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Item 3.3

MECHANICAL EFFECTS OF SHORT-CIRCUIT CURRENTS IN SUBSTATIONS WITH A STRAIN BUS SYSTEM

PARAMETER ANALYSIS AND SIMPLE METHOD OF CALCULATION

Paper presented in the name of Study Committee 23 (Substations)

by

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1. ABSTRACT

Today several methods (1,2) are available to compute accurately the mechanical effects (displacements, mechanical tensions) due to short-circuit currents in substations with a strain bus bars (flexible conductor) system.

These complex methods require considerable computer analysis (about 1 hour CPU on an IBM 370/158) and involve substantial memory capacity. The initial design of substations however require numerous calculations but of a non-precise nature.

Until now no simple method has been available for the calculation of cable bus bar as is the case for slack conductors (5,3).

Based on a pendulum model which takes into account a large number of parameters (cable elasticity, anchoring structure stiffness, temperature effects, inertial effect, etc.) the paper presents the parameter analysis and on this basis gives some proposals of simple formulas.

These proposed simple formulas give the two main maxima for mechanical tension (swing out and falling down) and movements of the cable (inward and outward) for a two phase fault condition. This is the most severe case.

This study does not include the pinch effect in a bundle, see reference (10).

key-words : substation - strain bus - short-circuit - mechanical effects - parametrisation - simplified formulas.

2. SIMPLIFIED MODEL

2.1 Hypothesis - Our simplified model is based on the main hypothesis of the well known pendulum model (8) :

- all forces are uniformly distributed
- cable has a parabola shape
- parabola remains in one plane during its motion
- anchoring points are at the same level.

The basic model has 3 degrees of freedom (D.O.F.) :

γ : angular position of the rigid insulator chain
β : angular position of the plane which contains the cable
s : instantaneous sag of the cable.

The displacement of the structure (a 4 th D.O.F.) can be incorporated if we include the first frequency of the anchoring structure by a spring mass model. This model is easily derived into a classical 2 D.O.F. pendulum if the insulator length is taken at zero. More details are available in (8). Tension and displacement are finally calculated by time integration from 3 (or 4) non-linear fully coupled second order differential equations.

2.2 Limitations - Inherent limitations of the model are imposed by hypothesis : we cannot take into account concentrated masses and droppers. Actual movement of the cable does not correspond to the in-plane movement after swinging out and the influence of in plane frequence is too large, for the same reason. End points must be at the same level. Only single conductor per phase are considered.

3. PARAMETER ANALYSIS

Reference (8) details the pendulum model and (1, 9) show some comparisons with other evaluations (tests and numerical calculations). Because of the good corelation between our simplified model and actual test results (1) it is possible to make some sensibility analysis taking into account numerous parameters, for a very low cost.
We do not reject the use of sophisticated calculations, but an initial simplified approach can give the design engineer some feeling for the concept of the structures, in order to limit complex calculations to specific cases and thus save time and money.

The PARAMETRIC APPROACH requires that we define some general parameters which are independent of the actual design and the relevant short-circuit conditions. These parameters should give information concerning maximal tensions (swing out and falling down maxima), and clearance.

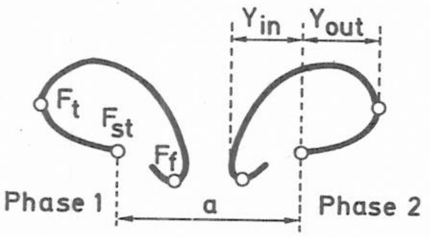


Fig. 1 movement at mid-span under a two phase fault condition.

In our contribution we have studied the evolution of four universal normalised variables, as follows :

relative to initial value of tension :

Ft/Fst : Swing out maximum
Ff/Fst : Falling down maximum

relative to initial value of sag :

Yin/so : Horizontal inwards movement
Yout/so : Horizontal outwards movement

NB. We only consider the critical case thus Yin = Yout.
We therefore wish to determine the effects of :

- r.m.s. intensity of the short-circuit currents
- time constant of the network at fault location
- short-circuit duration
- initial tension (or initial sag)
- span length
- distance between phases
- cable cross section
- anchoring structures stiffness
- ...

All the specific effects mentioned above have been studied separately for a basic case and we have attempted to give general curves in parametrising the curves so obtained.

The basic case is LABORELEC (1,2,11) with minor modifications. This case will permit extrapolations from the general curves to a practical disposition for 150 kV, or another.

This approach has been developed in order to define dimensionless parameters for the phenomenon of S-C-C effects on flexible busbar systems.

These parameters are as follows (notations and detailed expressions in appendix) :

LOAD FACTOR (P1) : Fm_2/M_2g
electromagnetic force on one phase divided by the weight of cable

NETWORK FACTOR (P2): $\omega\tau$
current pulsation multiplied by the time constant of the network

SHORT-CIRCUIT FACTOR (P3) : Tk/T
duration of fault divided by Natural Swing Period

STRUCTURAL FACTOR (P4) : $100\,\frac{S.so.so}{Fst.lc}$
anchoring stiffness divided by the sensibility of variation of tension as function of length.

(dl/dF and s_o^2 /(Fst.lc) are similar.

3.1 A specific approach

Each of the influences will be treated for several P1 values which is the main factor. Curves are also presented in this form.

3.1.1 Influence of short-circuit time duration (Tk)

P2 and P4 remain constant see fig. 2 and 3.

Ft/Fst logically increases with P1(=Fm2/M2.g) and P3(=Tk/T). Nevertheless Ft/Fst, at constant P1, leads to an asymptotic maximal value as soon as P3=0.25 (i.e. Tk=T/4). In this critical case, the short-circuit time is the same as the time for the cable to reach its extremal position. The increase of Ft/Fst becomes linear beyond P1=2.

The duration of short-circuit time (or more exactly P3) does not influence the maximum value for real falling down (fig. 2). But this maximum occurs for increasing P1 values when P3 decreases. As an approximation, maximum Ff occurs when P1.P3 = 0,35 (this product is an image of the input energy). This value will also vary with P2.

The influence of clearance results in a combination of heating, reaction of anchoring stiffness and elasticity of the cable (fig. 3).

3.1.2 Influence of span length (lc)

If Tk is modified to have a constant P3, with a constant ratio of sag to span length then P2 and P4 are also constant. Therefore the curves remain unchanged, i.e. for a span of 40 m (Tk=0.2s, Fst=7500 N) and 80 m (Tk=0.28 s, Fst=15000 N) then Ft/Fst, Ff/Fst and Yout/s0 are the same for a given P1 value, independently of the span length.

3.1.3 Influence of the initial tension (Fst)

If P2 and P3 remain constant, the influence of Fst is dependent only on P4 for a given P1 value (fig. 4 and 5).
The influence of increasing Fst only is a rapid decrease of P4 and a low increase of P3 : i.e. lower falling down and swing out ratios (F/Fst). The final gain on Ft and clearance is very limited.

The falling down maximum is located at a fixed P1 value (=2,5) and this maximum increases very quickly with P4 i.e. when Fst decreases.

3.1.4 Influence of anchoring stiffness (S)

If P2 and P3 remain constant, only P4 gives this impact (fig. 4 and 5). We have the same curves as for tension, thus an increase of anchoring stiffness has the same effect as a decrease of mechanical tension. Both effects can be compensated.

For the same electrodynamic stress, Ff maximum can be multiplied by about 3 in the normal range of use of substations (S from 10^2 to 10^4 N/mm). Influences on displacement could be easily deduced by the reader who will note the natural compromise between high mechanical tension and large clearance.

In calculations an infinite stiffness hypothesis would give large overdimensioning.

3.1.5 Influence of cross section of the conductor(A)

With a constant ratio of sag to span length, P3 and P2 can remain unchanged and again we have included this effect in parameter P4 and P1 (fig. 4 and 5).

Influence of thermal gradient has been taken into account in these figures but only for the normal range of practical use.

For a given short-circuit current and duration, P1 decreases very quickly with an increase of cross section. This has the beneficial effect of not increasing the final maximal value of Ft or Ff.

This advantage is also applicable to the clearance.

Any increase of cross section will always be advantageous, if it is possible.

3.1.6 Influence of time constant of the network

This influence is dependent upon P2 (fig. 6 and 7). An increase of P2 (with maximum asymmetry) could significantly increase the stresses for a given P4 value, up to 70% between a fault without asymmetry and another with asymmetry for large time constant.

The first maximum of falling down is not influenced by P2, as with P3.

3.2 General approach

Curves 2 to 7 show the influence on Ft/Fst, Ff/Fst, and Yin/SO related to parameter P1(=Fm2/M2.g) which leads the electromagnetic load. All these curves have been given for a range of variation of the other parameters P2, P3 and P4.

3.2.1 Swing out maximum (Ft) logically increases with increases of all the parameters. The increase is of quadratic form at the beginning and linear thereafter.

PARAMETER ANALYSIS

continuous line : Ft/Fst dotted line : Ff/Fst

$$P_1 = \frac{F_{m2}}{M_2 g} \qquad P_2 = \omega\tau \qquad P_3 = \frac{T_k}{T} \qquad P_4 = 10^5 \frac{S \cdot s_o^2}{F_{st} \cdot l_c}$$

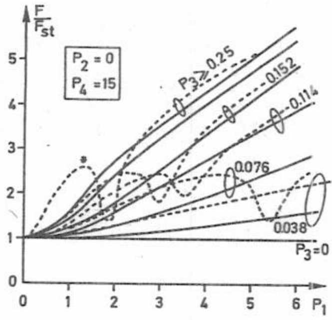


Fig. 2 : influence of load factor (P_1) on mechanical tensions for several short circuit factor

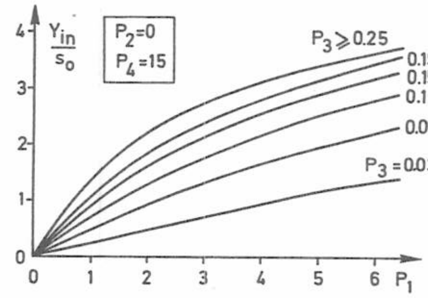


Fig. 3 : influence of load factor on displacements for several short circuit factor

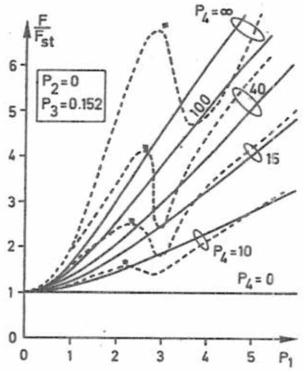


Fig. 4 : influence of load factor on mechanical tension for several structural factor

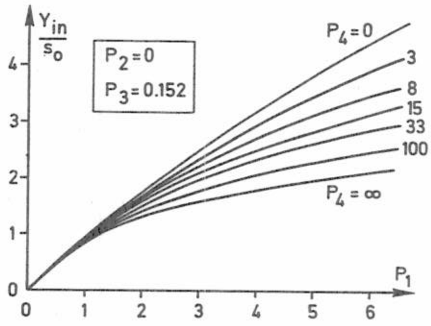


Fig. 5 : influence of load factor on displacements for several structural factors

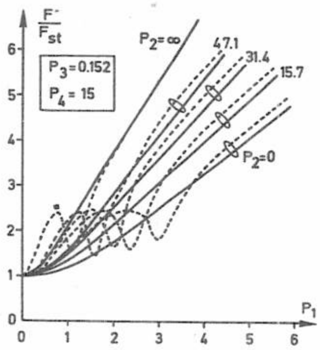


Fig. 6 : influence of load factor on mechanical tensions for several network factor

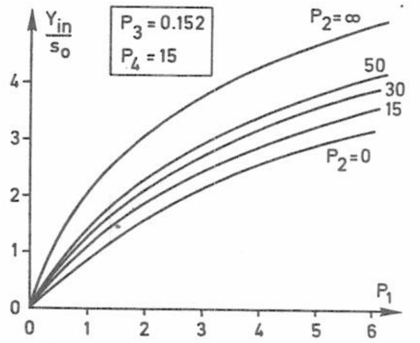


Fig. 7 : influence of load factor on displacements for several network factor

3.2.2 Falling down maximum (Ff) exhibits three different zones (I, II, III) of evolution in connection with the movement of the cable :

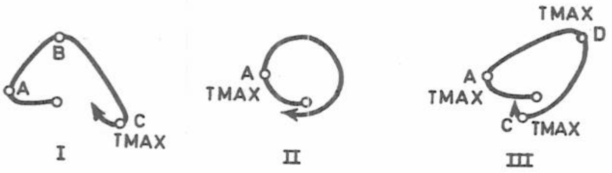


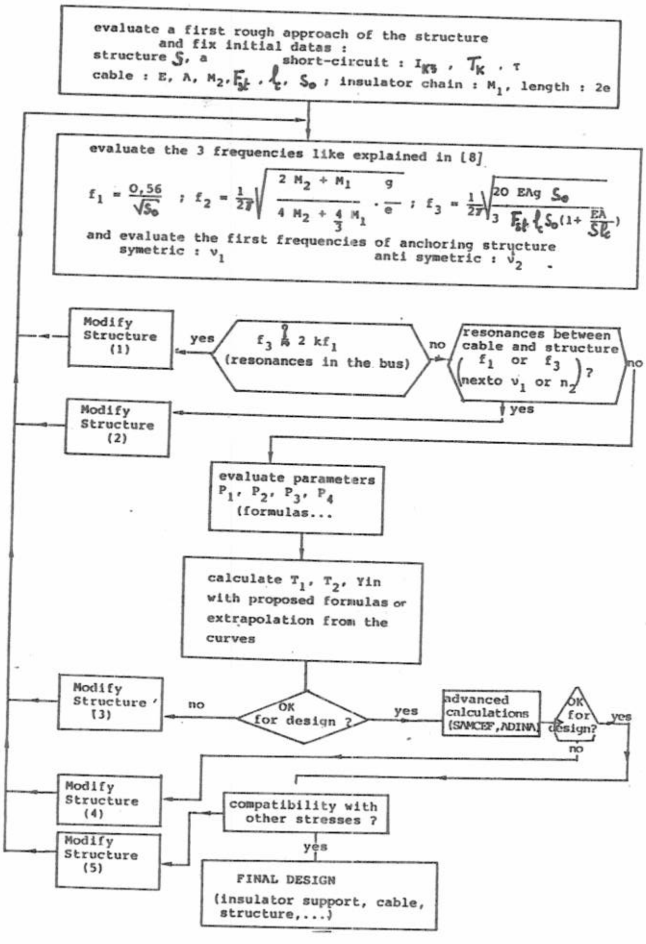
Fig.8 movement of the cable at mid span for increasing electrodynamic load from I to III

Configuration I corresponds to a large increase of Ff with increasing Pl. (Ff is higher than Ft in this case). Maximum of Ff for this configuration is mainly and very dependent of P4 only). This maximum will occur for a decreasing electromagnetic constraint (Pl) when P2 and P3 increase.(dotted line on fig. 2 and 6).

Critical cases for mechanical tension will be as follows :

Very high anchoring stiffness ($P4 \to \infty$), short-circuit duration of a quarter of T and high network time constant. In these cases very high falling down tension could occur for rather low short-circuit currents (Pl=1).

Beyond this maximum, the swing out maximum will be the main value influencing the design (configuration II and III).



3.2.3 Inwards (and outwards) movement initially increases linearly with Pl but a saturation phenomenon occurs for higher Pl values. Saturation is due to the fact that after a certain Pl, any additional increase of displacement could only arise from temperature and stiffness and not from geometry.

It must be noted that Yout could be higher than twice initial sag for high Pl values.

In appendix, deduced from this PARAMETRICAL APPROACH simple formulae are proposed. They are easier to use than a complex interpolation with 4 parameters. These formulae have been deduced by the synthesis of the curves. There are only proposed and not yet recommended by WG 23-02 for general use in design.

4. DESIGN OF STRUCTURE (see organigram)

How to modify structure :

(1) It is preferred to have f3 lower than twice fl, thus increasing fl in decreasing sag or decreasing f3 in decreasing 5, increasing Fst conditions.

(2) Generally νl, ν2 are larger than fl and f3. If not increase νl, ν2 in increasing S or decrease mass (preferred) or height. S should not be increased, if at all possible.

(3) Better results will be obtained by increasing Fst and cross section A and decreasing S. Other span lengths or increased distance between phases can also be tested. It is also possible to decrease load factor by increasing mass (additionnal concentrated weight f.e.).

(4) At this stage the disposition of the switch bays can be modified, i.e. position and length of the droppers.

(5) Design must fulfill also other requirement : mechanical (wind, ice, vibrations, narrow space for the station...) and electrical (corona...). Generally for Pl valuesup to 2, electrodynamic stress is higher than others.

5. CONCLUSIONS

We have proposed a new and original approach for the design of substations with flexible conductors, due to short-circuit electromagnetic forces, known as the PARAMETRICAL APPROACH.

By using this concept a simple formula can give an approximation in a short time, this will be of benefit to the design engineer.

Some examples are explained and numerous calculations have been performed at our Institute. More than 20 experiments with a large range of variation of the parameters have been performed. Obtained discrepancies on mechanical tension are in the range (-25%,+90%), and on the displacements (-40%,+95%).

Normal range of variation for the parameters are :

LOAD FACTOR : 2 to 6 (proportional to the square root of the current)

NETWORK FACTOR : 0 to 60

SHORT-CIRCUIT FACTOR : 0.05 to 0.40

STRUCTURAL FACTOR : 20 to 1000

The limitation of LOAD FACTOR is fundamental and can be easily done by increasing mass f.e.. NETWORK FACTOR is imposed by topology of the network. SHORT-CIRCUIT FACTOR can be reduced by proper elimination or increasing sag. STRUCTURAL FACTOR must be well choosen (as low as possible) during the design.

After an initial approach by this method the use of SAMCEF,ADINA or another finite element method will provide the designer with an accurate tool to obtain a more precise value.

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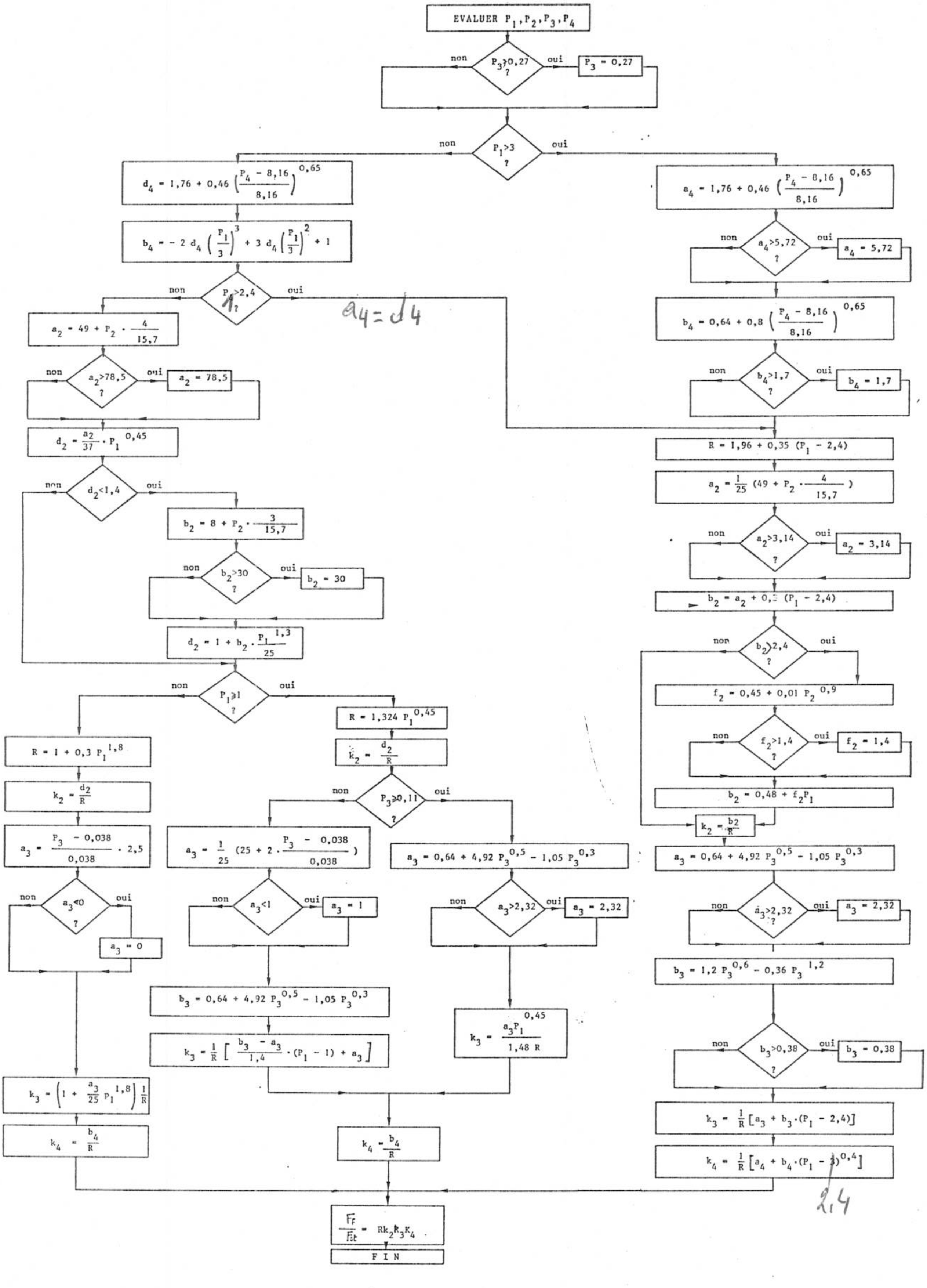
APPENDIX - NOTATIONS according IEC (5)

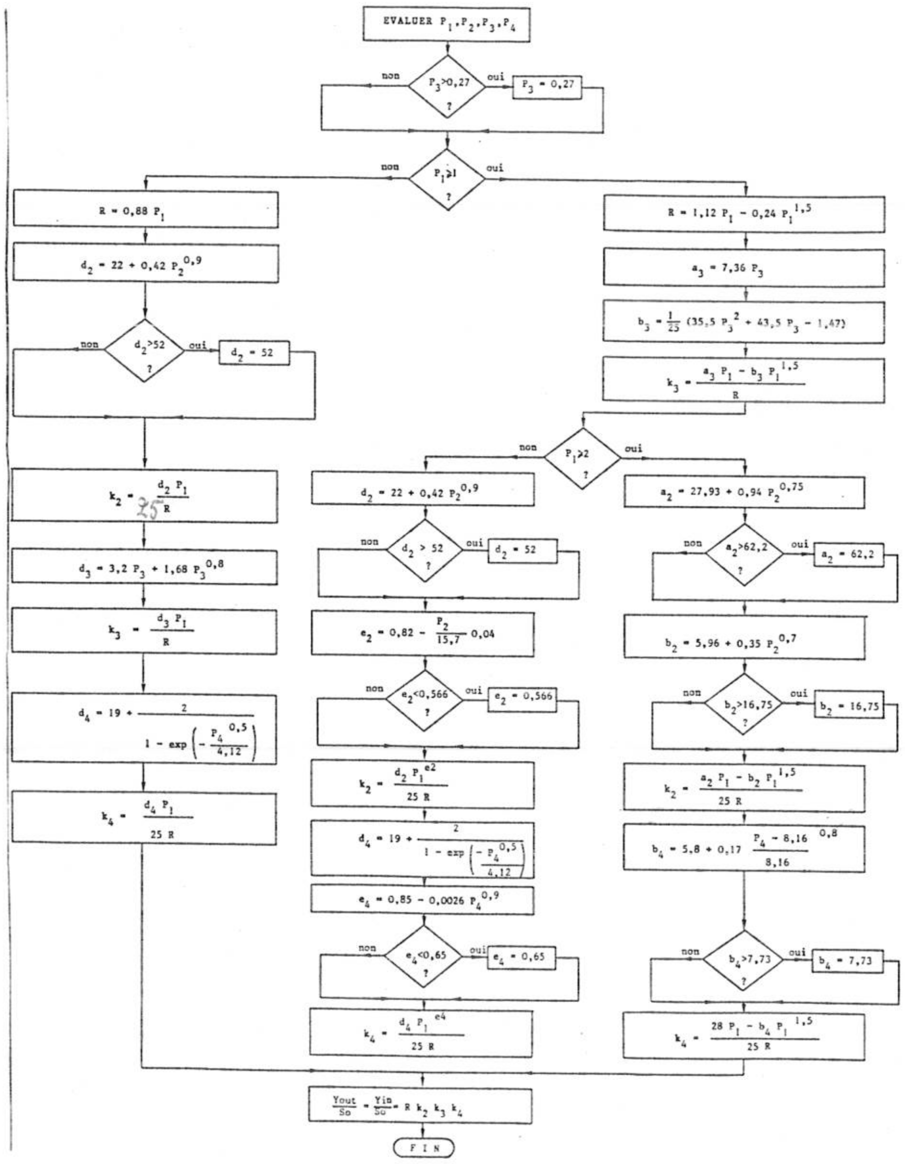
A	Conductor cross section of the cable bus bar (mm^2)
a	Interphase distance between conductors (m)
E	Young modulus (N/mm^2)
2e	sag of insulator chain at cable fixation (m)
Fm2	electromagnetic force in one phase for a two phase fault (N) $Fm2 = (0.2\ I^2k3 \cdot l_F/a$
Fst	Initial static tension (N)
Ft	"Swing out" mechanical tension (N)
Ff	"Falling down" mechanical tension (N)
f1,f2,f3	The three frequencies of the 3 dof simple model (Hz)
g	gravity constant = 9.81 m/s^2
Ik3	rms value of short circuit current (kA)
lso	Length of the cable bus bar (m)
lc	Span length of the cable only (m)
lF	Span length carrying current (where force in acting)(m)
M_1	Total mass of both insulator string (kg)
M_2	Total mass of the cable (kg) $M_2 = m'.lso$
m'	Main conductor mass p.u. length(kg/m)
P1	Fm_2/M_2g parameter (-)
P2	$\omega\tau$ parameter (-)
P3	Tk/T parameter (-)
P4	100000.S.so.so/(Fst.lc) parameter (-)
S	S1.S2/(S1+S2) equivalent structure stiffness (both end points S1,S2 in serie)(N/mm)
so	initial sag at mid-span (m)
Tk	duration of short-circuit (s)
T	Natural swing period of the cable (s) T = 0.56*sqrt(so)
Yin(Yout)	Inwards(outwards) movement of all the span (m)
$\omega\tau$	pulsation of the current (314 rad/s) multiplied by time constant of the network
$\nu 1, \nu 2$	First symmetric and antisymmetric mode of anchoring structure (Hz)
γ, β	Degree of freedom of pendulum model

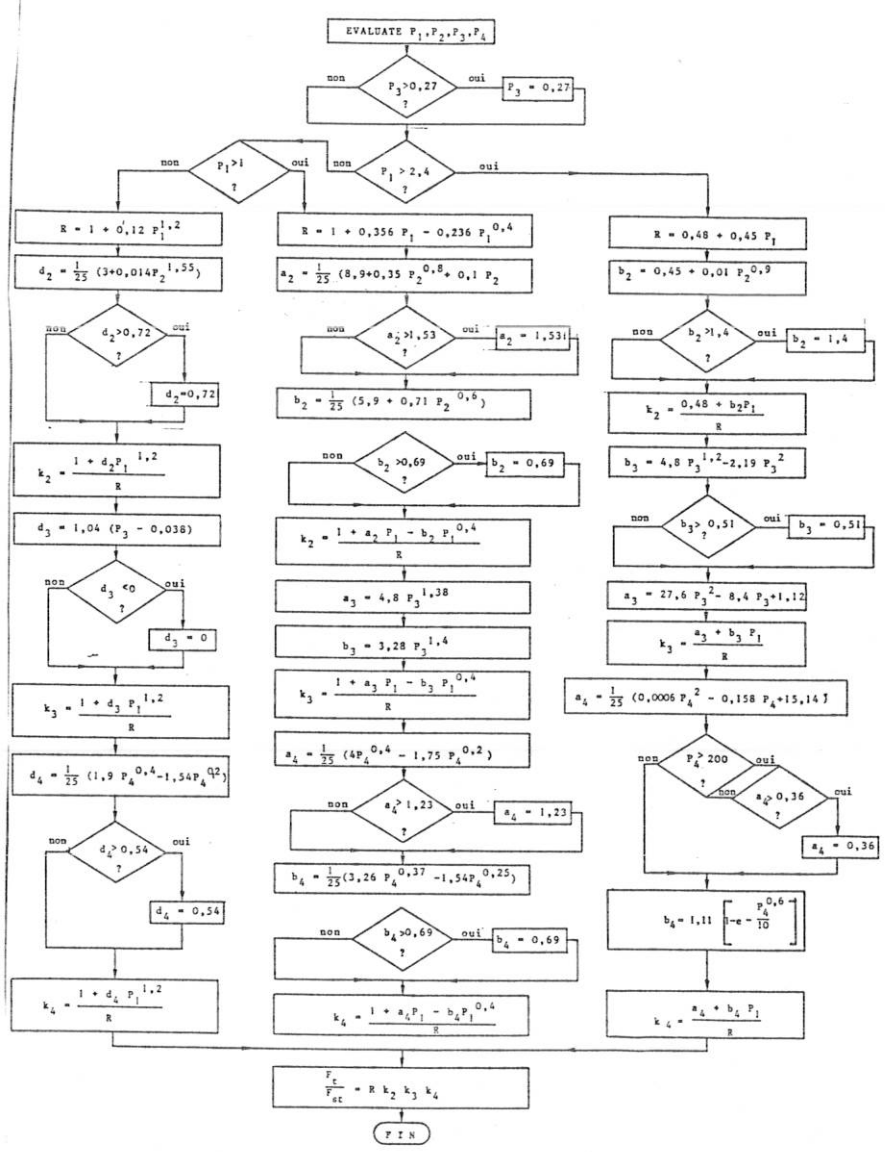
The Appendix gives one of the three organigrams mentioned in the Paper. The author is at your disposal to supply any complementary information concerning the other organigrams.

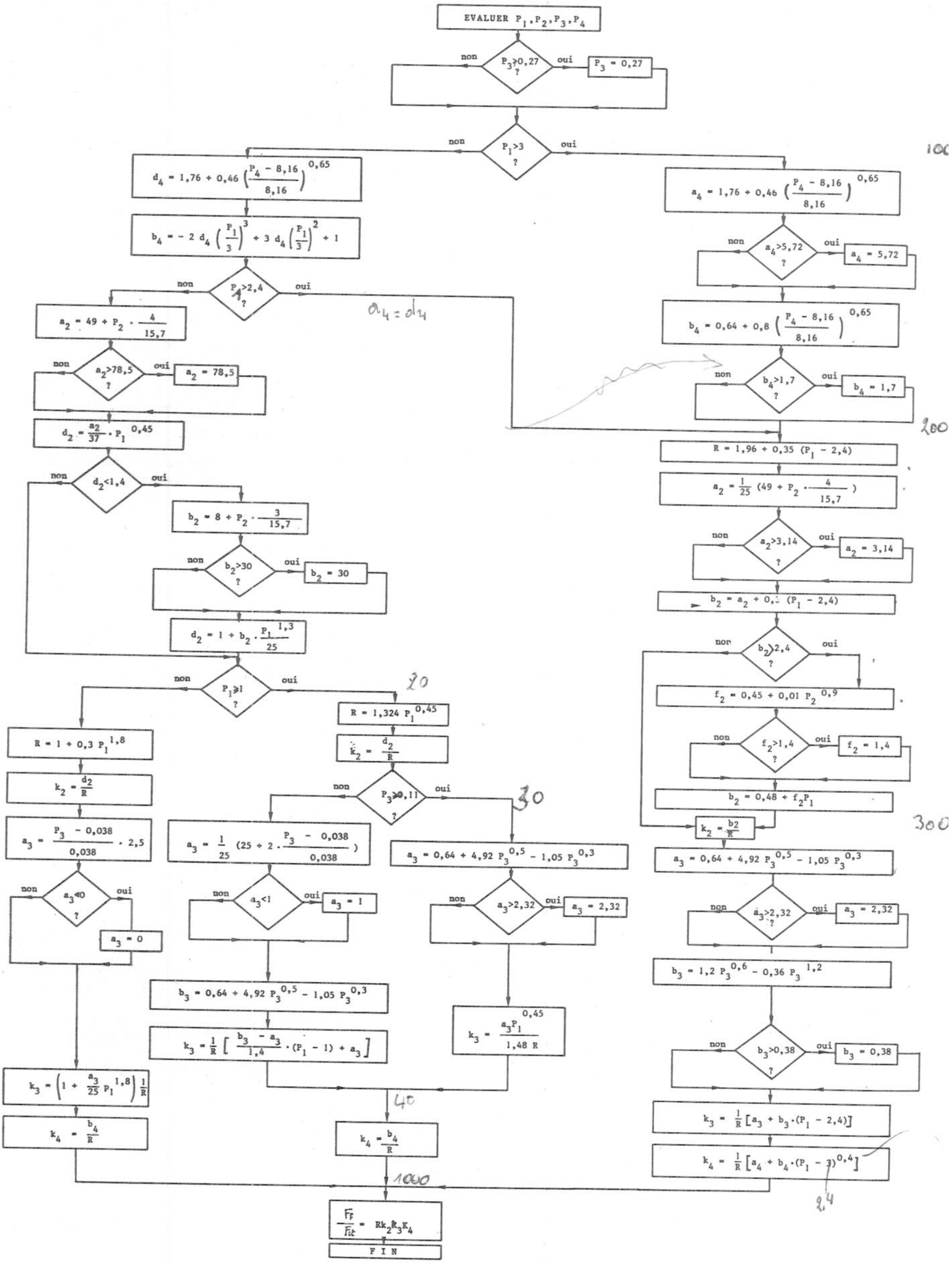
RESUME

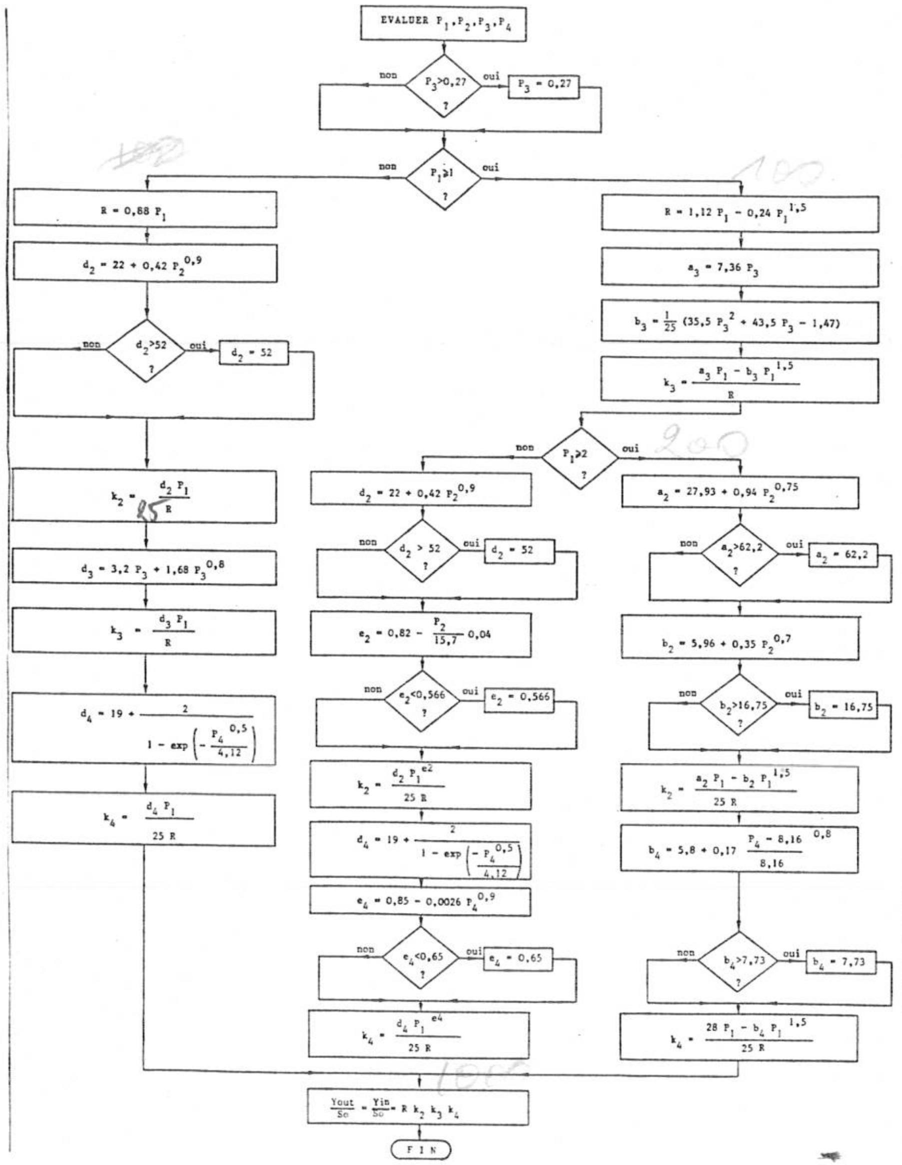
Cette étude originale est une aide à la conception des postes à jeux de barres tendus et soumis à de fortes intensités de courant. On envisage systématiquement l'impact de tous les paramètres importants sur le comportement des câbles tant les déplacements (distance d'isolement dans l'air) que les tensions mécaniques (dimensionnement des structures). Il apparaît que quatre paramètres sans dimension suffisent pour décrire le phénomène. Il en résulte des formules simplifiées très utiles au stade de la conception.

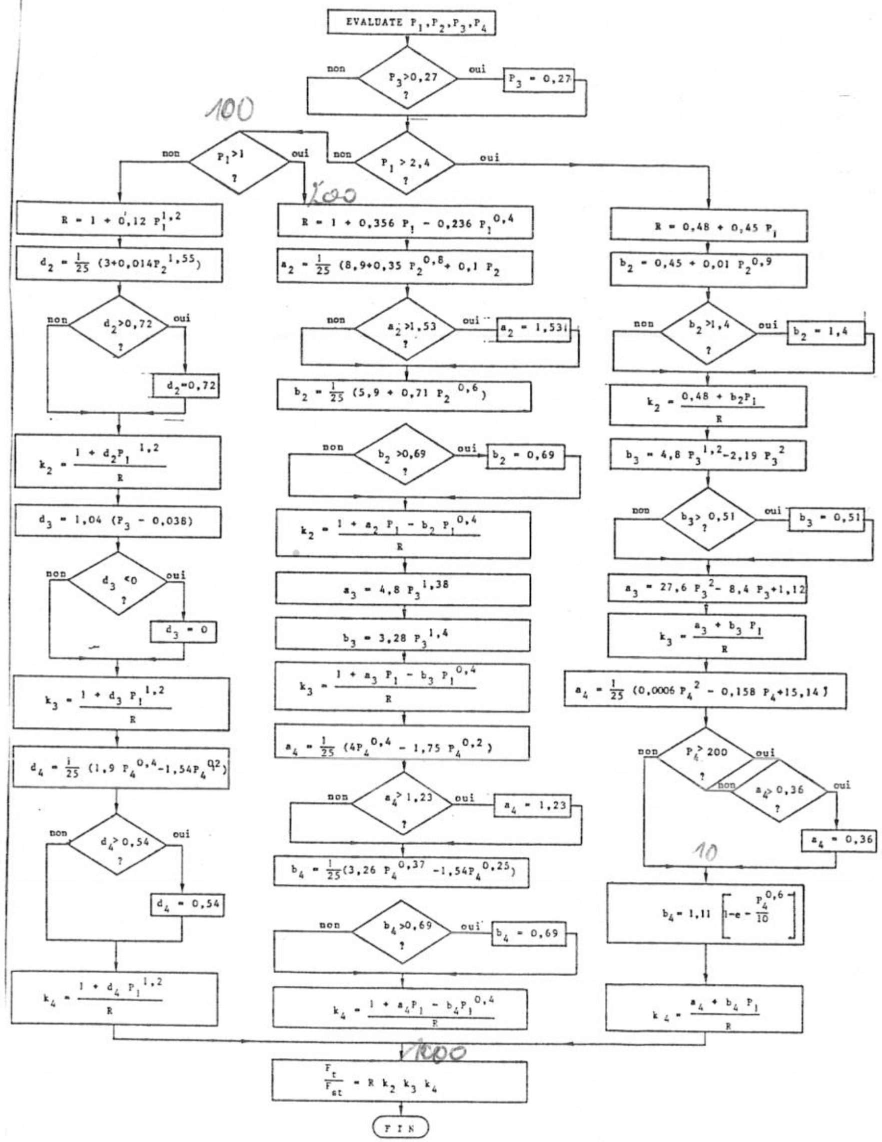

EVALUER P_1, P_2, P_3, P_4
$P_3 > 0,27$?
non
oui
$P_3 = 0,27$
$P_1 > 3$?
non
oui
$d_4 = 1,76 + 0,46 \left(\frac{P_4 - 8,16}{8,16}\right)^{0,65}$
$b_4 = -2\, d_4 \left(\frac{P_1}{3}\right)^3 + 3\, d_4 \left(\frac{P_1}{3}\right)^2 + 1$
$P_1 > 2,4$?
non
oui
a4=d4
$a_2 = 49 + P_2 \cdot \frac{4}{15,7}$
$a_2 > 78,5$?
non
oui
$a_2 = 78,5$
$d_2 = \frac{a_2}{37} \cdot P_1^{0,45}$
$d_2 < 1,4$?
non
oui
$b_2 = 8 + P_2 \cdot \frac{3}{15,7}$
$b_2 > 30$?
non
oui
$b_2 = 30$
$d_2 = 1 + b_2 \cdot \frac{P_1^{1,3}}{25}$
$P_1 \geq 1$?
non
oui
$R = 1 + 0,3\, P_1^{1,8}$
$k_2 = \frac{d_2}{R}$
$a_3 = \frac{P_3 - 0,038}{0,038} \cdot 2,5$
$a_3 < 0$?
non
oui
$a_3 = 0$
$k_3 = \left(1 + \frac{a_3}{25} P_1^{1,8}\right) \frac{1}{R}$
$k_4 = \frac{b_4}{R}$
$R = 1,324\, P_1^{0,45}$
$k_2 = \frac{d_2}{R}$
$P_3 \geq 0,11$?
non
oui
$a_3 = \frac{1}{25} \left(25 + 2 \cdot \frac{P_3 - 0,038}{0,038}\right)$
$a_3 < 1$
non
oui
$a_3 = 1$
$b_3 = 0,64 + 4,92\, P_3^{0,5} - 1,05\, P_3^{0,3}$
$k_3 = \frac{1}{R} \left[\frac{b_3 - a_3}{1,4} \cdot (P_1 - 1) + a_3 \right]$
$a_3 = 0,64 + 4,92\, P_3^{0,5} - 1,05\, P_3^{0,3}$
$a_3 > 2,32$
non
oui
$a_3 = 2,32$
$k_3 = \frac{a_3 P_1^{0,45}}{1,48\, R}$
$k_4 = \frac{b_4}{R}$
$a_4 = 1,76 + 0,46 \left(\frac{P_4 - 8,16}{8,16}\right)^{0,65}$
$a_4 > 5,72$?
non
oui
$a_4 = 5,72$
$b_4 = 0,64 + 0,8 \left(\frac{P_4 - 8,16}{8,16}\right)^{0,65}$
$b_4 > 1,7$?
non
oui
$b_4 = 1,7$
$R = 1,96 + 0,35\, (P_1 - 2,4)$
$a_2 = \frac{1}{25} \left(49 + P_2 \cdot \frac{4}{15,7}\right)$
$a_2 > 3,14$?
non
oui
$a_2 = 3,14$
$b_2 = a_2 + 0,3\, (P_1 - 2,4)$
$b_2 > 2,4$?
non
oui
$f_2 = 0,45 + 0,01\, P_2^{0,9}$
$f_2 > 1,4$?
non
oui
$f_2 = 1,4$
$b_2 = 0,48 + f_2 P_1$
$k_2 = \frac{b_2}{R}$
$a_3 = 0,64 + 4,92\, P_3^{0,5} - 1,05\, P_3^{0,3}$
$a_3 > 2,32$?
non
oui
$a_3 = 2,32$
$b_3 = 1,2\, P_3^{0,6} - 0,36\, P_3^{1,2}$
$b_3 > 0,38$?
non
oui
$b_3 = 0,38$
$k_3 = \frac{1}{R} \left[a_3 + b_3 \cdot (P_1 - 2,4) \right]$
$k_4 = \frac{1}{R} \left[a_4 + b_4 \cdot (P_1 - 3)^{0,4} \right]$
2,4
$\frac{F_f}{F_{st}} = R k_2 k_3 K_4$
F I N


EVALUER P_1, P_2, P_3, P_4
$P_3 > 0,27$?
non
oui
$P_3 = 0,27$
$P_1 \geq 1$?
non
oui
$R = 0,88\ P_1$
$d_2 = 22 + 0,42\ P_2^{0,9}$
$d_2 > 52$?
non
oui
$d_2 = 52$
$k_2 = \frac{d_2\ P_1}{R}$
25
$d_3 = 3,2\ P_3 + 1,68\ P_3^{0,8}$
$k_3 = \frac{d_3\ P_1}{R}$
$d_4 = 19 + \frac{2}{1 - \exp\left(-\frac{P_4^{0,5}}{4,12}\right)}$
$k_4 = \frac{d_4\ P_1}{25\ R}$
$R = 1,12\ P_1 - 0,24\ P_1^{1,5}$
$a_3 = 7,36\ P_3$
$b_3 = \frac{1}{25}\ (35,5\ P_3^2 + 43,5\ P_3 - 1,47)$
$k_3 = \frac{a_3\ P_1 - b_3\ P_1^{1,5}}{R}$
$P_1 \geq 2$?
non
oui
$d_2 = 22 + 0,42\ P_2^{0,9}$
$d_2 > 52$?
non
oui
$d_2 = 52$
$e_2 = 0,82 - \frac{P_2}{15,7}\ 0,04$
$e_2 < 0,566$?
non
oui
$e_2 = 0,566$
$k_2 = \frac{d_2\ P_1^{e2}}{25\ R}$
$d_4 = 19 + \frac{2}{1 - \exp\left(-\frac{P_4^{0,5}}{4,12}\right)}$
$e_4 = 0,85 - 0,0026\ P_4^{0,9}$
$e_4 < 0,65$?
non
oui
$e_4 = 0,65$
$k_4 = \frac{d_4\ P_1^{e4}}{25\ R}$
$a_2 = 27,93 + 0,94\ P_2^{0,75}$
$a_2 > 62,2$?
non
oui
$a_2 = 62,2$
$b_2 = 5,96 + 0,35\ P_2^{0,7}$
$b_2 > 16,75$?
non
oui
$b_2 = 16,75$
$k_2 = \frac{a_2\ P_1 - b_2\ P_1^{1,5}}{25\ R}$
$b_4 = 5,8 + 0,17\ \frac{P_4 - 8,16}{8,16}^{0,8}$
$b_4 > 7,73$?
non
oui
$b_4 = 7,73$
$k_4 = \frac{28\ P_1 - b_4\ P_1^{1,5}}{25\ R}$
$\frac{Yout}{So} = \frac{Yin}{So} = R\ k_2\ k_3\ k_4$
F I N


EVALUATE P_1, P_2, P_3, P_4
$P_3 > 0,27$?
non
oui
$P_3 = 0,27$
$P_1 > 2,4$?
non
oui
$P_1 > 1$?
non
oui
$R = 1 + 0,12\ P_1^{1,2}$
$d_2 = \frac{1}{25}\ (3 + 0,014 P_2^{1,55})$
$d_2 > 0,72$?
non
oui
$d_2 = 0,72$
$k_2 = \frac{1 + d_2 P_1^{1,2}}{R}$
$d_3 = 1,04\ (P_3 - 0,038)$
$d_3 < 0$?
non
oui
$d_3 = 0$
$k_3 = \frac{1 + d_3\ P_1^{1,2}}{R}$
$d_4 = \frac{1}{25}\ (1,9\ P_4^{0,4} - 1,54 P_4^{0,2})$
$d_4 > 0,54$?
non
oui
$d_4 = 0,54$
$k_4 = \frac{1 + d_4\ P_1^{1,2}}{R}$
$R = 1 + 0,356\ P_1 - 0,236\ P_1^{0,4}$
$a_2 = \frac{1}{25}\ (8,9 + 0,35\ P_2^{0,8} + 0,1\ P_2$
$a_2 > 1,53$?
non
oui
$a_2 = 1,53$
$b_2 = \frac{1}{25}\ (5,9 + 0,71\ P_2^{0,6})$
$b_2 > 0,69$?
non
oui
$b_2 = 0,69$
$k_2 = \frac{1 + a_2\ P_1 - b_2\ P_1^{0,4}}{R}$
$a_3 = 4,8\ P_3^{1,38}$
$b_3 = 3,28\ P_3^{1,4}$
$k_3 = \frac{1 + a_3\ P_1 - b_3\ P_1^{0,4}}{R}$
$a_4 = \frac{1}{25}\ (4P_4^{0,4} - 1,75\ P_4^{0,2})$
$a_4 > 1,23$?
non
oui
$a_4 = 1,23$
$b_4 = \frac{1}{25}(3,26\ P_4^{0,37} - 1,54 P_4^{0,25})$
$b_4 > 0,69$?
non
oui
$b_4 = 0,69$
$k_4 = \frac{1 + a_4 P_1 - b_4 P_1^{0,4}}{R}$
$R = 0,48 + 0,45\ P_1$
$b_2 = 0,45 + 0,01\ P_2^{0,9}$
$b_2 > 1,4$?
non
oui
$b_2 = 1,4$
$k_2 = \frac{0,48 + b_2 P_1}{R}$
$b_3 = 4,8\ P_3^{1,2} - 2,19\ P_3^2$
$b_3 > 0,51$?
non
oui
$b_3 = 0,51$
$a_3 = 27,6\ P_3^2 - 8,4\ P_3 + 1,12$
$k_3 = \frac{a_3 + b_3\ P_1}{R}$
$a_4 = \frac{1}{25}\ (0,0006\ P_4^2 - 0,158\ P_4 + 15,14]$
$P_4 > 200$?
non
oui
$a_4 > 0,36$?
non
oui
$a_4 = 0,36$
$b_4 = 1,11\ \left[1 - e - \frac{P_4^{0,6}}{10}\right]$
$k_4 = \frac{a_4 + b_4\ P_1}{R}$
$\frac{F_t}{F_{st}} = R\ k_2\ k_3\ k_4$
F I N


EVALUER P_1, P_2, P_3, P_4
$P_3 > 0,27$?
non
oui
$P_3 = 0,27$
$P_1 > 3$?
non
oui
$d_4 = 1,76 + 0,46 \left(\frac{P_4 - 8,16}{8,16}\right)^{0,65}$
$b_4 = -2\, d_4 \left(\frac{P_1}{3}\right)^3 + 3\, d_4 \left(\frac{P_1}{3}\right)^2 + 1$
$P_1 > 2,4$?
non
oui
$a_4 = d_4$
$a_2 = 49 + P_2 \cdot \frac{4}{15,7}$
$a_2 > 78,5$?
non
oui
$a_2 = 78,5$
$d_2 = \frac{a_2}{37} \cdot P_1^{0,45}$
$d_2 < 1,4$?
non
oui
$b_2 = 8 + P_2 \cdot \frac{3}{15,7}$
$b_2 > 30$?
non
oui
$b_2 = 30$
$d_2 = 1 + b_2 \cdot \frac{P_1^{1,3}}{25}$
10
$P_1 \geq 1$?
non
oui
20
$R = 1 + 0,3\, P_1^{1,8}$
$k_2 = \frac{d_2}{R}$
$a_3 = \frac{P_3 - 0,038}{0,038} \cdot 2,5$
$a_3 < 0$?
non
oui
$a_3 = 0$
$k_3 = \left(1 + \frac{a_3}{25} P_1^{1,8}\right) \frac{1}{R}$
$k_4 = \frac{b_4}{R}$
$R = 1,324\, P_1^{0,45}$
$k_2 = \frac{d_2}{R}$
$P_3 \geq 0,11$?
non
oui
30
$a_3 = \frac{1}{25} \left(25 + 2 \cdot \frac{P_3 - 0,038}{0,038}\right)$
$a_3 < 1$?
non
oui
$a_3 = 1$
$b_3 = 0,64 + 4,92\, P_3^{0,5} - 1,05\, P_3^{0,3}$
$k_3 = \frac{1}{R} \left[\frac{b_3 - a_3}{1,4} \cdot (P_1 - 1) + a_3 \right]$
$a_3 = 0,64 + 4,92\, P_3^{0,5} - 1,05\, P_3^{0,3}$
$a_3 > 2,32$?
non
oui
$a_3 = 2,32$
$k_3 = \frac{a_3 P_1^{0,45}}{1,48\, R}$
40
$k_4 = \frac{b_4}{R}$
1000
$\frac{F_F}{F_{it}} = R k_2 k_3 K_4$
F I N
100
$a_4 = 1,76 + 0,46 \left(\frac{P_4 - 8,16}{8,16}\right)^{0,65}$
$a_4 > 5,72$?
non
oui
$a_4 = 5,72$
$b_4 = 0,64 + 0,8 \left(\frac{P_4 - 8,16}{8,16}\right)^{0,65}$
$b_4 > 1,7$?
non
oui
$b_4 = 1,7$
200
$R = 1,96 + 0,35\, (P_1 - 2,4)$
$a_2 = \frac{1}{25} \left(49 + P_2 \cdot \frac{4}{15,7}\right)$
$a_2 > 3,14$?
non
oui
$a_2 = 3,14$
$b_2 = a_2 + 0,1\, (P_1 - 2,4)$
$b_2 \geq 2,4$?
non
oui
$f_2 = 0,45 + 0,01\, P_2^{0,9}$
$f_2 > 1,4$?
non
oui
$f_2 = 1,4$
$b_2 = 0,48 + f_2 P_1$
300
$k_2 = \frac{b_2}{R}$
$a_3 = 0,64 + 4,92\, P_3^{0,5} - 1,05\, P_3^{0,3}$
$a_3 > 2,32$?
non
oui
$a_3 = 2,32$
$b_3 = 1,2\, P_3^{0,6} - 0,36\, P_3^{1,2}$
$b_3 > 0,38$?
non
oui
$b_3 = 0,38$
$k_3 = \frac{1}{R} \left[a_3 + b_3 \cdot (P_1 - 2,4) \right]$
$k_4 = \frac{1}{R} \left[a_4 + b_4 \cdot (P_1 - 3)^{0,4} \right]$
2,4


EVALUER P1,P2,P3,P4
P3>0,27 ?
non
oui
P3 = 0,27
P1≥1 ?
non
oui
100
R = 0,88 P1
d2 = 22 + 0,42 P2^0,9
d2>52 ?
d2 = 52
k2 = d2 P1 / R
25
d3 = 3,2 P3 + 1,68 P3^0,8
k3 = d3 P1 / R
d4 = 19 + 2 / (1 - exp(- P4^0,5 / 4,12))
k4 = d4 P1 / 25 R
R = 1,12 P1 - 0,24 P1^1,5
a3 = 7,36 P3
b3 = 1/25 (35,5 P3^2 + 43,5 P3 - 1,47)
k3 = (a3 P1 - b3 P1^1,5) / R
P1≥2 ?
200
d2 = 22 + 0,42 P2^0,9
d2 > 52 ?
d2 = 52
e2 = 0,82 - P2/15,7 0,04
e2<0,566 ?
e2 = 0,566
k2 = d2 P1^e2 / 25 R
d4 = 19 + 2 / (1 - exp(- P4^0,5 / 4,12))
e4 = 0,85 - 0,0026 P4^0,9
e4<0,65 ?
e4 = 0,65
k4 = d4 P1^e4 / 25 R
a2 = 27,93 + 0,94 P2^0,75
a2>62,2 ?
a2 = 62,2
b2 = 5,96 + 0,35 P2^0,7
b2>16,75 ?
b2 = 16,75
k2 = (a2 P1 - b2 P1^1,5) / 25 R
b4 = 5,8 + 0,17 ((P4 - 8,16) / 8,16)^0,8
b4>7,73 ?
b4 = 7,73
k4 = (28 P1 - b4 P1^1,5) / 25 R
1000
Yout/So = Yin/So = R k2 k3 k4
F I N


EVALUATE P1,P2,P3,P4
P3>0,27 ?
non
oui
P3 = 0,27
P1 > 2,4 ?
100
P1>1 ?
200
R = 1 + 0,12 P1^1,2
d2 = 1/25 (3+0,014P2^1,55)
d2>0,72 ?
d2=0,72
k2 = (1 + d2P1^1,2) / R
d3 = 1,04 (P3 - 0,038)
d3 <0 ?
d3 = 0
k3 = (1 + d3 P1^1,2) / R
d4 = 1/25 (1,9 P4^0,4 -1,54P4^0,2)
d4> 0,54 ?
d4 = 0,54
k4 = (1 + d4 P1^1,2) / R
R = 1 + 0,356 P1 - 0,236 P1^0,4
a2 = 1/25 (8,9+0,35 P2^0,8 + 0,1 P2
a2>1,53 ?
a2 = 1,53
b2 = 1/25 (5,9 + 0,71 P2^0,6)
b2 >0,69 ?
b2 = 0,69
k2 = (1 + a2 P1 - b2 P1^0,4) / R
a3 = 4,8 P3^1,38
b3 = 3,28 P3^1,4
k3 = (1 + a3 P1 - b3 P1^0,4) / R
a4 = 1/25 (4P4^0,4 - 1,75 P4^0,2)
a4> 1,23 ?
a4 = 1,23
b4 = 1/25 (3,26 P4^0,37 -1,54P4^0,25)
b4 >0,69 ?
b4 = 0,69
k4 = (1 + a4P1 - b4P1^0,4) / R
R = 0,48 + 0,45 P1
b2 = 0,45 + 0,01 P2^0,9
b2 >1,4 ?
b2 = 1,4
k2 = (0,48 + b2P1) / R
b3 = 4,8 P3^1,2 -2,19 P3^2
b3> 0,51 ?
b3 = 0,51
a3 = 27,6 P3^2 - 8,4 P3+1,12
k3 = (a3 + b3 P1) / R
a4 = 1/25 (0,0006 P4^2 - 0,158 P4+15,14)
P4> 200 ?
a4> 0,36 ?
a4 = 0,36
10
b4 = 1,11 [1-e - P4^0,6 / 10]
k4 = (a4 + b4 P1) / R
1000
Fr/Fst = R k2 k3 k4
F I N