MEASUREMENT OF THE FORCE INDUCED BY THERMAL EXPANSION OF CONDUCTOR OF MV CABLES AND IMPACT ON MV JOINTS

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ABSTRACT

Cable links with a high current load become more usual, especially with wind power generation and third party access to mv cable networks. Analyses of failed medium voltage joints from high loaded cable links in The Netherlands tend to indicate that thermo-mechanical forces play an important role in most failure mechanisms. Theoretically, huge forces can be expected on MV joints, due to the expansion of the conductors. In order to compare the theoretical forces with those that can actually occur during the real life of the accessories, the forces exerted by the widely used stranded compacted and solid aluminium conductors of 240 and 630 mm² were measured. This paper presents the results of those measurements and points out that those forces are never considered during the qualification of the accessories according to the relevant standards.

INTRODUCTION

More and more, MV network operators throughout Europe are facing new challenges. Indeed, in addition to the increase of the average load some links experience extremely dynamic current cycles. This is especially true for the connection of wind farms where, for economical reasons, the cables are used close to their current limits when the maximum power is produced and close to zero load in the absence of wind.
Analyses performed on failed joints in The Netherlands [1], [2] confirm the dramatic effect of those forces. Also there are signs that less extreme but dynamic loads cause similar problems on the longer term. This all has led to an in-depth investigation by Dutch and Belgian laboratories and distribution companies.

In order to take into account the heat dissipation in the joint, some countries already demand additional tests (see paper 1377). Nevertheless, the forces induced by extension and contraction of the conductor are never considered.

As shown in [1] and [2], the forces theoretically can reach enormous values that are never applied to the accessories during their qualification.

Therefore, the main questions, handled in this paper, are:

- How big are the forces to be expected in reality during operation?

- Are the installed and newly designed joints able to manage these real forces?

- Should we not consider an addition to the existing standards in order to take into account this phenomenon (possibly applicable to a type of accessories especially designed for high loaded links)? It would help DNO's in getting more reliable networks (if operated under high current load) by adding the additional requirements in their future specifications.

THEORY

The calculations of the force for a blocked (no possible longitudinal nor sideward movement) conductor and for the extension of a “free to move” one are quite straightforward and are presented hereunder.
The forces are calculated for an aluminium conductor which corresponds to the tested samples.

Theoretical forces

The force due to the expansion of the conductor is equal to:

$$F_{tot} = F_t - F_w$$

Where

- F_{tot} = theoretical force at the end of a cable sample
- F_t = force due to the thermal expansion of the conductor
- F_w = force due to friction inside the cable sample (theoretically = 0 because there is no displacement during the measurement)

Therefore

$$F_{tot} = F_t = E \cdot A \cdot \alpha \cdot \Delta T$$

Where

- α = $24 \cdot 10^{-6}$ °C^{-1} = expansion coefficient of aluminium
- E = $7 \cdot 10^{10}$ N/m² = Young's modulus of aluminium
- A = conductor cross-section (m²)
- ΔT = temperature increase (°C)

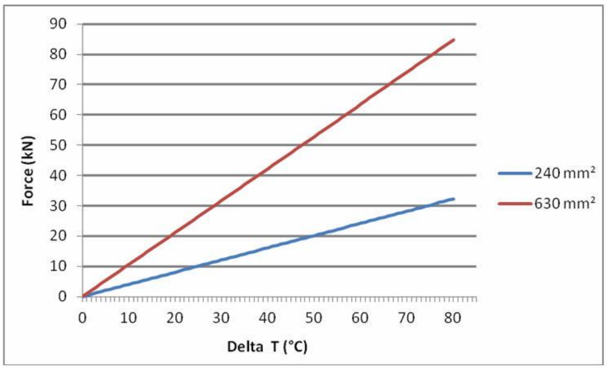

Figure 1: Theoretical forces exerted by a 240 and 630 mm² aluminium conductor in function of the temperature increase

In a blocked conductor (one that cannot expand) it has to be noticed that the theoretical force is proportional to the cross-section of the conductor but that the length of the sample has no influence. In theory forces up to 80 kN could be exerted on the joint and connector of a 630 mm² cable (Figure 1).

Theoretical extension

The extension of the conductor due to thermal effect (Figure 2) is equal to:

$$\Delta L = \alpha \cdot \Delta T \cdot L_0$$

Where

- ΔL = extension (mm)
- α = $24 \cdot 10^{-6}$ °C^{-1} = expansion coefficient of aluminium
- L_0 = initial length of the sample (mm)
- ΔT = temperature increase (°C)

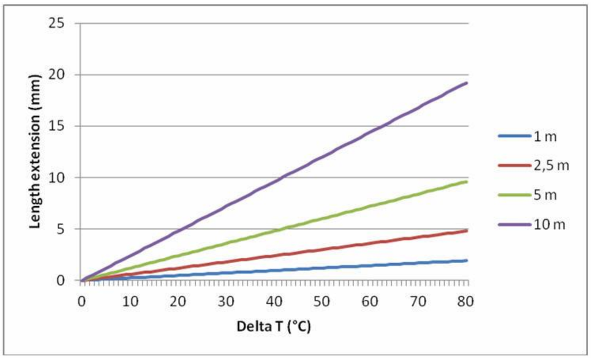

Figure 2: Theoretical length extension in function of the temperature increase for an aluminium conductor

In this case, the conductor cross-section has no influence whilst the extension is proportional to the length of the sample. Length extensions up to 2 cm are expected. For longer cable lengths the friction between the conductor and insulation material will probably limit this extension. (This has not been explored further).

STANDARDS

In the relevant standards [3], [4] and [5], thermal cycles and short-circuit tests are described. Nevertheless, those tests are all performed on a loop which is free to expand. The forces due to thermal expansion and contraction of the conductor of the cable are not applied in the way they do in operation.

The only mechanical test is required during the qualification of the conductor connector [6]. It consists in the application of a force of 9.6 kN for a 240 mm² and 20 kN for a 630 mm² aluminium cable during 1 minute. The requirement is that there should be no slipping during the test. The applied force is far below the theoretical value (but above the measured values as presented further in the paper). No combined electrical and mechanical tests and no mechanical cycle tests are performed.

TEST SET-UP

In order to learn the actual forces and conductor extension and how these relate to the theory, a test is done to measure these phenomena for extruded mv cables with lengths up to 10 m. The conductors of these cables were solid and stranded aluminium, with a cross-section between 240 mm^2 and 630 mm^2.

From theory it is expected that the (free) conductor extension is related to the cable length. The high friction between the conductor and insulation material makes it reasonable to assume that this (free) extension will come from the last few meters of cable only, reason to limit the maximum cable lengths to be tested 10 m.

The basis of the test set-up for extension and force measurements is a steel H-profile of 11 meters which allows to test cable samples of various lengths up to 10 m (Figure 3).

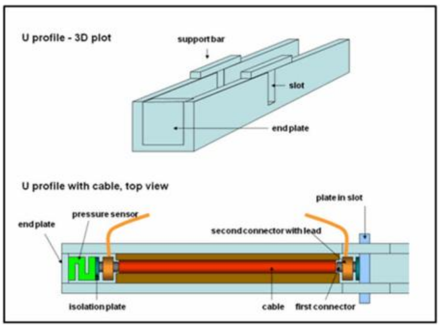

Figure 3: Principle of the test set-up

Two critical points were encountered:

- The injection point of the heating current must have a temperature close to the temperature of the cable. It was realized by means of a copper piece (Figure 4) tightened on a half crimp-connector for the stranded conductor and, because there was no need to hold the wires together, directly on the conductor for the solid conductor.

Figure 4: Injection point

- The mechanical support of the cable in order to avoid a lateral deformation that would lead to a decrease in the measured force. V-shaped wooden blocks were used to maintain the cable in its position (Figure 5).

Figure 5: Cables maintained by wooden pieces

The advantage of this method is the possibility to use the same wooden blocks for all cable diameters. The disadvantage is that the cable is not completely fastened.
The force is measured by a strain gauge load cell at the end of the cable sample.
The injected current, the force and the temperature at 4 different locations were recorded.

TEST RESULTS

Extension

The measurements were performed on XLPE cables with solid or stranded compacted aluminium conductor of 240 and 630 mm² and with lengths of 1, 2.5, 5 and 10 meters.

In Figure 6, the graph shows the extension of a 5 meter cable sample with stranded and solid 630 mm² aluminium conductor. The measurements appear to be in accordance with the theory.

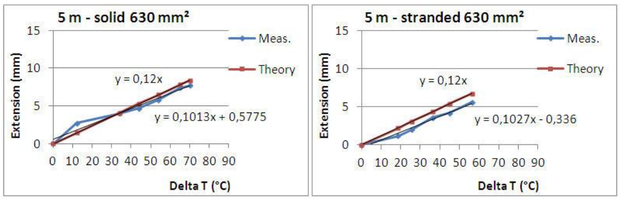

Figure 6: Extension of a 5 meters 630 mm² sample

In Table 1, the linear regression obtained for the various measured samples is compared with the theory. In the equations, y is the expansion (mm) and x the temperature increase (°C).

L (m)	Solid 240 mm²	Stranded 240 mm²	Solid 630 mm²	Stranded 630 mm²	Theory
10	y=0,17x	y=0,19x+0,3	y=0,17–0,4	y=0,14x–0,4	y=0,24x
5	y=0,12x+0,1	y=0,15x–0,2	y=0,10x+0,6	y=0,10x–0,3	y=0,12x
2,5	y=0,075x	y=0,068x–0,2	Y=0,066x+0,1	y=0,083x–0,1	y=0,06x
1	y=0,037x-0,1	y=0,039x+0,2	Y=0,034x– 0,1	y=0,047+0,2	y=0,024x

Table 1: Comparison of the linear regression with theory

For cable samples of 2,5 and 5 meters, the measurements seem to be in accordance with the theory.
For 1 meter samples, the expansion appears to be over the theoretical values. No scientific explanation has been found for this and it was therefore concluded that the measurement was not accurate enough (due to relatively large end-effects).
For 10 meter samples, on the contrary, the expansion remains below the expected value (probably due to the friction between the conductor and the insulation).

Forces

The results of measurements performed on 630 mm² cable samples of various lengths are given in Figure 7.

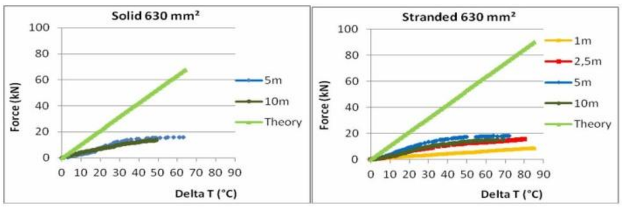

Figure 7: Force (kN) exerted by 630 mm² cable samples in function of the temperature increase (°C) and for various lengths

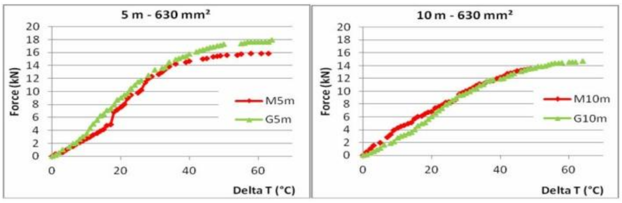

Figure 8: Force (kN) induced by solid and stranded conductor with similar sample length and section (M : Solid and G : Stranded)

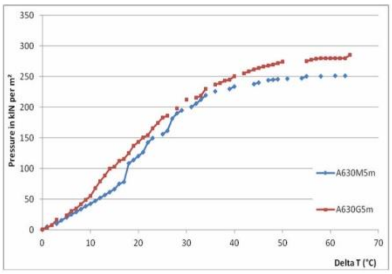

Figure 9: Pressure (kN/m²) for a length of 5 meters for 630 mm² ("M" = solid and "G" = stranded)

We can observe that:

- The difference in force between solid and stranded conductor is insignificant (Figure 8). It was expected that the stranded conductor would produce lower forces due to some lateral displacement.
- The measured forces are lower than theoretically expected and there seems to be a maximum force. It can probably be explained by the fact that the cable is not completely blocked and some slight lateral displacement is reducing the total force considerably, especially at higher temperatures when the plastics are getting soft/weak.
- The measured values are proportional to the cross-section of the conductor (Figure 9) which is in accordance with the theory.
- The force is, as expected, not influenced by the length of the sample.

CONCLUSION

Currently, most cable links installed in distribution networks are not subjected to extremely dynamic current load profiles and therefore are not expected to suffer from the thermo-mechanical forces discussed in this paper. Nevertheless, the tendency is an evolution of the average load and of the load profiles which could lead to an increase in dramatic failures in the future.
The length extension and force caused by the thermal expansion of the aluminium conductor of medium voltage XLPE insulated cables with a cross-section of 240 mm² and 630 mm², solid and compact stranded, were measured and compared with the theoretical values.
The measured forces, even if they remain far below the expected (and alarming) huge theoretical values, can be considered as dangerous for the health of the joints. A maximum seems to be reached at about 6 kN for 240 mm² and 16.5 kN for 630 mm². No significant difference was noticed between the compact stranded and the solid conductor.
From those observations, we can conclude that joints installed on highly loaded cable links can be subject to forces that are never applied during the qualification cycles of the accessory. Indeed, during the thermal cycles at type testing, the cable is not fastened and therefore the forces applied to the accessory are different from the forces in operation.
The forces measured during the presented study could serve as basis for the development of a test that reproduces the forces encountered by the MV joints. Of course, other options can be considered, like an adaptation of the laying procedure to reduce mechanical constraints on the accessory. For existing cable installations, one could investigate the permissible loading by distributed energy generation (DEG) systems.
Once such a test is available, it could serve DNO's in getting more reliable networks (if operated under high current load) by adding the test (requirements) in their future specifications.

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