INVESTIGATIONS ON THE LONG-TERM BEHAVIOR OF CURRENT-CARRYING FITTINGS FOR HIGH TEMPERATURE LOW SAG CONDUCTORS

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ABSTRACT

Uprating of overhead using high temperature low sag (HTLS) conductors becomes more and more an issue for the system operators. The weakest links of a conductor system are often the connectors. These are supposed to work reliably for several decades. Especially at the high temperature operation there is less experience about the connectors' behaviour. In order to investigate the long-term behaviour considering permanent high temperature and additional tensile loads extensive experiments were done. The paper presents the considerations, on which the test procedures are based on and the results from the long-term tests. Beyond the mentioned aspects, an electric model is applied from which a deeper understanding of compression type connections is gained.

INTRODUCTION

One common type of conductor for overhead transmission lines (OTL) is the aluminium conductor steel reinforced (ACSR). These composite conductors consist of inner layers of steel strands and outer layers of hard drawn aluminium strands. While the conductors' ampacity is mainly provided by the aluminium strands the mechanical function is fulfilled by the steel as well as by the aluminium strands [1]. If an ACSR conductor is intended to be operated at temperatures above the usual 80 °C the hard drawn aluminium will anneal and therewith change its physical properties. The constructions of HTLS conductors face these challenges by using different materials (Fig. 1). The used conductor materials are pure annealed aluminium Al 99.5 or an aluminium alloy with a small percentage of zirconium. The mechanical properties of both materials are not affected within a certain temperature range. The mechanical load on the aluminium strands is low for high conductor temperatures anyway. Hence, to ensure the HTLS conductors mechanical strength in the full temperature range the core must be able to carry the tension load predominantly. Additionally, the most core materials have a low linear expansion coefficient and thus ensure low sag even at high operation temperatures.

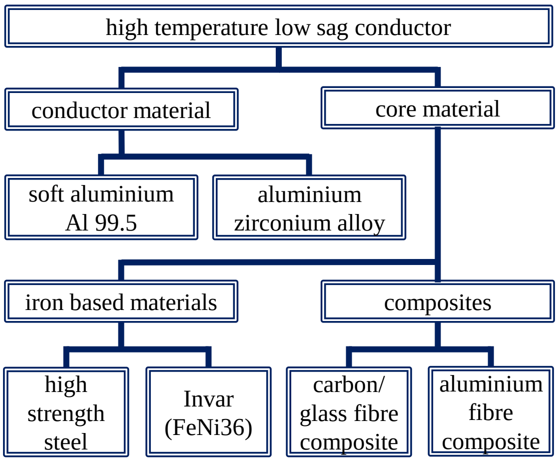

Fig. 1: Materials for HTLS conductors

Therewith the fittings for HTLS conductors are also stressed to higher temperatures in particular cases up to 130 °C. Nevertheless, the fittings must ensure the mechanical strength and the electrical connection in the full range of operation temperatures. Simultaneously, the operator demands at least the same reliability and life time as with the common ACSR conductors. In the context of a current industrial partnership project, some issues were discussed concerning the technical safety of fittings for HTLS conductors. One of these issues was to proof the proper electrical function of a fitting according to a type test. However, there is no current obligatory standard, which regulates test procedures and criteria for the fittings of HTLS conductors. At present, the Cigré TB 426 suggests adjusted test procedures for current cycle tests according to the common standards ANSI C119.4 and IEC 61284 [2]. In both cases, the test time is limited to a few 100 hours and the test focuses on the ability to overload the conductor and the fittings. These are thereby stressed to temperatures which would never occur in practice. Hence, a test program is set up in order to investigate the influence of realistic loading conditions on the electric long-term behaviour of fittings for HTLS conductors. The aim is to determine the electric long-term behaviour of the fittings depending on electrical and mechanical loads and to check the technical safety of the fittings.

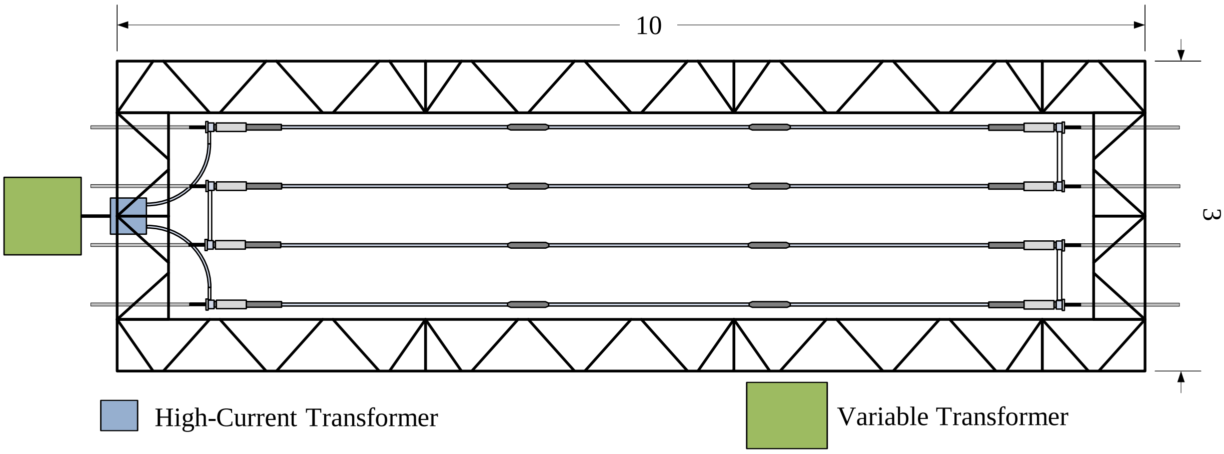

Fig. 2: Schematic test stand - top view (dimensions in m)

Table I: Conductor data

Conductor type (cross sec.)	I_r / A	ϑ_r / °C
ACSS/RW Starling(362/59) [3]	1585	200
ACCR Drake (403/64) [4]	1716	175
ACCC Stockholm (458/60) [5]	1629	210
ACSR (382/49) [6]	840	80

LONG-TERM TESTS

Test Programm

The test program covers tension-proof fittings (compression dead-ends and compression joints) for four types of OTL conductors (Table I). The conductors have approximately the same diameters and cross sections. Besides the fittings for the common ACSR conductor, which was intended to be the reference, fittings for three types of HTLS conductors were chosen. The first one is an ACSS conductor consisting of round strands of pure annealed aluminium and high strength steel. The second one is an ACCC conductor with trapezoidal strands of pure annealed aluminium and a polymer composite core. The third HTLS conductor is an ACCR conductor with strands of an aluminium-zirconium alloy and an aluminium fibre composite core. The rated current and the rated temperature of the HTLS conductors vary (Table I). The fittings are specific for each single HTLS conductor.

Test Setup

The fittings of each conductor type were arranged within a separate test stand. For that purpose the fittings and the conductors were assembled to lines each consisting of two dead ends, two compression joints and an at least 1.5 m long OTL conductor between two fittings (Fig. 2). The fittings assembly followed the particular manufacturer's specifications. Each line was separately fixed inside a solid steel frame. It was possible to load two of the four lines per test stand with a tensile force. The applied forces were measured with a hydraulic load cells. The four lines of a test stand were connected in series by jumpers (Fig. 2). Every circuit was fed by a high-current transformer, which was separately controlled by a variable transformer. Overall, five test stands were built up. These stands are located indoor.

Test procedure and applied loads

So far, there is no binding standard, which regulates test procedures and test criteria for the fittings of HTLS conductors. Recommendations for the test procedures concerning electrical and thermal as well as mechanical properties of fittings are given in the Cigré TB 426 [2]. Here the electrical test is done with a current cycling test procedure. The test leans on existing test procedures given in the IEC 61284:1997 and the ANSI C119.4:2004 only with modified load conditions. The previous evaluation criteria of the standards are maintained. However, the defined thermal loads from Cigré TB 426 are to some extent even higher than the emergency ratings of a conductor. Hence, such a test focuses on the capability to overload the conductor and the fittings in terms of an accelerated ageing test. An accelerated test is based on the idea to apply higher thermal loads in order to have shorter test times [7]. If the fittings experience temperatures far beyond their rated values, physical processes might be activated which do not proceed at lower temperatures than the rated values. Hence, those physical processes do not contribute to the ageing process of a fitting under regular service conditions. In addition, Williamson noted the different self-healing behaviour of connectors under normal and elevated current load [8]. Further, it is known that ageing of electrical connections is caused by several independent mechanisms [9]. The most relevant mechanisms for aluminium to aluminium compression connections are chemical reactions such as corrosion or oxidation and force relaxation. The speed of both mechanisms especially depends on the temperature [10], [11]. Thus, a permanent high temperature promotes the ageing of fitting more than a temperature cycling. This has already been proven for other electrical joints used in power engineering [12]. In order to investigate whether current cycling or a permanent high current stresses the fittings of OTL conductors more a fifth separate test stand was arranged. Further, the influence of the tension on the electrical contact and long-term behaviour of fittings is not known so far. Due to these considerations the following load conditions for the long-term tests were defined:

- Application of a permanent current so the temperature of the OTL conductor is in the range of the specific rated temperature.
- One extra test stand was setup to investigate and compare the impact of a permanent current and current cycling - for the fittings of a chosen conductor type
- Electrical tests with tensioned and non-tensioned specimen. Tension is in the magnitude of the every-day-stress for the selected conductor sizes.
- Run-time of the tests up to two years

Electrical and thermal load

A permanent current was applied to four of five test circuits. The value of the current had to be adjusted according to the ambient temperatures in the test facility. The resulting thermal loads on the conductors and fittings were continuously measured during the total test time and statistically evaluated (Fig. 3). The load profile for the current cycling test was predominantly adopted from IEC 61284:1997 [13]. The sole modification of this procedure was to set the highest applied conductor temperature to the rated temperature of the conductor.

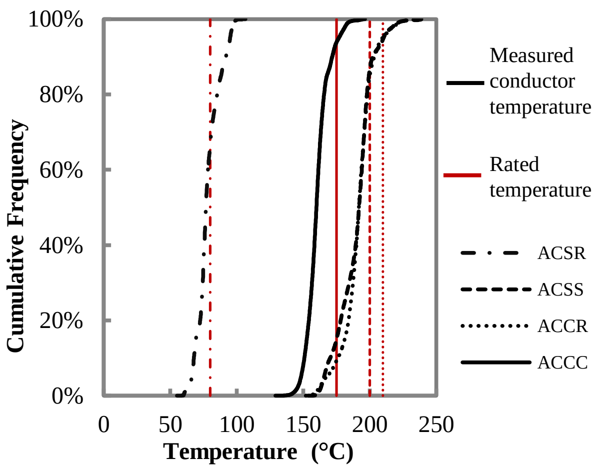

Fig. 3: Thermal load of the conductors during total test time

Tension load

A uniform tensile force of 20 kN was applied to two of four lines of every test stand at ambient temperature. This tension corresponds to every-day-stress values for these conductor sizes [1]. Due to the varying thermal expansion coefficients of the core materials the tensile force decreased to a different value for every conductor type.

Resistance measurements

The joint resistances were measured with the four-point measurement method using a microohmmeter. Therefore, a potential equalizer was used to tap the potential from the conductor next to the fitting. The second potential measuring point was located next to the compressed section of the fittings (Fig. 4). The finally determined joint resistances are resistance values at 20 °C and do not contain the material resistance of the 25 mm OTL conductor.

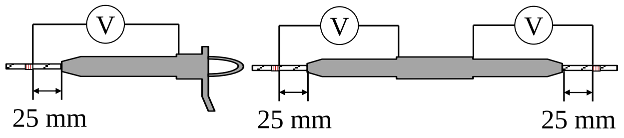

Fig. 4 Potential measuring points for joint resistance measurement (schematic)

RESULTS

The joint resistance of the tested compression dead-ends and compression joints were frequently measured and evaluated. The error bars mark the minimal und the maximal resistance value of each type of fitting (Fig. 5 - Fig. 9). First of all, no critical increase in joint resistance was found at all investigated fittings and load conditions. The joint resistances of fittings for conductor types with hard-drawn aluminium strands (ACSR, ACCR) were unchanged within the tests independent whether they were tensioned or not. The impact of the tensile force on the joint resistance is detectable at some of the tested fittings. These fittings have in common that they are joint with an OTL conductor having soft aluminium strands (ACCC and ACSS, Fig. 5, Fig. 7). As it has already been shown previously it is more challenging to connect a fitting and a conductor with soft aluminium strands [14]. Due to the soft material the elastic spring-back of the conductor in a compression connection immediately after the assembly is small. Hence, only a small contact force on the connector-conductor interface is established [15], [16]. The residual contact forces at compression connections with conductors having hard-drawn aluminium strands are higher. Thus, it is reasonable that the electrical contact behaviour of those fittings is unaffected by the applied tensile force. Even though the fittings were thermally loaded for approximately 15000 h the contact force is presumed to remain high enough so that the electrical connections are still stable. The fittings for the ACCR conductor were tested in two test stands separately (Fig. 2). In the first test stand, a permanent current was applied. The fittings in the second test stand were loaded cyclic. The joint resistances of the fittings for the ACCR conductor are unchanged under either permanent or cycling current load (Fig. 8, Fig. 9). There was also no impact of the tensile force on the joint resistance in both tests. So it cannot be clarified whether permanent or cyclic current leads to a faster ageing of fittings for OTL conductors. The tests are still going on.

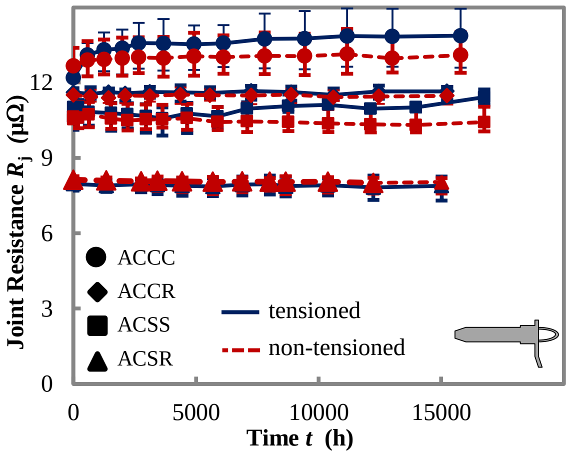

Fig. 5: Joint resistances of permanently loaded dead-end fittings depending on tensile force and time

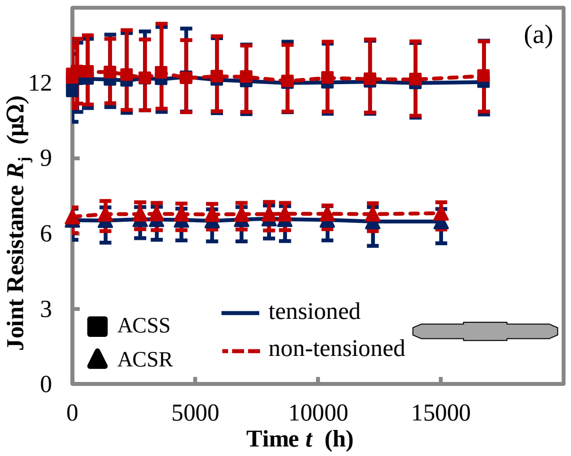

Fig. 6: Joint resistances of permanently loaded compression joints depending on tensile force and time (a)

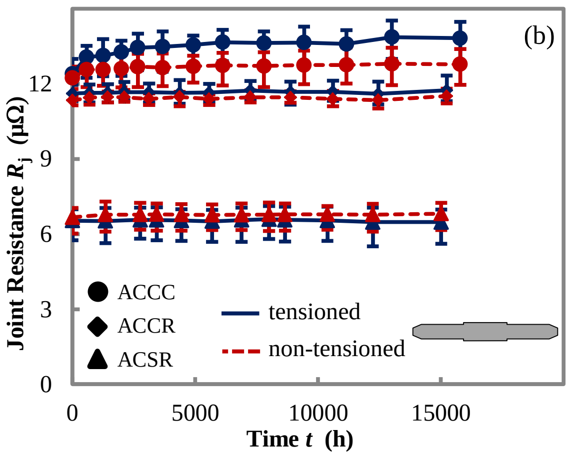

Fig. 7 Joint resistances of permanently loaded compression joints depending on tensile force and time (b)

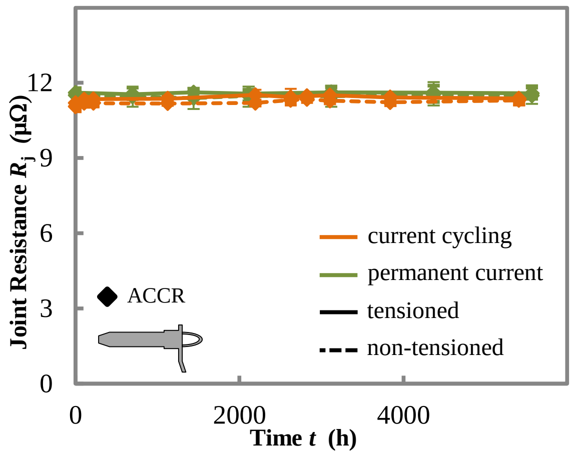

Fig. 8: Joint resistance of dead-end fittings dependent on load conditions

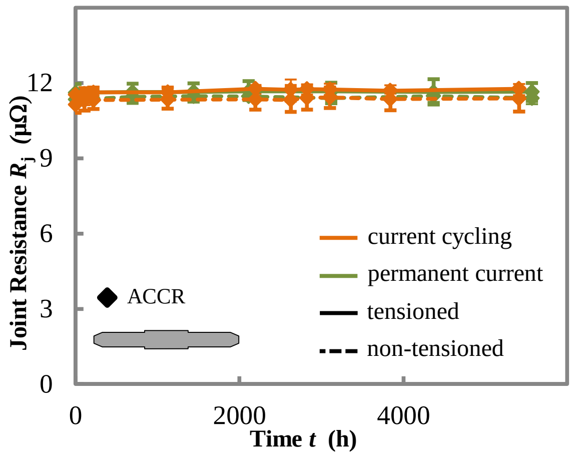

Fig. 9: Joint resistance of compression joints dependent on load conditions

ELECTRIC MODELLING

A useful way to get more detailed information about the electric contact behaviour of compression type connections is to apply an electric model [17]. Thereby an equivalent circuit with infinite electric resistances is used to calculate e.g. joint resistance or current distribution within the connection (Fig. 10) [16].

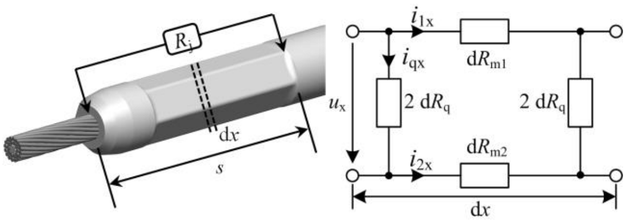

Fig. 10: Equivalent circuit with infinite resistances acc. to [16]

In the next step, a simplified equivalent circuit is derived from the circuit with infinite resistances (Fig. 11 - top) [12]. This equivalent circuit splits the joint resistance in three parts: The bulk resistances of sleeve and conductor and a resistance R_q, which contains for example the contact resistances. The evaluation of connections with this model enables even a direct comparison of the electric contact behaviour of different types of fittings (Fig. 11). Thereby, the electric contact behaviour is primarily included in the resistance R_q. Thus, the ageing of a connection increases the resistance R_q basically. Thereby the resistance R_q is just a small part of the joint resistance. Thus, the increase in the joint resistance of fittings for the ACCC conductor is understandable. As mentioned above the contact forces are low and the initial value of resistance R_q was one of the highest.

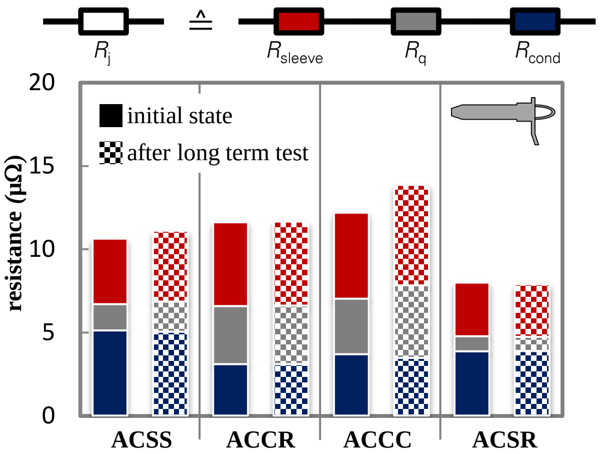

Fig. 11: Composition of the joint resistances of tensioned dead-end fittings

SUMMARY

Electrical long-term tests were carried out especially for the fittings of HTLS conductors. Therewith, the influence of electrical, thermal and mechanical loads based on the actual service conditions on the long-term behaviour of those fittings was investigated. Until now, the long-term test revealed a stable operating behaviour of the tested fittings for HTLS conductors. Further, the impact of moderate tensile on the electric contact behaviour was detected in particular for the fittings of conductors with soft aluminium strands. The further course of aging may also be influenced by the moderate tensile forces, especially if the reduction of contact force continues. It has to be clarified to what extent higher tensile forces may influence the electric long-term behaviour. Unfortunately it could not be shown whether a permanent current or a cyclic current load is the higher stress for fittings of OTL. The therefore chosen type of fitting was not at all affected from the applied loads. Furthermore, the evaluation of compression type connections with an electric model was presented. This model helps to understand the function principle and ageing mechanisms of such connections.

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