Analysis of Traditional Suspension Strings With GTACSR Conductors

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***Abstract*—The technological development experienced by industrialized countries has brought about a huge increase of demand for electric power. As a result, the utilities in charge of electric power transmission and distribution have noticed that the high-voltage overhead lines are reaching critical values of ampacity and sag. In order to tackle this issue, we have undertaken the analysis of the eventual replacement of traditional aluminum conductor steel reinforced (ACSR) conductors with other conductors of better thermal properties.**

In the present paper, we report on the results obtained about how well the suspension strings of the ACSR conductors perform with the gap-type aluminum conductor steel reinforced (GTACSR) conductors. This study has been achieved using a multipurpose finite-element analysis (FEM) software package for both design and simulation.

***Index Terms*—finite-element method, GTACSR, low-sag conductors, simulation, suspension string, thermal performance.**

I. Introduction

BOTH the technological growth and the increase of the quality of life experienced in recent decades by the most industrialized countries in the world have led to a growing demand for electrical power. In order to meet this increase in demand, existing electrical transmission lines are being forced to transmit increasingly higher power loads. As a result, two major problems are faced.

- The ampacity of some transmission lines is close to its critical limit. This limit should be reached only in contingency situations.
- The higher power transmission automatically results in a higher temperature in the conductor; the ensuing dilatation has the effect of augmenting the total length of the conductor and, as a result, the increasing sag may eventually overcome the safety limits.

The most obvious action that can be taken in order to cope with this increase in demand is the installation of new transmission lines. However, the high population density, together with the intensive use of land, as well as the increasing rejection that the setting up of new electrical installations causes in important sectors of society, determine that an ever smaller amount of space is available to be dedicated to transmission systems. Therefore, the space available for laying out electric power transmission and distribution lines must be optimized.

The current Spanish legislation ruling the construction of overhead transmission lines establishes a great number of previous steps such as permissions, public presentation of the project, rights for the presentation of allegations, etc. As a matter of fact, it clearly follows that in many cases, the period of time elapsed since the need for the installation of a line arises until the line is finally commissioned can easily be a decade or longer.

In this situation, one of the most accessible solutions to be considered appears to be the use of high-temperature, low-sag conductors [1]–[5]. For instance, the so-called GTACSR-type conductors allow for continuous working temperatures as high as 150 °C, whereas the conventional conductors currently installed in electrical lines can withstand only 80 °C.

These high-temperature low-sag conductors can replace the current ones without either modifying the original design of the supporting structures, or requiring new rights of way that could alter the present use of the land involved.

Nevertheless, the extent to which the suspension strings of the original conductors can be used with the new high thermal performance conductors has to be carefully evaluated for the considerable temperature increment of the conductor (from 80 °C up to 150 °C) which might invalidate the correct functionality of the suspension string and/or that of the insulator chain [6]–[8].

A previous step before laboratory test is the computer simulation. The simulation will allow to develop laboratory tests with a higher security range.

In this paper, we present the theoretic analysis of the behavior of the suspension strings, performed under different operating conditions so as to test the validity of the traditional suspension strings with the GTACSR conductors.

II. General Characteristics of GTACSR Conductors

The so-called GTACSR "gap"-type construction conductors are modified traditional ACSR conductors capable to operate at 150 °C while maintaining sags similar to ACSR conductors and, thus, capable of carrying an approximately 1.6 times higher current.

These conductors, made up with several layers of aluminum wires of 60% conductivity surrounding a steel core, are characterized by the fact that the aluminum wires of the innermost layer are trapezoidal in section so that a gap is cleared between

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TABLE I
PROPERTIES OF CONDUCTORS ACSR-HEN AND GTACSR-260

	ACSR (HEN)	GTACSR (260)
Diameter (mm)	22.4	23.1
Cross sectional area (mm2)	241.7	261.3
Steel area (mm2)	56.4	56.3
Mass (kg/km)	1112	1188
D.C. Resistance 20ºC (Ω/km)	0.120	0.113
Rated tensile strength (daN)	10534	13020

the steel core and the aluminum layers. This gap is usually filled with a grease resistant to high temperatures. This construction method allows the reduction of the friction between the core and the aluminum layers.

These GTACSR conductors show a transition temperature (between 10 °C and 20 °C) above which all of the mechanical resistance of the conductor is provided by the steel core. Hence, the GTACSR conductors can be strung by tightening only the steel core, leaving the aluminum layers untightened.

The fact that the mechanical stress of the core is at any time independent of the aluminum stress implies that sag increase in these conductors is smaller than in the ACSR type, because the sag depends almost exclusively on the linear expansion coefficient and on elongation characteristics of the steel core. Considering that only the steel core supports the mechanical stresses, the steel used in GTACSR-type conductors has a high breaking strength (180 $\mathrm{kgf/mm^2}$ compared to 130 $\mathrm{kgf/mm^2}$ of an ACSR).

GTACSR conductors exhibit external dimensions similar to ACSR conductors, although the presence of the aluminum layer of trapezoidal section enables to adopt new dimensions better adapted to the conditions of the line where they are to be installed [8].

Also, it is worth commenting that the stringing procedure for these conductors is more cumbersome than for conventional conductors, because the mechanical stress has to be applied only to the core of the conductor. The general characteristics of ACSR (HEN type) and GTACSR (260 type) conductors are shown in Table I. These conductors have been compared due to their similar external diameter that will make it possible to develop the substitution as simple maintenance work.

III. TRADITIONAL SUSPENSION STRINGS

The conductors in the overhead electrical lines are always used without any insulation so that they ought to be insulated in the corresponding towers. Hence, the need arises for an intermediate element of good insulation properties, required to completely insulate conductors under voltage from the towers supporting the line. The primary purpose of the insulator is to avoid the current circulating from the conductor to the tower. The dielectric behavior of insulating materials is only stable for a given range of temperatures. Once the temperature is elevated beyond that acceptable range, thermal runaway could occur, leading to insulation failure.

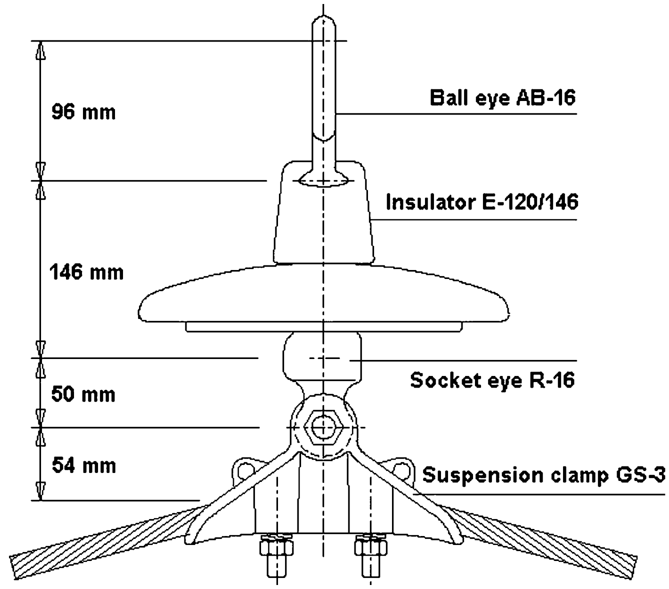

Fig. 1. Single suspension string for single conductor.

According to the information provided by manufacturers of insulators, these elements work correctly with temperatures under 100 °C. This temperature limit never was achieved with ACSR conductors, since these conductors work up, in Spain, to a maximum temperature of 80 °C. However, GTACSR conductors are capable of working at a temperature of 150 °C. Consequently, it is of the utmost importance to know the temperature distribution along the suspension string and, particularly, the temperature reached by the insulator taking into account that GTACSR conductors operate at temperatures of nearly 150 °C.

The other components of a suspension string (Ball eye AB-16, Socket eye R-16, Suspension clamp GS-3) are made either of aluminum alloy or of forged steel so their temperature limitations are higher than 100 °C.

An often-utilized suspension string is represented in Fig. 1.

Depending on the technical and structural needs, there are, at our disposal, many combinations to erect the suspension strings. Thus, there are single chains for double conductors, double chains for single conductors, double chains for double conductors, "V"-shaped double chains for double and triple conductors, etc. Nevertheless, all of these combinations share the property that the first insulator (closest to the conductor) is farther from the conductor than in case of single suspension chains for single conductors so that the temperature reached by the first insulator will be lower, at any rate.

This is the reason why we have more thoroughly analyzed the configuration shown in Fig. 1 since it is the configuration that will bring about the highest temperature increase in the insulator chain.

IV. SIMULATION OF THE SUSPENSION STRINGS

A. Characteristics of the Software Used

The modeling of the suspension strings has been performed using the solid-edge application, a software tool that has high

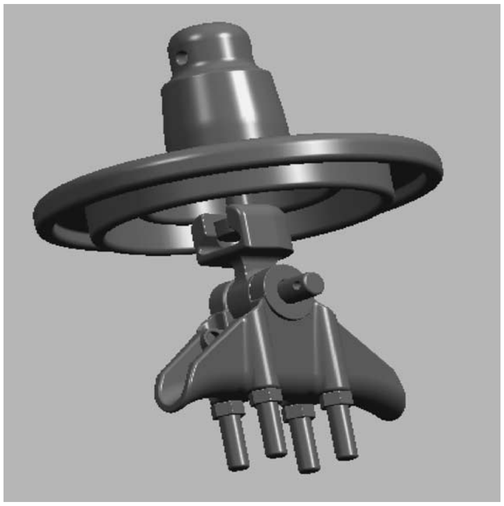

Fig. 2. Assembly of 15 pieces.

graphic power in three-dimensional (3-D). Likewise, this software allows to depict the set of assembled pieces, as represented in Fig. 2.

Once the pieces have been modeled, the analysis of the temperature distribution in the aforementioned suspension chains is accomplished with a software tool relying upon the finite-element method (FEM).

The general idea behind the FEM amounts to divide a continuous system into a denumerable set of small, discrete elements interconnected at points called nodes. The equations ruling the behavior of the continuum are discretized at each element so that the basic variables to be solved for are nodal variables. For that reason, we are able to transform a continuous system with infinitely many degrees of freedom, obeying a differential equation, or a system of coupled differential equations, into an "equivalent" system with a finite number of degrees of freedom whose behavior is described by a system of algebraic equations, linear or not [9], [10]. We have carried out the FEM simulations of the suspension string by means of the COSMOS/DesignStar software application.

This software provides a wide spectrum of analysis skills, such as

- modeling, meshing, and visualization of pieces and/or assemblies;
- thorough set of analysis tools: stress, displacements, frequencies, heat transmission, nonlinear behavior, dynamic response, fatigue;
- design optimization;
- low-/high-frequency electromagnetic analysis;
- 2-D/3-D fluid analysis.

B. Conditions of the Simulation

We have carried out a number of simulations with the modeled systems by means of the software in order to achieve a thermal study under the following conditions of simulation.

In regards to the material corresponding to each element of the ensemble, Fig. 2, the pieces in close contact with the conductor are made of an aluminum alloy, the insulator is made of glass, and the remaining elements are made of steel. Also, the cement joining the different parts of the insulator has been considered as an independent piece. The values of the different parameters entering the simulation are selected according to the material of each element. For instance, Fig. 3 shows the values adopted for the aluminum alloy.

Applied boundary conditions [11]:

- Temperature: The worst-case simulation occurs when GTACSR conductor reaches a temperature of 150 °C. Acknowledging this fact, a boundary condition corresponding to the suspension chain has been enforced such that the faces pertaining to the pieces of the chain in direct contact with the conductor will actually reach the same maximum temperature.
- Convection: The suspension string is situated in open air, so that a net energetic exchange between the system, which loses heat, and the air exists. For the purpose of calculating this exchange, a so-called "film coefficient" must be provided. This coefficient displays values ranging around 5–15 $\mathrm{N/m^2K}$ with natural convection (without wind), and around 15–300 $\mathrm{N/m^2K}$ with forced convection (with wind).
- Thermal charge: This condition takes into account the effects caused by a heat source in the system. Thus, it has been considered the incident solar radiation and the power loss as a result of the Joule effect.
- Radiation: The walls of the suspension string naturally radiate energy according to the value of the emissivity of the material. We have considered an approximate value for the emissivity of 0.8. At any rate, the phenomenon of radiation at the temperatures discussed here is utterly negligible if forced convection is also present.

In connection with the type of union, we have considered that the different surfaces in contact in the suspension string are stiffly bound.

The meshing of the system is certainly the most critical step of the FEM analysis, requiring a great deal of experience and a thoughtful insight into the problem at hand. The total number of elements used to mesh the model bears a strong command upon the precision of the solution. Indeed, the use of very fine meshes provides us with solutions as close as we like to the true solution of the problem; however, the burden of computational effort may well be exceeding. A coarser mesh takes less computer time to solve, and correspondingly the results fare worse. Clearly, we should arrive at a tradeoff between the total number of elements used in the simulation and the precision required. On the other hand, the number of elements is not the only factor that affects precision, because additionally we have to determine the type of elements to be used. We have used throughout second-order tetrahedra. On account of this, all we have used are the meshes displayed in Table II. Fig. 4 depicts one of the meshes for the suspension chain. To begin with, we run several simulations using sparse meshes (first two options from Table II), whereas afterwards, confronted with more accurate analyses, we did use quite refined meshes (last two options from Table II).

Before proceeding to the solution step, some additional parameters must be furnished to the program, such as the maximum number of iterations, the type of mathematical algorithm to be used, the convergence radius, the "solver" chosen, etc.

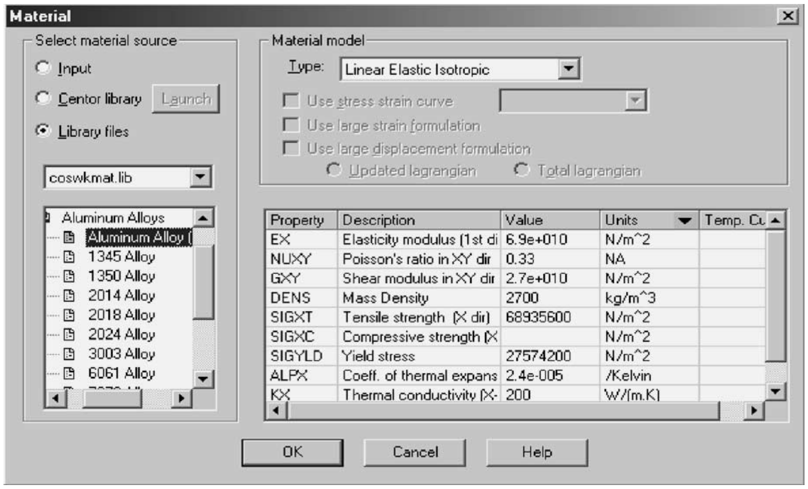

Fig. 3. Physical properties of the aluminum alloy.

TABLE II
DIFFERENT MESHES USED IN THE SUSPENSION STRING

Global size of the elements	Total number of elements	Total number of nodes (equations)
1 cm	31709	55337
0.8 cm	36146	62726
0.5 cm	105480	169069
0.3 cm	379653	574868

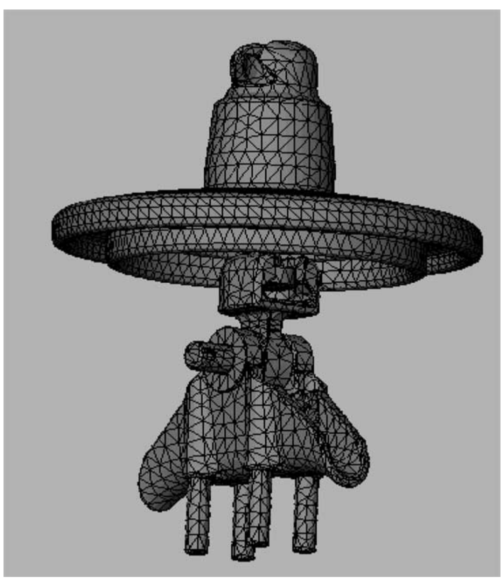

Fig. 4. Mesh with a global element size of 0.8 cm as applied to the suspension string.

Once the FEM model is solved, the typical temperature distribution obtained for the conditions mentioned above is given in Fig. 5.

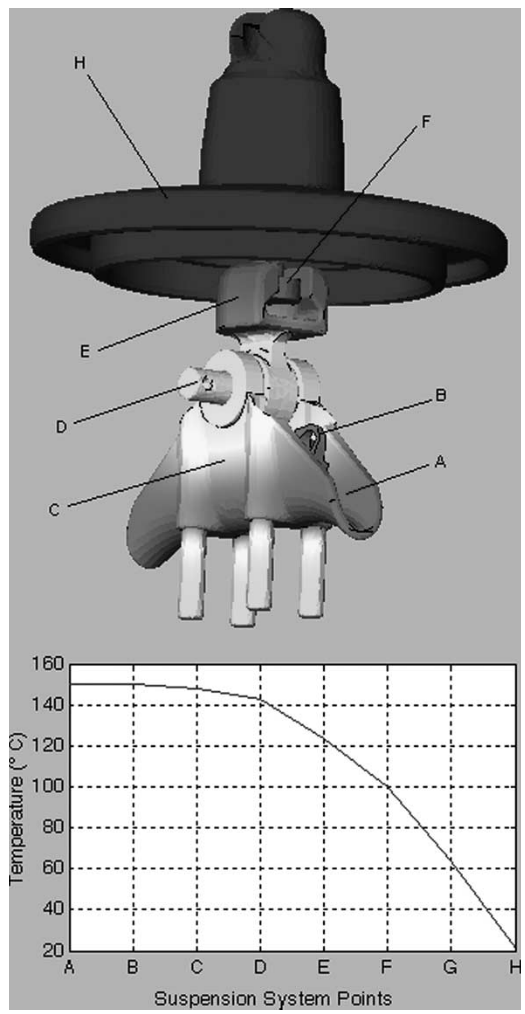

Fig. 5. Temperature distribution.

V. RESULTS

We have run four sets of simulations under differing assumptions, so the following cases have been considered:

- Case I: Ambient temperature of 20 °C, with natural convective effects but no radiation;
- Case II: Ambient temperature of 20 °C, with natural convective effects and radiation;
- Case III: Ambient temperature of 20 °C, with forced convective effects (parameters as defined in Section IV). In this case, radiation effects are utterly negligible;

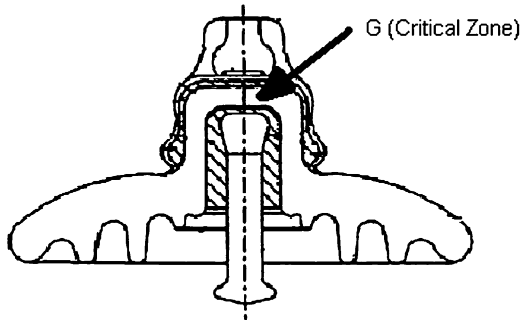

Fig. 6. Critical zone of the insulator.

TABLE III
TEMPERATURES OF DIFFERENT PARTS OF THE SUSPENSION STRING

Conductor Type	Conductor temperature	Case	Body temperature (ºC)	Temperature of the critical region (ºC)
ACSR (HEN)	80ºC	I	78.89	40.2
		II	78.36	35.21
		III	69.9	21.7
		IV	79.1	53.5
GTACSR (260)	150ºC	I	147.57	63.77
		II	146.1	51.75
		III	128.12	23.68
		IV	147.6	77

- Case IV: Ambient temperature of 40 °C, with natural convective effects but no radiation.

The analysis performed has made allowance for these four situations for each conductor type. In these worst-case simulations, we have imposed circulating currents such that both conductors reach their maximum limit temperatures. We recall that this temperature is 80 °C for ACSR conductors and 150 °C for GTACSR conductors.

The most sensitive element of the suspension string is the first insulator of the chain. For this reason, the study has been concentrated on calculating the temperature distribution of the suspension string in general, and of the first insulator in particular.

In all simulation and laboratory tests realized, it has proved that a zone of the part of the insulator exists that is made of glass where the temperature reaches the highest value. In Fig. 6, we have specifically indicated this zone, point G, which amounts to the single most critical zone of the system. The results obtained in the different analysis are summarized in Table III.

Fig. 7 shows the temperature distribution along the suspension chain obtained for both conductors and for the four cases analyzed, in different elements of the suspension chain (A, B, C, D, E, F, G, and H are elements from Fig. 5 and 6).

It is readily observed that in the worst case, the replacement of the conductor introduces a temperature increase of 25 °C, approximately in the critical region of the insulator by comparison with the ACSR conductor. Thus, the highest temperatures attained anywhere in the insulator do not preclude it from working correctly.

The results obtained are coherent with the data provided by the tests included in the existent bibliography about the subject [6]–[8]. Also, a GTACSR-260 conductor has been tested and the

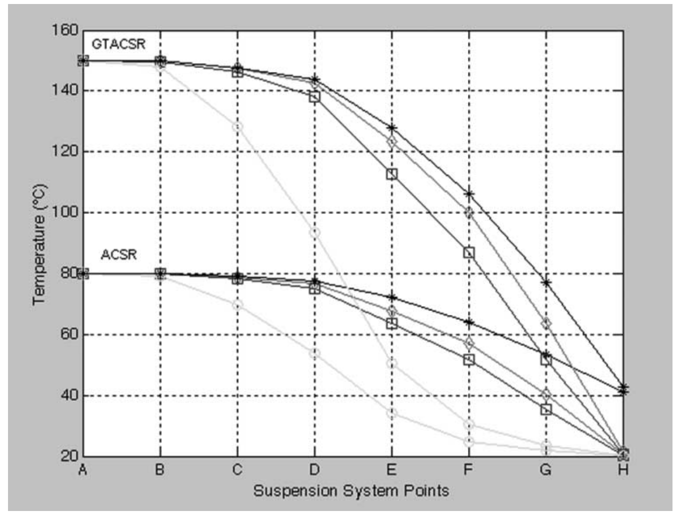

Fig. 7. Temperature distribution along the suspension string (A, B, C, D, E, F, G, and H elements, from Fig. 5 and 6). Red diamond: case I./blue square: case II./green circle: case III./black asterisk: case IV.

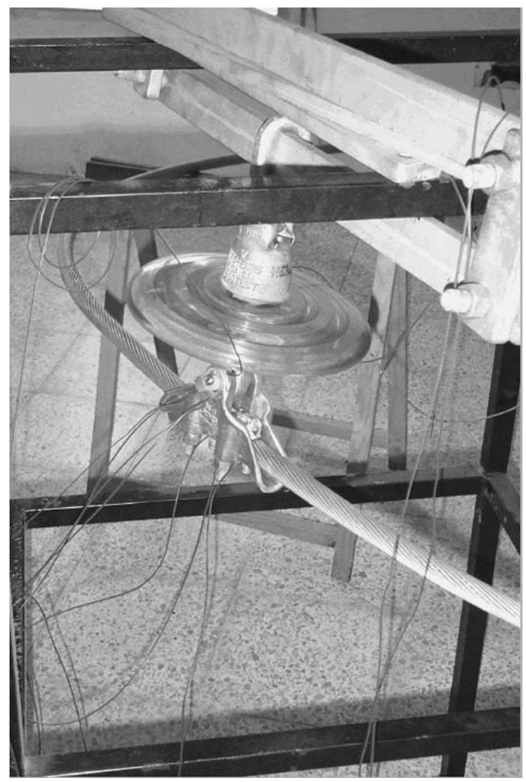

Fig. 8. Laboratory test.

simulation results have been contrasted with these laboratory tests.

With the theoretic models, it has tried to duplicate the boundary conditions of laboratory test, with the purpose of comparing theoretic with real results. The tests have consisted in connecting a conductor that is held up with a suspension string, to the terminals of a current generator. This generator supplies power enough to increase the conductor temperature until study temperature. Simultaneously, by means of thermocouples, the temperature has been measured in different points of the suspension string, Fig. 8.

TABLE IV
TEMPERATURES IN DIFFERENT ELEMENTS OF THE SUSPENSION STRING

Component	Simulation temperature (° C)	Laboratory test (° C)
Keeper	148	146
body	140	138
socket eye	84	80
Insulator axis	72	69

After obtaining the first laboratory test, both results—theoretic and real—were compared. The thermic differences were about 12%. With the intention of improving the simulation results, the changes in the suspension string model have been realized. These changes have consisted on reducing contact surface between different pieces and include air pieces in the model. With this new model, the thermic differences have been lower than 5% (Table IV).

VI. CONCLUSION

The present paper has shown the analysis developed regarding the thermal behavior of conventional suspension strings when using GTACSR conductors. The objective aimed at this has been to check the maximum temperature reached by the first insulator when this type of conductor is used.

In order to develop this study, we have used a software application based on the FEM.

After the first trial studies, we have been able to confirm that the suspension strings used for the stringing of ACSR conductors are valid as well for the stringing of GTACSR conductors of the equal size, because the insulator never reaches dangerous temperatures.

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