Combined mechanical and thermal Behaviour of Overhead Line Conductors

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Abstract: Transmission lines are the backbone of electrical power girds. In Europe, a widespread intermeshed grid was formed from the local power supplies during the last century. With the change in the operation mode as a result of the liberalisation of the energy market, the operators tend to exploit the existing potentials of transmission systems.

One point of interest for an overhead line are the active parts of the current path like conductor, joints and fittings. Especially components, which are under mechanical stress and conducting the load current, are critical parts for the personal and system safety. This combined stress is significant for the condition and behaviour evaluation of the equipment.

In this work, the typical Austrian 230kV aluminium conductor steel reinforced (ACSR) overhead line conductor was chosen in respect to evaluate the thermal-mechanical behaviour. With a realistically model of the elongation behaviour, sag calculations, which are the base for safety clearance or thermal rating systems, can be made with more accuracy. As the investigations shows, the irreversible elongation of the conductor affects the thermal behaviour of the sag of overhead lines significant.

1 INTRODUCTION

For a high reliably and high-capacity electrical power supply, the most technical expedient and economized way is an intermeshed grid of power lines. In Europe are at the moment in the "Union for the Coordination of Transmission of Electricity" network (UCTE) 24 countries with a providing area of 430 mil people with 200000 km of 230 and 400 kV lines. Parts of this grid are in operation since 1950 or earlier. Due to the operating time of more than 30 years, each power grid operator must ask how reliable are the line components and how much capability is remaining. The construction documents (if they are available) will give only in the minority of cases a satisfactory answer. Therefore, modern diagnostic tools are required to evaluate the condition of the individual devices.

One possibility for condition evaluation is an overhead line monitoring system. These systems work on valuation different mechanical, thermal and/or environmental parameters to evaluate the capability, the sag and/or the conductor temperature of the line. In many cases is the limiting factor of the transmission capability the sag of line or respectively the specified minimum ground clearance (safety distance) from the wire to objects or the grassroots. The sag again is formed by the rope tension and length. The thermal-mechanical behaviour of the conductor is the decisive parameter for the sag.

2 THERMAL AND MECHANICAL BEHAVIOUR OF OVERHEAT LINE CONDUCTOR

Overhead lines are usual made of high conductive materials like copper or aluminium. For improving the mechanical properties high-strength materials like steel or aluminium alloy are in use for reinforcement. New developments with composite core and special steel alloys are in progress.

In most cases, an aluminium conductor with a steel core is the typical conductor for overhead lines. The area ratio of aluminium and steel is usually between 3:1 and 14:1 depending on the mechanical requirements [4].

The different mechanical and thermal properties of steel and aluminium lead to a variable force distribution within the conductor rope. The elongation of an overhead line conductor is the deciding factor of the sag behaviour. Equation (1) describes the elongation of a homogeneous bar [5][11].

$$\varepsilon = \frac{F}{A \cdot E} + \alpha \cdot \Delta\vartheta \qquad (1)$$

ε ....elongation in p.u.
F ....mechanical force in N
A...........cross-sectional area in mm^2
E ....elasticity modulus in Nmm^{-2}
α ....thermal expansion coefficient (linear) in K^{-1}
$\Delta\vartheta$.........temperature difference in K

The wire stranding of the conductor leads to a torsion moment and a reduction of force in rope axes depending on the stranding angle. The torsion moment will be reduced by alternating direction of lay. The stranding angle of the layers is an important factor for the bending stiffness and the vibration property of the rope. The different angles for the layers lead also to different wire tensions.

For the following calculations the typical conductor (340/110 ACSR) of an Austrian 230kV overhead line is chosen (Fig. 1) [12]. With the typical values for stranding angle and material properties, the following elongation behaviour depending on temperature and mechanical force can be achieved (Fig. 2).

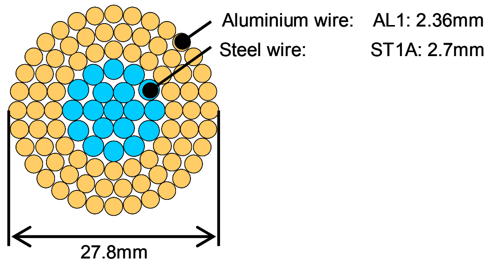

Fig. 1: Cross section of the 341-AL1/109-ST1A conductor

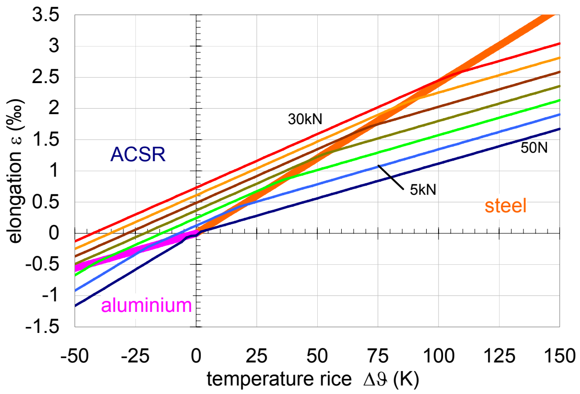

Fig. 2: Temperature elongation behaviour depending on mechanical force

The behaviour can be divided in three areas: the rope behaves like a steel rope, like an aluminium rope and like a composite material (ACSR). The aluminium rope area is not really a momentous range for an overheat line conductor. Generally, the forces are high and increase with decreasing conductor temperature. The more interesting area is the changeover from the composite behaviour to the steel behaviour (Aluminium Conductor Steel Supported ACSS) where only the steel core is load carrying also called transition point or knee point. The mechanic-thermal properties will change by crossing the borderline. In this case, the aluminium wires would be compressed. The strands cannot carry any compression stress and will react in a small unscrew movement. The surface wires lift-off first from the below layers and a small gap arise. At full released aluminium wires, the gap between the steel core and the aluminium is dominating [6][10].

Tab. 1: Gap between stranded layers in mm

temperature rise in K	55	60	65
3rd layer	0.005	0.035	0.065
4th layer	0.006	0.006	0.007
5th layer (surface)	0.008	0.005	0.001

In ropes with low amount of steel is this gap neglect able. At the investigated conductor rope (340/110), about 10% of the conductor current flow though the core and generates thermal losses. With this gap, the radial thermal conductivity is reduced and the core temperature will increase additionally. In Europe are the steel wires of ACSR conductors zinc-plated and for corrosion protection additional greased. This grease will reduce this effect by filling into the gap.

3 AGING OF ACSR CONDUCTOR

The low melting point of aluminium (660°C) leads at room temperature to a beginning fine grain creeping within the crystalline structure of the wire. The steel core shows normally no irreversible creeping [2]. For the calculation of the aluminium creeping, the elongation model 8b from the Cirgé was taken with values for pure aluminium ropes (2) [2: p.77].

$$\varepsilon_c = K \cdot \vartheta^{\phi} \cdot \sigma^{\alpha} \cdot t^{\mu} \qquad (2)$$

ε_c..........elongation by creeping in ppm
ϑ ....temperature in °C
σ ....mechanical tension in kg/mm²
t.............time in hour
K, ϕ, α, μ coefficients

The modified elongation equation for the aluminium layers is given in (3).

$$\varepsilon_{AL}(j) = \varepsilon_{mech}(j) + \varepsilon_{therm} + \varepsilon_c(j) \qquad (3)$$

$\varepsilon_{AL}(j)$.....aluminium elongation of the layer j in p.u.
$\varepsilon_{mech}(j)$...mechanical elongation of the layer j in p.u.
ε_{therm}......thermal elongation in p.u.
$\varepsilon_c(j)$.......creeping elongation in p.u.

The creeping speed depends on the aging temperature combined with the wire tension and leads to an unequal unloading of the aluminium wires in the rope layers (Fig. 3). At the same time, the steel core gets a higher loading and a higher mechanical elongation.

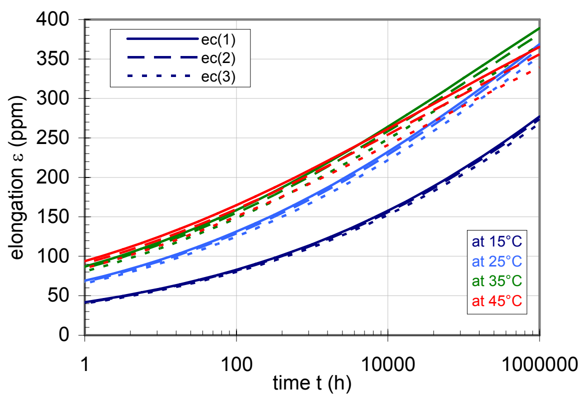

Fig. 3: Aluminium elongation of layers (1) ÷ (3) at 22kN force depending on the conductor temperature

With the interrelationship between tension division and aging velocity depending on temperature and tension, the conductor creeping becomes a kind of temperature independency at higher temperatures. With the higher temperatures, the mechanical stress in the aluminium wire will be reduced and as consequence the creeping speed too.

The elongation of the aluminium leads also to a change of the thermal-mechanical properties. The initial point at rope manufacture does not longer give the equilibrium point at no-load. Affected by the aluminium elongation is the area where only the aluminium is carrying the load and the changeover from composite to the steel behaviour (Fig. 4). The tension free point is now at lower temperature rises (-24K).

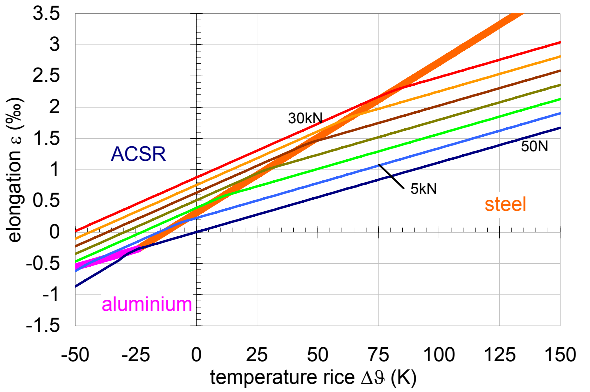

Fig. 4: Temperature elongation behaviour depending on mechanical force with 0.3‰ elongation of the aluminium wires

4 SAG CALCUALTION WITH THERMAL-MECHANICAL BEHAVIOUR OF THE CONDUCTOR

The thermal-mechanical behaviour dominates the sag of an overhead line. A single span is used for the following sag calculations. The model is typical for a 230kV overhead line. The length is 300m and the nominal sag at 15°C is about 9m.

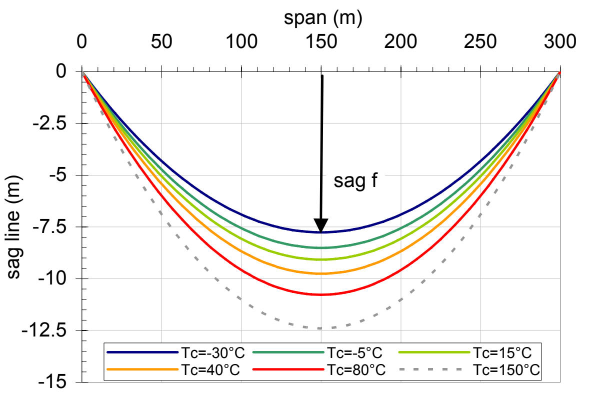

Fig. 5: Sag line depending on the conductor temperature, linear model according to standard

Assuming that the conductor acts like a uniform composite material, the sag line is given in Fig. 5. In most cases, this linear behaviour of thermal and mechanical elongation is stated by the relevant standards. In this calculation example, the sag is increasing about 30cm by 10K temperature increasing over a wide temperature range [8][9].

For the homogeneous composite, a uniform irreversible elongation can assumed. In Fig. 6, an equal elongation of 0.3‰ for the steel core and the aluminium is calculated [1][3][4].

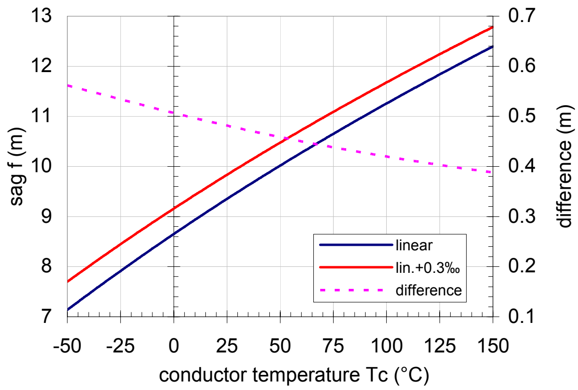

Fig. 6: Sag behaviour depending on the conductor temperature comparing a uniform composite and an aged linear model (additional elongation 0.3‰)

The calculation shows an addition sag increase between 0.55m and 0.39m depending on the conductor temperature. When the nonlinear model is used, the transitions point of 67°C leads to a change of the sag behaviour as shown in Fig. 7.

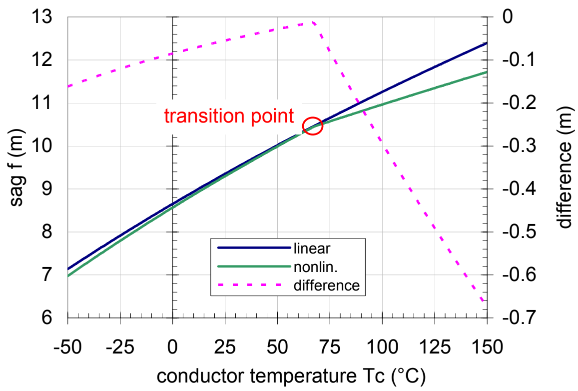

Fig. 7: Sag behaviour depending on the conductor temperature comparing a uniform composite and a nonlinear model

In the temperature range from -50°C up to the transition point, the difference between both models is marginal (max. 16cm). The disagreement can be explained by unequal thermal expansion coefficients and elasticity modulus. Above the transition point, the sag behaviour is significant different [6]. The lower thermal expansion coefficient of steel leads to a slower sag increase than with the uniform model. The deviation at 150°C is 68cm. For the normal operation, the disagreement is neglect able. In the high temperature area, with will be reached be overload current like short circuits, the nonlinear behaviour gives an additional security reserve.

Fig. 8 shows the irreversible elongation based on linear and nonlinear model.

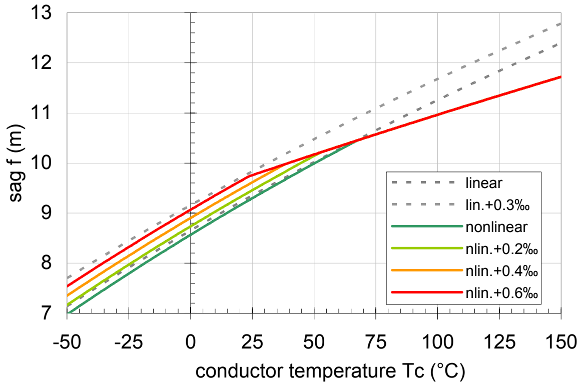

Fig. 8: Sag behaviour with different elongation of the aluminium wires depending on the conductor temperature

With the elongation, the transition point declines to lower temperatures. At temperatures below the knee point, the sag increases with increasing aluminium elongation. At temperatures above the transition point the sag is unaffected by the irreversible elongation of the aluminium strands and follows the non-elongated curve. This effect results from the assumed model of the conductor, where only the aluminium wires irreversible elongate and not the steel core.

5 SAG PREDICTION OF EXISTING OVERHEAD LINES

For the owner and operator of overhead lines, it is very interesting to know the actual capability of the transmission. In most cases, are the limiting factors:

- the low maximum conductor temperature given by the drop point of the used grease
- the small reserves for the ground clearance given by the line design or given by irreversible elongation caused by aging or mechanical overload.

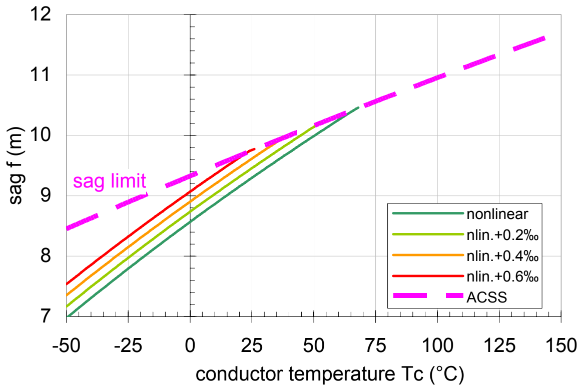

Fig. 9: Sag behaviour depending on the conductor temperature comparing with ACSS behaviour

The conductor will acts instead of an ACSR like an ACSS. This knowledge can be considered by new design of overhead lines. According to the developed model of the thermal-mechanical behaviour with aging of the aluminium wires, the complete charged steel core gives the sag limitation (Fig. 9).

6 FUTHER INVESTIGATIONS

For the evaluation of overhead line conductors, a test stand is actually at the Institute of High Voltage Engineering and System Management of the Graz University of Technology in development. The aim of the future investigations is to evaluate the mechanical behaviour of the stranded composite material at different temperatures and aging states. Therefore, a tension machine with a maximum capability of 500kN is under construction. A spindle drive applies the force without jolt. The thermal stress will be simulated by electrical load. Currents up to 3kA require not only a powerful supply also sufficed clearance between conductor and mechanical structure to avoid unacceptable thermal expansions of the test stand caused by eddy current. The rope fixing will be done by spelter sockets with resin cast. Linear displacement transducer placed on the rope or an incremental shaft encoder at the spindle drive are available for elongation measurements.

7 SUMMERY

The mechanical properties of the used overhead line conductor dominate the sag behaviour. Usually, a linear model for the mechanical-thermal elongation is presupposed in the standards for sag calculation. A more realistic model was developed for describing the transition from ACSR to ACSS performance at higher temperature. Additional an aging model for irreversible elongation is combined.

For new lines the difference are low for the standard temperature range of -50°C up to maximum operating temperature of 80°C. The significant deviation is in the high temperature area (short circuit up to 150°C) where the linear model results higher sag than the nonlinear model. With irreversible elongation by aging in the aluminium wires, the transition point or knee point sink to lower temperatures and affects the normal operation.

For existing overhead lines, a physical limit is given by the sag behaviour of an ACSS performance. In this case, the steel core carries the full mechanical force and the aluminium is unstressed. The compression of the aluminium strands leads to a formation of a gap between the aluminium layers especial the innermost aluminium layer and the steel core. These gaps reduce the radial thermal conductivity and may lead to significant higher core temperatures than in the external layers. The thermal properties of the conductor and the behaviour of the sag are the fundamental parameters for every overhead line monitoring.

8 ACKNOWLEDGEMENT

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