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Item 3.3

MECHANICAL EFFECTS OF SHORT-CIRCUIT CURRENTS IN SUBSTATIONS WITH STRAIN BUS SYSTEMS—MEDIUM COMPLEXITY CALCULATION METHODS

Paper presented in the name of WG 23.02 of SC 23 (Substations)

by

L. GAUFFIN and J.L. LILIEN

SUMMARY

This report provides an overwiew of the work within CIGRE WG 23-02 with various methods for calculation of conductor tensions and displacements of suspenison us under short-circuit loading. It is possible to calculate the actual forces in the conductors, strain insulators and other accessories and to compare them with the permissible loads. It is also possible to obtain a check of the reduced air clearances, caused by the conductor movements, during and after the short-circuit.
All the calculation methods accounted for have been converted into special computer programmes designed for quick calculation of short-circuit effects.

KEYWORDS

Short-circuit force, strain bus system, substation.

Introduction and general description of methods and prerequisites.

Conductor tensions and displacements of suspension bus under short-circuit loading can be calculated by different calculation methods. Only an approximative division in simple, advanced and medium complexity calculation methods has been found useful in the work with these methods.
A simple calculation method implies that manual calculation is possible and an advanced method means the use of a large multi-purpose programme such as ADINA, SAMCEF etc. All methods in between the simple and the advanced methods have simply been called medium complexity methods.
typical conductor arrangement in an outdoor substation shown in figure 1. The model of the strain bus A for medium complexity calculation methods is shown in figure 2. This configuration is called the pure case A. Analysis of the case A arrangement is a dynamic and a non-linear problem.
The non-linearity mainly refers to two aspects

1. The great deflections of the main bus including conductors and string insulators.
2. The dependence of the amlitude of the short-circuit force of the positions of the short-circuit current carrying conductors.

Table I gives a quick view of the medium complexity methods available at present. The medium complexity methods can be classified into 2 main groups.

The first group uses a physical model here named the pendulum model.
The names of the computer programmes belonging to the first group are PEND 02, SWINGT, PENDBL and PENDULUM.
The second group uses a more detailed model here called the compounded pendulum model. The programmes CONEX and SACS/DACS belong to this group.

The pendulum model /4/, /5/.

In the pendulum model the span including conductors, strain insulators and supporting structures are transformed into a simple elastic pendulum with 2, 3 or 4 degrees of freedom (figure 3).
One of the pendulum methods with 4 degrees of freedom has been called "the double pendulum" and consists of 2 simple pendula and each one has 2 degrees of freedom (PENDBL). This means that in PENDBL each one of the two studied phases is simulated by a pendulum with 2 degrees of freedom.
PENDULUM also works with a 4 degrees-of-freedom system, but in this case it is one pendulum that contains 4 independent degrees of freedom.
The "concentrated" pendulum approach refers to SWINGT, PENDBL, PENDULUM and the "distributed" pendulum refers to PEND 02.
The notation "concentrated" pendulum and "distributed" pendulum describes how the mass of the pendulum is distributed along the pendulum arm. In the first case all of the pendulum mass is placed at one point at the end of the pendulum arm. In the second case, the mass is distributed along the length of the pendulum arm with the same amount of mass per unit of length of the arm.
The "concentrated" pendulum approach as well as the "distributed" one are both characterized by the assumption that the conductor remains in a plane.
The "concentrated" model has the following special characteristics.

- The shape of the conductor is assumed to be a parabola throughout its motion.
- The stiffness of the pendulum arm is a function of the tension in the cable.
- The electromagnetic force is assumed to be that created by two conductors of finite length, situated at the instantaneous position of each gravity center, and to act there in the direction joining the gravity centers of the two conductors.
- The conductors are assumed to be incompressible, so the lowest value of the tension is limited to zero.

The "distributed" model has the following special characteristics/4/.

- Each point of the conductor is assumed to receive the same resulting force.
- The formula for the length variation of the catenary constitutes a central part.
- In a simplified form this model has been adopted for slack conductors by IEC TC 73 and VDE 0103. In this model strain insulators are not included.

The compounded pendulum model

The CONEX approach /1/, /2/, /3/.
Electrodynamic forces and displacements of flexible

conductors, towers, insulators induced by very high short-circuit currents may be important.
A computer programme CONEX has then been developed by EdF in order to calculate these forces and displacements.

In this programme:

- the conductor is assumed perfectly flexible which disregards the stiffness of the conductor
- the suspension set is assumed elastic and flexible
- the dead end support is simulated by an equivalent mass and spring
- the forces taken into account are: the weight, the electro-magnetic forces, the resistance of the air against the movement of the conductor, the friction forces between the strands of the conductor.
- the temperature rise during the first moments of the short-circuit has been introduced.

The analysis provides a complete time-history response with respect to an asymmetric short-circuit current between two phases. A finite difference method is used for solving the system of equations. But the method is explicit in time for each point of the conductor and implicit for the points of the insulator set and the portal frame /3/.

The SACS/DACS approach /6/,/8/.
The SACS programme is used for static analysis of flexible cable and wire strained spans suspended at each end.
The DACS programme is used for dynamic analysis (2-phase short-circuit) of the same suspension bus.
The 3-D calculation model is shown in figure 4 and 5.

The SACS/DACS approach includes the following special characteristics.

- The nodes are assumed to remain in a plane perpendicular to the axial direction of the suspension bus at its initial position.
  In the case of portal structure deflections this plane is moved in axial direction of the conductor to a corresponding degree.

The analysis provides a complete time-history response in two directions with respect to a 2-phase short-circuit force computed by a fourth order RUNGE-KUTTA method with an adaptive time step or by a modified Euler backward method.

Modelling

In this section, additional information on modelling is provided including technical aspects which give a better understanding of some approaches.
Both SWINGT and PENDBL make use of the simple pendulum model with 2 degrees of freedom (figure 3).

One of the circumstances of the simple pendulum to ponder over is how to find a good solution to the formula below. This formula gives the parabola gravity centre.

$$d = 2/3*f$$

f= the sag of the parabola
d= the length of the pendulum "arm"

Another consideration is how to find the mass of the pendulum. It is called an equivalent mass and consists of the mass of the cable and a certain part of the mass of the strain insulators.
In the SWINGT programme the conductor is modelled as a pendulum connected to its pivot point by a non-linear spring and acted on by the electromagnetic forces as described in the previous section.

The non-linear spring represents the relationship between tension and sag. The conductor is assumed to remain in a plane and maintain the shape of a parabola throughout the motion. Because it is assumed that the frequency of swing-out is low compared to the natural frequency of the structures, the structures are represented by massless springs. The change in conductor length due to changes in the geometry of the parabola can be equated to the change in length of conductor due to stretching to obtain the expression given below for the change in conductor tension in terms of geometrical and physical parameters of the conductors and span.

$$T = T_o + \left(\frac{8}{3} \frac{r^2 - r_o^2}{L} \right) \Big/ \left(\frac{L}{AE} + \frac{1}{K} \right)$$

In addition, the equations of motion of the span (modelled as a simple pendulum) forced by the instantaneous short-circuit force relationship are obtained

$$\frac{2}{3} M (r \ddot{\alpha} + 2 \dot{r}\dot{\alpha}) = -Mg \sin\alpha + F \cos\alpha \; ;$$

$$\frac{2}{3} M (\ddot{r} - r \dot{\alpha}^2) = Mg \cos\alpha + F \sin\alpha - 8 r \frac{T}{L} \; ;$$

This set of two second order ordinary differential equations and one non-linear algebraic equation are solved simultaneously using the Runge-Kutta-Gill method.
In PENDBL the 4 linear differential equations of the second order are solved by using the Runge-Kutta method of the sixth order with the Fehlberg automatic step size control.

Modelling in PENDULUM /7/

Pendulum models are well adapted to analyse horizontal flexible spans of the structure A type. One of the main problems which limitates the range of application of this model, is related to the way in which take the insulator chain into account.

At the university of Liège a new model has been developed which includes the simple pendulum and which adds a new arm which gives the possibility to take the insulator chain into account. This model also includes the rotation inertia effects of the span. Thereby the pendulum oscillations frequency are changed accordingly:

out of plane or (pendulum) oscillation of the cable:

$$f1 = \frac{1}{2 \pi} \sqrt{\frac{5}{4} \frac{g}{f_0}} \simeq \frac{0.56}{\sqrt{f_0}}$$

in plane (or vertical) oscillation of the cable:

$$f2 = \frac{1}{2 \pi} \sqrt{\frac{20}{3} \frac{EA\, g\, f_0}{T_0\, Sl_0 \left(1 + \frac{EA}{Kl_0} \right)}}$$

pendulum oscillation of the insulator chain

$$f3 = \frac{1}{2 \pi} \sqrt{\frac{2 M_2 + M_1}{4 M_2 + \frac{4}{3} M_1} \frac{g}{l}}$$

EA = sectional stiffness of the cable (N)
l_0 = length of the cable (m)
K= stiffness of supporting structure (N/m)
M_1 = total mass for both insulator chains (Kg)
M_2 = total mass of the cable
$2\,l$ = initial sag of the end of one insulator chain (m)
f_0 = initial sag of the cable only
T_0 = initial tension in the cable (N)
S = span length (m)

Resonances will occur if
$f_2 = 2 k f_1$ (k = 1,2 ....)
and will be amplified if $f_1 = f_3$

The behaviour of the two arms pendulum is given by solving simultaneously a set of three non linear fully coupled second order differential equations. The number of equations increases to five if we include the inertial effect of supporting structure.
Fig 3c points out the hypothesis:

- the parabola of the cable (without the insulators) remains in a plane. This plane has a deviation from the vertical plane. (This is the same as for the classical pendulum but the end points can move on a circle line)
- the ends of the insulator chains (supposed inextensible) are moving on a circle line so that we can express its movement by one degree of freedom: the angle which specifies the deviation of the projection of the chain in the circle. So the arm of the insulator chain pendulum has a constant length equal to the initial projection in the circle
- anchoring points have the possibility to be simulated by a spring-mass model which respects the stiffness and the first frequency (first symmetrical mode). Spring constant is evaluated taking into account the action of the other phases.

Modelling in CONEX

The conductor is assumed to be a perfectly flexible curvi-linear material subject to localized or distributed forces (weight, electromagnetic forces). This assumption, which disregards the stiffness of the conductor, becomes increasingly justified as the ratio of the external forces to the bending resistance of the conductor becomes greater. This is true for the electrodynamic forces of high short-circuit currents.

. The suspension sets are assumed to be elastic and flexible.

Hence the dynamic equation of the conductor may be written:

$$\rho \cdot \frac{\delta^2 x_i}{\delta t^2} = \frac{\delta}{\delta S}\left(T \frac{\delta x_i}{\delta S}\right) + F_i (S,t) - R \frac{d_i}{dt}$$

in which:

$x_i(S, t)$	represents the coordinates of the points of the conductor in a system of axis.
t	the time
S	the curved abscissa along the deformed conductor
$F_i(S,t)$	the external forces
$\rho(S,t)$	the variable mass per unit length
T	the tension
R	the resistance due to friction between wires.

Moreover, the following equations are to be considered:

a. the equation of mass conservation

$$\rho (1 + \varepsilon) = \rho_0$$

in which ρ is the relative strain of the conductor and ρ_0 the mass per unit length in an unstressed state.

b. the equation of the elasticity of the material:

$$T = T (\varepsilon, \theta)$$

in which θ is the temperature of the cable. It has been proved necessary to introduce a corrective term for temperature rise in order to express the decrease in stress which occurs during the first moments of a short-circuit. As this heating can be considered adiabatic and the material as having elastic properties, the following relationship is found:

$$dS\ (T,\theta) = dS_0\ (T_0, \theta_0) \left[1 + \alpha\ (\theta - \theta_0)\right] \cdot \left[1 + \frac{T - T_0}{EA}\right]$$

in which

E	is the Young modulus of the material
A	the conductor cross-section
α	the coefficient of linear expansion of the material
T_0	the initial tension

c. boundary conditions : flexibility and inertia of towers:

The equations of dynamic are written for bending and torsion:

$$M \frac{d^2 x_s}{dt^2} + \frac{d\ x_s}{ft} = - k_f\ x_s + T_1 + T_2$$

$$I \frac{d^2 \theta}{dt^2} + \mu t \frac{d\theta}{dt} = - \theta + d_1 \cdot T_1 + d_2\ T_2$$

in which:

M	is the equivalent mass of the tower
μ_f, μ_t	are the damping coefficient for bending and torsion
k_f, k_t	are the bending and torsional stiffness of towers
T_1, T_2	are the tensions of the two phases
x_s	represents the coordinates of the dead-end point of the tower
I	is the inertial momentum of the tower
θ	is the angle of rotation of the two phases
d_1, d_2	are the length of the arms of the two phases

d. initial conditions: static profile and zero speed which are characterized by index $_0$

The system of equations (1) is hyperbolic and is solved by means of a finite difference method explicit in time for each point of the conductor.

The stability condition of the numerical method, expressed in terms of time and space increments, involves the following relationship:

$$\sqrt{\frac{EA}{\rho_0}}\ \frac{\Delta\ t}{\Delta\ s} < 1$$

The previous inequality is classical for hyperbloc systems since $\sqrt{EA/\rho_0}$ is the propagation velocity of longitudinal waves in the material.

On the other hand, for dead-end and suspension points the method which is used is implicit.

It is thus possible to calculate the tension and the coordinates at any time and at any point on the conductor in terms of the applied forces. The electromagnetic force depends upon the characteristics of the short-circuit current as well as upon the positions of the conductor at any time.

Modelling in SACS/DACS

The strain insulators are always supposed to connect node 1-2 and node 22-23 in figure 5. The suspension bus connects node 2-22. The suspension bus can be simulated by up to 20 different components parts with different characteristics. Masses to simulate dropper connections can be applied at the nodes between parts. In addition to that the suspension bus can be divided into a desired number of calculation points. The recommended number of calculation points is 100. The axial stiffness (elongation) of the strain insulators and the conductors are the true values.

Connections between the crossarms and the strain insulators are flexible values.

In SACS, the loads can be given in two perpendicular directions:

The dead weight in vertical direction and wind load in horizontal direction.

Addition loads due to ice and wind on the conductor, on droppers and on strain insulators can also be taken in account by applying different factors on the dead weight. The calculation is controlled by the given value of one of the following five parameters. The given value is valid at a certain given temperature.

- Total unstrained length of suspension bus. Length of insulators is not included.
- Maximum vertical sag. A in figure 4.
- Maximum sag measured perpendicular from the connection line between the supports to the suspension bus. B in figure 4.
- Horizontal force at the attachment points to the crossarm. H in figure 4.
- Force in the axial direction of the strain insulator at the right attachement point to the crossarm. SR in figure 4.

The subsequent calculation can be done at optional temperatures.

For the calculation of the short-circuit force the following alternatives are available:

- The current function is selected and approximate or exact consideration of phase distance and phase displacement can be taken /9/.
- The current function is used without periodical variation and instead a time mean value is used and approximate or exact consideration to phase distance and phase displacement can be used.
- The current function can be given as a traverse. The actual value is calculated by using linear interpolation.

The short-circuit force can be specified in different ways:

- The first method integrates the contribution from different parts of the actual electrical circuit during each time step of the short-circuit time. In this case the displacement is very important.
- The second method is used if the sag is small compared with the cable length. In this case the displacement of the conductor is not considered. This method is referred to as the approximate method.

Computer programme output results

A common medium complexity time history analysis includes output results for each time step or an optional number of time steps of each information mentioned below.

Minimum and maximum value and corresponding time at the mid-span point of the phase of the
- angel
- sag
- tension
- horizontal displacement
- vertical displacement

The extreme values of the tensions in the phase and the corresponding time for each time step at which the sense of the variation of the tension changes.

Plot of the tension in the phase as a function of time.

Plot of the positions of the phase

Examples of typical plots can be seen in figure 6. The computer programmes do have some variations in their printout and plotting possibilities at the moment but these differences can be modified easily.

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Résumé :

L'objet du présent examen est de fournir un compte rendu sommaire sur les travaux poursuivis dans le GT 23.02 de la CIGRE, concernant les différentes méthodes utilisables pour le calcul des tensions mécaniques qui apparaissent dans les conducteurs et les déplacements des barres omnibus du type suspendu, pour les conditions de charge engendrées par un court-circuit.

Pour l'essentiel, on étudie dans cet examen l'utilisation de méthodes de calcul dites de complexité moyenne, c'est-à-dire de méthodes qui peuvent se distinguer des méthodes de calcul simples et des méthodes de calcul avancées.

Une méthode de calcul simple suppose que ledit calcul peut s'effectuer manuellement et une méthode avancée implique la nécessité de recourir à l'utilisation d'un programme étendu, à applications multiples, tel que le ADINA, le SAMCEF, etc. On a tout simplement baptisé méthodes de complexité moyenne toutes celles qui se situent entre les méthodes simples et les méthodes dites avancées.

En utilisant ces méthodes d'analyse, il est possible de calculer les valeurs des contraintes effectivement imposées aux conducteurs, aux isolateurs d'ancrage ainsi qu'aux autres éléments accessoires et de la comparer avec les valeurs admissibles.

Il est possible également de déterminer les distances d'isolement dans l'air, réduites du fait des déplacements des conducteurs pendant et après le court-circuit. Toutes les méthodes de complexité moyenne ont été converties en programme de calculs spéciaux, conçus pour un calcul rapide des effets provoqués par les courts-circuits.

Le Tableau 1 donne un aperçu des méthodes de complexité moyenne actuellement disponibles.

Les méthodes de complexité moyenne peuvent être réparties en deux groupes principaux. Dans le premier groupe, on utilise un modèle physique que l'on a baptisé ici le modèle pendule. Les programmes de calcul appartenant au premier groupe ont été appelés PEND 02, SWINGT, PENDBL et PENDULUM. Les méthodes du deuxième groupe font appel à un modèle plus élaboré plus détaillé que nous avons appelé ici le modèle de pendule composite. Les programmes CONEX et SACS/DACS appartiennent à ce groupe. Le premier groupe peut ensuite être subdivisé en deux sous-groupes que l'on a définis par le mode de traitement adopté, dans l'un on considère un "pendule concentré", dans l'autre, un "pendule réparti" ou "balancier". Le "pendule concentré" est à la base des programmes SWINGT,, PENDBL,PENDULUM, quant au programme PEND 02, il est élaboré à partir de l'hypothèse d'un "pendule réparti". Le terme "concentré" ou "réparti" indique comment la masse du pendule est répartie le long du rayon d'oscillation. Dans le premier cas, la totalité de la masse est concentrée en un point, à l'extrémité du rayon d'oscillation. Dans le deuxième cas, on a une masse uniformément répartie le long d'un balancier oscillant autour de l'une de ces extrémités, avec une valeur constante de la masse par unité de longueur.

L'examen comprend essentiellement une étude technique des méthodes de complexité moyenne décrivant des exemples types de dispositions, modélisations et hypothèses détaillées utilisées dans les méthodes de complexité moyenne. Cette partie se termine avec une description de programme de calcul selon les méthodes de complexité moyenne et par une présentation d'exemples typiques des résultats obtenus en sortie.

Nous n'avons pas pu donner ici plus que des informations très limitées sur les fondements mathématiques étendus des différentes méthodes qui font l'objet du présent examen.

SWINGT et PENDBL sont quant au principe un même programme et nous pensons donc qu'il suffit de mentionner les détails du SWINGT dans la partie modélisation.

Nous avons laissé de côté les détails du PEND 02; nous supposons que la théorie de ce programme est déjà bien connue par les publications de la CEI et de la VDE.

ITEM		QUESTION	ANSWER CONEX	PEND 02	PENDULUM	SACS/DACS	PENDBL	SWINGT
A1	GENERAL INFORMATION	**Programme designation**	CONEX	PEND 02	PENDULUM	SACS/DACS	PENDBL	SWINGT
A2		Program developed an available at	ELECTRICITE DE FRANCE	UNIVERSITY of ERLANGEN	UNIVERSITY LIEGE	ASEA AB	ELECTROBEL BELGIUM	ONTARIO HYDRO
A3		References	/1/, /2/, /3/	/4/	/5/, /6/	/7/	-	-
A4		Data generation: manual = 1, automatic = 2	1	1	interact.gen.	1, 2	1	1
A5		Time discretization: explicit = 1, implicit = 2	1	1	1	1	1	1
A6		Time step: optional = 1	1	1	1	1	1	1
A7		Damping optional = 1, no = 0	1	0	0	1	0	0
A8		Results print output (1) and/or in graphical form (2) displacements and stresses for any prescribed point	1	1	1 (only one point)	1	1, 2	1, 2
A9		code FORTRAN = 1 PASCAL = 2		code BASIC	1	1	1 + 2	1
A10		Computer requirements in core memory	600-1200 K	very low	very low	min 250 kB	80 kB	80 kB
B1	CONDUCTORS AND STRAIN INSULATORS	Mass: concentrated (lumped) = 1 distributed (consistent) = 2	1, 2	2	1	1	1	1
B2		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, 3, 5	1, 3	1, 3, 5	1, 3	1, 3, 5	1, 3
B3		Displacements: large (nonlinear) = 1 small (linear) = 2	1	1	1	1	1	1
B4		Space discretization: finite elements = 1 finite differences = 2	2	2	2	1	2	2
C1	SUPPORTING STRUCTURES	Structures of arrangement A in Fig 1: solid web structure, arbitrary shape = 1 truss, full structure = 2 reduced to frame = 3 reduced to spring = 4	Spring constant and equivalent mass	4	4	4	4	4
D1	LOADING	Electrodynamic forces distributed (Biot-Savart) = 1 interactions: phase-to-phase = 2 unsuccessfull auto-reclosure = 3	1, 2, 3	1, 2	1, 2, 3	1, 2, 3	1, 2, 3	1, 2, 3
D2		Any static loads: gravity = 1, ice = 2, wind = 3	1, 2	1, 2	1, 2, 3	1, 2, 3	1, 2, 3	1, 2, 3

Table 1 Comparison of medium complexity method computer programmes analysing mechanical effects of short-circuit currents in substations with flexible conductors.

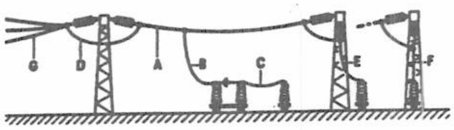


Fig. 1 Typical arrangements for flexible conductors in outdoor substations

A Horizontal strain bus secured 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

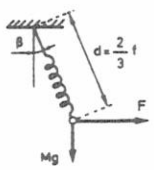
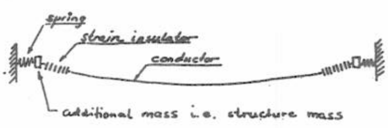


Figure 3a
Pendulum with two degrees of freedom



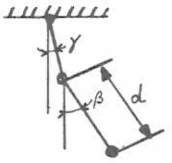


Figure 3b
Pendulum with four degrees of freedom

3 degrees : γ(angle of insulator considered as a rigid body)

β, d : the same as before

4th degree: displacement of anchoring point given by $M\ddot{x} + Kx = T$

where $\frac{1}{2\pi}\sqrt{\frac{K}{M}}$ is the first eigenfrequency of the gantry.

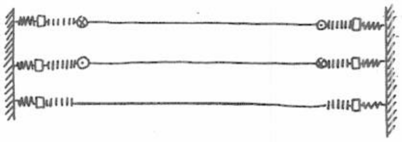


Figure 2
Model for simple and medium complexity methods,
the pure case A.

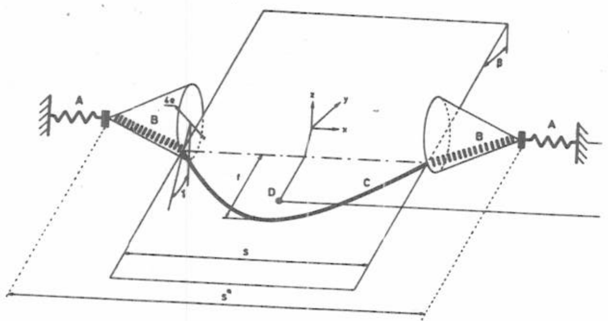


Figure 3c

A Spring-mass equivalent structure
B Insulator string like rigid body
C Busbar
D Gravity center of parabola

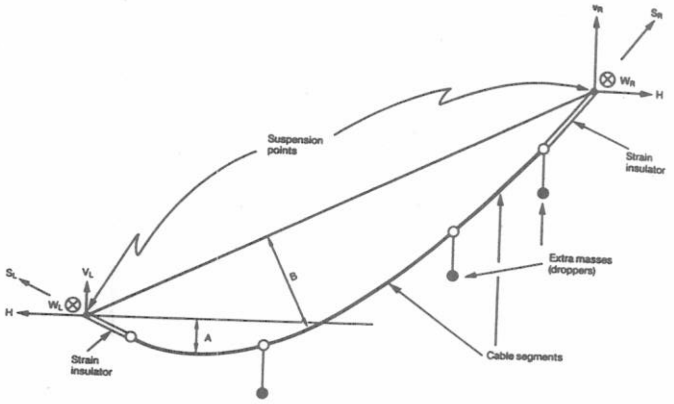


Figure 4 Span calculation model with loads. Wind load not shown.

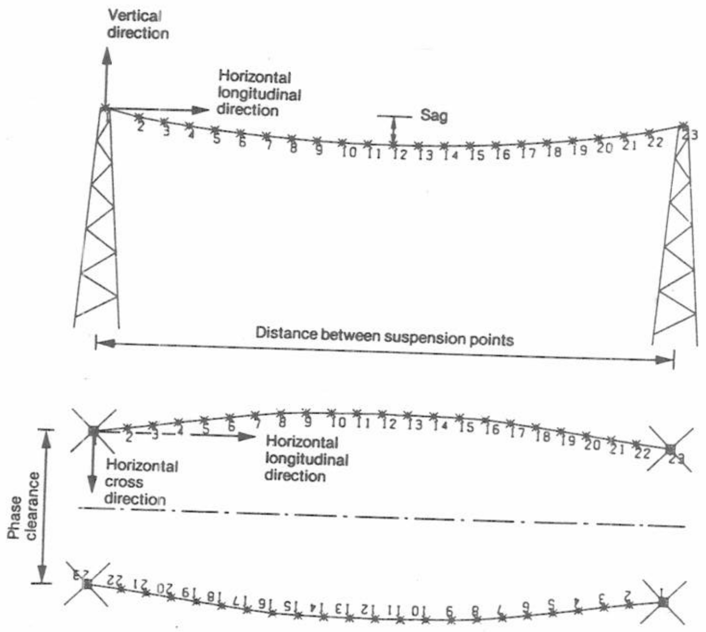


Figure 5
2-phase span calculation model, example with 23 nodes.

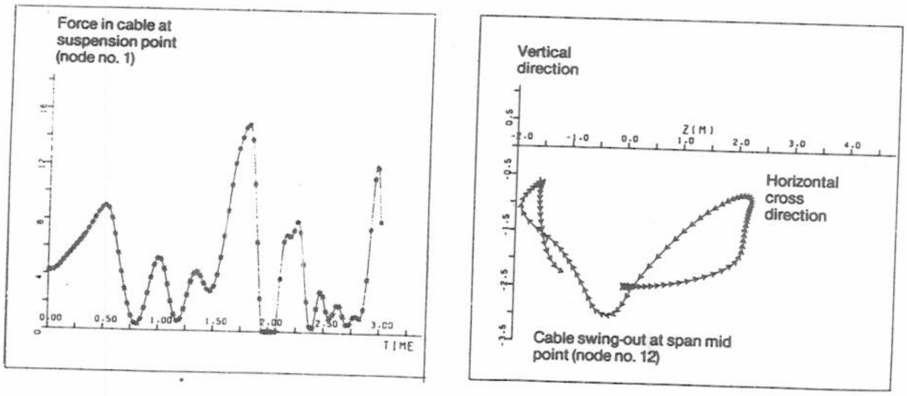


Figure 6
SACS/DACS graphic result presentation.
Forces and swing-outs can be plotted for each node and time-step.