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CONTRIBUTION TO LINE DESIGN BY ACCURATE PREDETERMINATION OF SEVERE BUT OCCASIONAL STRESSES

by

J.L. LILIEN* F. DAL MASO
Université de Liège

(Belgium)

SUMMARY

The design of overhead lines must consider both static stresses (such as extreme temperatures, ice, asy metrical ice, wind, erection loads, combined loadings,etc...) and dynamic stresses (such as conductor breakage, ice shedding, galopping, short-circuit, wind gusts).
Generally, if static loads can be easily evaluated, such is not the case for dynamic overloads which occur only very occasionally.
The predetermination of such overloads with a guaranteed accuracy (mainly through empirical correlations) would enable the designer to accept reduced factors of safety, and hence to reduce the overall cost of a line while maintaining its reliability.
This report provides such a tool, which is also suitable for the calculations of stresses under static conditions,even in complex combinations,taking particularly into account the flexibility of the supports.

KEY WORDS
Lines - design - overloads - dynamics - calculations - short-circuit - breakage.

INTRODUCTION

Overhead lines are an important sector of the electrical industry, hence their reliability is of paramount importance.
All overhead lines, from UHT to LV must satisfy complex requirements resulting, on the one hand, from the need of their harmonious insertion in the environment, and on the other hand, from the need to withstand severe loading conditions. This is why a high operational mechanical reliability is required from overhead lines, and hence from each of their components.

An inadequate design of the line and/or of the towers can result in a few years, in serious damages to the conductors and the accessories.
In order to optimise the design of the lines, the designer must always bear in mind the control in the extent of damages when deciding on loading conditions, because he must acknowledge that it is impossible and/or excessively expensive to consider, and design for, all catastrophic failures. Some failures are virtually unavoidable.

* Institut d'Electricité Montefiore (B28) - B-4000 Liège.

I.STRESSES ON THE LINES

Four types of stresses can be distinguished:

1) stresses representing *the system at rest*, in an average static condition. Such stresses are easy to define and to evaluate when the corresponding loads (dead weight, wind, ice) and the characteristics of the conductors, sometimes of the towers, are clearly stated.

2) *cyclic stresses of small amplitude*, which are different for different elements and which give rise to fatigue through alternating bending of external conductor strands at fixing points (clamps, spacers). For conductor bundles, the subconductor clashing is an obvious consequence the of the configuration.

Aeolian vibrations are induced by shedding of alternating wind vortices of Benard-von-Karman, their frequency is in the range of 3 to 120 Hz [1] for peak-peak amplitudes of the order of the conductor diameter. The installation of dampers (Stockbridge, dogbone, etc...) reduces their damaging influences. Subspan oscillations have a smaller frequency range, from 1 to 3 Hz with amplitudes which can vary from a few centimetres to some tens of centimetres. Unequality of adjacent subspan lengths and the installation of spacer-dampers are two means of combatting this phenomenon.

There is another type of low frequency vibrations (some tens of Hz) which are due to corona (especially during rain). This is explained by the fact that corona stress created by the modulation of the space charge is proportional to the speed of the conductor (within a given range) and this gives rise to instability. The amounts of energy involved are rather small, the amplitude is generally only of the order of several conductor diameters under no wind condition, and decreases very rapidly when wind does appear.

Such oscillatory phenomena will give rise to problems related to fatigue resistance of the line components. The designer will obviously endeavour to maintain the resulting stresses below values internationally accepted and confirmed by experience to achieve a life of some 30 years.

3) *stresses of large amplitude caused by external action*

Situations which must be considered are due to wind action (maximum wind with gusts, galloping ...), dynamic ice shedding from a phase (sudden detachment of all or part of the ice sleeve) and short-circuits. Each of these phenomena causes a transient movement of the conductors, affecting either two adjacent phases, or vertically towards ground reducing the clearance which should never be less than the insulation clearance, or the safety value required by National specifications.

An analysis of the movements caused by the above phenomena leads to the acceptance of some relative distances between phases at rest.

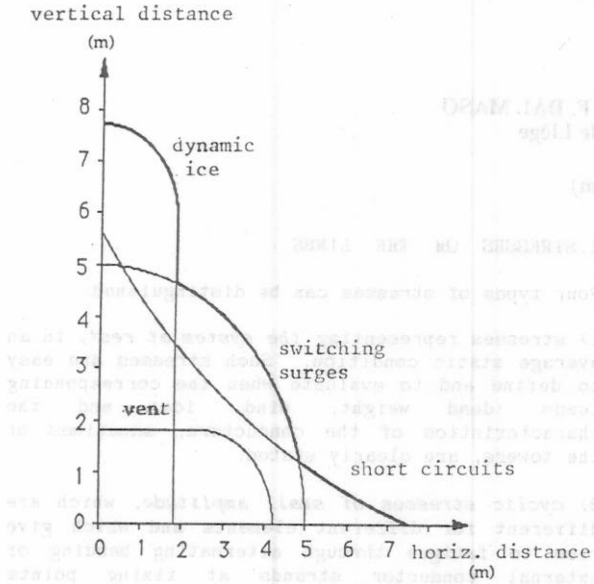

Fig.1: Example of distances between phases at rest for a 400 kV line, according to [3].

The main reason for considering to-day, even more than in the past the influence of short-circuit currents in the design of line element is due to their increased values (in some parts of Europe, they can reach 80 kA). This is explained logically by the increased density of transmission networks and by the multiplication of large generating centres.

During a polyphase short-circuit, the conductors are subjected not only to an important heating effect (several tens of degrees) but also to electrodynamic forces giving rise to conductor movements and to variations in the conductor tensions. The tensile stresses in the conductors and the movements of the conductors are translated into longitudinal and/or transverse loads on insulator tension sets or suspension sets, which apply severe stresses in the towers and their foundations. Besides, on bundle conductor lines, efforts of attraction or repulsion can impress compressive loads in the spacers which can reach, or even exceed, 15000 N.

We have calculated, as indicative values, the short-circuit currents above which electrodynamic stresses must be taken into account for deciding the phase spacings of conductors in horizontal formation.

phase spacing [m]	voltage [kV]	span [m]	critical value [kA]	minimum phase spacing (*)[m]
4	150	250	>23	1.0
5	220	300	>25	1.5
5	(compact)400	300	>23	2.9
8.5	400	400	>48	2.9

The various critical values of short-circuit current have been calculated by our program SAMCEF-CABLE for a duration of short-circuit of 100 ms with a maximum asymmetry (time constant = 60 ms).

For 400kV, we have considered a twin bundle ASTER 2 x 570 mm². (AAAC)

For 220 kV and 150 kV, we have considered a single conductor 620 mm² AAAC.

Remark: In the case of reclosing, the critical values can, in fact, be lower.

Galloping is low frequency, high amplitude oscillation (half amplitude can reach the value of the sag) caused by wind action on a conductor whose section, as seen by the wind, had been modified, in most cases by ice accretion. A recent analysis of faults on the CEGB HV network indicates that at least 20% and up to 40% of all faults on the lines are due to galloping. Damages can be quite severe and can result in a failure of the line.

Every winter incidents occur on MV and HV lines because of the presence, or of the shedding of ice sleeves, or of wet snow on the phase conductors. The shedding causes the conductor to jump vertically up with dielectric and mechanical consequences which can be easily visualised.

4) special loadings due to *element failures*.

A particularly serious type of failure with damaging consequences on the operation of the network is the cascading type of failure affecting many successive supports. Such a type of failure, happily very rare, is generally initiated by the failure of a single tower, the breakage of a conductor or of an insulator set, and it is the unavoidable consequence of inadequate longitudinal strength of the supports.

The assumption of a broken conductor leads to a minimum resistance to torsion and flexion of the metallic supports. The transient phenomena connected with a broken conductor last, at the most, only a few seconds; nevertheless, they have a major influence, especially on a tower, which is then subjected to fairly high dynamic loads, be it only for a few fractions of a second.

An anchor tower, for HV lines, should be able to withstand the transient oscillations connected with a broken conductor which can give rise to much higher stresses than those under normal conditions.

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*The dimensioning criterium is the minimum phase spacing to withstand a switching surge:

$$U_{50}[kV] = 1.5 \frac{3400}{1 + \frac{8}{d[m]}}$$

where $U_{50} = \frac{U_T}{0.88}$ $\quad U_T = \frac{\sqrt{2}}{\sqrt{3}} U_{max}\ 3.5$

U_{50} = average voltage

U_T = withstand voltage

d = phase spacing in metres

Quite often, for various reasons related to design, handling, specification, etc... insulator sets consisting of multiple parallel strings are selected. In such case, special attention must be given during design to the problems of dynamic stresses induced by load transfer on other strings, should one of them be broken [16].

All such stresses (static, high amplitude dynamic) can now be predetermined at a ridiculously low cost by using appropriate calculation techniques.

The presence of a qualified engineer is obviously of paramount importance for the interpretation and the parametric studies which are necessary to achieve a realistic strength of the components to withstand such stresses which, although rare, cannot be neglected. We propose to give below some results which we shall attempt to relate, through a simple logical reasoning, on energy principles.

II. THEORETICAL BACKGROUND

The equation of vertical and horizontal motion of a conductor on an HV line is given by the following equation with partial derivatives:

$$\frac{\partial^2 y}{\partial t^2} - \frac{T}{m}\frac{\partial^2 y}{\partial z^2} = \frac{f_e(z)}{m} \qquad (1)$$

It expresses the equilibrium condition between inertia forces, elastic forces due to the conductor reaction and external forces applied on an element dz of the conductor.
The variation in the mechanical tension T is given by Hooke's law (where K is the rigidity of the anchor tower) which gives the relationship between the conductor tension and its strain.

$$\Delta T = \frac{E\Lambda}{L}\left(\Delta l - \frac{\Delta T}{K}\right) = K_c\,\Delta l \qquad (2)$$

The solution of equation (1) is not evident, particularly for situations when movements with large displacements (galopping, short-circuit, ice shedding, breakage) are involved. It requires the application of modern methods of solution (such as finite element techniques) because of the complexities of geometric non-linearities which affect constantly the conductor reaction by instantaneous modifications to the tension. Besides, in the case of short-circuit, calculation of the electromagnetic force is not easy. We do not propose to explain, here, the general method of solution; and we refer the reader to [8].

Discussion on tension variation.

It is obvious that the line (i.e. conductors, insulator sets, towers and foundations) will be more heavily stressed, the higher the tension variations. There is a real incentive to reduce to a minimum such tension variations.
The equation for tension variation (2) shows that in order to achieve such an objective, it is necessary to reduce as much as possible the equivalent rigidity of the line, i.e. to make it as flexible as possible.
In order to achieve this goal, action is possible on various parameters; as follows:

- Tower type.
Anchor towers should be as flexible as possible. It is worth mentioning the utilisation of guyed towers in some countries.
Analytical studies and test resuts [5] have in fact confirmed that dynamic stresses induced in a line with "chaînette" tower are smaller than those induced in a line with conventional towers.

- Conductor type.
It is preferable to use conductors with an apparent low modulus of elasticity. Table 1 give some indicative values corresponding to sections within the 300 to 600 mm² range.

Table 1 - Young's modulus for different conductor types.

Type	Section [mm²] (al/st)	Modulus of Elasticity [10^{10}N/m²]
AACSR	298(241,5/56,5)	8,4
ACSR	298(241,5/56,5)	7,9
ACAR	304	6,9
AAAC	298	6
AACSR	592(525/67)	6,9-7,5
ACSR	592(525/67)	6,7-7,1
ACAR	608	6,9
AAAC	617	5,4

The utilisation of a material with a lower elasticity modulus will result in a reduction of the equivalent rigidity of the line; hence, the same loading influence will produce smaller tension variations.

It must be observed that this proposal seems to be in contradiction with some statements made during the discussions of the 1988 Session of CIGRE, when it was pointed out that recordings by Hydro Quebec had indicated - when all other parameters were equal - that the ratio measured load/calculated load applied to the tower was higher for ACAR than for ACSR conductors of the same diameter.

- the conductor section
The utilisation of bundle conductors leads to a reduction of the total cross-sectional area of conductor per phase, when all electrical constraints are satisfied. Such a reduction in cross-sectional area is mechanically expressed by a reduction in the conductor rigidity, and hence in a reduction of the equivalent rigidity of the line.

Another way of reducing the tension variations would obviously be the result from a reduction of external loads. As examples, we can quote: "smooth body" conductors which, apart from a reduction in the drag coefficient, have an increased self-dampimp when compared with classical conductors [18], all anti-galopping devices (pendulums, dampers, etc...) phase spacers, mechanical fuses (such as controlled sliding clamps) which lead to somewhat smaller exceptional longitudinal loads, than anticipated, on the supports [17].
In all cases, care must be taken to take into account all secondary phenomena which could be generated by such devices.

III. VIBRATION MODES OF A LINE

. The pendulum frequency of a span is:

$$f_p = \frac{1}{2L_s}\sqrt{\frac{T}{m}} \qquad (3)$$

. The vertical frequency of a span (oscillation of the conductor in its own plane) is:

$$f_v = \frac{1}{2L_s}\sqrt{\frac{T}{m}}\sqrt{1+M} \qquad (4)$$

where "M" is the structural factor of the line which takes into account the rigidity of the attachment points

$$M = \frac{8\,a^2 K_e L}{\pi^2\, m\, \Omega_p^2} \quad \text{où} \quad a = \frac{mg}{To} \qquad \Omega_p = 2\pi f_p \qquad (5)$$

. Frequency and risk of *longitudinal* oscillation.

The travelling speed of a longitudinal wave $\sqrt{\frac{E}{\rho}}$, reflected at the ends of a section of length L is of the order of 5000 m/s.
The frequency of such a wave is given by:

$$f_L = \frac{1}{2\,L}\sqrt{\frac{E}{\rho}} \qquad (6)$$

typically, "f_L" varies between 1 and 10 Hz.

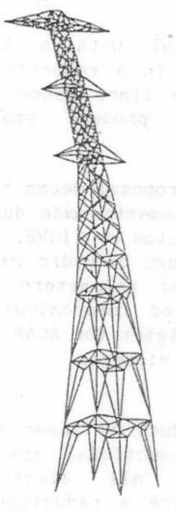

Fig.2, First natural mode of a tower commonly used in Belgium (frequency = 1,1,Hz) (calculation TRACTEBEL)

This vibration mode was recently observed on the Belgian experimental line at Villeroux. It was superimposed on galloping oscillations.

The fundamental natural frequency of classical towers is generally between 1 and 4 Hz, as can be seen in the particular illustrated case.

Therefore, resonance phenomena can be expected and they will induce dangerous stresses in the towers. The line designer must take care that there is no resonance between these two frequencies.

IV. PREDETERMINATION OF MECHANICAL STRESSES.

IV.1. General.

Practically, there are three methods for the analysis of mechanical stresses applied to a HV line.

Full scale experimental approach

This is the method which gives the most reliable results, provided that the test conditions are clearly defined and reproduce the normal operating conditions of the line. A theoretical investigation is always recommended in order to appreciate the main parameters of the problem, and to avoid, thus, testing in marginal conditions which would lead the designer to draw general conclusions from a very particular case.

The main disadvantage of this technique is that it is always very expensive and requires the availability of major equipment (e.g. main generating station for analysis of short-circuits).

Experimental approach on reduced models

Once the elements of a reduced model are set, such an approach requires little time for the preparation of the data and for carrying out several tests.
The main disadvantage of this approach is that the test engineer is faced with the classical incompatibility of having to satisfy simultaneously Cauchy's number (ratio between elastic and inertia forces) and Froude's number (ratio between gravity and inertia forces).

$$Ca = \frac{\rho\, l^2}{E\, t^2} \qquad Fr = \frac{\sqrt{l}}{t} \qquad (7)$$

l : length (span, phase spacing, sag, etc...)[m]
t : time (duration of short-circuit, time constant, period of current, time development, etc...) [s]
ρ : volumic mass [kg / m³]
E : modulus of elasticity [N / m²]
These two dimensionless numbers illustrate the incompatibility, for identical materials (i.e. identical E and ρ) to obtain a scale ratio with respect to lengths to vary simultaneously as the scale ratio with respect to time and to the square of time.
Young's modulus which has a fondamental influence on the behaviour of conductor elasticity cannot be easily reduced in the ratio of lengths. In some cases, some astute solutions can be considered. For example, reference can be made to the analysis by PARIS [9] on conductor breakage and that achieved by CESTMIR [10] on short-circuits.
If the scale factor is neglected, the experiments will give a transient response of the model which is similar to that observed in a real case. Thus, such a method is useful for a qualitative analysis of the phenomenon.

Numerical approach to analysis

When preparing the mathematical model, a numerical simulation must take into account many different factors such as towers, conductors, anchoring devices, line geometry, etc...).

The model must also express non conservative forces (i.e. those which vary as function of motion). This applies to electromagnetic forces (analysis of short-circuits) and forces due to aerodynamic phenomena.
In the case of extreme loadings, large movements of the conductors (and eventually of the spacers) take place which introduce geometrical non-linearities thus complicating the problem.
However, once the model is established, simulation becomes easy for different loading cases and it is easy to analyse separately the influences of the main parameters (conductor type, different attachment and suspension arrangements, short-circuit characteristics, etc..)
The program CABLE of SAMCEF was developed for this purpose at the Liege University (Service de Transport et Distribution de l'Energie Electrique), and while it can be used for the analysis of dynamic phenomena on guyed structures, it was particularly developed for the design of HV lines and substations.

IV.2. Simulation

The analysis of short-circuits can be divided into two, practically, independant parts; on the one hand: the study of the effects within a phase (bundle of conductors) [13,14] and, on the other hand, the study of the effects between phases [11,13]
SAMCEF - CABLE can carry out the analysis of the behaviour of bundles of conductors at the moment of short-circuit by taking into account the

phenomena of impulse, contacts and interaction with the remainder of the structure, etc..
Let us assume a short-circuit current of 60 kA (peak value = 163 kA) with a time constant of 120 ms. The bundle of conductors is ASTER 2x570mm² with a spacing of 40cm and 4 subspans of 57m. Insulator sets have a mass of 327 kg and a length of 4.64m.
Figure (3) shows the good agreement in the relationships between numerical simulation and experimental results.

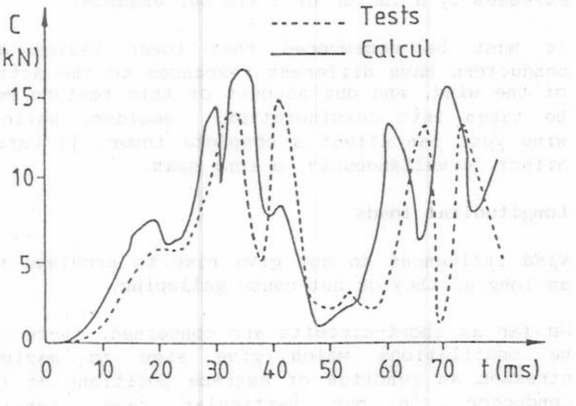

Figure 3: Comparison calculation/test results of the compression force in a twin spacer for twin bundle ASTER 2x570mm² (tested at EDF [12]).

However, within the framework of this type of problems, it is recommended to adopt a design philosophy rather than the execution of complex calculations which could be influenced by some details. Such a philosophy is summarized in the CIGRE publication [13] prepared by Working Group 23-02 which recommends, whenever possible, the longest practical subspans with the smallest bundle spacing. Quite often, such a recommendation is in contradiction with other requirements for other phenomena (subspan oscillations, kissing, corona effects). However, for the configurations used so far (Icc (<= 63 kA) these problems are not insuperable provided that the spacers are properly designed (loads of the order of 15000 N, which could be excentric to the axis).
In order to analyse the effects between phases, conductor bundles can be replaced by equivalent single conductors, of the same total cross-sectional area. Comparisons with experimental data have shown that the model is quite suitable for the analysis of this type of problem [11,13,15].
In order to illustrate some of the possibilities of calculation offered by SAMCEF-CABLE, we have investigated several loading conditions (see table) on a 400 m. span between anchors.

type of loading	Characteristics
Two-phase short-circuit	duration 100 ms , τ=60 ms phases RY,63 kA (165 kA peak) phases RY,45 kA (118 kA peak) phases RY,30 kA (79 kA peak) phases RB,63 kA (165 kA peak) phases YB,63 kA (165 kA peak)
Three-phase short-circuit	duration 100 ms , τ=60 ms 72,3 kA (2/√3 63).(phases:R 185,Y 166, B124kA peak)
ice	sudden shedding of an ice sleeve of 6kg/m
wind	steady wind of 60 km/h increasing suddenly to 100 km/h for 5 s on one quarter span (from L/4 to L/2)

Note : phase rotation RST in France corresponds to British system RYB (Red / Yellow /Blue)

The configuration of the phases is identical to that of "Beaubourg" towers. Conductors are equivalent to ASTER 2x570 mm². We have represented the towers with a stiffness: K = 50000 N/m.
The mathematical model could have taken into account tension insulator sets, suspension insulator sets, the dynamic characteristics of towers, different attachment arrangements, presence of phase spacers, etc...). We intentionally accepted a simplified example in order to illustrate the variety of loading conditions (static and dynamic) which the model can consider.

Dynamic characteristics of the line

The line pendulum frequency is:

$$f_p = \frac{1}{2L}\sqrt{\frac{T}{m}} \approx 0.175 \text{ Hz}$$

T = phase tension (61800 N)

m = unit mass (3.1 kg/m)

The vertical frequency is:

$$f_v = \frac{1}{2L}\sqrt{\frac{T}{m}}\ \sqrt{1+M} \approx 0.30 \text{ Hz}$$

where M is the structural factor of the line which takes into account the stiffness of the dead-ends.

$$M = \frac{8\, a^2 K_e L}{\pi^2 m\, \Omega_p^2} = 2.03 \qquad a = \frac{mg}{To} = \frac{1}{2000}\ [m^{-1}]$$

The frequency of the longitudinal travelling wave is:

$$f_{long} = \frac{1}{2L}\sqrt{\frac{E}{\rho}} \approx 5.6 \text{ Hz}$$

Results of the simulation

For the different loading conditions, it has been possible to draw the global envelopes of conductor movements. (fig.4)

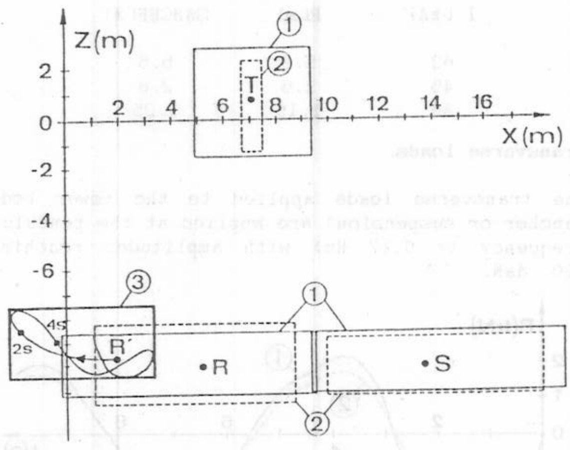

Fig. 4 Calculated envelopes of phase conductor movements for 3 types of loading conditions on a tower type Beaubourg.

1, 2 phase short-circuit RY, RB, YB of 63 kA
2, 3-phase short-circuitof 72,3 kA
3, initial wind speed of 60 km/h followed by a gust of 100 km/h during 5 sec, on a quarter span

The assumed values of current were particularly high, and the minimum phase clearance - of the order of 2.9 m. at 400 kV - is no longer achieved. A comparison was made with current intensities of 30, 45 and 63 kA (fig.5).

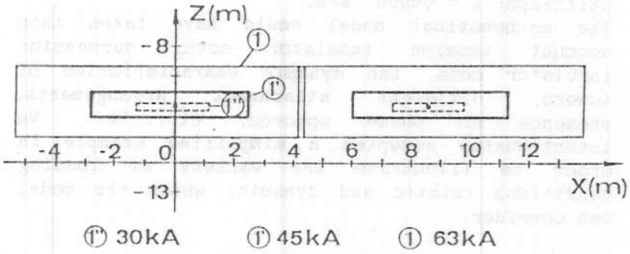

Fig. 5. Calculated envelope of phase conductor movements for 3 two-phase faults on a tower type "Beaubourg".
1 ; 2 phase short-circuit of 63 kA
1'; 2 phase short-circuit of 45 kA
1"; 2 phase short-circut of 30 kA

It can therefore be stated that the configuration which we have investigated does not give rise to problems under mechanical stresses, but can only be used for short-circuit currents less than 45 kA.

So as to avoid the systematic simulation of all short-circuits, it would be interesting to be able to estimate rapidly the movement due to attraction of adjacent phases and to check whether there was a danger of flashover. Appendix 1 describes such a simplified approach for horizontal conductors subjected to a short-circit whose duration is much smaller than a quarter of the period of pendulum oscillation. By applying this approach to the above simple case -which has given answers by numerical simulation- we have:

Example

d = 8.5 m ; m=3.1 kg/m ; t_{cc} =100 ms
τ = 60 ms ; f=10 m ; T_0=61800 N

Table 2: maximum amplitudes of phase displacements for different values of short-circuit current (comparison simplified method/SAMCEF).

I [kA]	R[m]	SAMCEF[M]
63	5.2	5.5
45	2.6	2.8
30	1.15	1.25

Transverse loads.

The transverse loads applied to the tower body (anchor or suspension) are applied at the pendulum frequency (= 0.17 Hz) with amplitudes reaching 450 daN.

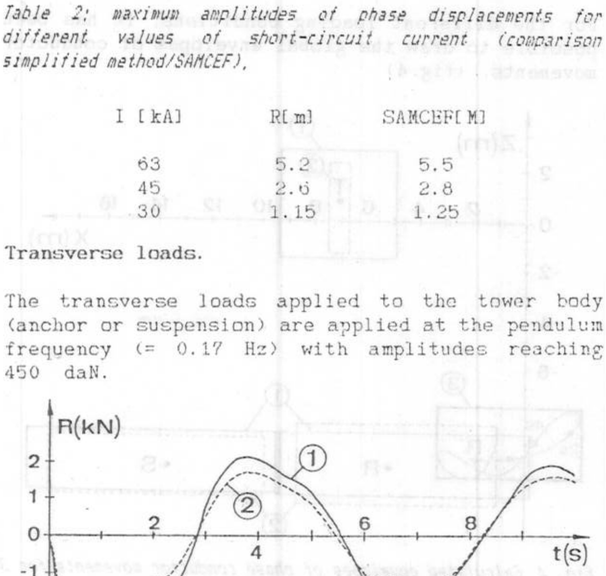

Fig. 6; Transverse loading (calculated) applied to one of the attachment points at crossarm level of tower "Beaubourg" for 3 types of loading conditions;
1; 2 phase short-circuit of 63 kA
2; 3 phase short-circuit of 72,3 kA
3; initial wind of 60 km/h followed by a gust of 100 km/h for 5 sec, on a quarter span.

Two-phase and three-phase short-circuits give rise to a reasonable amplitude of loading whose magnitude is of the order of the transverse load due to a steady wind of 60 km/h (in this particular case). A wind gust multiplies those stresses by a factor of 2 (in our example).

It must be remembered that tower bodies and conductors have different responses to the action of the wind, and due account of this feature must be taken into consideration. Besides, while a wind gust can affect a complete tower, it cannot affect, simultaneously, a long span.

Longitudinal loads

Wind influences do not give rise to problems for as long as they do not cause galloping.

So far as short-circuits are concerned, there can be oscillations which give rise to maximum stresses as function of extreme positions of the conductor. In our particular case, tension variations between 60% and 140% of the initial tension can be observed, and from a mechanical point of view this should not create any special problems (a 40% increase in tension would correspond, in any case, to reduction of conductor temperature of 60°C).

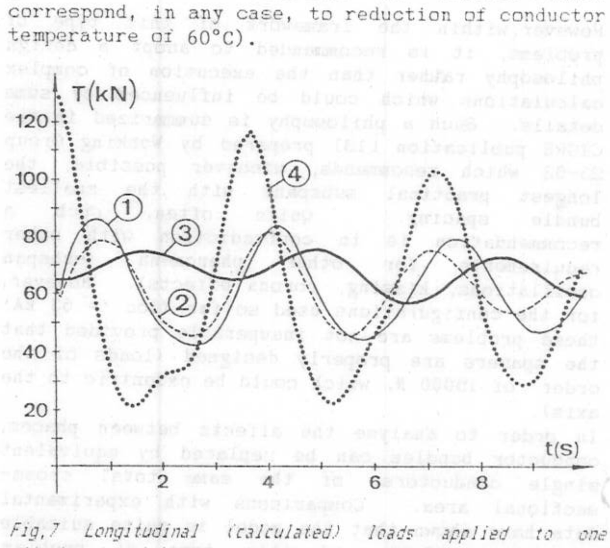

Fig.7 Longitudinal (calculated) loads applied to one attachment point on a crossarm on a "Beaubourg" tower for 4 loading conditions.
1, Two-phase short-circuit of 63 kA
2, Three-phase short-circuit of 72,3 kA
3, Initial wind of 60 km/h followed by a gust of 100 km/h for 5 seconds on a quarter span.
4, shedding of ice sleeve of 6 kg/m.

The most stressing condition is the sudden shedding of an ice sleeve of 6 kg/m. When starting from an initial tension almost equal to double the previous values, (taking into account the ice overload), the oscillation leads to a return to the original tension with variations comprised between 0.3 and twice the initial unloaded value without wind nor ice.

The prevalence of a loading case with respect to another can only be defined in function of a line within its environment. Nevertheless, it is obvious that, in the future, the influence of short-circuits cannot be neglected (especially for the choice of phase spacings). In this respect, phase-spacers would permit to increase the short-circuit levels of overhead lines if they are designed to withstand the resulting loads.

Conductor breakage.

SAMCEF CABLE can be used for the analysis of the transient loading conditions resulting from the breakage of some components (suspension insulator sets, yoke plates, conductors, etc...)

In the particular case of broken conductors, we shall submit a comparison with EPRI test results [7].

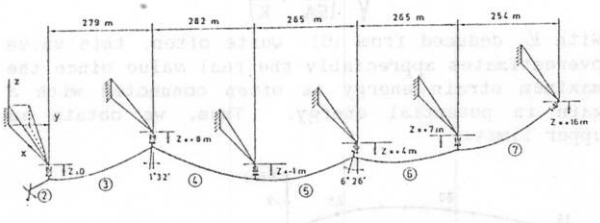

Fig. 8, Section of 7 spans with a broken conductor at location indicated by scissors (tests EPRI [7]

The phenomenon is rather complex. Depending on the lengths of the spans, the characteristics of the suspension insulator sets, it is possible to obtain quite variable behaviours leading occasionally to appreciable increases in the tension during the transient regime (in this example, limited to 25%)

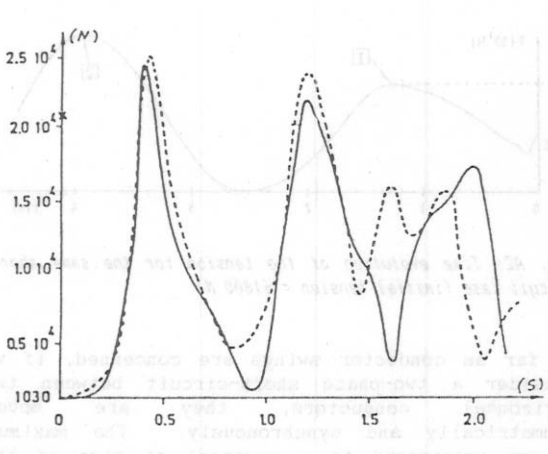

Figure 9: Comparison test/calculation of tension variation in a conductor in close proximity of the broken location

In all cases of calculation, a theoretical assessment based on some simple physical reasoning would permit to decide fairly easily if a calculation is justified or whether the design could be started afresh.

Galloping

Another type of dynamic loading condition which can cause exceedingly severe damages on HV lines is due to conductor galloping. This extremely complex phenomenon has already been responsible for the failures of several constructions, either during galloping as such, or as a result of the cumulative effects on increased number of smaller amplitudes of galloping leading to failures by fatigue.

A report submitted to this CIGRE session gives some information on this subject.

CONCLUSIONS.

The design of overhead lines requires the analysis of the effects of an extensive range of static and dynamic loading conditions. In most cases, it is important to include the maximum number of parameters in the calculation in order to avoid under - or over - designing of the particular component. A simplified, preliminary, approach is always recommended, and we are proposing one such simplified method. Besides, the utilisation of an adequate design code, validated by comparison with experimental results, would enable the designer to refine his design, often quite appreciably. A suggestion is also given. Finally, we believe that we have shown in a convincing manner the need to consider the influences of short-circuit currents for the definition of phase-spacings. This factor can have a serious impact on the design of future compact lines.

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APPENDIX I

Simplified approach on the behaviour of overhead line conductors during a short two-phase short-circuit

With a spacing of "d" metres, and a current "i(t)"kA in each, two single, straight and parallel conductors are subjected per unit length

(1 metre) to a force given by Laplace's equation:

$$F = \frac{0.2\, i^2}{d} \quad [N/m] \qquad (1)$$

where i(t) can be expressed, as a first approximation, because of the low pendulum frequency (compared with 50 Hz) by :

$$i(t) = \sqrt{2}\, I_{eff} \sqrt{\frac{1}{2} + e^{-\frac{2t}{\tau}} \sin^2\phi} \quad [kA] \qquad (2)$$

F produces on the mass "m" of the conductor an acceleration

$$\gamma = \frac{F}{m} = \frac{0.2\, i^2}{d\, m} \quad [m/s^2] \qquad (3)$$

At the end of the time "t_{cc}" of the short-circuit, the conductor will acquire a speed (assuming maximum asymmetry i.e. sin.ø = 1)

$$V = \int_0^{t_{cc}} \gamma\, dt \approx \frac{0.2\, I_{eff}^2 (tcc + \tau)}{d\, m} \quad [m/s] \qquad (4)$$

If we accept that the conductor movement is fairly small between the beginning and the end of the short-circuit (cf. fig. A.1), which is a fairly valid assumption for overhead lines, then, at the end of the fault, there has not been an appreciable transformation into strain or/and potential energy. Hence, the energy imparted to the conductor by the short-circuit can be equated to the kinetic energy of the conductor at the end of the fault, i.e. the integral of the quantity ($mv^2/2$) along the span. If we assume further that there was a constant speed on 3/4 of the span-to allow for end effects- we get the energy E_o imparted to the conductor:

$$E_o = \frac{1}{2}\, m \left[\frac{0.2\, I^2 (tcc + \tau)}{d\, m}\right]^2 \frac{3\, L}{4} \qquad (5)$$

To be accurate, we should deduct the part which contributes to conductor heating, but we shall ignore it.
By assuming a loss-free system, which is valid for the first oscillation, it can be stated that at each instant, the initial energy imparted to the conductor is converted into kinetic energy, in potential energy and in strain energy; there:

$$\text{kinetic energy: } E_1 = \frac{1}{2}\, m\, v_{max}^2 \frac{L}{2} \text{ (valeur efficace)} \qquad (6)$$

$$\text{potential energy: } E_2 \approx \frac{2}{3}\, m\, L\, g\, f^* (1 - \cos\beta) \qquad (7)$$

where f* is the instantaneous sag and β the pendulum swing angle.

The strain energy is:

$$E_3 = \frac{1}{2}\, EA \frac{(l - lo)^2}{lo} \approx \frac{1}{2}(T - To)^2 \left[\frac{L}{EA} + \frac{2}{K}\right] \qquad (8)$$

where T is the instantaneous value of tension.

The fundamental impact of the rigidity of the attachments will be noticed, especially when it contributes appreciably to the extensional stiffness of the conductor (EA/L), which is normally the case. Should we want to take into account the inertia of the anchors, we should add their kinetic energy to expression (6).
The energy balance provides a means of evaluating extremal values with some assumptions on conductor movement: it can be assumed that the initial energy is totally converted in any one of the three quantities (6), (7), (8). This tantamounts to stating, e.g. that the maximum conductor tension will be reached when the speed is zero (obviously at a reversal of sign i.e. when the conductor is at an extreme position) and when the gravity potential energy is the lowest. This would correspond to positions which could be termed [13] the "swing out" and the "falling down" (points 1 and 2 circled on fig.A1).

$$T_{max} = T_o + \sqrt{\frac{2E_o}{\left(\frac{L}{EA} + \frac{2}{K}\right)}} \qquad (9)$$

with E_o deduced from (5). Quite often, this value overestimates appreciably the real value since the maximum strain energy is often connected with a gain in potential energy. Thus, we obtain an upper limit.

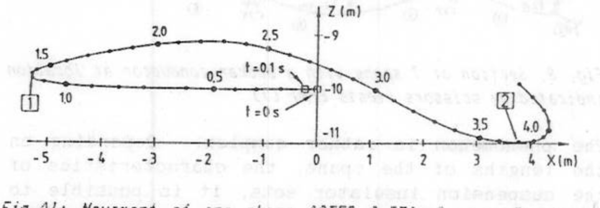
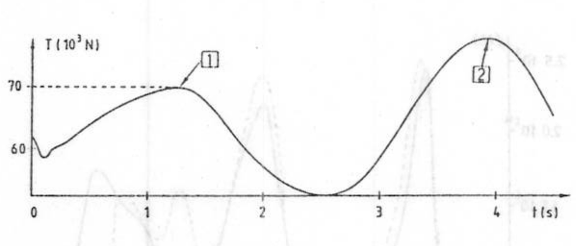


Fig.A1; Movement of one phase ASTER 2x570mm² on a Beaubourg tower, subjected to a 2ph short-circuit of 63 kA during 0,1 sec, (point 1 circled correspond to the "swing out" and point 2 circled to the "falling down").



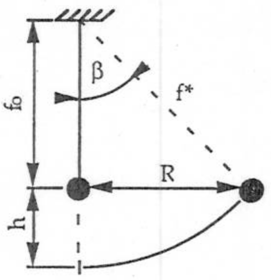
Fig, A2; Time evolution of the tension for the same short-circuit case (initial tension = 61800 N)

So far as conductor swings are concerned, if we consider a two-phase short-circuit between two horizontal conductors, they are moved symmetrically and synchronously. The maximum swings correspond to a reversal of sign of the velocity, and hence to zero kinetic energy. In this position, it is difficult to separate the part of energy contributing to strain (always present for an extensible conductor) from that corresponding to acquired potential energy.
We suggest, when dealing with overhead lines, to neglect the contribution to strain energy. Hence, the rise due to swing of the conductor is obtained directly.

$$E_o = \frac{2}{3}\, mgLh \quad \text{ou} \quad h = \frac{E_o}{\frac{2}{3}\, mgL} \qquad (10) \quad (10)$$

The maximum displacement is obtained at the intersection of the arc of circle of radius(f_o+h) from which we can calculate the contribution to reduction in phase spacing (which is assumed equal to the horizontal swing):

$$R^2 = (f_o + h)^2 - f_o^2 \qquad (11)$$



Calculation example:

Two-phase short-circuit of 63kA, t_{cc}=100 ms, τ=60 ms

ASTER 2x570, phase spacing 8.5 m., span 400 m., K= 5 10^5 N/m, f_o = 10m., T_o = 62000 N.

v = 4.8 m/s according to (4)
E_c = 10700 Joules according to (5)
T_{max} = 110000 N according to (9), calculated by SAMCEF : 90000 N at falling down

h = 1.29 m. according to (10)

R = 5.2 m. according to (11) (calculated by SAMCEF : 5.5 m in repulsion and 4.5 m. in attraction)

APPENDIX 2.

Symbols:

y vertical displacement [m]

z horizontal position in the span [m]

t time [s]

T instantaneous tension in one phase [N]
(T_o = initial static value)

$f_{ex}(z)$ external vertical force per unit length [N/m]

m apparent mass of one phase per unit length [kg/m]

ΔT tension variation in one phase [N]

Δl length variation in one phase [m]

EA/L extensional stiffness of one phase [N/m]

K stiffness of an anchor tower [N/m]

L Section length (N_p spans) [m]

$$L = \sum_{i=1}^{Np} L_i$$

K_e equivalent stiffness of the section [N/m]

$$\frac{1}{K_e} = \frac{L}{EA} + \frac{2}{K}$$

f mid-span sag