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B3-107

Session 2004
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SHORT-CIRCUIT MECHANICAL EFFECTS ON OUTDOOR HV SUBSTATIONS WITH WIDE BUNDLING

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Abstract

This paper presents results of a research project investigating the mechanical effects of short-circuit currents in high-voltage substations with conductor bundles. The experimental part was performed on two set-ups, called "100-kV-arrangement" and "400-kV-arrangement". Those two set-ups differed in the height of the crossarm, the phase-to-phase distance and the static tensile force. Additional parameters which were varied in the course of the experiments included the height and duration of the short-circuit current, the type and number of the spacers used and the bundle spacing. Various forces in the flexible busbar and the supporting structure were recorded during the tests and the stiffness as well as the eigenfrequency of the portals used for supporting the conductors were determined.

The test results were evaluated with respect to the maxima of the pinch force, the short-circuit tensile force and the drop force. They are presented and compared with existing assumptions and calculation methods. The results of this project shall enable IEC standardization committees and CIGRE working groups to carry on with their intended studies and establish a comprehensive method of calculating the mechanical effects in substations with conductor bundles.

The AIF research project No. 12260N presented in this paper was subsidised from funds of the German Federal Ministry of Economy and Labour via the Arbeitsgemeinschaft industrieller Forschungsvereinigungen "Otto von Guericke" e.V. (AiF).

Keywords: Short-circuit - HV substations - Wide bundling – Sub-conductor - Pinch force

1 INTRODUCTION

FGH together with DKE (German Electrotechnical Committee) UK 121.2 ‘Substation short-circuit strength’, assisted by its Working Group AK 121.2.2 ‘Short-circuit tests’ as well as the CIGRE SC23-03 ESCC-Task Force (Effects of short-circuit currents) have recently concluded a comprehensive series of systematic experimental studies on the short-circuit effects and the short-circuit constraints produced by strained stranded duplex conductors of open-air substations in a series of practical bundle sub-conductor arrangements. Experimental research of the present kind has been demanded since long by the bodies involved. The ultimate interests of the study and its results are to further the work of IEC TC 73 WG 2 ‘Short-circuit effects’ on IEC Standard 60865-1 [1] .

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The calculation methods of [1] for the assessment of the short-circuit strength rely, to the widest extent, on the basis of and on their validation by full scale experimental studies. It is generally acknowledged that this can not be done otherwise, though parameter studies now employing modern Finite Element Methods (FEM) will, in the future, be able to reduce the experimental part.

Since the advent of "close" bundles for multiple-conductor flexible busbars in open-air substations in the early 70ties, theoretical and experimental research has concentrated on these arrangements that are used up to the 400-kV-level. Small sub-conductor distance a_s associated with a minimum number n_{AH} of spacers reduces short-circuit contraction of the sub-conductors to an unimportant effect [2,3]. Substantial peak forces F_{pi} due to that same contraction, however, will occur at the dead end when the sub-conductor spacing is increased and also the number of the spacers. Wide sub-conductor distances are still quite usual in older installations, also below the 400-kV-threshhold, whose reserves now need to be investigated, and are, of course, employed for the system voltages above that value.

For these configurations the standard IEC 60865-1 [1] offers, as for the so-called close bundles, a simplified method to calculate the individual maxima of the reaction forces onto the support structure: The tensile force F_{pi} during the contraction of the sub-conductors (pinch force), the tensile force F_t caused by phase-conductor swing-out (short-circuit tensile force) and the tensile force F_f at fall-of-span (drop force) which occur during and after the short-circuit duration T_k. The experimental data for pinch in [1] come from an elegant test arrangement with concentric return conductors [4] and outdoor tests [3,5], while the other maxima are deemed to follow the close bundle experience. CIGRE 23-03 and its ESCC Task Force have in their CIGRE Technical Brochures [3,6] of theoretical studies and compilations of all available test results not been able to detect further reliable systematic experimental data for "wide" bundles.

The main first aim of the study described in the present paper is the confirmation of the assumptions and derived methods for the assessment of the dynamic forces exerted by the conductors submitted to short-circuit current onto their fixing points on their mechanical support structure (e.g. steel portal) or, in the case of non-conformity, to provide the basis for the necessary corrections.

Conductors and support structures, in reality, form a highly complex and interdependent mechanical system that is only considered in terms of components for the simpler practical strength assessment. The maximum of the mechanical constraints in the structure and on its foundations can be expressed in terms of a static force applied at the fixing points of the conductors and that produces the same maximum value of material stress as the one observed in the course of the dynamic phenomenon. This static force has been given the name "Equivalent Static Load" ESL by the ESCC TF [3]. This is a practical value that can serve as a design load for the civil engineering.

The present rules in IEC ask for applying the maximum value out of the calculated F_{pi}, F_t, F_f as the static load responsible for the maximum stresses, i.e. the strength of the structure and the foundations. This means an ESL-factor of 1 (dynamic = static) and has given much reason for discussion in either direction - too high or too low. For instance, the full effect of a very short and steep phenomenon as the pinch on the large-mass structure has been very much doubted and strong expectations regarding a massive reduction as one possible result of full scale studies exist. Earlier experimental studies [3,6] have shown that it will greatly depend on the oscillatory properties of the structure itself in the context of the complete system whether the ESL-factors will be above or below unity. Both cases have been observed and urgently require further studies that could apply modern theoretical methods. Therefore the results of the experimental studies described in this paper will contribute to the solution of that crucial problem, also by the validation of the necessary parameter studies on structures against the measurements, but will not lead the problem to a definite immediate solution.

Measurements on various types of spacers which have been performed in the interest of the pending discussion on spacer compression [3,7,8,9] do not fit into the present context will have to be dealt with separately.

2 TEST ARRANGEMENT AND PROGRAMME

2.1 Test set-up

A schematic drawing of the test set-up is shown in Figure 1: two lattice-type portal towers (mid and north) with adjustable crossarms supported a two-phase flexible busbar with a centre-line distance between towers of 40 m (conductor type: ACSR 537/53). At the mid portal the current was fed into the busbar, at the north portal the busbar was short-circuited.

The lower edge of the crossarm was placed at a height of 8,22 m above ground for the 100-kV- and 11,22 m for the 400-kV-arrangement. The centre-line phase distance was 2,0 m (100 kV), or 3,0 m respectively (400 kV). The static tensile force of the span was adjusted in such a way that the conductor sag in mid-span was 600 mm (100 kV) or 800 mm (400 kV). The double insulator strings used consisted of 2 x 7 (100 kV) or 2 x 24 (400 kV) cap and pin insulators.

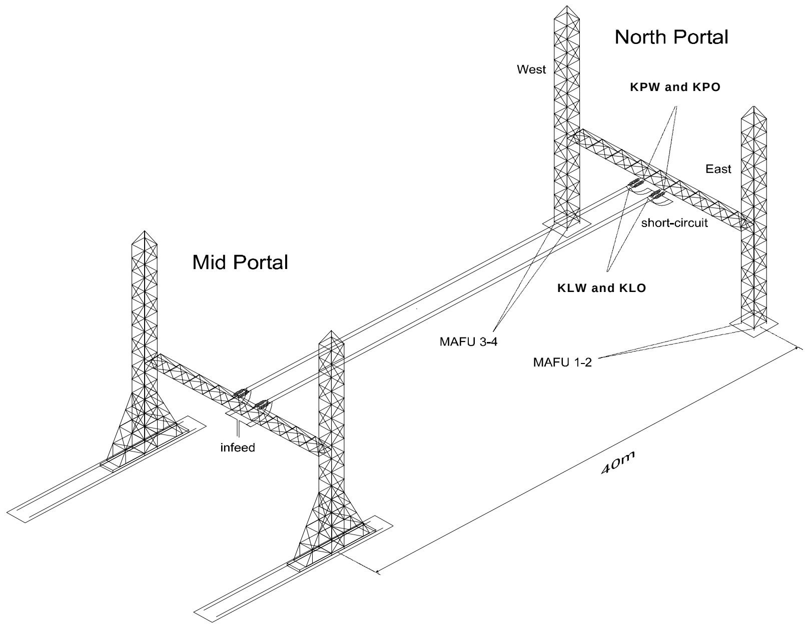

Figure 1: Test set-up with measuring points

2.2 Measured forces and stresses

The forces exerted by the conductors were measured at the north portal using thermally compensated force transducers able to measure static loads. They output a positive signal when pushed. The forces were measured at the transition from the conductors to the insulation strings and at anchoring points of the insulator string on the portal, see Figure 1. The signals recorded in parallel for each conductor bundle were added in time to obtain a summary conductor force (KLW, KLO, KPW and KPO). As the dynamic component of the forces is of main interest, all measuring was referenced to the cleanly recorded static tensile forces of the conductors.

In the structure of the north portal strain gauges were installed at 14 locations in order to measure the material stress of the lattice construction. The gauges were positioned in the middle of the respective girder and, if possible, at its cross-sectional centre of gravity.

The bases of the towers of the north portal rest on four short steel shafts set into the concrete of the foundation. The two shafts on the span side of the towers were equipped with full bridge strain gauges, called MAFU 1 to MAFU 4. They were used to measure the forces relevant for the dimensioning of the foundations. They have a defined sensitivity and output a positive signal when stretched. Due to the height of the crossarm of 11,22 m and the distance of the towerlegs of 1,2 m, a static tensile force will be measured by MAFU with an amplification of 9,35.

2.3 Test programme

The test programme included tests on the 100-kV-arrangement with a spacing of 100 mm, 200 mm and 330 mm and on the 400-kV-arrangement with a spacing of 200 mm and 400 mm. For each spacing there were tests without spacers, with one spacer and with two spacers. The short-circuit tests were made with short-circuit current values (r.m.s.) of 20 kA, 28 kA and 40 kA, each with current durations of 0,1 s, 0,2 s and 0,3 s for all mechanical arrangement variants.

If the distance between two conductors influencing each other is kept constant, the force generated by the current flowing through these conductors is proportional to the square of the current's value. With the chosen currents of 20 kA, 28 kA and 40 kA a ratio of the stimulus of 1 : 2 : 4 is used for all test variants. But while the stimulating current is clearly defined, the phase-distance between the conductors is changing in the process of the short-circuit because they are pushed apart. The force ratios mentioned are thus only valid in the initial stage of the short-circuit.

The r.m.s. value of the current is unchanged over the duration of the short-circuit, the initial short-circuit current I_k'' is equal to the continuous short-circuit current I_k. The ratio i_p/I_k was 2,5 throughout the tests, which corresponds to the value generally specified in standards for high-voltage substations.

3 TEST RESULTS

3.1 Interpretation of dynamic behaviour

Figure 2 shows recorded forces exerted by the conductor (first line) and measured on the foundation (second line) of the portal for an 400-kV-arrangement with very close bundling (additionally performed reference test with $a_s \approx 0$) during a test with a short-circuit current of 40 kA and a duration of 0,3 s. Due to the close bundling there is no considerable sub-conductor pinch force F_{pi}. Compared to recordings for single conductors, however, oscillations can be seen, which because of the low eigenfrequency of the portal (3,1 Hz) are not brought forward to the foundation.

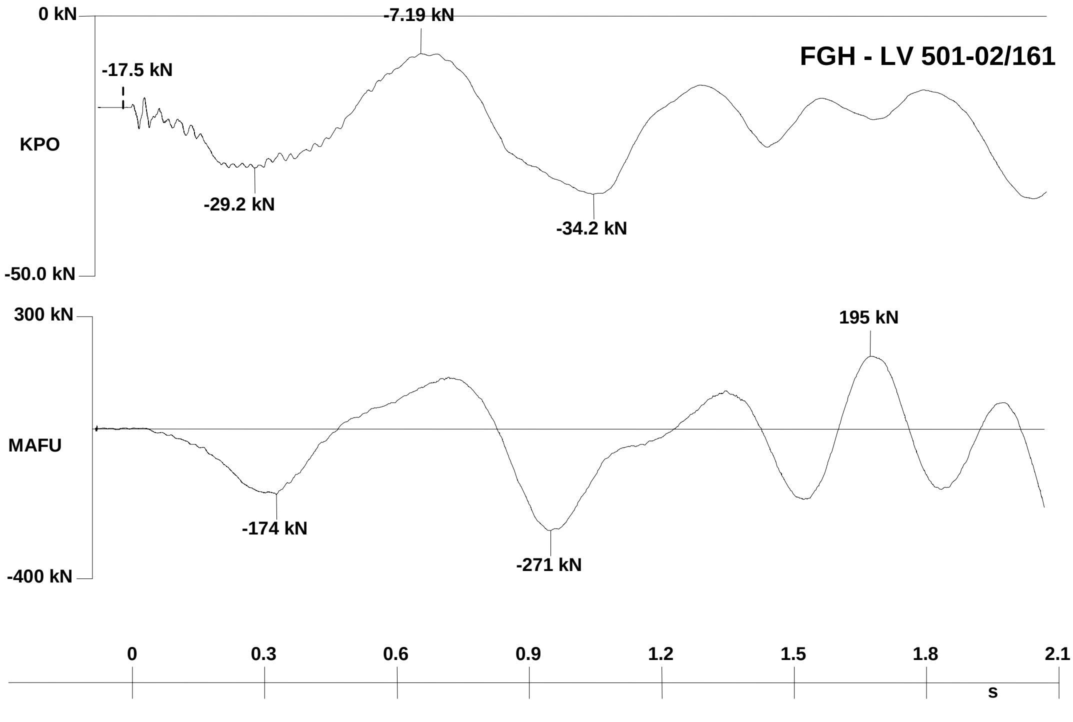

Figure 2: Recorded forces of the conductor (KPO) and at the foundation of the portal (MAFU) for close bundling

Therefore the portal is following the forces by the phase-conductor swing-out synchronously, is been bent according to its stiffness of 1086 N/mm and producing a force of 174 kN in the shafts of the portal foundation. Because of the high short-circuit current of 40 kA and the long short-circuit duration of 0,3 s the conductor bundle swings out more than 90 degrees. This leads to releases of the tension force exerted by the conductor to values below the static load. Even though the portal shows about the double frequency of the conductor tensile force, it is swinging back in synchrony to the release of the tensile force and causes at its foundation, also due to its relatively low damping, tensions of the same size but with changed sign.

For a free oscillation now a sinusoidal shape of the force could be expected, which here can only be seen for a half oscillation period. This is because the oscillation is damped for the present by the beginning growth of the drop force. Only when this new stimulation of the portal is decreased damped oscillations with 3,1 Hz can be identified.

The evaluation of the ESL factor according to the criterions given in [3] is possible for the swing-out force F_t. For the evaluation of the drop force F_f the still effective mechanisms of the swing-out-force due to the eigenfrequency of the portal must be considered.

Figure 3 gives the measurements for the same arrangement, short-circuit current and short-circuit duration, but with wide bundling. Due to the high sub-conductor distance a_s of 400 mm and two spacers there is a distinct contraction effect of the sub-conductors, which results in a high pinch force F_{pi} of short duration and in a remarkable high-frequent superposed oscillation in the following recording of the conductor force. The effects of swing-out and fall-of-span can be recognised only by comparing the recording with the one of the close bundling.

Since the eigenfrequency of the portal is low compared to the one of the distinctive pinch force by sub-conductor contraction, the portal is not bent by the time the pinch force appears. The pinch force rather is effective like a sinusoidal impulse on the portal structure. In the case shown the energy of this impulse is sufficient to cause an evident reaction of the portal.

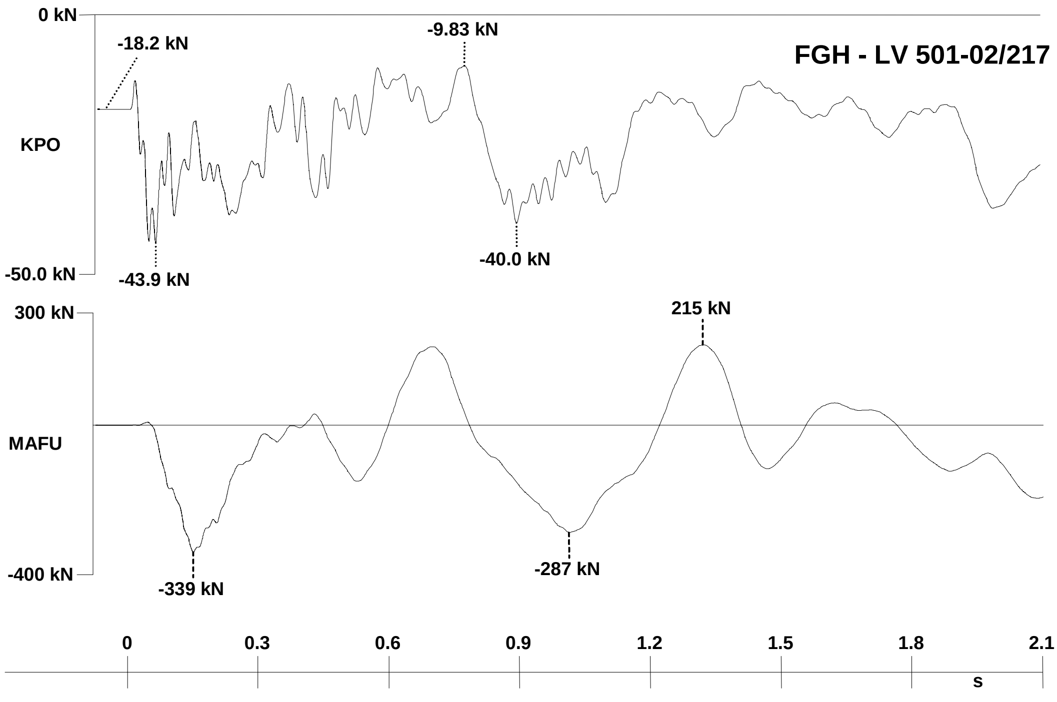

Figure 3: Recorded forces of the conductor (KPO) and at the foundation of the portal (MAFU) for wide bundling

The free oscillation back is – similar to the effect mentioned above for the fall-of-span force – largely compensated by the phase-conductor swing-out force. It releases the portal and forms an only small amplitude at about 0,55 s. This effect is specific for the test and caused by the fact, that the eigenfrequency of the portal is about double the frequency of the conductor force. By the same reason the fall-of-span force maximum here occurs at the same time as the forward oscillating of the portal again and forms a maximum force of 287 kN, a value, which would not be reached, if the ratio of the stimulating frequency and the eigenfrequency would differ. The free oscillating of the portal with its eigenfrequency can be seen only later when the stimulation by conductor forces is decreased.

Here the evaluation of the ESL factors is possible only for the pinch force by sub-conductor contraction, because the phase-conductor swing-out does not yet play an important role at the time the maximum force at the portal foundation is measured. All further maxima recorded on the portal foundation are generated by a mix of sub-conductor pinch force, phase-conductor swing-out force and fall-of-span force and can therefore not be used to evaluate ESL factors.

By that it can be stated, that with the tests in question it is not possible to define ESL factors separated for each of the maxima named in [1] without further investigation. Rather it is necessary to take a view of the complete course of the force, i.e. the dynamic collaboration of F_{pi}, F_t and F_f at the foundation of the portal. A clear relation of conductor forces and forces at the portal foundation separated for each single maximum is possible only, if one of both forces F_{pi} or F_t is dominant, where the dominance is not only depending on its amplitude but also on its frequency and mainly on the ratio of its frequency to the eigenfrequency of the portal.

3.2 Systematic evaluation of test results

Out of the recorded time histories of the tensile force, the three maxima are determined: F_{pi} during the contraction of the sub-conductors (pinch force), F_{so} during the swing-out of the conductor bundle and F_f when the span falls down. In this chapter, the results of the 400-kV-arrangement are dealt with. The results with 100 kV do not essentially differ. When investigating bundle effects, it is favourable to present the tensile forces depending on l_s/a_s, and to use the parameters a_s/d_s and I_k [3,6].

Figure 4 shows F_{pi} and F_{so} for T_k = 0,1 s. The values are connected by lines for better readability. Because F_{pi} occurs within 0,1 s, the extension of short-circuit duration has no influence, whereas F_{so} increases with longer short-circuit duration, also the maximum F_f during the fall down of the span.

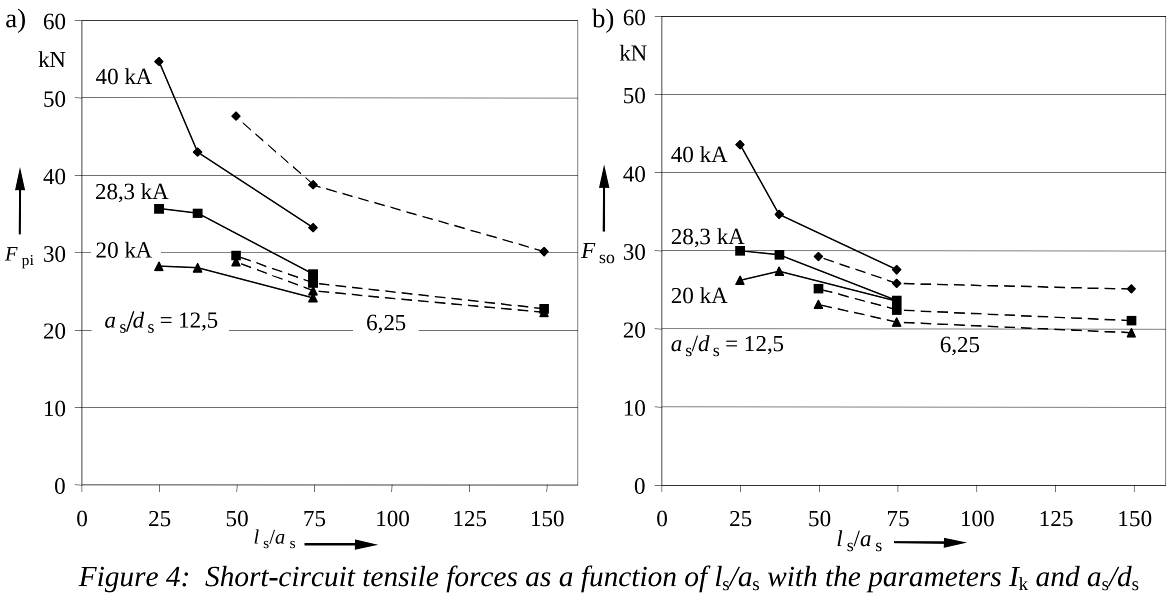

Figure 4: Short-circuit tensile forces as a function of l_s/a_s with the parameters I_k and a_s/d_s
a) Pinch force F_{pi} b) Swing-out force F_{so} for T_k = 0,1 s

Closer bundling (a_s/d_s = 6,25, broken lines) results in small difference between 20 and 28 kA for l_s/a_s = 150, and in distinct increase with 40 kA. l_s/a_s = 75, i.e. bisection of l_s, causes an increase of F_{pi} with all currents due to reduction of contact zone of sub-conductors. On the other hand, F_{so} remains nearly constant for l_s/a_s = 75...150. The stresses in the tower shafts are caused by the movement of the conductor bundle as depicted out in Figure 2. The same is with a_s/d_s = 12,5 (straight lines) when l_s/a_s=75.

Wide bundling ($l_s/a_s \leq 50$) leads to a remarkable increase of the forces at the shafts even during the sub-conductor contraction with both a_s/d_s = 6,25 and a_s/d_s = 12,5, as shown in Figure 3. F_{so} increases similar to F_{pi} as a result from the build up of the oscillation during the pinch and the superposition of this higher frequent oscillation during swing-out. This is strongly developed in Figure 3 with l_s/a_s = 25 and 40 kA. In contrast, the drop force F_f is nearly independent of the bundel configuration.

4 CALCULATION ACCORDING TO IEC 60865-1

In IEC 60865-1 [1] a method is stated for the simplified calculation of the mechanical effects of substation buses with flexible conductors caused by short-circuit currents. The three maxima of the tensile forces F_{pi}, F_t and F_f can be determined analytically . The physical background, the assumptions made and the derivation of the method are described in detail in [6]. The confrontation with many tests gives a good agreement [3]. Now, the tests reported in this paper allow to verify the standardized method in the case of strained conductors with wide bundling. For this reason all measured configurations the forces F_{pi}, F_t and F_f are calculated with the actual geometric data, static tensile forces, short-circuit currents and short-circuit durations using a PC program [10] in which the standard is implemented.

In a first step, the maximum of the tensile forces F_{pi}, F_t and F_f is determined which is decisive for the conductors, clamps, insulators and their anchoring: the maximum F_m for each measured case and the maximum F_c for its corresponding calculation. In Figure 5 each symbol marks a pair of measured and calculated maxima. Parameter is the sub-conductor distance as. In the reference case, the sub-conductors are very close, in Figure 5 marked by +. In addition, the relative error 0 % and the technical limit ±25 % are depicted as broken lines; above the 0 %-line the calculated values are on the safe side.

Figure 5 points out a remarkable agreement. With the 100-kV-structure, as good as all calculated values are on the safe side. With 400 kV, most of them are safe, the error of the values under the 0 % line is tolerable. The standardized method leads to the same decisive maxima as find out by the tests.

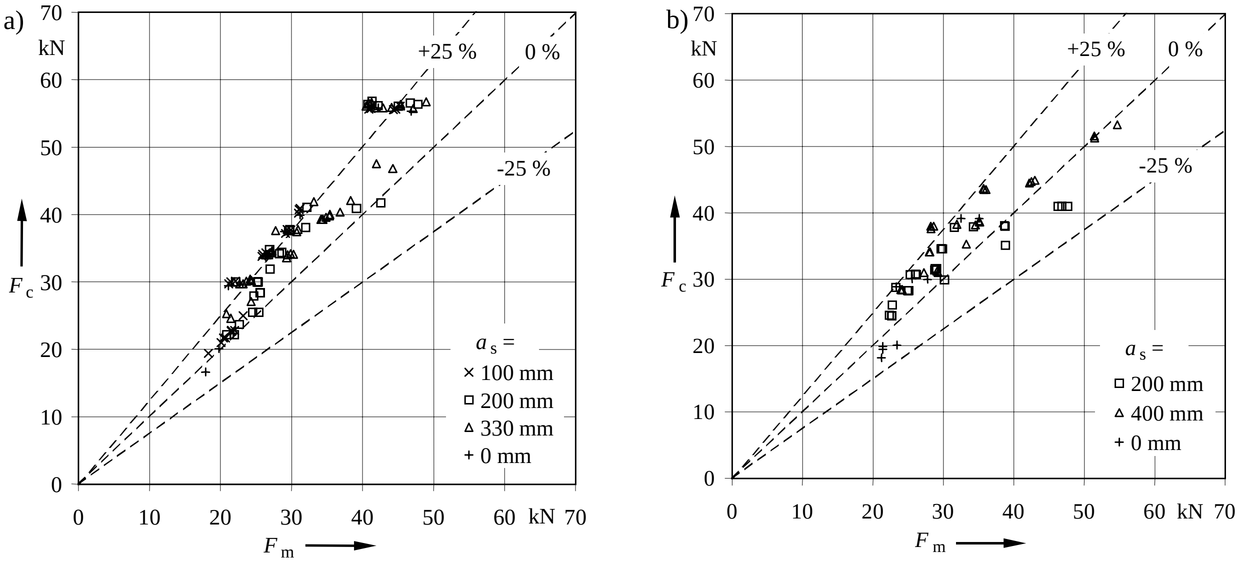

Figure 5: Comparison between calculations and tests for the tensile force
a) 100-kV-arrangement (108 tests) b) 400-kV-arrangement (63 tests)

For the 100-kV-structure, with a_s = 100 mm, 200 mm the pinch force is the highest one when I_k = 20 kA. Swing-out force or drop force dominates when I_k increases. With a_s = 330 mm and no spacer, swing-out and drop stresses are higher than pinch. Spacers build in lead to greater pinch force, except for the highest values of I_k and T_k. For the 400-kV-arrangement, the pinch force is mainly the decisive force due to the larger main conductor distance.

5 CONCLUSIONS

The calculation methods of IEC standard [1] for the assessment of the short-circuit strength rely on the basis of and on their validation by full scale experimental studies. A comprehensive series of systematic experimental studies on the short-circuit effects and the short-circuit constraints produced by strained stranded duplex conductors of open-air substations in a series of practical bundle sub-conductor arrangements has recently been performed by FGH.

The present rules in IEC ask for applying the maximum value out of the calculated F_{pi}, F_t, F_f as the static load responsible for the maximum stresses on the the structure and the foundations (ESL = 1, i.e. dynamic = static). The test results show that for close bundling the evaluation of the ESL factor is possible for the swing-out force F_t. For the evaluation of the fall-of-span force F_f the still effective mechanisms of the swing-out-force due to the eigenfrequency of the portal must be considered. For wide bundling, however, the evaluation of the ESL factors is possible only for the pinch force by sub-conductor contraction, because the phase-conductor swing-out does not yet play an important role at the time the maximum force at the portal foundation is measured. All further maxima recorded on the portal foundation are generated by a mix of sub-conductor pinch force, phase-conductor swing-out force and fall-of-span force and can therefore not be used to evaluate ESL factors. Further investigations with advanced methods are necessary before transformation of existing knowledge of ESL to IEC standard is possible.

The comparison between calculations and tests for the tensile force points out a remarkable agreement. With the 100-kV-structure, as good as all calculated values are on the safe side. With 400 kV, most of them are safe, the error of the values under the 0 % line is tolerable. The standardized method leads to the same decisive maxima as find out by the tests.

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