Calculation of Spacer Compression for Bundle Lines Under Short-Circuit

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***Abstract*—In a recent Institute paper [1], the authors presented experimental results on spacer compression, which showed clearly, that the simplified analytical calculation method used today, the so called Manuzio formula [2], leads to severe underestimation of spacer compression and thus to faulty spacer design. In this paper, further test results are presented covering today's practical range of bundle configurations, subspan lengths, sagging tensions and short-circuit levels for transmission lines. Based on these results, the authors present here a new calculation method for spacer compression, which builds up on well accepted IEC standards [3], [4].**

***Index Terms*—Short-circuit, spacer, compression, pinch.**

I. INTRODUCTION

SHORT-CIRCUIT mechanical effects are one of the main concerns for the design of substations and overhead lines in general and for the design of the related spacers and spacer dampers in particular. This paper is dealing with spacer loads during short-circuit, covering mainly overhead line parameters.

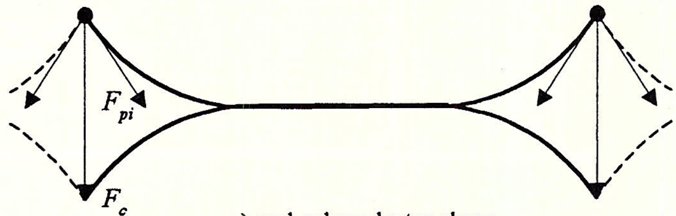
In 1967, Manuzio published one of the most interesting papers on the subject [2]. A simple formula had been deduced, which is still widely used and even recommended in recent IEC standards [5].

This paper re-examines the Manuzio formula and is complementary to a paper published recently by the authors [1]. New short-circuit tests have been performed on subspan lengths ranging from 10 to 20 meters, with r.m.s. short-circuit currents from 30 kA to 50 kA with maximum asymmetry. Also the sagging tension of the subconductors was varied from 15 to 25 to 35 kN.

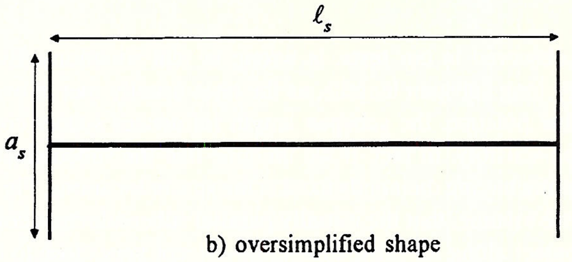
Together with the Manuzio tests, we recollected 28 well documented test cases: 7 on twin Curlew conductors, 5 on triple Cardinal conductors, 16 on twin Condor conductors. All these tests have been done on rigid spacers with measurement of both the pinch effect in the subconductors and the spacer compression. We have carried out further tests on a variety of spacer dampers (twin, triple and quad) which showed basically similar results as for the rigid spacers. For the sake of brevity and simplicity, we have decided to detail here only the rigid spacer tests.

Based on these 28 tests, we developed a new simple method to calculate spacer compression. This method is then compared to the Manuzio formula, showing that spacer under-valuation up to 30% does occur by using this formula.

The authors would finally like to stress, that the design of spacers (and spacer dampers) cannot be based any more on the Manuzio formula, in particular when short-circuit levels are as high as in most networks today.



a) real subconductor shape



b) oversimplified shape

Fig. 1. The pinch effect schematically: (a) real subconductor shape and (b) oversimplified shape.

II. WHY A NEW METHOD

As we discussed already in [1], the Manuzio simple formula [2], Appendix I, neglects some important effects, namely:

1) Pinch effect: During the contraction of the subconductors and the contact period, the tension changes in the subconductor. This effect can be quite large and so the pinch can reach several times the initial conductor tension [6]. For example, in our tests presented in this document, the pinch is up to two times the initial value of the tension of the subconductors. In [1] even higher tension increases were measured. It is quite clear that spacer compression, which is directly related to the pinch (both pinch and spacer compression are quasisimultaneous), is also affected by the pinch.

2) Asymmetry of the short-circuit current: With increasing short-circuit current, the time to contact (of the subconductors) and also to maximum pinch and maximum spacer compression becomes smaller and smaller (lower than 0.1 s in our cases). This means, that the energy input, which is proportional to the square of the current, is severely increased by the asymmetry of the current (the first peak of the short-circuit current can be more than 2.5 times its r.m.s. value). This high initial energy is fully "injected" in the subconductors and increases their tension which then creates the pinch.

3) Subspan length effect: Manuzio neglected the subspan length effect, which was consistent with no pinch, but which,

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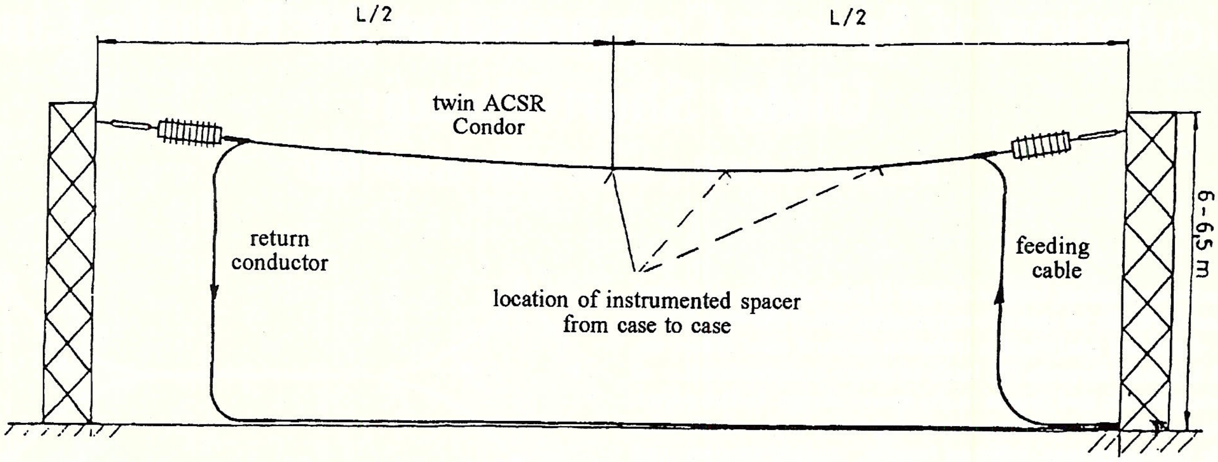

Fig. 2. Schematic of test span.

as we observed in our tests, is wrong in real situations. Even for very long subspan lengths, as the ones usually met in overhead line practice, the subspan length influences spacer compression sensibly. In fact, if we imagine that the subconductor are moving having their ends fixed at the spacer locations, Fig. 1, and if we assume, that the initially parallel subconductors come into contact along all subspan length—except very close to the spacers—, the subconductor length ℓ_s, in a first rough estimate will have to increase by about the subconductor spacing a_s. It means that, following Hooke's law, the pinch in each subconductor could be estimated by:

$$\sigma = E\varepsilon \text{ or } F_{pi}/A_s = Ea_s/\ell_s \text{ or } F_{pi} = A_sEa_s/\ell_s.$$

Here σ is stress and ε strain in the subconductor, A_sE is the product of Young's modulus E times the subconductor cross section A_s (for a complete list of symbols see Appendix II). This oversimplified approach clearly points out, that subconductor tension cannot remain constant during contact and that subspan length affects spacer compression.

III. New Test Results

Some new selected tests cases are reproduced in this document. The tests were performed in VEIKI (Budapest, Hungary). Further tests, including the results from [1] and [2], are detailed in Appendix A.

The test arrangement is shown schematically in Fig. 2. The main test parameters are summarized in the following list:

Subconductor:	ACSR Condor (A_s = 455 mm^2, d_s = 27.7 mm m_s = 1.52 kg/m, UTS = 125 kN)
Spacing:	0.457 m
Sagging tension:	15, 25 or 35 kN
Short-circuit data:	
Current:	35 kA (90 kA peak) or 48 kA (122 kA peak)
Time constant:	43 ms
Duration:	0.1 to 0.2 s, one case 1 s
Span length:	60 or 120 m
Supporting structure:	
Stiffness:	about 8.5 × 10^6 N/m
First eigenfrequency:	about 14 Hz

All cases are one-phase faults with the return path on the ground. To obtain a good range of precision, most of the cases have been tested with two spacers separated by 0.5 m, each being equipped with two full bridges of strain gauges. Further some tests have been carried out twice to ensure repeatability of the test setup. By these precautions the error on measurements can be estimated to be about 10%.

In the following, three cases are picked out and presented in detail. They are deemed to be representative of the whole test series carried out, as they cover subspan lengths of 10, 30 and 60 in and short-circuit currents up to 122 kA peak and extreme long duration of 1 s. They are case 2, case 10 and case 14 from Appendix I.

IV. Calculation of Spacer Compression

The new simple method developed and presented here, must include the parameters mentioned in Chapter II. Looking for the simplest possible way and trying at the same time to be as close to known and accepted IEC standards, we finally decided to use as basis of our method the procedure given in IEC 865-1 [3], for evaluation of pinch tension in substations. This is again based on the work developed inside CIGRE and recently published in [6]. We adapted this method also for overhead lines by implementing a constant tower stiffness (100 N/mm for both supports of one span) and we used the output of IEC 865—the pinch force—to calculate spacer compression. Our suggested procedure is as follows:

In Fig. 6 one subconductor—its center line—is reproduced near the spacer location, at the instant of maximum pinch and thus maximum spacer compression. The x-axis coincides with the bundle center line. Where the subconductors are in contact, their centers are keeping a certain distance equal to the subconductor diameter d_s. The distance ℓ_{nc} is the so-called noncontact length, which is unknown and must be evaluated. Further, between the spacer location and the contact point, the subconductor shape $y(x)$ is assumed to be a parabola [6], following the equation:

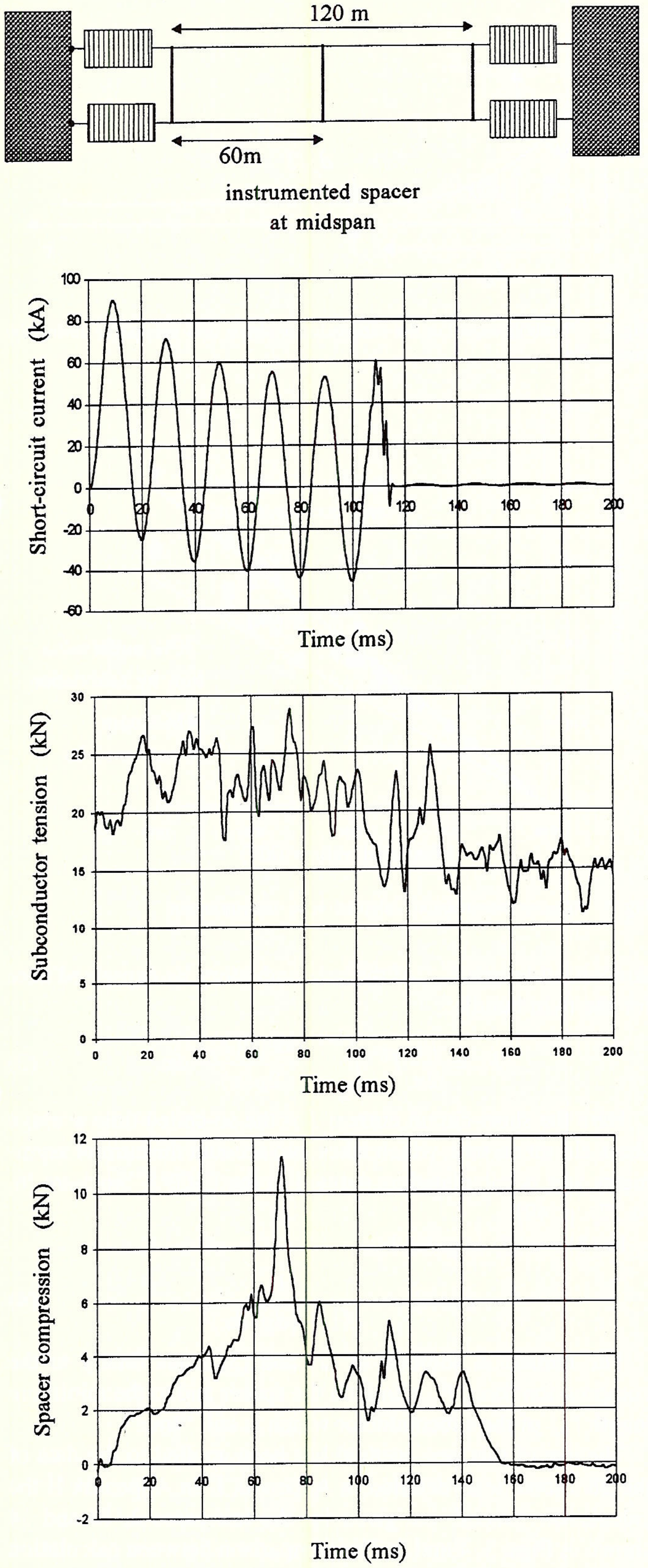

Fig. 3. Oscillograms for test no. 2.

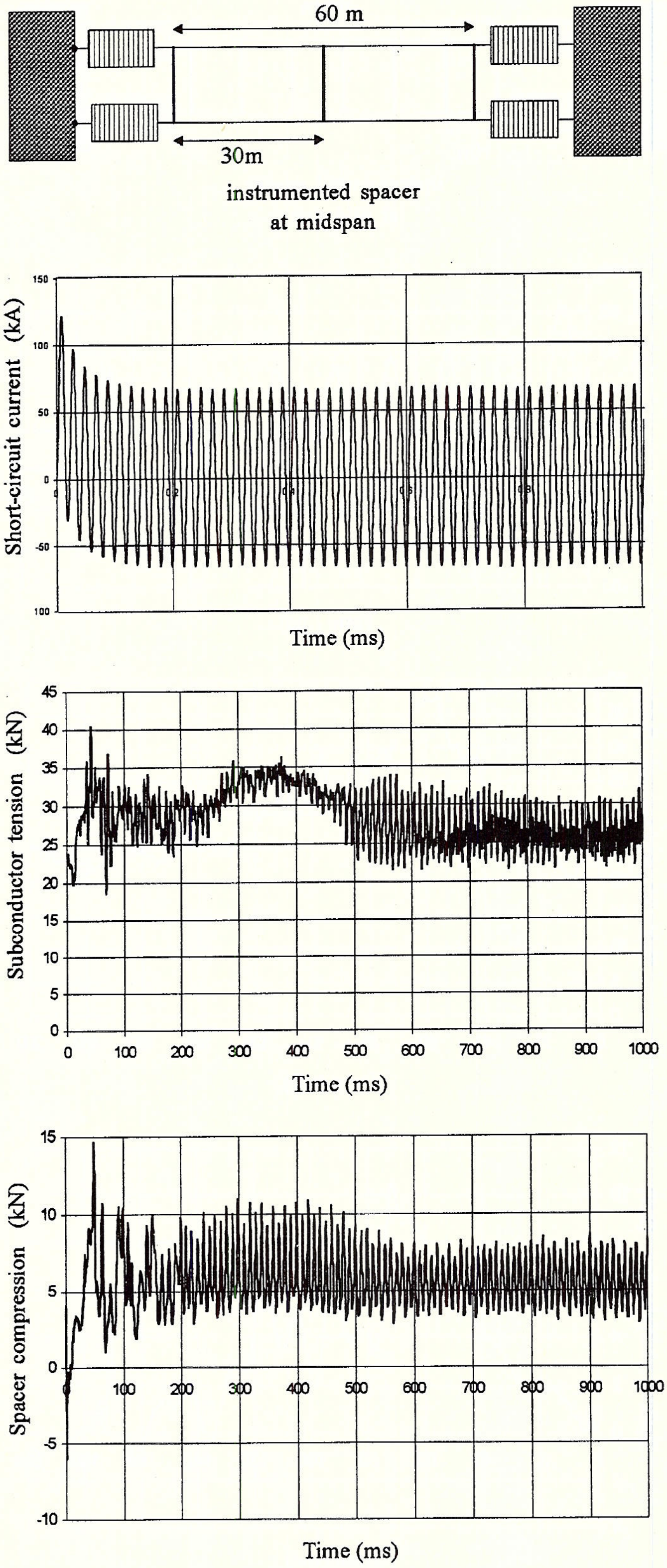

Fig. 4. Oscillograms for test no. 10 (2 × 30 m, 25 kN, 47/120 kA, 1 s).

$$y(x) = \frac{a_s - d}{2} \cdot \left(\frac{x}{\ell_{nc}}\right)^2 - (a_s - d_s) \cdot \left(\frac{x}{\ell_{nc}}\right) + \frac{a_s}{2}. \quad (1)$$

The compression spacer force F_c is the projection of the pinch force F_{pi} on the spacer at the spacer location. The pinch force is the traction in the subconductor, which is assumed to constant along the subconductor. The pinch direction is given by the tangent, which has a deviation ϑ from the horizontal. In this simple approach, the conductor bending is completely neglected, so that the subconductor shape near the spacer can be reproduced

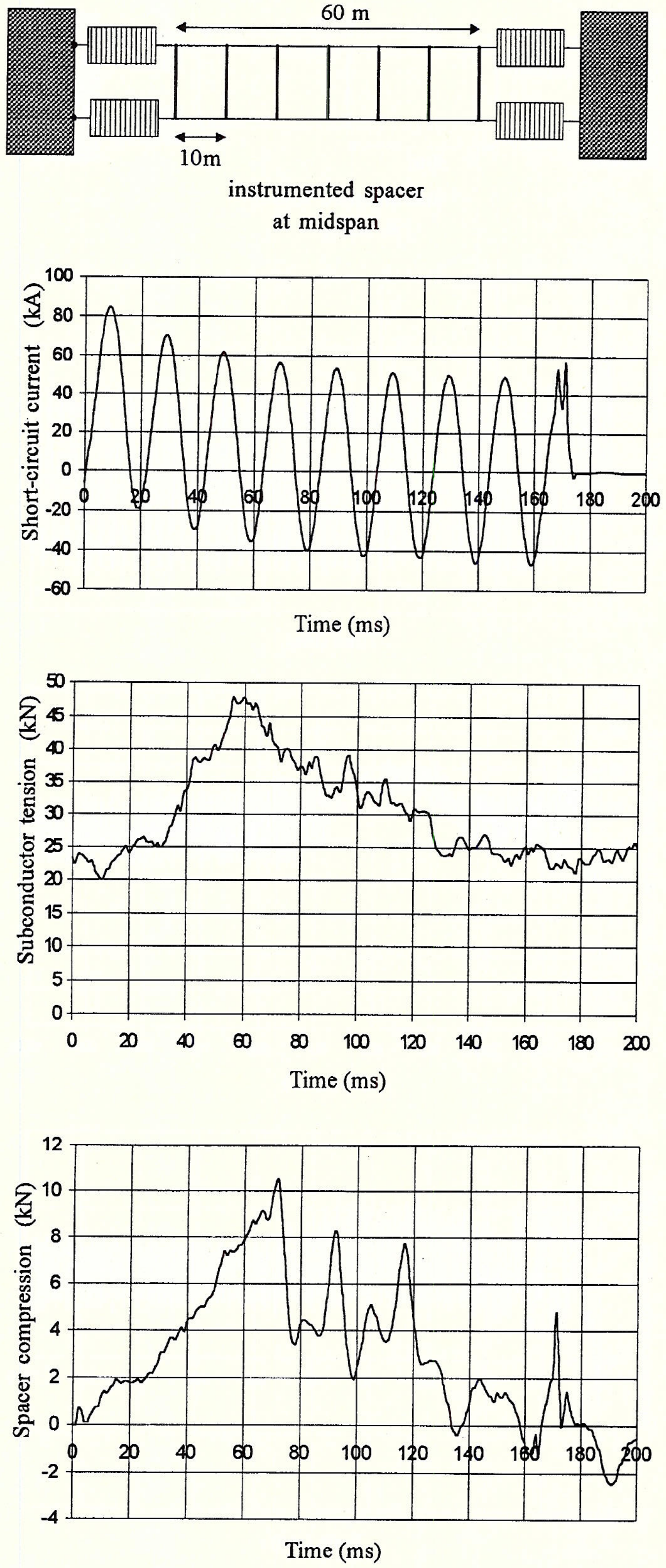

Fig. 5. Oscillograms for test no. 14 (6 × 10 m, 25 kN, 33/85 kA, 0.17 s).

as shown in Fig. 6. Conclusively half of the spacer compression is given by:

$$F_c/2 = F_{pi} \cdot \sin(\vartheta)|_{x=0} = \frac{F_{pi}}{\sqrt{1 + (\ell_{nc}/(a_s - d_s))^2}}. \quad (2)$$

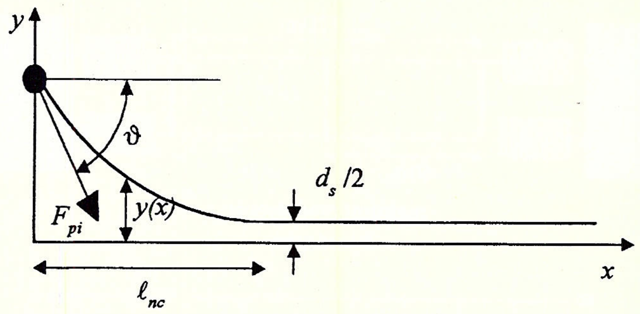

Fig. 6. Parabola model of the subconductor shape near the spacer during the pinch effect.

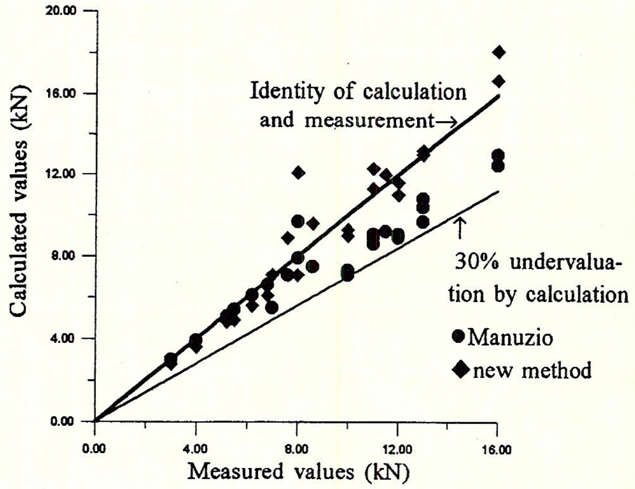

Fig. 7. Spacer compression: calculation vs. measurement.

On the other hand, spacer compression can be gained from the equilibrium equation with the electromagnetic load on the noncontact length ℓ_{nc}, of the subconductors, as expressed here for the twin bundle:

$$F_c = \frac{\mu_0}{2\pi} I^2 \int_0^{\ell_{nc}} \frac{\cos(\vartheta(x))}{2y(x)} dx. \quad (3)$$

Here the short-circuit current I is the so-called time average short-circuit current, which takes into account the current asymmetry and is calculated as defined in the CIGRE brochure [6, (4.27), p. 49].

In (3) $\cos(\vartheta)$ is given by:

$$\cos(\vartheta) = \frac{1}{\sqrt{1 + (dy/dx)^2}}. \quad (4)$$

The numerical solution of (2) and (3) leads finally to the compression force F_c acting on the spacer and to the minimum length ℓ_{nc} of the subconductor which is still "free."

The use of this new method has been applied to the data of the 28 known tests detailed in Appendix I. In Appendix II the calculation "traces" are given for the test cases 2, 10 and 14 shown in Figs. 3, 4 and 5. The comparison between calculation and measurement results is summarized in Fig. 7.

From this figure it is clear, that the Manuzio formula is adequate for low spacer compression—the first dots (below 5 kN) are coming from the Manuzio tests—, but deviates up to 30% for all other cases. On the other hand, the new method, as described in this paper, remains practically always in the range of measurement precision. Only one dot is clearly out of the range (case 1), probably because of measurement error.

V. Conclusions

We have developed a new method for spacer compression evaluation. It has also been pointed out that the Manuzio formula cannot be used any more for safe spacer design.

The simple method presented here, is based on the well known IEC 865 [3], [4], basically used for the design of substations, which has been adapted to overhead lines and also extended to cover the calculation of spacer compression.

Since most of the validation cases are in the range of overhead line practice (subspans of 30, 40, 60 and 120 meters), more results would be needed to extend our proposal to substations, especially when there is no contact between subconductors. Nevertheless, we can point out to the good correlation for 10 m subspan length.

Of course more complex situations, like asymmetric bundles, very wide bundles or when other parameters substantially differ from those used here for validation, these can be evaluated by complex, advanced calculation methods, as shown in [1]. In most practical cases though, this method can be used for evaluating spacer (and spacer damper) compression and thus can replace tedious short-circuit tests by equivalent static mechanical tests.

Appendix I

Summary of Short-Circuit Test Results and Validation of the New Method

Case No.	Span arrangement: Subspan number x subspan length (m)	Initial tension per subconductor F_{st} (kN)	Short-circuit current (kA) r.m.s./peak	Pinch per subconductor F_{pi} (kN)	Full spacer compression F_c (kN)	New method F_c (kN)	Manuzio formula* F_c (kN)
A. Twin Condor subconductors with 0.457 m separation (unless otherwise stated)							
1	1x120	25	35 / 90	27.5	8	12.1	9.7
2	2 x 60	23	35 / 90	28.5	11.5	12	9.2
3	2 x 60	20	35 / 90	25.5	11	11.3	8.6
4	4 x 30	25	35 / 90	38	13	13	9.7
5	1 x 60	13	33 / 85	19	7.6	8.9	7.1
6	2 x 30	15	33 / 85	28	10	9.3	7.1
7	2 x 30	33	33 / 85	45	13	13	10.4
8	1 x 60	35	33 / 85	42	13	13.2	10.8
9	1 x 60	23	47 / 120	36	16	16.7	12.5
10	2 x 30	25	47 / 120	40	15	18.1	13
11	1 x 60	25	33 / 85	30.5	11	11.3	9.1
12	2 x 30	25	33 / 85	35	12	11.6	9.1
13	2 x 30	25	33 / 85	37	[a]	-	-
14	6 x 10	24	33 / 85	50	11	12.3	8.9
15 (triple)	2 x 30	25	50 / 130	37	[a]	-	-
16 (quad)	2 x 30	25	48.6/128	35	[a]	-	-
B. Triple Cardinal subconductors with 0.4 m separation from [1]							
17	1 x 40	13.3	40 / 102	22.6	10	9	7.3
18	1 x 40	20	40 / 102	30	12	11	8.9
19	1 x 40	7.7	40 / 102	18.5	7	7.1	5.5
20	2 x 20	14.3	40 / 102	33	8.6	9.6	7.5
21	2 x 20	14.3	40 / 102	34	8.2	9.6	7.5
C. Twin Curlew subconductors (Manuzio test results) from [2]							
22	2 x 65	20	13 / 18.4[c]	[b]	3	2.8	3
23	2 x 65	20	22 / 31.1[c]	[b]	5.2	4.8	5.1
24	2 x 65	20	26 / 36.7[c]	[b]	6.2	5.6	6.1
25	2 x 65	33	13 / 18.4[c]	[b]	4	3.6	3.9
26	2 x 65	33	18 / 25.4[c]	[b]	4	3.6	3.9
27	2 x 65	33	22 / 31.1[c]	[b]	6.8	6.1	6.6
28	2 x 65	33	26 / 36.7[c]	[b]	8.0	7.1	7.9

[a] Not measured [b] No information [c] No asymmetry

* The Manuzio formula is presented in [2]: $F_c = k\, I_k''\sqrt{F_{St}\log_{10} s/d_s}$,
where s is the diameter of the circle through the axis of the subconductors and given by $s = a_s/\sin(180^\circ/n)$,
k is a correction factor depending on the number of subconductors with the values (for I_k'' in kA and F_{st} in N) k(twin)=1.585, k(triple)=1.45, k(quad)=1.26 and the other symbols are explained in Appendix II. Examples:

Case 1: $F_c = 1.585 \cdot 35\sqrt{25000 \cdot \log_{10} 0.457/0.0277} = 9678\,N$

Case 17: $F_c = 1.45 \cdot 40\sqrt{13300 \cdot \log_{10} 0.461/0.030} = 7286\,N$ (with $0.461 = 0.4/\sin 60^\circ$)

APPENDIX II

"TRACES" OF COMPLETE CALCULATIONS FOR SELECTED TEST CASES (NOS. 2, 10 AND 14) ACCORDING TO IEC 865

Parameter's significance	Symbol (IEC 865)	Equation (IEC 865)	Dimension	Case 2	Case 10	Case 14
A. Input data						
Initial short circuit current (r.m.s.)	I''_k	-	kA	35.1	47.0	33.0
Time constant of network	τ	-	ms	43	43	43
Peak current	i_p	-	kA	89.59	119.96	84.23
System frequency	f	-	Hz	50	50	50
Mass per unit length of one subconductor	m_s	-	kg/m	1.524	1.524	1.524
Diameter of one subconductor	d_s	-	mm	27.72	27.72	27.72
Cross-section of one subconductor	A_s	-	mm^2	455	455	455
Centre-line distance between subconductors	a_s	-	mm	457	457	457
Number of subconductors	n	-	1	2	2	2
Resultant spring constant of both supports of one span	S	-	N/mm	100	100	100
Centre line distance between supports (span-length)	ℓ	-	m	120	60	60
Subspan-length	ℓ_s	-	m	60	30	10
Young's modulus	E	-	N/mm^2	100000	100000	100000
Thermal linear expansion coefficient	α_ϑ	-	1/°C	23×10^{-6}	23×10^{-6}	23×10^{-6}
Static tensile force per subconductor [a]	F_{st}	-	kN	23	25	24
B. Output data						
Impedance angle of network	γ	A.6	rad	1.50	1.50	1.50
Factor for calculating F_{pi}	ν_1	(46)	1	3.48	2.60	3.71
Equivalent current	I	*	kA	46.1	66.1	42.9
Time from short-circuit initiation until reaching pinch force F_{pi}	T_{pi}	A.6	ms	53	37	57
Equivalent stiffness coefficient (stiffness norm)	N	(25)	1/N	9.4×10^{-7}	1.78×10^{-8}	1.78×10^{-8}
Factor for calculating F_{pi}	ν_2	A.6	1	1.73	1.98	1.69
Short-circuit current force between subconductos	F_ν	(43)	N	77391	79398	11152
Strain factor of the bundle contraction	ε_{pi}	(48)	1	14949	3611	18.78
Strain factor of the bundle contraction	ε_{st}	(47)	1	127.1	65.1	6.94
Parameter determining the bundle situation during short-circuit (clashing or no-clashing of subconductors)	j	(49)	1	10.8	7.4	1.5
Factor for caclculating F_{pi} in the case of clashing sub-conductors	ξ	(51)	1	10.8	7.4	1.5
Factor for calculating F_{pi}	ν_3	A.7	1	0.181	0.181	0.181
Factor for calculating F_{pi}	ν_4	(53)	1	15.47	15.47	15.47
Factor for calculating F_{pi}	ν_e	(52)	1	2.57	2.28	1.89
Pinch force per subconductor [a]	F_{pi}	(50)	kN	28.0	31.5	33.7
Spacer compression force	F_c	[b]	kN	12.0	18.1	12.3
Non-contact length	ℓ_{nc}	[b]	m	2.18	1.62	2.58

[a] In IEC 865 forces are given for one main conductor (per phase)   [b] Calculation by solving (2) and (3) of this paper

* The calculation of the so-called equivalent current I is given in detail in [6], page 49:

$$I^2 = \frac{1}{T_{pi}} \int_0^{T_{pi}} i^2(t)\,dt \text{ with } T_{pi} = \frac{1}{sin(180^\circ/n)} \cdot \sqrt{\frac{(a_s - d_s)\cdot m_s}{(\mu_0/2\pi)\cdot(I/n)^2\cdot((n-1)/a_s)}} \text{ and } i(t) = I''_k\sqrt{2}\left[sin(\omega t - \gamma) + e^{t/\tau} sin\gamma\right];\ \mu_o = 4\pi\ 10^{-7} \text{ H/m}$$

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