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A3-303

CIGRE 2016

REDUCED SCALE FEASIBILITY OF TEMPERATURE RISE TESTS IN SUBSTATION CONNECTORS

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SUMMARY

Due to the important increase of the power of electrical transmission and distribution grids expected for the following years, especially in developing countries such as Kenya, Brazil, Philippines or Mexico among others, that have planes of generating energy from clean sources far away from the centres of consumption [1] it becomes a matter of special importance adapting and developing new substation connectors' testing methods according to the power and temperature regimes at which they are expected to work. The international normative frame of substation connectors established both by the International Electrotechnical Committee (IEC) [2] and the National Electrical Manufacturers Association (NEMA) [3] sets standardized tests for the evaluation of high voltage connectors. These tests are routinely done within the quality plans of the manufacturers.

At the moment, testing of substation connectors –and in general switchgear and fittings- is time demanding and costly due to the energy consumed by such tests. The expectations for the following years are that the power consumption of these tests will not do nothing but grow due to expected increase of power of worldwide overhead lines. For instance, today temperature rise tests in substation connectors involve power ranges up to 100 kVA, which are applied in cycles that can last several weeks. These tests are only feasible in few laboratories and at a very high cost: temporary, monetary, energetic and environmental. For this reason, following the line of other technologies such as aeronautics, naval engineering, or automotive as well as other studies done in the field of electrical engineering specially related to the corona effect [4], this study proposes to develop a reduced scale test system to perform temperature rise tests for substation connectors.

Both, a theoretical framework based on analytical formulas, finite element method (FEM) simulations and experimental data has been developed to conduct reduced scale temperature rise tests and to set the conditions at which they provide comparable results to those attained in the original scale tests. Firstly, two circular loops (original and reduced scale loops) composed of a power conductor and two terminal connectors were analysed. The aim of this first study was to determine in an easy and trustful way the voltage and current values to be applied in experimental reduced scale tests to achieve the same steady-state temperature as in the original scale temperature rise test. The scale relationship between tests was set in 1:1.8, although the method proposed in this study can deal with any other scale factor. This study was useful in order to have a first sight of the final results of the procedure using substation connectors.

KEYWORDS

Temperature rise test, reduced scale, similarity, HTLS, substation connectors, high-currents.

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1. NOMENCLATURE

r	Conductor radius [m]	P_e	Active power [W]
R	Resistance [Ω]	Q_e	Reactive power [VAr]
X	Reactance [Ω]	S_e	Apparent power [VA]
L	Inductance [H]	$cos\varphi$	Power factor
ρ	Resistivity [Ω·m]	t	Time [s]
h	Convective coefficient [W/(m^{2}K)]	n	Scale relationship
ε	Emissivity	σ	Stefan-Boltzmann constant [W/(m^{2}K^4)]
J	Current density [A/m^2]	S	Radiative/convective area[m^2]
T	Temperature [K]		

2. SCALE SELECTION

All reduced-scale tests have a series of constrictions to be applied. Focusing in our problem, the two main constrictions to build reduced-scale tests (see Figure 1) are imposed by the availability of materials. Firstly, both connectors had to fit in commercially-available HTLS conductors. Therefore, the reduced-scale one (RS), has been designed to fit in a GTACSR131-19 conductor which was the smallest HTLS conductors available for us. On the other hand, the original-scale one (OS) uses a GTACSR 464 CONDOR conductor which was the largest one available.

The second market constriction was screws metrics. The metrics for the OS connector is M10 whereas the smallest that fitted the RS connector is the M6. As a result, the studied loops have a scale relationship of 1:1.74.

Figure 1: HTLS connector's reduced-scale (left) and original-scale (right) used to perform the tests described in the following lines

2.1.2 Description of the conductors

GTACSR131-19

Table 1: Relevant data of conductor's datasheet

Outer diameter of the conductor [mm]	15.79
Outer diameter of the steel core [mm]	5.55
Electrical resistance per unit length at 20ºC [Ω/km]	0.2241
Maximum admissible temperature [ºC]	150
Dimensionless thermal emissivity factor ε	0.5

GTACSR 464 CONDOR

Table 2: Relevant data of conductor's datasheet

Outer diameter of the conductor [mm]	27.60
Outer diameter of the steel core [mm]	9.00
Electrical resistance per unit length at 20ºC [Ω/km]	0.0708
Maximum admissible temperature [ºC]	150
Dimensionless thermal emissivity factor ε	0.5

2.1.3 Description of the connectors

Table 3: Dimensions and relevant physical properties of connectors

	Original scale	Reduced scale
Height [mm]	188	104
Width [mm]	95	58
Maximum outer diameter [mm]	28	18
Screws and bolts metrics	M10	M6
Resistivity of aluminium alloy [Ω·m]	$4.5 \cdot 10^{-8}$	$4.5 \cdot 10^{-8}$
Dimensionless thermal emissivity factor ε	0.45	0.45

3. TEMPERATURE RISE TEST FOR BARE-ALUMINUM CONDUCTORS

3.1 Theoretical approach

An initial study was performed to determine the temperature rise of two very simple loops (reduced-scale, RS and original-scale, OS), just consisting of bare aluminium conductors. The goal of this initial study is to find out the ratio between the steady-state currents to be applied in each loop to obtain the same thermal stress that is the same steady-state temperature.

3.1.1 Hypothesis

The hypothesis selected to model the transient temperature profile of an aluminium bare-conductor are shown in Table 4. This is a Multiphysics -electromagnetic-thermal- problem. Heat is generated by means of the Joule effect due to the current pass through a conductive material.

Table 4: Hypothesis to model the thermal behaviour of aluminium bare-conductors.

1	Steady-state regime
2	Variable physical constraints
3	Heat generated through Joule effect
4	Natural convection for cylinders Churchill Model [5]
5	Grey body
6	Diffuse radiation
7	Circular cross-section
8	Toroidal shape
9	Aluminium conductors

3.2 Steady-state calculation method

A simple steady-state model of the conductor is used for to determine the current level to apply in each loop (RS and OS) to attain the same steady-state temperatures.

To this end the steady-state energy balance equation is applied,

$$\dot{Q}_{generation} = \dot{Q}_{radiation} + \dot{Q}_{convection} \tag{1}$$

$\dot{Q}$ [W] being the rate of energy with respect to time.

$$\begin{cases} \dot{Q}_{generation} = Q_{Joule} = I^2 \cdot R = 2J^2 \pi^2 r^2 \rho R \\ \dot{Q}_{convection} = h \cdot S \cdot [T\text{-}T_{air}] \\ \dot{Q}_{radiation} = \varepsilon \cdot \sigma \cdot S \cdot [T^4\text{-}T_{air}^4] \end{cases} \tag{2}$$

Rearranging the terms of (2) the required current density *J* [A/m^2] (3) to heat the conductor of the test loop can be expressed as,

$$J = \sqrt{\frac{2}{\mathrm{r} \cdot \rho}[\varepsilon \cdot \sigma \cdot (\mathrm{T_C}^4 - \mathrm{T_{air}}^4) + \mathrm{h}(\mathrm{T_c} - \mathrm{T_{air}})]} \tag{3}$$

The current density calculated from (3) will be used as the input value of the FEM simulation to analyse the thermal behaviour of the circular loop.

The resistance and impedance of the circular loop are calculated as,

$$R = \rho \frac{2 \cdot \pi \cdot Radius_{loop}}{\pi r^2} \tag{4}$$

$$X = 2\pi L = 2\pi \mu_0 R \left(\ln\left(\frac{8 \cdot Radius_{loop}}{r} \right) - 7/4 \right) \tag{5}$$

3.3 FEM simulation

For this simple configuration the 2D-Axisymmetric model (Figures 2 and 3) has been used. The control volume consists of two parts. The first consists of a circular loop of aluminium with a “Finer” free-triangular mesh. The second part is the surrounding air of the loop which has been meshed with a “Finer” free-triangular mesh as well. The dimensions of the considered domain are important because the total inductance *L* of the loop is calculated to obtain the reactive power consumption. Whether this domain is too small the calculated loop inductance *L* will be low and unrealistic. This would be reflected in inaccurate results of the simulated conductor impedance.

FEM formulation

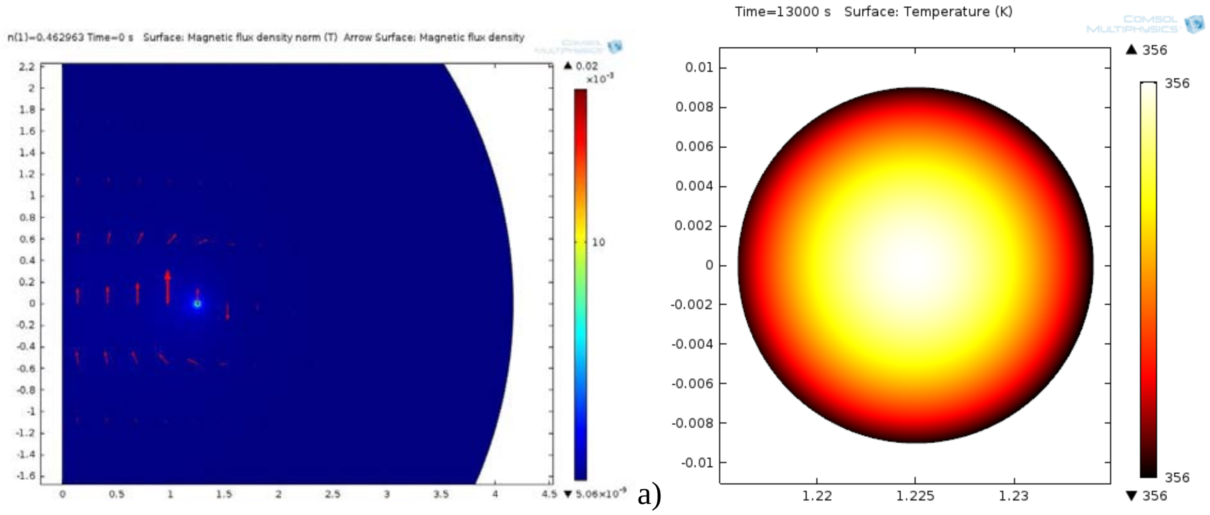
Maxwell’s equations under the quasi-static approximation and the charge continuity equation have been applied.

An energy balance formulation similar to the one presented in (1) is also applied to calculate the evolution of the temperature on the conductor.

By this way a 2D axisymmetric FEM model is obtained.

Boundary conditions of the FEM simulation

It is assumed that the conductor is surrounded by air and the heat is evacuated from the conductor surface by means of free convection and radiation.



a)

b)

Figure 2: a) 2D- axisymmetric distribution of the magnetic flux density. b) Steady-state temperature of the original scale conductor. J_{RMS}=1.99·10^6[A/m^2]

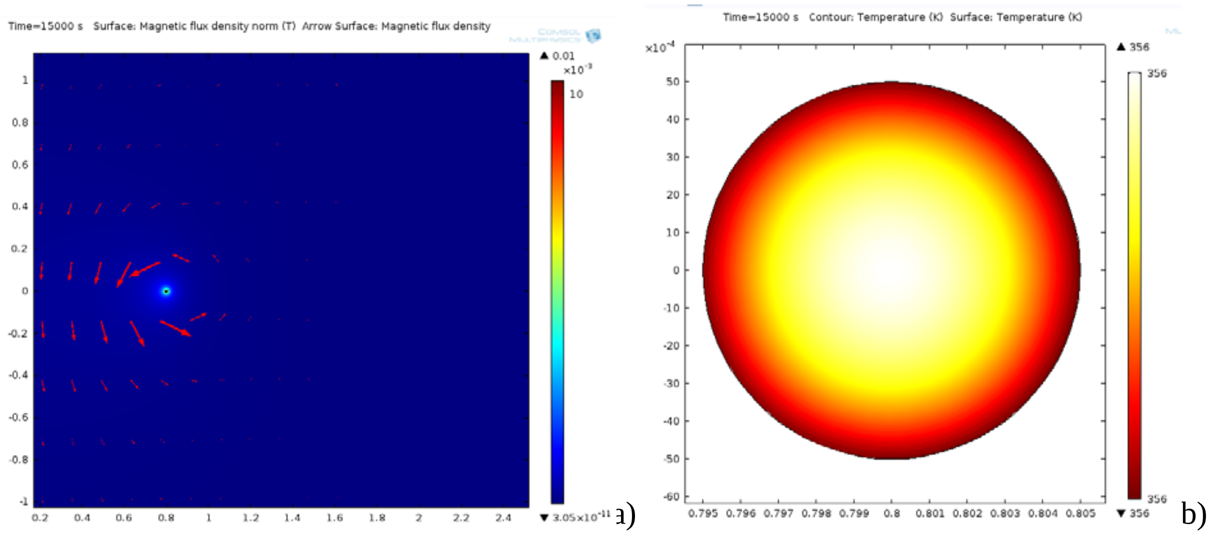
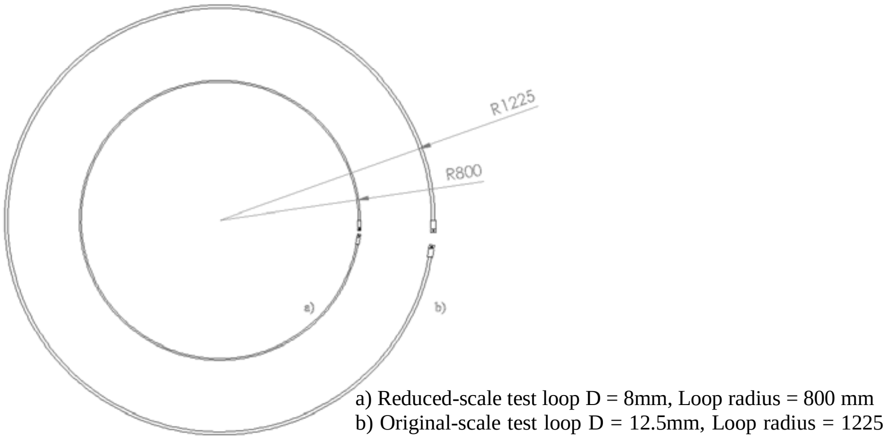


Figure 3: a) 2D- axisymmetric distribution of the magnetic flux density. b) Steady-state temperature of the reduced scale conductor. J_{RMS}=2.28·10^6[A/m^2]

Results shown in Figures 2b and 3b clearly show that due to the good thermal conductivity of aluminium, there is almost no temperature gradient between the central and outer parts of the conductor. Figures 2 and 3 also show that the steady-state temperature will be the same regardless the scale considered.

3.4 Calculated vs. Experimental results

Two aluminium conductors with a scale ratio 1:1.8, which is close to the scale defined for the loops with attached connectors, where tested (see Figure 1). The result of these tests brought us empirical confidence about the reliability of the reduced scale tests for the temperature rise test of connectors.



a) Reduced-scale test loop D = 8mm, Loop radius = 800 mm
b) Original-scale test loop D = 12.5mm, Loop radius = 1225

Figure 4: Assembly of the original and reduced scale circular loops for the temperature rise test

Figure 5 shows the temperature evolution of both OS and RS loops as predicted by the FEM simulation and the calculation method compared to experimental data. Results presented also prove that the time constant decreases almost linearly with the scale of the problem. Furthermore, when reducing the scale of the test loop the power requirements decrease almost with the power of two with the scale. In the case under analysis the energy consumption of the RS test is about 5.5 times less than the one of the OS test.

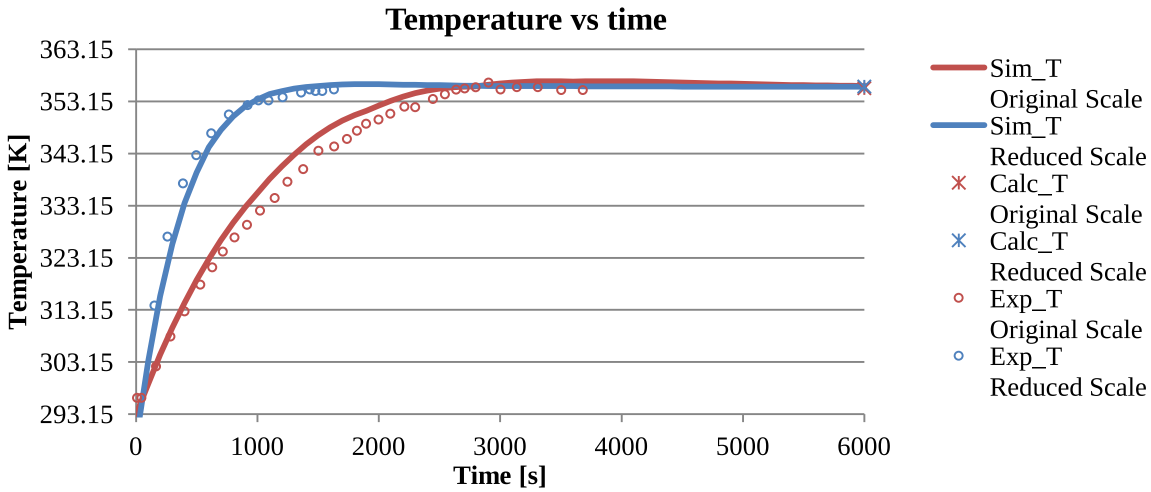


Figure 5: Temperature rise test. Surface temperature during the temperature rise test. Comparison between reduced and original scaled test samples.

Table 5 compares the results attained by FEM simulations and the calculation method with experimental data at steady-state for the test loops composed of aluminium conductors.

Table 5: Steady-state results. Comparison among simulated, calculated and experimental values for circular loops of aluminium conductors

	Scale ratio	Conductor's diameter (mm)	T_{final} (K)	V_{RMS} (V)	L (microH)	I_{RMS} (A)	R (miliΩ)	X_L (miliΩ)	P_e (W)	S_e (VA)	Q_e (VAr)	cosφ
REDUCED SCALE (RS)												
Simulated (FEM)	0.56	12.5	355.97	0.83	5.43	177.42	4.34	1.71	136.50	146.66	53.72	0.93
Calculated	0.56		355.15	0.83	5.43	179.30	4.28	1.71	137.71	148.22	54.81	0.93
Experimental	0.56		355.15	0.85	5.62	173.38	4.55	1.77	136.75	146.70	53.10	0.93
Error (%) Sim-Exp	0.56		0.23	2.35	3.38	2.33	4.62	3.39	0.18	0.03	1.17	0.00
Error (%) Calc-Exp	0.56		0.00	2.35	3.38	3.41	5.93	3.39	0.70	1.04	3.22	0.00
ORIGINAL SCALE (OS)												
Simulated (FEM)	1	8	355.67	1.43	8.07	499.18	1.32	2.53	329.20	712.27	631.61	0.46
Calculated	1		355.15	1.43	8.07	508.75	1.20	2.54	310.89	725.92	655.97	0.43
Experimental	1		355.65	1.44	8.51	486.23	1.27	2.67	300.60	699.59	631.72	0.43
Error (%) Sim-Exp	1		0.01	0.69	5.17	2.66	3.94	5.24	9.51	1.81	0.02	6.98
Error (%) Calc-Exp	1		0.14	0.69	5.17	4.63	5.51	4.87	3.42	3.76	3.84	0.00

As deduced from Table 5, the scale reduction results in an important increase of the power factor of the test loop and thus a decrease of the required reactive power. For this specific setup the reactive power is reduced by a factor of about 12. Such great results suggest that scale-testing should be a valuable option to perform temperature rise tests in medium or small facilities.

4. TEMPERATURE RISE TESTS FOR LOOPS INCLUDING HTLS SUBSTATION CONNECTORS

In this section a more realistic approach is carried out, since HTLS substation connectors are included in the RS and OS test loops.

4.1 Theoretical approach

The conclusions obtained in the previous point encouraged us to perform the same study for a real loop including substation connectors according to the ANSI/NEMA CC1-2009 standard [3]. The steady-state behavior of the temperature of the conductors has been once again obtained by means of FEM simulations and the calculation method.

4.1.1 Hypothesis

The hypothesis selected to model the electro-thermal problem for defining the steady-state behaviour of an HTLS aluminium-steel bare-conductor are shown in Table 6. For this experience, the section of the loops has not been entirely scaled due to the inherent difficulties in manipulating HTLS stranded conductors with steel core (see Figure 7). These differences are reflected in the impedance of the test loops and do not affect the conclusions of this study.

Table 6: Hypothesis to model the temperature-rise-test loop

1	Steady-state regime
2	Variable physical constraints
3	Heat generated through Joule effect
4	Natural convection for cylinders Churchill Model used [5]
5	Grey body
6	Diffuse radiation

4.2 FEM simulation

Three-dimensional FEM simulations have been implemented to obtain the connector's temperature distribution (see Figure 6).

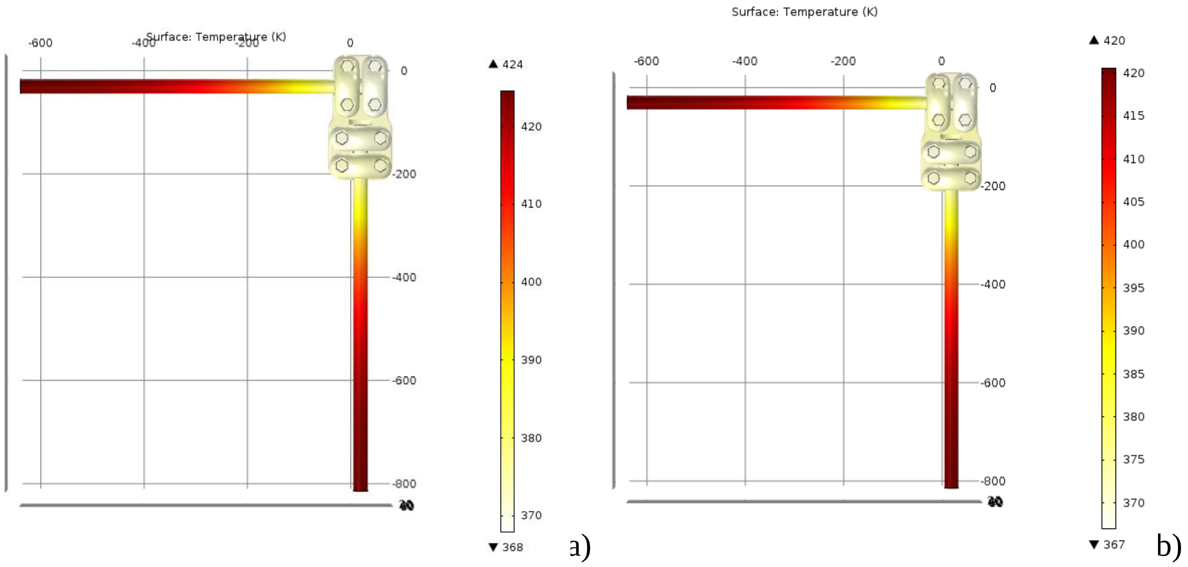


Figure 6: FEM simulations. a) Surface temperature distribution for reduced scale connectors. b) Surface temperature distribution for original scale connectors.

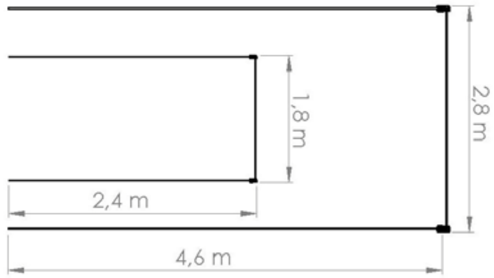


Figure 7: Diagram with the dimensions of the HTLS test loops. The real loops tend to have an irregular shape closer to the circle due to the lack of elasticity of HTLS conductors

4.3 Comparison between FEM simulation and experimental results

Figure 8 compares the steady-state temperature obtained through FEM simulations with experimental results. Information about the time-constants of the described heating curves are shown in Table 7.

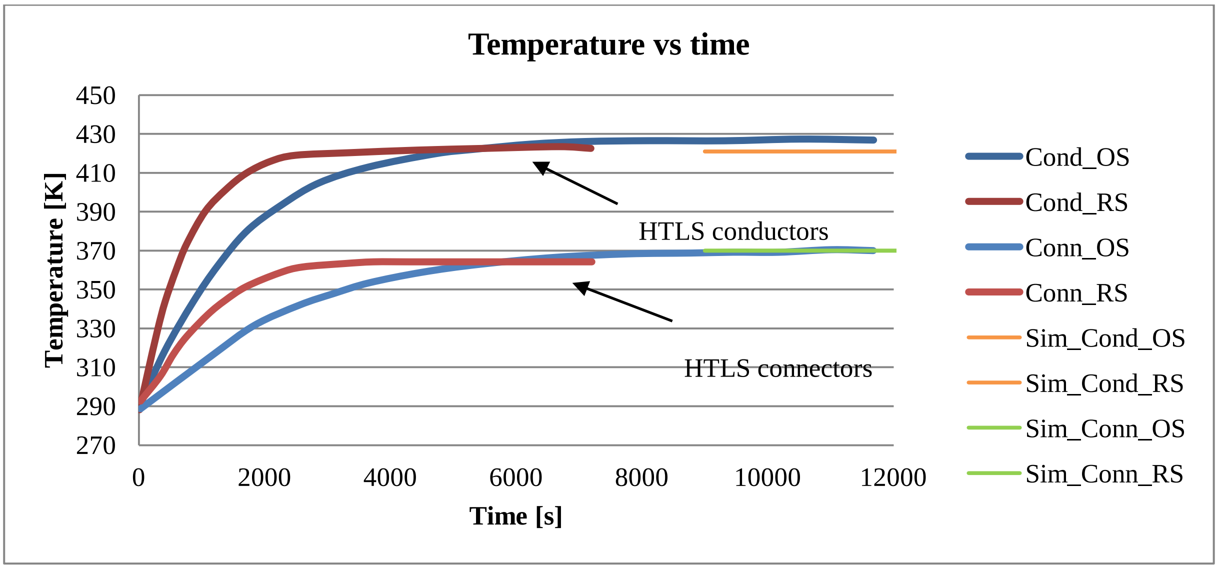


Figure 8: Conductors and connectors temperature evolution due to a temperature-rise-test. Comparison between reduced and original scale test loops.

The small difference at steady-state conditions appreciated in Figure 8 is mainly attributed to the voltage resolution (one turn) of the autotransformer that regulates the voltage at the primary winding of the power transformer.

Table 7 shows the ratio between time-constants of the temperature rise curves of the RS and OS loops, being very close to the scale ratio, i.e. 0.57.

Table 7: Time-constants of the experimental temperature rise curves shown in Figure 7

	Time constant	Time-constant ratio
Cond_OS	900	$\tau_{R,conductor} = 0.53$
Cond_RS	1200	
Conn_OS	1700	$\tau_{R,connector} = 0.52$
Conn_RS	2300	

Table 8 compares the steady-state results attained by FEM simulations with experimental data of the test loops composed of HTLS conductors and connectors.

Table 8: Steady-state results. Comparison among FEM simulations, calculation method and experimental values for circular loops including HTLS substation connectors

	Scale ratio	Conductor's diameter (mm)	T (K)	V_{RMS} (V)	L (microH)	I_{RMS} (A)	R (miliΩ)	X_L (miliΩ)	P_e (W)	S_e (VA)	Q_e (VAr)	cosφ
REDUCED SCALE (RS)												
Simulated (FEM)	0.57	15.79	423	1.86	8.05	539.33	0.00234	0.00253	681.24	1002.49	735.26	0.68
Experimental	0.57		423	1.89	8.78	545.00	0.00209	0.00276	622.10	1028.95	819.59	0.60
Error (%) Sim-Exp	0.57		0.00	1.59	8.31	1.04	11.96	8.33	9.51	2.57	10.29	13.33
ORIGINAL SCALE (OS)												
Simulated (FEM)	1	27.6	423	5.57	1.46	1206.52	1.29E-03	0.00458	1883.07	6714.92	6445.43	0.28
Experimental	1		426	5.59	1.47	1171	1.19E-03	0.00462	1626.9	6541.37	6335.85	0.25
Error (%) Sim-Exp	1		0.70	0.36	0.68	3.03	8.40	0.87	15.75	2.65	1.73	12.00

4.4 Experimental results. Non-dimensional comparison of experimental results

In order to check the similarity between both experiences, a non-dimensioning of the experimental results has been carried out. The non-dimensional results were obtained by applying the formulas shown in Tables 9 and 10 [6].

Figure 9 shows that both experiments have a very similar behavior. Differences between them are basically related to the limited experimental accuracy, and to the discrete resolution of the autotransformer (one turn) that regulates the input voltage of the transformer used for heating the loop.

Table 9: Formulas for non-dimensioning the obtained results

Non-dimensional Temperature	$\frac{T - T_{air}}{T_{steady-state,conductor} - T_{air}}$
Non-dimensional time for OS test	$t_{conductor} \cdot \frac{\tau_{\mathrm{R,conductor}}}{t_{steady-state,RS}}$, $t_{connector} \cdot \frac{\tau_{\mathrm{R,connector}}}{t_{steady-state,RS}}$
Non-dimensional time for RS test	$t_{conductor} \cdot \frac{1}{t_{steady-state,RS}}$, $t_{connector} \cdot \frac{1}{t_{steady-state,RS}}$

Table 8: Values used for non-dimensioning the experimental results

T_{air} [K]	293.15
$T_{\max}$ [K]	423.15 (maximum admissible temperature of the HTLS conductors)
$t_{steady-state}$ [s]	7000 Time to reach the temperature equilibrium, that is, a constant temperature within +/-2°C accuracy during three consecutive temperature readings taken every five minutes.

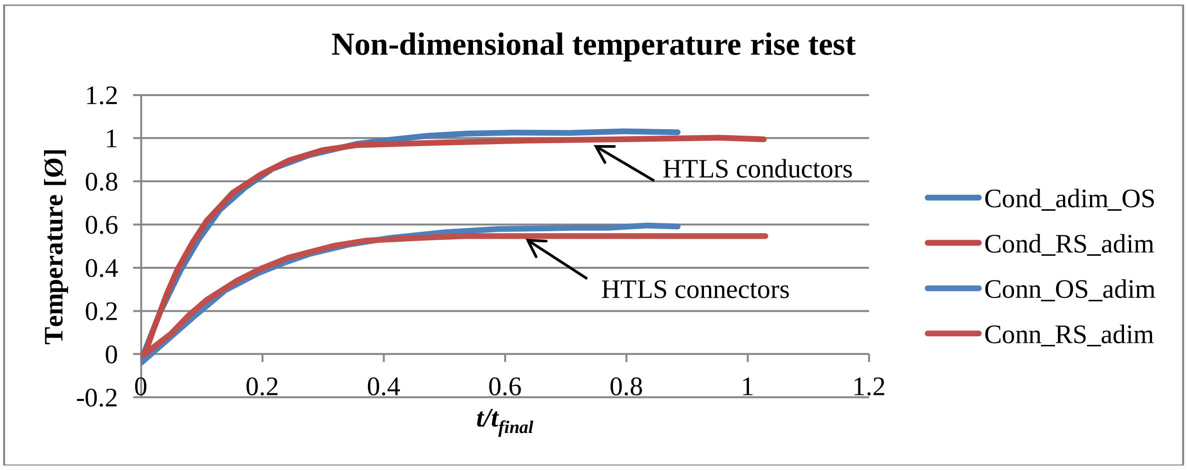


Figure 9: Non-dimensional of the experimental temperature rise test of the HTLS connectors and the associated HTLS conductors for the two studied scales.

CONCLUSIONS

This document sets the path for the study of reduced-scale tests for high-voltage switchgear. The results attained, despite of their simplistic approach are important. This study shows that the reduced-scale temperature rise tests are not only feasible but can be a realistic technological advance to carry out faster, cheaper and reliable industrial tests during the product optimization stage. Surprisingly, its development comes late compared with other technology fields. Firstly, the model developed for a simple geometry of a circular loop consisting of an only bare all-aluminium conductor and the experimental tests carried out at two different scales with a ratio 1:1.8 provided experimental insight of the feasibility of such reduced-scale tests. Results presented in this work also demonstrate the evident reduction in both electrical power and time requirements to run such reduced-scale experimental tests. For example, the results presented show a reduction of the apparent power by a factor of about 6.4, which is closely related to an increment of the cos(φ) from 0.24 to 0.60. In addition, the time required to reach the steady-state condition has dropped by approximately the scale factor.

Finally, it has been proved (see Figure 9) that when non-dimensioning the experimental results, RS and OS experiments can be regarded as similar. Therefore there is an inherent time-dynamics of the heating problem, which seems to be almost independent of the dimensions of the test loops.

This work aims to provide relevant information to the power industry to perform thermal tests in a reduced-scale manner. Although the procedure here described has been applied to substation connectors according to the ANSI/NEMA CC1 [3], it can also be extended to perform reduced scale thermal-cycling tests for low-voltage connectors according to the IEC 61238-1 [7] or even applied to other power devices and components.

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