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THE MECHANICAL EFFECTS OF SHORT-CIRCUIT CURRENTS IN SUBSTATIONS WITH FLEXIBLE CONDUCTORS

NUMERICAL METHODS - COMPUTER APPROACH

Paper presented in the Name of Study Committee 23 - (Substations)

by

W. LEHMANN
Siemens AG, Erlangen
(Germany)

J.L. LILIEN
Univ. de Liège
(Belgium)

J. ORKISZ
Techn. Univ. Cracow
(Poland)

SUMMARY

This paper provides a review of the application of advanced computer methods to the evaluation of the mechanical effects caused by the electromagnetic forces associated with short-circuit currents.

The parameters and results which may be calculated, mechanical modelling of conductors and structures and calculation methods using the presently available advanced computer programs are described.

The calculation methods are compared on several bases including accuracy, computational costs, storage requirements and the complexity of the modelling.

KEYWORDS

Bundle, Conductor, Finite Difference, Finite Element, Nonlinear structure analysis, Short-circuit force, Substation.

1 INTRODUCTION

1.1 Formulation of the problem

A big portion of HV and EHV substations has bare flexible conductors, single or bundle (Fig. 1).

Flexible conductors are subjected to large displacements and tensions when acted on by high short-circuit currents. The evaluation of the mechanical effects in such situations by computer methods which are precise enough for engineering purposes, is the subject of the present paper. It is a very complex problem that can hardly be solved by simple methods. The problems concerned are essential subjects in the studies of the CIGRE Working Group 23.02. Besides the present paper this work should result in three other papers:

- the conductor deflections and choice of clearences, especially for conductors A and D in Fig. 1;
- the stresses for the strain bus A;
- the stresses for the connections C.

These papers will be based on many tests and investigations [1-4]. They will summarize the calculation methods, which it is hoped, can be found from analytical considerations e.g. the pendulum model, which do not necessarily require the use of a computer. These methods will be relatively simple but on the other hand they

- may give a very rough evaluation of the results;
- are only formulated for particular arrangements;
- cannot supply the user with all desirable information such as time distribution of various quantities desired.

Therefore it is of great interest to have, in addition to the results of full scale tests, calculation methods for the time variation of displacements, forces and moments of all the components of the actual substations such as conductors, clamps, insulators, steel structures, foundations. From the mechanical point of view, due to the very low probability of heavy faults, it is important to know their

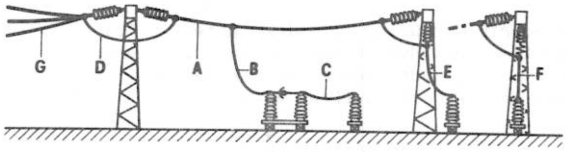


Fig. 1 Typical arrangements for flexible conductors in outdoor substations

A Horizontal strain bus connected by insulator strings to the steel structures
B Vertical connection to span (dropper)
C Connection between components
D Jumper
E Dropper at span end
F Dropper at span end, spring-loaded
G Line connection, not parallel as A

consequences with a sufficient accuracy in order to suit the safety margins to the random nature of the faults. Obviously, discretization procedures with large computers are qualified for this task. Today the use of a computer is not cheap but justifiable, the more the mechanical short-circuit effects become the dominant factor in the design of substations with flexible conductors due to the increasing values of the short-circuit currents.

1.2 State of the art in computer calculations

In recent years the analysis of complex structures has become possible through the use of electronic digital computers operating on discrete models. Precise evaluation of mechanical effects (displacements, stresses) caused by short-circuit current in substations with multiplex flexible conductors is, however, no trivial problem. It cannot be solved in a satisfactory way by the direct application of any available general computer program, though these can possibly be adapted, e.g. ADINA [5].

On the other hand, some attempts have been made to prepare some special purpose programs for the examination of short-circuit effects [6-10]. Though a discrete, computer-aided approach allows for a much better simulation of the real structure than is the case for any simple method, the programs differ from one another both in the assumed physical model and in the mathematical methods used.

1.3 The aim and the content of the present paper

The present paper provides design engineers with brief information on the application of advanced computer methods for the evaluation of mechanical effects of short-circuit currents in EHV substations. The following questions are especially discussed:

- What can be calculated?
- Which methods are preferred?
- Which are the most advanced programs available?
- What is the "price" of such calculations?

In the next sections electromagnetic short-circuit forces are discussed (2) followed by a description of mechanical models of structures (3) as well as computer methods and programs (4). The relation to experimental results is also presented (5). Final conclusions (6) are given.

2 ELECTROMAGNETIC SHORT-CIRCUIT FORCES

One electric conductor carrying current $i_1(t)$, in a magnetic field due to another conductor carrying current $i_2(t)$, undergoes an electromagnetic force defined by the formula (Fig. 2):

$$\overrightarrow{d^2F} = i_1(t) \cdot i_2(t) \cdot \vec{K} \qquad (1)$$

with

$$\vec{K} = \frac{\mu_0}{4\pi} \cdot \frac{\overrightarrow{ds_1} \wedge (\overrightarrow{ds_2} \wedge \vec{r})}{r^3} \qquad (2)$$

where $\wedge$ denotes the vector product.

Note that we do not have the reciprocity due to considering only conductor elements.

The force is to be calculated for every two elements which one wants to consider; it is obviously also possible to have two elements of the same conductor.

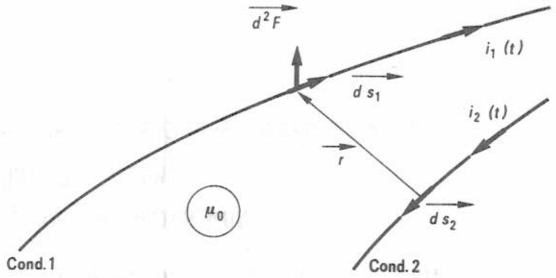


Fig. 2 Electromagnetic force $\overrightarrow{d^2F}$ acting on $\overrightarrow{ds_1}$ in the magnetic field of $\overrightarrow{ds_2}$ (μ_0 magnetic constant)

Eq. (1) shows that the local force intensity on conductor 1 is the product of a function which varies with time $i_1(t) \cdot i_2(t)$ and a spatial distribution $\vec{K}$ of the force.

The time dependance is connected with the evaluation of the short-circuit current, which is usually written in the form

$$i(t) = \sqrt{2}\, I_{rms} \left[\sin(\omega t - \gamma + \Phi) + e^{-t/\tau} \sin(\gamma - \Phi)\right] \qquad (3)$$

where:

$f = \omega/2\pi$	is the frequency of the current
$\sqrt{2}\, I_{rms}$	is the peak value of the permanent short-circuit current
$\gamma = \arctan X/R$	is the angle of impedance
Φ	is an angle related to the instant the fault appears
$\tau = X/(\omega R)$	is the time constant of the network at the fault point (from 30 ms to 150 ms if we are near the generator group)

The resulting time function $i_1(t) \cdot i_2(t)$ depends on the type of short-circuit considered:

phase-to-phase fault or three-phase fault.

It is always a superimposition of three components: a near-continuous component and two near-periodic components of the frequencies f and 2f [19].

The spatial distribution. In a finite element context, the spatial distribution of forces can be calculated numerically in a consistent manner on the basis of the shape functions utilized to construct the mechanical model as described in [10, 11]. It may be also done by the finite difference approach [7, 8, 12]. Another possibility is to evaluate the influence of each element by analytical considerations as given in [13].

The integration of the force will be done taking into account:

The spatial distribution of forces is dependent on the motion of the cable, but it undergoes relatively slow changes in time compared with those of the time distribution. It is thus not necessary to update it at each step of the time-integration process.

The elementary contributions due to remote elements decrease as 1/r and it is possible to stop the integration when the relative incremental contribution becomes less than a given tolerance.

3 MECHANICAL MODEL OF THE STRUCTURE

3.1 Brief description of typical real structures

In an actual structure everything included is represented by straight buses of single or bundle conductors, insulator strings, steel towers or gantries, apparatuses (insulators), substructures, foundations. The bus systems of the substation illustrated in Fig. 3 are rated for 6000 A and the feeders in the second and third level for 3000 A. Consequently for the buses four conductors of 1045/45 mm^2 ACSR are bundled together and bundles of two are used for the feeders (Fig. 4). The buses are secured to the steel structures by insulator strings and the individual spans are supported such that axial movement is permitted. The strain insulators are either of the cap-and-pin type (glass or porcelain) with many elements, for Fig. 4, or they are of the longrod type (porcelain) with few elements. For the steel structures the lattice type predominates over the solid-web types. The bases of supporting structures which only have to bear vertical loads may be hinged. The foundations are designed to meet all given loads but they do not remain motionless in the earth if large short-circuit forces occur. Referring to the apparatuses it should be pointed out that for many components attention must be paid to the reduction in stiffness caused by coupling links. For instance, a complete insulator assembly is more elastic than the actual porcelain column. For optimum calculation conditions, the availability of measured data such as deflections and spring constants is often imperative.

3.2 Mechanical model used in calculations

In calculations the actual structure mentioned above is replaced by an ideal one called a mechanical model. It consists of bars, cables and possibly rigid bodies. We distinguish between two kind of bars, namely truss and beam elements.

Truss elements are straight bars which are only subject to axial forces (tension or compression). They are connected as hinges.

Beam elements are able to transmit arbitrary forces and moments i.e. besides axial forces they may be subjected to bending and torsion forces.

In calculations truss elements are characterized by cross-sectional area, mass density, Young's modulus and Poisson's ratio. In the case of beam elements torsional and bending moments of inertia are also needed.

In substations we may distinguish between conductors (single or bundle), insulators, supporting structure (gantry, steel tower, apparatuses foundations) and some auxiliary arrangements such as jumpers and droppers.

Conductors play the key role in the success of any mechanical model of a substation. Under the influence of short-circuit forces they display a strong nonlinear behaviour such as large displacements and a rapid change of shape in the neighbourhood of spacers (Fig.4). Conductors are modelled by tensioned cables that may be considered as a chain of cable elements of required order. Insulators are replaced by a chain of rigid or semirigid bodies. Jumpers and droppers, if considered, are also modelled like cables, or at least assumed to be concentrated masses. Usually multiple conductors (Fig. 4) are considered; their motion is restricted by spacers (truss elements).

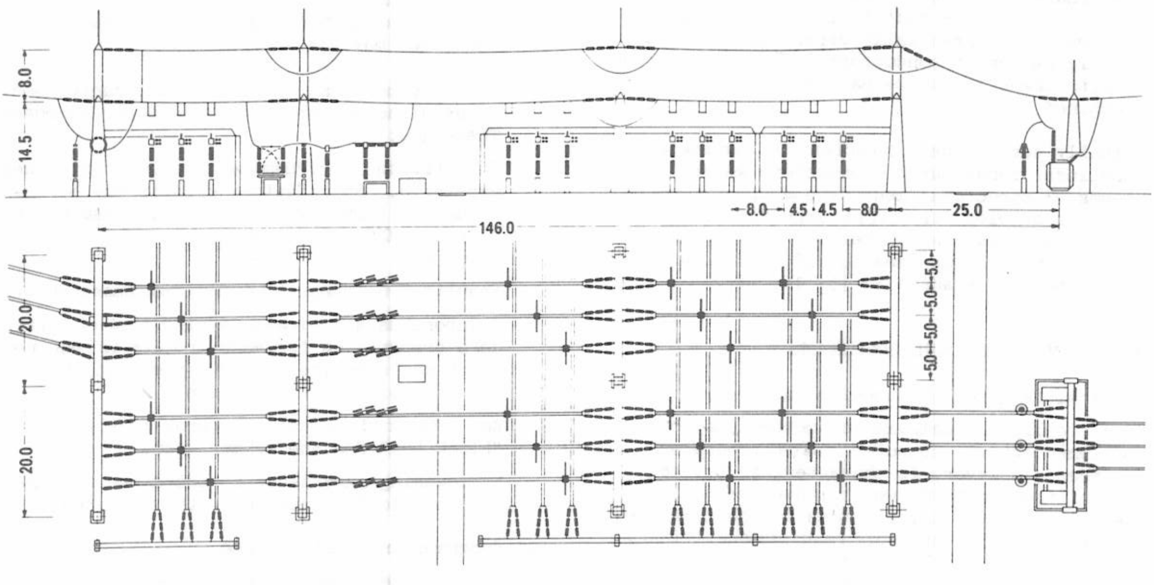


Fig. 3 420 kV outdoor substation with triplicate bus and bypass; Dimensions in metres

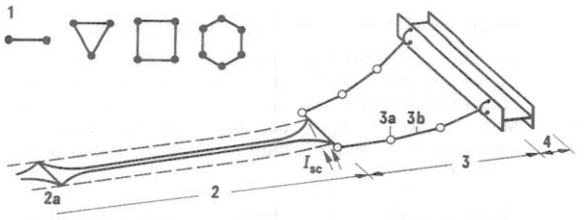


Fig. 4 Bundled conductors

1 Usual bundle arrangements: 2, 3, 4 and 6 single conductors
2 Horizontal bundle with 2 single conductors
----- normal position
——— position due to short-circuit current I_{SC}
2a spacer
3 Chain model of insulators
3a hinge, 3b element; e.g. rigid bar
4 Supporting structure: e.g. deformable bar elements

A real supporting structure is represented by a space frame (structure composed of beam elements) or trusses (structure composed of truss elements). Due to the relatively small displacements its motion may well be described in terms of linear theory, contrary to the non-linear theory necessary in the case of conductors.

A reasonable mechanical model of a substation should permit not only large displacements of cables (non-linear theory) but also temperature and damping effects, as well as various boundary conditions e. g. clamped, free-supported (especially significant is the type of foundation for the supporting structures in the ground) and service conditions such as kind duration of short-circuit current, multiple reclosure, actual short-circuit electromagnetic forces.

A very important problem is the exact system loading caused by electromagnetic short-circuit current forces. These are both conductor to conductor interactions in a bundle and phase to phase interactions. It is necessary to emphasize that these electrodynamic interactions essentially depend on the actual configuration of conductors. In this way electromagnetic and mechanical effects are combined.

Finally due to the character of loading and nonlinear behaviour of conductors we deal in terms of structural mechanics with a nonlinear dynamic problem for cable structures. Such theory and calculation methods in the general case of non-linear dynamics of structures are described for example in [5, 14, 15].

4 COMPUTER METHODS AND PROGRAMS

4.1 General features of numerical approach

Practically all calculation methods may be implemented by a computer. The computer approach, however, is characterized by the use of those methods which leave the most of decisions in the calculations to the computer itself. Such an approach requires preliminary discretization of the problem considered. Discretization in numerical analysis is understood as a replacement of the problem expressed in terms of differential or integral equations by another problem described in terms of algebraic equations involving discrete quantities (numbers). In the dynamics of structures we deal with both space and time discretization. Nowadays in the first case the finite element (FEM) or finite difference (FDM) methods are mostly applied, while time discretization is usually performed by various forward integration methods (FIM) like Newmark [16], Wilson [14] etc.

The dynamic equation of discrete systems is of the form

$$\mathbf{K}\mathbf{u} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{M}\ddot{\mathbf{u}} = \mathbf{R}(t) \tag{4}$$

where $\mathbf{K} = \mathbf{K}(u)$, $\mathbf{C}$ and $\mathbf{M}$ are respectively stiffness, damping and mass matrices, $\mathbf{u}$ and $\mathbf{R}$ displacement and force vectors. Usually various step-by-step methods are applied to get a numerical solution of these equations. In each step a nonlinear boundary value problem, consequently a system of simultaneous nonlinear algebraic equations, is to be solved. Much computer time is then required, since usually some hundred time steps are necessary. A detailed description of numerical solution procedures of FE systems is presented in [14].

For the user the important questions are what are the possibilities and what is the "price" of the computer approach. Its main advantages are:

Possibility of consideration of relatively complex models precisely enough to get satisfactory agreement with the actual conditions.

Satisfactory solutions may be obtained in cases that are not predictable by any simple methods (and experiments if they are available) such as for structures of a new type or structures with a significant change of parameters.

Results may be obtained in the form of distribution in time for any quantity wanted e.g. displacements $\mathbf{u}(t)$, stresses $\sigma(t)$ at any required point of the structure. This would not be possible for any other calculation method.

Results may be presented in a graphical form suitable for any design engineer; in well equipped computer centres an interactive technique may also be applied.

On the other hand there are of course some clear disadvantages of the computer approach. These are:

Computation of dynamical problems is rather expensive. Satisfactory results may be obtained in time that is usually measured in hours of CPU of contemporary middle-class computer.

Results do not have to be obtained immediately.

A laborious and time-consuming task of initial data preparation for each problem is required, which may sometimes be decreased in the case of automatic data generation.

Any advanced computer program is a kind of "black box" for the common user.

Engineering experience is therefore required for a critical evaluation of the final results.

4.2 Programs in practical use

We now present very briefly some most-advanced computer programs used for a numerical analysis of mechanical effects in substations due to short-circuit currents. A typical mechanical model more or less common to these programs is shown in Fig. 5. For comparison of the assumptions made, discretization methods used and range of possibilities offered to user by particular programs, Table 1 was worked out.

	PROGRAM	ADINA	SAMCEF-CABLE	STANAN
GENERAL INFORMATIONS	program developed and available at	M.I.T. Cambridge (USA)	University of Liege (Belgium)	Techn. University of Cracow (Poland)
	references	[5], [6]	[9]-[11], [17]	[7], [8], [12], [18]
	data generation: manual = 1, automatic = 2	1, 2	1, 2	1, 2
	time discretization: explicit = 1, implicit = 2	1, 2	1, 2	1, 2
	time step: optional = 1	1	1	1
	damping: optional = 1, no = 0	1	0	1
	results (print output and/or in graphical form): displacements and stresses for any prescribed point = 1	1	1	1
	computer requirements: code FORTRAN = 1	1	1	1
	computer requirements: memory in core	min. 350 kB	min. 256 kB	
	computer requirements: memory mass = 2	2	2	2
CONDUCTORS AND STRAIN INSULATORS	mass: concentrated (lumped) = 1; distributed (consistent) = 2	1, 2	1, 2	1, 2
	elements: transmit axial forces only (no moments) = 1; material: optional, e.g. elastic plastic = 2; linear elastic = 3; insulators not extensible = 4; short-circuit heating = 5	1, 2, 5	1, 3, 4, 5	1, 3, 4, 5
	arrangements per phase: single = 1, duplex = 2; multiplex = n conductor(s); bundles with spacers = 3; with collapse during short-circuit = 4; jumpers = 5, droppers = 6	1, 2, n, 3, 4, 5, 6	1, 2, n, 3, 5, 6	1, 2, 3, 4
	displacements: large (nonlinear) = 1; small (linear) = 2	1	1, 2	1
	space discretization: finite elements = 1; finite differences = 2	1	1	2
SUPPORTING STRUCTURES	structures of arrangement A in Fig. 1: solid web structure, arbitrary shape = 1; truss, full structure = 2; reduced to frame = 3	1, 2, 3	1, 2, 3	1, 2, 3
	apparatuses of arrangement C in Fig. 1: optional = 1, no = 0	1	1	0
	space discretization: finite elements = 1; finite differences = 2	1	1	1
LOADING	electrodynamic forces distributed (Biot-Savart) = 1; interactions: phase to phase = 2; in bundle = 3; unsuccessfull auto-reclosure = 4	1, 2, 3, 4 program supplements by SIEMENS AG Erlangen (Germany)	1, 2, 3, 4	1, 2, 3, 4
	any static loads: gravity = 1, ice = 2, wind = 3	1, 2, 3	1, 2, 3	1, 2, 3
	other dynamic loads, e.g. earthquake = 1	1	1	1

Table 1 Comparison of advanced computer programs analysing mechanical effects of short-circuit currents in substations with flexible conductors

5 SAMPLE ANALYSIS

In order to demonstrate the capabilities of the numerical methods, we present a practical substation layout tested by LABORELEC (Belgium) and analysed with ADINA, SAMCEF and STANAN.

The reliable base for the comparison consists of the basic information given in Fig. 5 and additional knowledge from diverse checks of the test facilities. The necessity to have these latter re-examinations can be seen from the results: It was found that the frames (No. 7 and 8 in Fig. 5) have only 2/3 of the theoretical stiffness given by the profile data. This was taken into consideration for SAMCEF as well as for STANAN with appropriate frame properties and for ADINA with additional foundation movability. So we can say we have had identical assumptions for test and calculations. A small speciality is only worth mentioning for STANAN: Since the present version of STANAN may not take droppers into consideration, the data for both conductors were averaged to secure the required symmetry.

Referring to Fig. 5 the first impression may be that the layout and the short-circuit data of the example chosen are on a low level compared with modern substations. However there are reasons for the preference of a simple model and a low short-circuit current:

- With uncomplicated structures the physical insights into the essential events are well explicable.
- The expenditure for tests rises noticeably with the data of the sample.

5.1 Verification of the results

For this it must be pointed out that:

- the test results may be considered as reliable, because they were repeated several times and the measurement devices were well calibrated.
- the possibilities to record results are less for tests than for the numerical methods. Consequently the comparisons are restricted to the behaviour measured at six points of the structure (Figs. 6 - 10).

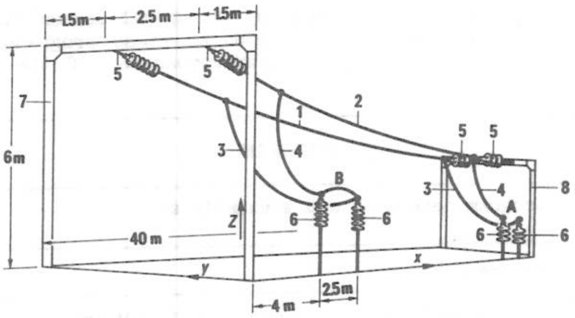


Fig. 5 Section of an outdoor substation, tested by LABORELEC with I_{rms} = 29.4 kA ($\hat{I}$= 72.7 kA), time constant τ = 0.033 s, short-circuit duration t = 0.8 s, current incoming in A and short-circuit connection in B.

1...4 Single conductor of 324 mm² with 19 hard drawn copper wires
- 1 east span with 7.85 kN initial tension
- 2 west span with 7.65 kN initial tension
- 3 droppers of 5.6 m length
- 4 droppers of 4.0 m length

5 Securing device l = 1.4 m, m = 8 kg, EA = $18 \cdot 10^6$ N; Single insulator chain l = 1.54 m, m = 52.3 kg, EA = $30 \cdot 10^6$ N

6 Insulators C8-750 (IEC-type) on rigid foundation, total height 2.3 m

7 north, 8 south) rigid frames with fixed supports
vertical members HE-B260 EURONORM 53-62
horizontal members HE-B240 EURONORM 53-62
additional mass in the corners 62.2 kg

The diagrams demonstrate the satisfactorily agreement between the experimental results and those obtained by the numerical methods.

Discrepancies between the two phases are explained by the presence of the droppers. It is worth noting, however, that such good agreement was influenced to some extent by the relative simplicity of the structure examined and the fact that the conductors were single instead of bundled.

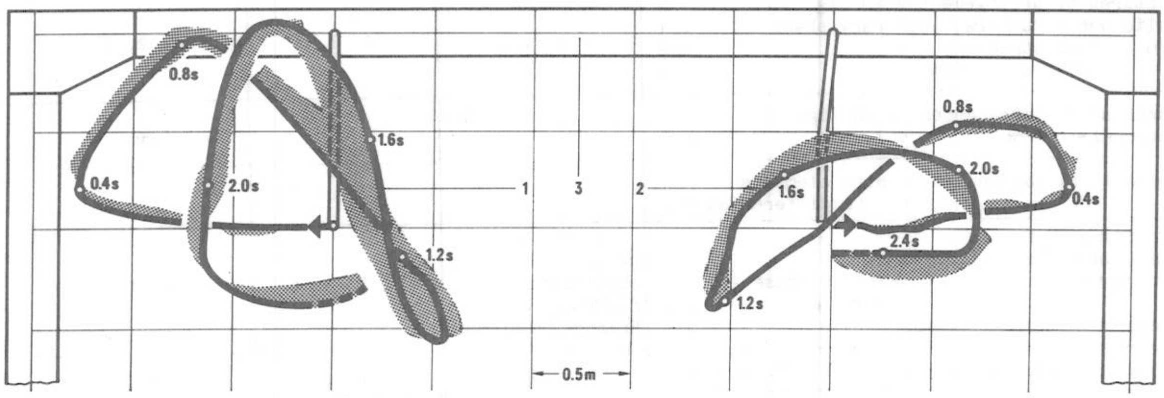
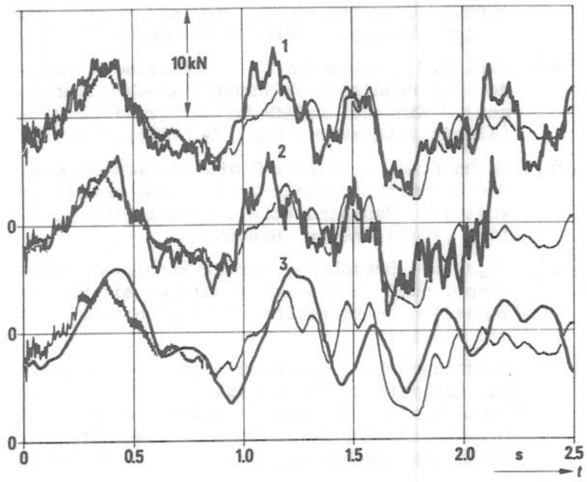
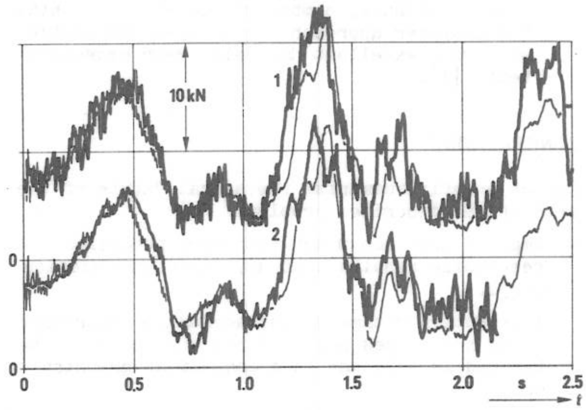


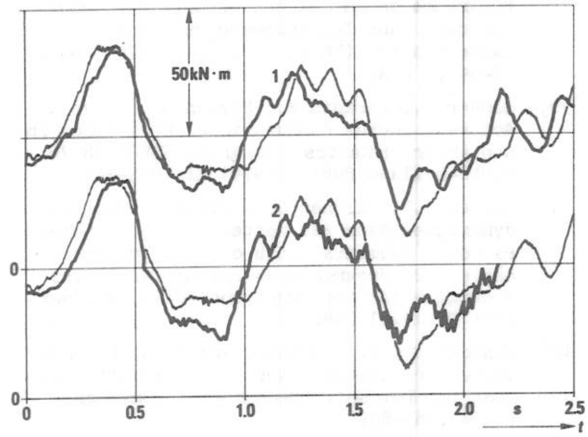
Fig. 6 Conductor displacements at the midpoint of the span. Experimental curves with the divergence bands of the numerical results.
1 west conductor, 2 east conductor, 3 north frame in the background



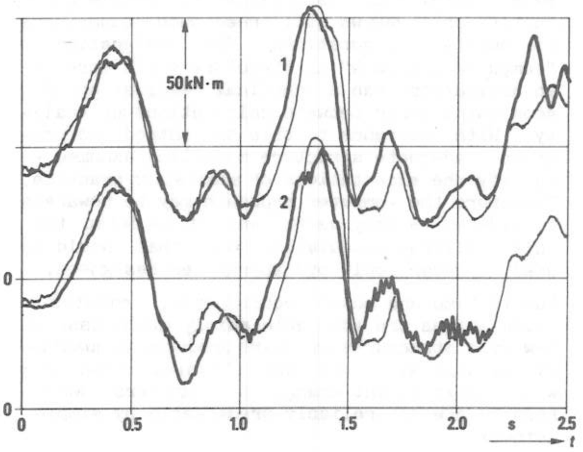
<u>Fig. 7</u> Tension in the east conductor
thin lines: experimental curves of LABORELEC
1 ADINA, 2 SAMCEF, 3 STANAN



<u>Fig. 8</u> Tension in the west conductor
thin lines: experimental curves of LABORELEC
1 ADINA, 2 SAMCEF



<u>Fig. 9</u> North frame; bending moment in the east vertical member at Z = 0.78 m height
thin lines: experimental curves of LABORELEC
1 ADINA, 2 SAMCEF



<u>Fig. 10</u> North frame; bending moment in the west vertical member at Z = 0.78 m height
thin lines: experimental curves of LABORELEC
1 ADINA, 2 SAMCEF

5.2 Interpretation of the results

The results obtainable by numerical calculations are
- helpful and in some cases (such as structures, which are not typical, new structures in quantity production) are basic for the design of the substation concerned,
- a help to understand the short-circuit occurrences,
- a basis to propound simple calculation methods,
- the requisites for parameter studies.

Using the results of the examples presented in the Fig. 6 - 10 we would now like to make some general observations that were also confirmed by other results not mentioned here:

The first peaks of the conductor tensions and bending moments in the frames correspond to the first maximum horizontal displacements, which can reach much greater values than the initial vertical sag mainly due to the heating, the conductor elasticity and the flexibility of the frames under the short-circuit forces.

The short-circuit duration is an important parameter for bouncing energy of the conductors. Unfavorable durations as assumed for the sample calculation not only decrease the clearance between the phases to a minimum near the first turning-point of the sag, they also cause stresses at the same time, which are often the absolutely maxima (falling down maxima).

In the path of stresses from the anchoring point to the foundation, the inertia of the structure members consumes only small quotas of high-frequency stress-alternations. But this may not be true in general, e.g. for apparatus-insulators as anchoring points.

If the displacements of the main conductors do not straighten the droppers completely, the stresses on the apparatuses are moderate.

Further tests and calculations are required to check whether these findings remain valid on the whole if substations are equipped with bundle conductors instead of single conductor. However, the consequence may be much work for the computation and interpretation of the influence of bundle parameters such as subconductor distance, number of spacers etc. until the computer approach is at a level comparable with the excellent but also very expensive tests [1].

6 CONCLUSIONS

Let us briefly summarize the actual "state of the art" of the described problem.

- Computer approach offers much more precision and free-choice results than any other calculation method.

  Distribution in time of displacements and stresses at any prescribed point of the structure may be obtained in this way in a convenient graphical form.
- Available computer programs offer the technical possibility of analysis of structures with flexible conductors.
- Actually the agreement between computation and experimental test is verified for single conductors only, but we still need such comparisons for bundle configurations. The designation "computer approach" is therefore still more of an aspiration than a practical realization of a good coincidence between calculations and reality. With reference to this the introduced programs - adequate structure modelling assumed - satisfy the expectations of substation practice. Therefore the computer approach may be nowadays considered as very useful and it is often the only available calculation tool, that should be used, however, only by experienced designers.
- Due to time and money requirements, computer calculations are advisable mainly in the case of new type structures which are produced in quantity, as well as in the case of typical structures with a significant change of parameters, where results are not reliably predictable by simple methods.

Topics for the further development are:

- Further comparisons with experiments. Full scale tests at site are very expensive, especially in case of many bundle conductors. Nevertheless the WG 02 of SC 23 expects to get some new experimental results.
- Improvement of quality, efficiency and versatility of computer programs, to make possible more automatic data generation, interactive techniques, faster calculations and more convenient post-processing as yet available.
- Investigation of the general applicability of the computer approach. Parameter studies are also required. Eventually a reliable background for some simple methods for practical design purposes may be obtained as in the case of rigid conductors [19].

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