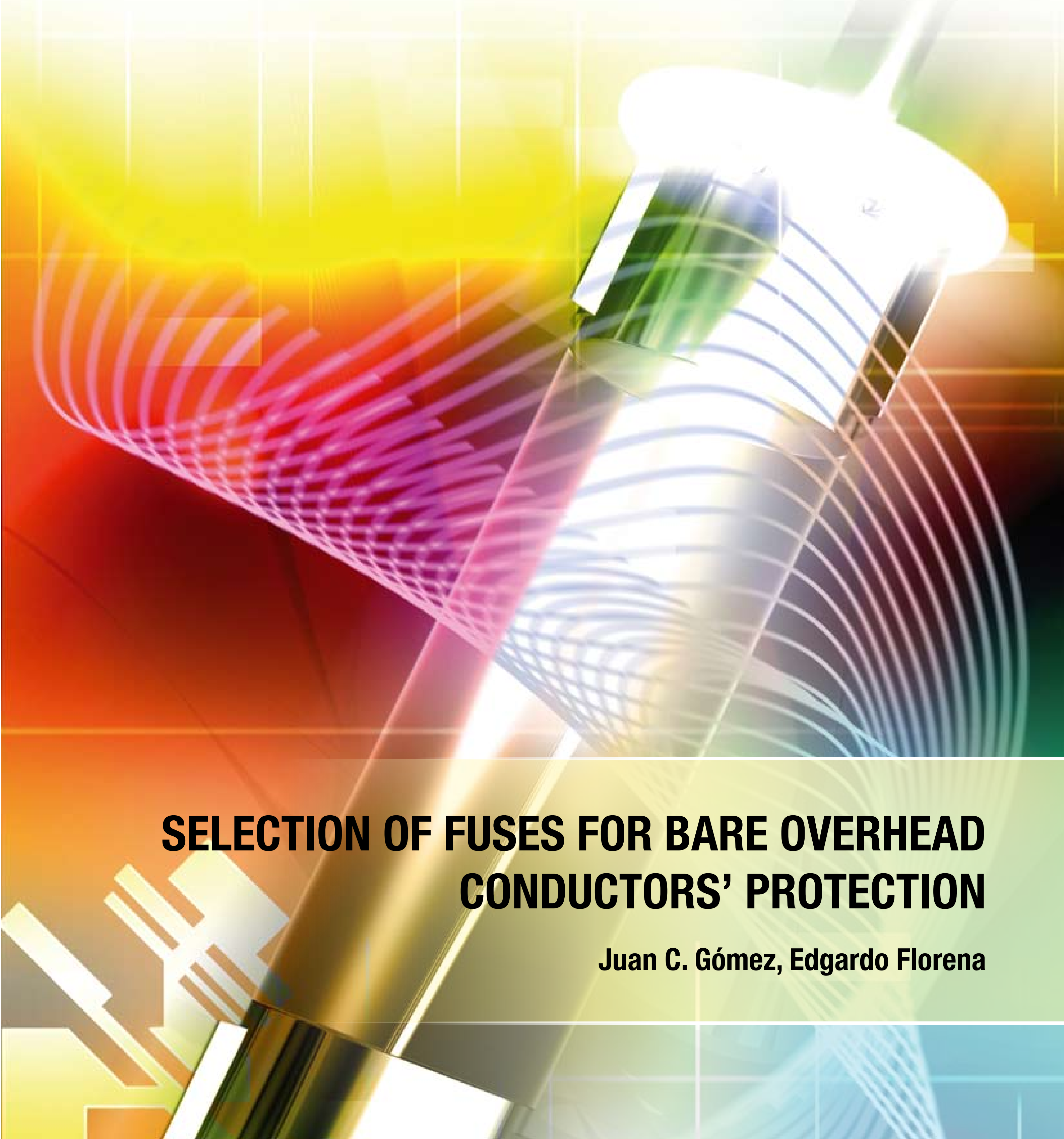

SELECTION OF FUSES FOR BARE OVERHEAD CONDUCTORS' PROTECTION

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Abstract

One of the most widespread applications of fuses in medium voltage distribution systems is the overhead lines protection, but unfortunately and very frequently the people on charge of the fuse selection leave aside important facts of the protection. Usually the fuse is selected taking into account only the selective coordination with other up-stream and down-stream protective devices. Due to this procedure, really the overhead line is not protected against its main problem, the overheating. This over-heating is the cause of the two bare overhead conductors application limits, a. the mechanical strength weakening (annealing), and b. the minimum distance to earth (maximum sag). The paper firstly presents a summarized study of the thermal behavior of bare overhead conductors, under steady-state condition and also for transient conditions after a step change in current, analyzing the heat losses and gains, due to conduction, radiation, convection, overcurrent flow, sun effect, etc. The conductor over-temperature for steady-state conditions can be easily assessed by using a simple exponential equation, after doing two o three iterative temperature estimations and the corresponding recalculations. This analysis allows the determination of the conductor rated current, based on the maximum steady-state temperature normally recommended by the conductor manufacturers. The relationship between the conductor temperature and conductor lengthening and thus sag, is shortly explained. The general equation for transient condition after a current jump is given, explaining the temperature dependence of part of its terms and the difficulties for finding the accurate solution. A simplified solution by linearizing the non-linear equation terms is proposed, which is of easy application and also allows determining for each current value the time needed to reach the limit temperature. With the described methodology a time-current characteristic for the conductor could be draw which can be directly compared with the fuse characteristic in order to assess the protected and not-protected zones. By applying the cooling equation, the over-temperature as time function was assessed, in order to calculate the useful life lost and the conductor creep. This simple methodology allows a more rational fuse selection for the bare overhead conductor protection.

Keywords: overhead conductor, conductor ampacity, conductor sag, alloy annealing, medium voltage fuses, expulsion fuses.

1. Introduction

One of the most widespread applications of fuses in medium voltage distribution systems is the overhead lines protection, but unfortunately and very frequently the people on charge of the fuse selection leave aside important facts of the protection. Usually the fuse is selected taking into account only the selective coordination with other up-stream and down-stream protective devices.

The more used fuse for this application is the expulsion type, which due to its operation principle have the particularities of not being current limiter (low breaking capacity) and its overload protection is not accumulative on time due to the lack of M effect [1].

Elsewhere a thermal model designed for this type of fuse has been presented which has been successfully applied during many years exclusively to the coordination of expulsion fuses and reclosers [2].

Frequently, the fuse protective task is left aside or forgotten. The fuse must protect the overhead conductor against overloads and short-circuits. The overcurrents cause two phenomena, thermal and electro-dynamical stresses, which are the origin of conductor overheating and conductor movement that for the last phenomenon could produce a new up-stream short-circuit.

Due to electro-dynamical forces the conductors can slap together violently and traveling waves moving longitudinally along the line can be also generated. Experience and testing have shown that this action is not damaging to the mechanical strength of conductors or insulators, but it must be carefully considered in the design and selection of spacers and dampers [3]. Thus, if the conductor distances have been properly considered during the line design and construction, the only remaining aspect to be take into account is the overheating; besides, in the medium voltage distribution systems where expulsion fuses are used short-circuit currents are of low magnitude as to produce significant conductor movements or displacement.

The conductor overheating determines the maximum temperature limit that will cause damaging annealing or excessive conductor sag (violating the minimum conductor – earth distance).

There are numerous antecedents of complex studies over bare conductors, for fundamentally determine their ampacity based on the actual current, solar radiation and wind speed and wind direction. The objective of such studies is the determination of the conditions of maximum current capacity to allow the system operator of taking suitable operating decisions. These studies can extend from permanent régime to transients (including short circuits) [4].

The ampacity factors such as current, wind characteristics and solar radiation can be measured, by using expensive and complex equipment in order to extend ampacity of transmission lines, but due to its cost it is not usually applicable to distribution lines protected by expulsion fuses [5].

The conductor, depending of the conductor type, is named:

- AAC All Aluminum Conductor
- ACSR Aluminum Conductor Steel Reinforced
- ACAR Aluminum Conductor Alloy Reinforced

Due to this erroneous procedure of studying only the selective coordination and not the conductor protection, really the overhead line is not protected against its main problem, the overheating. This overheating is the cause of the two bare overhead conductors application limits, a. the mechanical strength weakening (annealing), and b. the minimum distance to earth (maximum sag).

2. Conductor temperature limits

Firstly, it is necessary to present some very important definitions related to overhead conductor applications [3]:

Thermal Limit (as associated with steady-state overload conditions): The maximum temperature at which a conductor can operate continuously yet maintain the minimum tensile properties established by the manufacturer or the user.

Fault-Current Burndown: Failure caused by overheating as a result of a current overload. The conductor strength decreases sufficiently to cause tension failure.

For the present study it is necessary to consider the worst load and ambient conditions as well for the conductor as for the fuse, taking into account pre-load, ambient temperature, sun radiation and wind speed.

The ampacity information generally applies to steady-state normal operation for bare ACSR and all-aluminum conductors for temperatures up to 100ºC (60ºC rise over 40ºC ambient). Each country has its own regulations about critical conditions related to temperature, sun radiation, wind speed, ice covering, etc. This temperature, 100 °C is frequently adopted since the aluminum conductor strands retain approximately 90 percent of rated strength after 10,000 hours at this temperature. For ACSR the strength is even less affected because the steel core is essentially unaffected at these temperatures [3].

2.1. Temperature limit based on mechanical strength weakening (annealing)

- *Under emergency conditions*

The question of what maximum conductor temperatures should be permitted for emergency operation depends on how much loss of strength is allowable and how long the emergency-load temperature continues. The effect of heating is cumulative. As an example, if a conductor is heated under emergency loading for ten hours each year for a period of ten years, the total effect is nearly the same as heating the conductor continuously at that temperature for 100 hours [3].

As explained, the loss of conductor strength due to time at temperature is a cumulative effect, thus heating due to short circuit occurrence should therefore be added to heating due to other circumstances to estimate the condition of the conductor. In actual practice, however, the total time of fault currents is usually very small relative to emergency operating time and is therefore ignored as an effect on conductor strength. A typical practice is to limit emergency load temperatures to a maximum of 125ºC.

The temperature-time strength loss relationship is elsewhere covered in more detail [6].

Figure 1 delineates the effect of time on a type of aluminum conductor strand strength at three temperatures which are of interest to power engineers [3]. The curves permit estimates the change in strength of conductors which have carried emergency overloads.

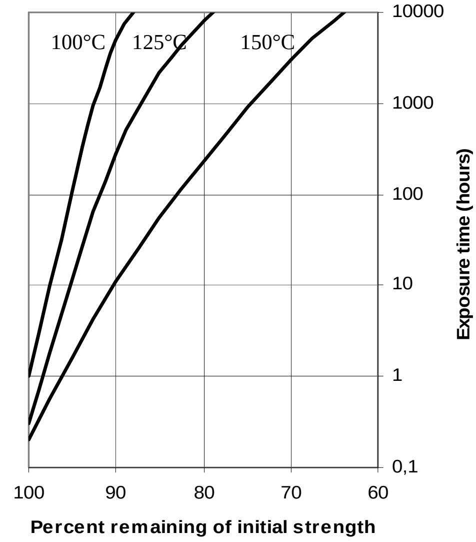

Fig. 1: Time-temperature percent strength remaining (tensile tests made at room temperature after wire exposure to the given temperatures) [3].

- *Under overload and short-circuit conditions*

In establishing suitable fault-current limits, 340ºC has been selected as the maximum temperature for all-aluminum conductors since momentary exposure to this temperature does not result in a significant loss of strength. For ACSR or AWAC conductors with sizeable steel content an upper limit of 645ºC represents the threshold of melting for aluminum with the steel expected to supply the needed mechanical strength [3].

The curves of Figure 2 and 3 apply this criterion to typical bare conductors, using an average specific heat and assuming no heat loss from the aluminum strands during the short duration of the fault current, for 340ºC and 645ºC limits respectively [3].

There are conditions where a lower temperature, limit could be advisable, such as when the bare cable is confined in switchgear or in switching compartments. Other condition such as the use of soldered, copper terminal pads; also may warrant a lower temperature limit.

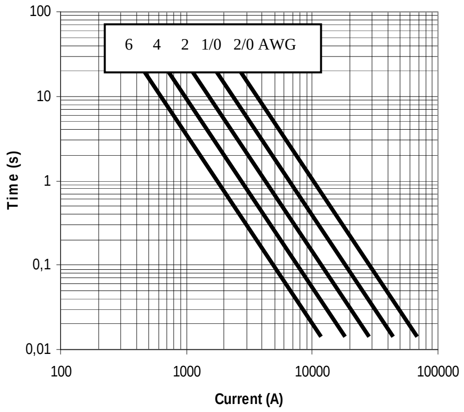

Fig. 2: Maximum fault-current operating limit for stranded aluminum conductor, Upper temperature limit 340°C, ambient temperature 40°C. Note: Time plotted is that required for a given rms fault current to cause conductor damage due to annealing [3].

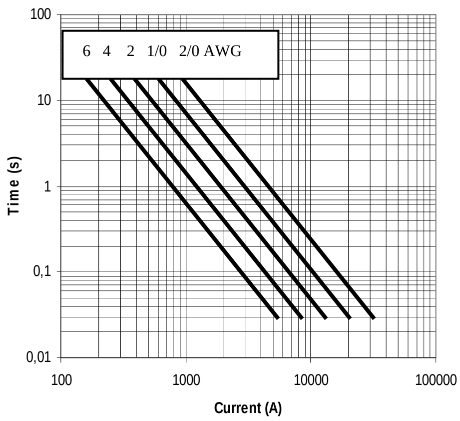

Fig. 3: Maximum fault-current operating limit for stranded aluminum conductor, Upper temperature limit 645ºC, ambient temperature 40°C. Note: Time plotted is that required for a given rms fault current to bring aluminum strands to the threshold of melting [3].

While arcing failure times are so short that little if any change in tension can occur prior to failure, high fault currents can heat the entire line. With modern relaying, the duration of the 60 Hz fault current is usually only from 3 to 20 cycles for transmission circuits but may be longer for distribution lines protected by expulsion fuses.

The resulting increase in sag can establish contact with ground or other conductor, initiating an arcing problem. Clearances can, therefore, be as significant a constraint on maximum acceptable current as is conductor strength.

2.2. Temperature limits based on the minimum distance to ground (maximum sag).

The energized conductors of distribution lines must be placed to totally eliminate the possibility of injury to people. Overhead conductors, however, elongate with time, temperature, and tension, thereby changing their original positions after installation. Despite the effects of weather and loading on a line, the conductors must remain at safe distances from buildings, objects, and people or vehicles passing beneath the line at all times. To ensure this safety, the shape of the terrain along the right-of-way, the height and lateral position of the conductor support points, and the position of the conductor between support points under all wind, ice, and temperature conditions must be known.

Bare overhead transmission or distribution conductors are typically quite flexible and uniform in weight along their length. Because of these characteristics, they take the form of a catenary between support points. The shape of the catenary changes with conductor temperature, ice and wind loading, and also is time function [7].

To ensure adequate vertical and horizontal clearance under all weather and electrical loadings, and to ensure that the breaking strength of the conductor is not exceeded, the behavior of the conductor catenary under all conditions must be known before the line is designed. The future behavior of the conductor is determined through calculations commonly referred to as “sag-tension calculations”.

Sag-tension calculations predict the behavior of conductors based on recommended tension limits under varying loading conditions. These tension limits specify certain percentages of the conductor’s rated breaking strength that are not to be exceeded upon installation or during the life of the line. These conditions, along with the elastic and permanent elongation properties of the conductor, provide the basis for the determination of the amount of resulting sag during installation and long-term operation of the line.

Besides, not all the line spans have the same mechanical tension, neither length nor geographical direction, thus there are too much uncertainties for the precise study.

Accurately determined initial sag limits are essential in the line design process. Final sags and tensions depend on initial installed sags and tensions and on proper handling during installation. The final sag shape of conductors is used to select support point heights and span lengths so that the minimum clearances will be maintained over the life of the line. If the conductor is damaged or the initial sags are incorrect, the line clearances may be violated or the conductor may break during heavy ice or wind loadings.

- *Catenary conductors*

A bare-stranded overhead conductor is normally held clear of objects, people, and other conductors by periodic attachment to insulators. The elevation differences between the supporting structures affect the shape of the conductor catenary. The catenary's shape has a distinct effect on the sag and tension of the conductor, and therefore, must be determined using well-defined mathematical equations.

For level span, the shape of a catenary is a function of the conductor weight per unit length, w, the horizontal component of tension, H, span length, S, and the maximum sag of the conductor, D.

Conductor sag and span length are illustrated in Figure 4, for a level span.

The exact catenary equation uses hyperbolic functions. Relative to the low point of the catenary curve shown in Figure 4, the height of the conductor, y(x), above this low point is given by the following equation (1):

$$y(x)=\frac{H}{w}\cosh\left(\left(\frac{w}{H}x\right)-1\right)=\frac{w(x^2)}{2H} \qquad (1)$$

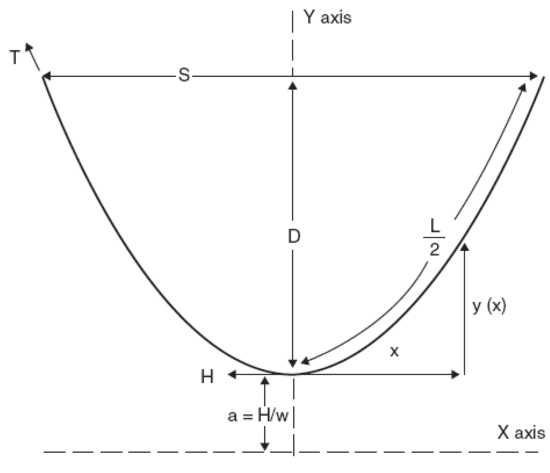

Fig. 4: Catenary curve for level spans.

For a level span, the low point is in the center, and the sag, D, is found by substituting x=S/2 in the preceding equations. The exact and approximate parabolic equations for sag become the following:

$$D=\frac{H}{w}\left(\cosh\left(\frac{wS}{2H}\right)-1\right)=\frac{w(S^2)}{8H} \qquad (2)$$

Doing some changes into the catenary equation it allows the calculation of the conductor length, L(x), measured along the conductor from the low point of the catenary in either direction.

The resulting equation becomes:

$$L(x)=\frac{H}{w}\sinh\left(\frac{wx}{H}\right)=x\left(1+\frac{x^2(w^2)}{6H^2}\right) \qquad (3)$$

For a level span, the conductor length corresponding to x=S/2 is half of the total conductor length and the total length, L, is:

$$L=\left(\frac{2H}{w}\right)\sinh\left(\frac{Sw}{2H}\right)=S\left(1+\frac{S^2(w^2)}{24H^2}\right) \qquad (4)$$

The parabolic equation for conductor length can also be expressed as a function of sag, D, by substitution of the sag parabolic equation, giving:

$$L=S+\frac{8D^2}{3S} \qquad (5)$$

The difference between the conductor length, L, and the span length, S, is called slack. The parabolic equations for slack may be found by combining the preceding parabolic equations for conductor length, L, and sag, D:

$$L-S=S^3\left(\frac{w^2}{24H^2}\right)=D^2\left(\frac{8}{3S}\right) \qquad (6)$$

While slack has units of length, it is often expressed as the percentage of slack relative to the span length. Note that slack is related to the cube of span length for a given H/w ratio and to the square of sag for a given span. For a series of spans having the same H/w ratio, the total slack is largely determined by the longest spans. It is for this reason that the ruling span is nearly equal to the longest span rather than the average span in a series of suspension spans.

The previous equation can be changed in order to obtain a more interesting relationship showing the dependence of sag, D, upon slack, L-S:

$$D = \sqrt{\frac{3S(L-S)}{8}} \quad (7)$$

As can be seen from the preceding equation, small changes in slack typically yield large changes in conductor sag.

- *Effect of the temperature change on conductor sag*

If the conductor temperature changes from a reference temperature, TREF , to another temperature, T, the conductor length, L, changes in proportion to the product of the conductor's effective thermal elongation coefficient, α_{AS}, and the change in temperature, T – TREF , as shown below:

$$L_T = L_{T_{REF}} \left(1 + \alpha_{AS}\left(T - T_{REF}\right)\right) \quad (8)$$

For example, if the temperature of the certain conductor increases from 15ºC to 75ºC, then the length at 15ºC increases by 0.21 m from 182.96 m to 183.17 m:

$$L_{(75°C)} = 182.96\left(1 + \left(19.13*10^{-6}\right)\left(75-15\right)\right) = 183.17m$$

Ignoring for the moment any change in length due to change in tension, the sag at 75ºC may be calculated for the conductor length of 183.17 m using Equation (7), resulting:

$$D = 4.456m$$

Using a rearrangement of Equation (6), this increased sag is found to correspond to a decreased tension of:

$$H = 1{,}527kg$$

If the conductor were inextensible, that is, if it had an infinite modulus of elasticity, then these values of sag and tension for a conductor temperature of 75ºC would be correct. For any real conductor, however, the elastic modulus of the conductor is finite and changes in tension do change the conductor length. Use of the preceding calculation, therefore, will overstate the increase in sag.

For the present study, it is not worthwhile to consider the change in H and of there to recalculate the new change in D.

The analysis of the interaction of the thermal expansion rates, component stress levels and differing creep rates at elevated temperatures to determine the effect of high temperatures on final sags is very complex. High temperatures for time periods which may seem short in terms of the life of the conductor can result in significant changes in sag, especially for the conductor constructions which do not have significant proportions of steel. A method of practical calculations has been presented elsewhere [6].

3. Conductor thermal analysis

A detailed and justified analysis of the aluminum conductor thermal calculation can be seen in specific publications [8].

The conductor over-temperature for steady-state conditions can be easily assessed by using a simple exponential equation, after doing two o three iterative temperature estimations and the corresponding recalculations. This analysis allows the determination of the conductor rated current, based on the maximum steady-state temperature normally recommended by the conductor manufacturers. Here the simple analysis is presented to solve the general equation for transient condition after a current jump, explaining the temperature dependence of part of its terms and the difficulties for finding the accurate solution.

3.1. Simplified solution

A simplified solution by linearizing the non-linear equation terms follows which is of easy application and also allows determining for each current value the time needed to reach the limit temperature.

The conductor surface temperatures are a function of the following properties [9]:

- Conductor material properties
- Conductor diameter
- Conductor surface conditions
- Ambient weather conditions
- Conductor electrical current

The first two of these properties are specific chemical and physical properties. The third may vary with time and be dependent upon ambient atmospheric conditions other than weather. The fourth, weather, varies greatly with the hour and season. The fifth, conductor electrical current, may be constant or may vary with power system loading, generation dispatch, and other factors.

The equations relating electrical current to conductor temperature may be used in either of the following two ways:

- To calculate the conductor temperature when the electrical current is known.
- To calculate the current that yields a given maximum allowable conductor temperature.
- To select the more suitable overcurrent protection

For the purposes of this article, either the electrical current is assumed constant for all time or it is assumed to undergo a step change from an initial current to a final current. The ambient weather conditions are assumed to be constant with time in both the steady-state and transient calculation methods described in this standard [9].

Maximum allowable conductor temperature: The maximum temperature limit that is selected in order to minimize loss of strength, sag, line losses, or a combination of the above.

The non-steady-state heat balance of the bare conductor is as follows:

$$q_c + q_r + mC_p \frac{dT_c}{dt} = q_s + I^2 R(T_c) \qquad (9)$$

Where

q_c	Convected heat loss
q_r	Radiated heat loss
q_s	Solar gain
mC_p	Total conductor heat capacity
$R(T_c)$	Conductor electrical resistance

Once the steady-state conditions are reached (the term of temperature variation on time disappears), the previous equation becomes:

$$q_c + q_r = q_s + I^2 R(T_c) \qquad (10)$$

$$I = \sqrt{\frac{q_c + q_r - q_s}{R(T_c)}} \qquad (11)$$

The non-steady-state heat balance Equation (9) cannot be solved analytically for conductor temperature as a function of time since certain of its terms are non-linear [9].

Considering the equation term by term, it may be seen that the ohmic heating term, and the forced convection equation term are linear in conductor temperature. The solar heating term is also linear since it is independent of conductor temperature. The radiation heat loss term and the natural convection (zero wind speed) term are both non-linear in conductor temperature.

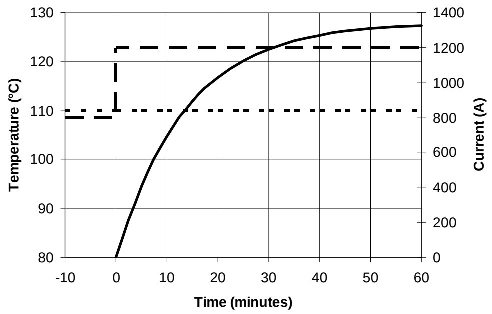

Fig. 5: Step change in current.

A method of approximating the radiation cooling equation as a linear function of temperature has been described. Doing so yields a linear non-steady-state heat balance equation of the form shown in Equation (12) [10]:

$$\frac{d}{dt}(T_c - T_a) = K_1 (T_c - T_a) + K_2 I^2 \qquad (12)$$

For a step change in electrical current, the solution of the linearized non-steady-state heat balance equation is shown in Equation 13.

$$T_c(t) = T_i + (T_f - T_i)(1 - e^{-t/\tau}) \qquad (13)$$

The steady-state conductor temperature prior to the step increase in current is Ti. The steady-state conductor temperature which occurs long after the step increase in current is Tf. The thermal time constant, τ, may be calculated by use of Equation (14).

$$\tau = (T_f - T_i)\, m\, C_p \,/\, (R(T_c)\, (I_f^2 - I_i^2)) \qquad (14)$$

Where the conductor resistance is that corresponding to the average conductor temperature, that is $(T_i + T_f)/2$.

Consider the exponential change in conductor temperature shown in Figure 5, due to a current step change. The initial conductor temperature is 80

°C. The final conductor temperature is 128 °C. The current undergoes a step change from 800 to 1200 amperes. If the average conductor temperature is taken as 100 °C, the resistance of the conductor is 9.38 × 10-5 ohms/m and the heat capacity of the conductor is 984 W-s/m-°C. The time constant calculated by applying equation (14) results:

$\tau = 13.8$ min

Alternatively, the temperature change reaches 63% of its final value at a conductor temperature of:

80 °C + (128 – 80) × 0.63 = 110 °C.

From Figure 5, this corresponds to a time of about 14 min.

4. Conductor time – current characteristic

With the described methodology, from the temperature – time graph a time-current characteristic for the conductor could be draw which can be directly compared with the fuse characteristic in order to assess the protected and not-protected zones. For each current value the crossing point of the corresponding curve and the 110ºC horizontal line (figure 6) indicate the time for the time – current characteristic curve of figure 7.

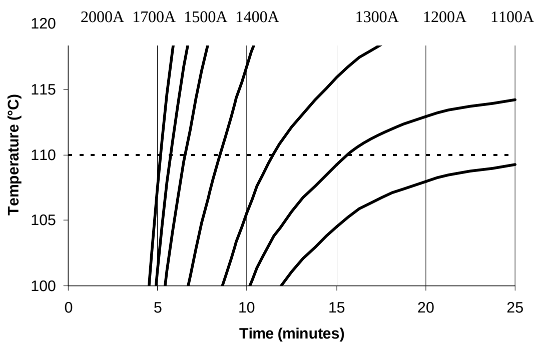

Fig. 6: Time for reaching the limit temperature as function of overload current.

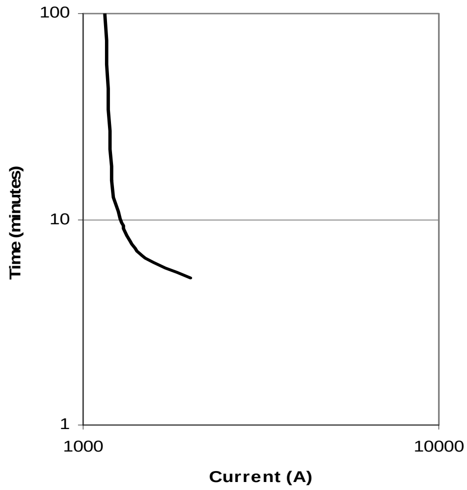

Fig. 7: Time – current characteristic obtained from figure 6.

5. Useful life lost

The permanent elongation caused by everyday tension levels is called creep, which is plastic deformation that occurs in metal at stresses below its yield strength. Creep elongation in aluminum conductors is quite predictable as a function of time and obeys a simple exponential relationship. Creep is assumed exponential with time. Thus, conductor elongation during the first day under tension is equal to elongation over the next week (first six months equals to the next 9 ½ years). Using creep estimation formulas, the creep strain can be estimated and adjustments made to the stringing sag tables in terms of an equivalent temperature.

Thus, the permanent elongation due to creep at everyday tension can be found for any period of time after initial installation. Creep elongation of copper and steel conductors is much less and is normally ignored [7]. It must be remembered that the aluminum conductors loss useful life or in other words suffer of an accumulative phenomenon called “creep”, which is due to the time, tension, temperature. Besides, creep of an overhead conductor at high temperature is a single-valued function of the sum of the time the conductor was operated at the elevated temperature [6].

As previously mentioned, expulsion fuse has not the ability to “accumulate or remember” the duration of damaging conditions unlikely the high breaking capacity fuse provided with M effect. In spite of its low application in this type of distribution systems, fuses provided with M effect can consider or represent the conductor “useful life lost” by the increase of the main fuse element dissolution due to the low melting temperature component diffusion into it. The coordination or protection selection is given by using thermal models including this diffusion [11].

6. Conductor – fuse coordination

Having the conductor behavior represented by a simple exponential equation and by a time-current characteristic, the conductor – fuse coordination can be given by direct comparison of the homologues curves. Normally it is chosen to work on the time-current characteristics due to the other protective devices characteristics are given in this way.

7. Conclusions

A simple methodology has been presented, which allows a more rational fuse selection for the bare overhead conductor protection. The methodology permits to carry out the bare conductor protection against over-temperature considering conductors annealing and maximum sag (or minimum conductor – soil distance).

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