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# SHORT-CIRCUIT MECHANICAL EFFECTS ON OPEN-AIR SUBSTATION STRUCTURES AND APPARATUSES.THE EQUIVALENT STATIC LOAD (ESL)

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*Abstract*

**Short-circuit currents mechanical effects is nowadays a key factor for the design of open-air substations. This paper deals with the way to take into account the dynamic aspects of the load by a simple method : the equivalent static load. The paper is focused on typical impulse load like dropper stretch. Dropper are derivation from the main busbars(flexible) to ground apparatuses (isolators, circuit breakers, bushings, measuring transformers, etc...) . This paper explains new development after the SCC'94 [3] in Liège. Actual dropper stretch (from experiments and simulations) are included in this approach.**

## Introduction

Mechanical effects have been studied inside CIGRE for more than 15 years[4]. Actual IEC recommendations 865-1 (TC73) help the designer to take these effects into account.
The load deduced from IEC gives no direct access to the true constraint, in the structure. The trouble is coming from the fact that dynamic loads does not affect a structure as a static load, especially if the characteristic frequencies of the load are high compared to basic structural frequencies. This is physically connected to the effect of inertial loads initiated in the structure due to its local acceleration. This is obvious for impulse loading (like dropper stretch).

There is no reason to design on the peak instantaneous load, if the basic frequency of the structure on which the load is applied, is as low as a few hertz (like 420 kV insulators, isolators, measuring transformers, surge arresters, bushing, etc...)

After the paper of SCC 94, introducing mathematical background[3], this paper will develop pragmatic approach to evaluate the ESL based on maximum instantaneous peak load applied on apparatuses. The ESL will be given frequency dependent, so that a rough evaluation of the first frequency of the apparatus (which is mainly voltage dependent) will give access to actual design load.

## Dynamics of structures in HV substations

Typical range of eigenfrequencies of substation apparatuses are given in table 1.

| | rated voltage (kV) | | |
|---|---|---|---|
| | 123 | 245 | 420 |
| Typical apparatus height(m) | 1...1.7 | 2.1..2.5 | 3.1..4.5 |
| post insulators | | | |
| frequency range (mode 1) (Hz) | 20..60 | 7...14 | 4...12 |
| measuring transformers/ isolators/circuit breakers | | | |
| frequency range (mode 1) (Hz) | 10..40 | 3...7 | 1.5...6 |
| supporting structures (gantries) | | | |
| Typical height(m) | 5...6 | 8...10 | 12...15 |
| frequency range (mode 1) (Hz) | 3...6 | 3...5 | 1...4 |

Table 1 : typical values for frequency range of apparatuses and supporting structures, following [4]

Post insulators have typically a uniform mass distributed along the height whereas other apparatuses have typically very heavy mass at the top.

## Static equivalent load

The static equivalent load is a static load which can be taken into account for the design of structures which are stressed by dynamic loading. The equivalent static load is a load, which would induce in the structure the same maximum constraint as the dynamic load.

For electrical apparatuses which have to be designed for substations, we can consider that the structure looks like a clamped-free beam on which the dynamic load is applied at the top. The maximum constraint for short-circuit loads can be located at the bottom and is directly connected to the bending moment at the bottom of the apparatus.

## The method

As detailed in [4] , we decided to split the problem in two parts :

1) analysis of the load
the result of this analysis will define a load participation factor "n".

2) analysis of the structure (apparatuses)
the result of this analysis will define a structural participation factor "k".

The static equivalent load will be the product of « n » and « k ».

In this paper we will consider apparatuses which look like clamped-free beams, with or without a local mass at the top (typical insulator support, measuring transformers, bushing, surge arresters, isolators and some circuit breakers)..

## The converters « n » for load and « k » for structure

As explained in [3] we can get for substation apparatuses :

modal frequencies (rad/s) :

$$\omega_i = \lambda_i^2 \cdot \sqrt{\frac{EI}{mL^4}} \qquad (1)$$

where $\lambda_i$ are given by the solutions of :

$$1 + \cos(\lambda).ch(\lambda) - \beta.\lambda.[\sin(\lambda).ch(\lambda) - sh(\lambda).\cos(\lambda)] = 0 \qquad (2)$$

where $\beta = M/mL$

(M is the concentrated mass at the top, m the distributed mass along the body of the apparatus , L is the total height of the apparatus). $\beta = 0$ for post insulators. $\beta = 1$ for measuring transformers.

the structural participation factor $k_i$ (Converter B) :

$$k_i = -2C_i \cdot \frac{y_i(1)}{\lambda_i^2 \left[ \beta y_i^2(1) + \int_0^1 y_i^2(\eta)d\eta \right]} \qquad (3)$$

where :

$$y_i(\eta) = sh(\lambda_i \eta) - \sin(\lambda_i \eta) - C_i\{ch(\lambda_i \eta) - \cos(\lambda_i \eta)\}$$

and :

$$C_i = \frac{\sin\lambda_i + sh\lambda_i}{ch\lambda_i + \cos\lambda_i}$$

If $\beta = 0$ (means post insulators), $\lambda_1 = 1.875$, k1 = 1.138

If $\beta = 1$ (means typical current transformer) $\lambda_1 = 1.184$, k1 = 1.031

the load participation factor $n_i$ (Converter A) :

$$p(L).\omega_i . \left[ \int_0^t f(\tau).e^{-\xi_i \omega_i (t-\tau)}.\sin(\omega_i (t-\tau)).d\tau \right]_{max} \qquad (4)$$

$\xi_i$ is the modal percentage of critical damping, following Clough [3]

$n_i$ is only a function of the applied dynamic load(peak value p(L), shape f(t) , duration of its application), $\omega_i$ and $\xi_i$, the frequency and damping of the structure.

Because we would like to get $n_i$ only as a function of the load independently of the structure, $n_i$ would be given in diagram with the frequencies in abscissa, frequencies which would cover all the range of actual values for substation apparatuses and will be given for minimum damping values (about 2%) measured.

Due to our kind of problems and excitations, and for sake of simplicity, we can limit the approach to the first mode of the structure. Finaly :

$$\boxed{ESL = n_1 k_1 F_{peak}}$$

Where Fpeak is the peak instantaneous load during the dropper stretch.

# Application

We will apply the theory to the stress occuring on apparatuses during the stretching of a cable connection from apparatuses to the main bus located at an upper level (fig. 1). This kind of connection will be called dropper. The phenomenon is called dropper stretch. The dropper stretch is a rapid increase of the stress in the dropper, from about zero (in its initial configuration, only the weight is supported, there is pactually no prestressing of such cable in most of the cases) to a maximum when the dropper is stretched (means becomes a straight line between apparatus and main busbars).

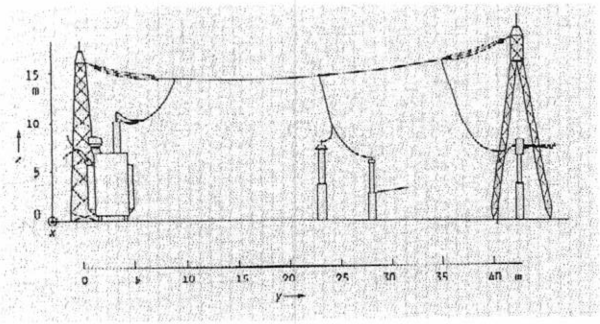

Fig. 1: typical arrangement in a 420 kV substation. (courtesy Prof. A.M. Miri)

The dropper stretch induces vertical and horizontal loads on the apparatuses. The most dangerous one is the maximum horizontal load which must be in relation with actual cantilever strength of the apparatus.

Based on some tests and computations, typical dropper load looks like the fig.2.

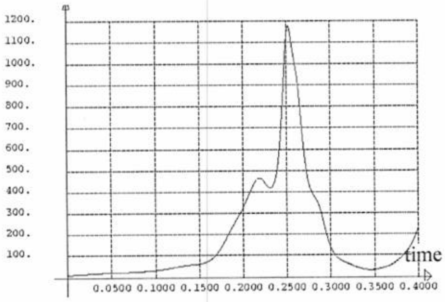

Fig.2 Typical time history for .dropper load in Short-circuit direction for case 19 (table 2 here after) .

We have computed about 20 typical structures (basic datas on table 2), from 123kV to 420 kV, for short-circuit level from 40 to 63 kA and for typical apparatuses in the range of frequencies detailed in table 1. Number of droppers per span were 1 or 3.

n factors are given overprinted on fig. 3 (the damping influence is very low). In order to generalise the n factor, we have choosen the ordinates n/p(L). A synthetic envelop curve is also proposed on the same figure and will be used for following investigations.

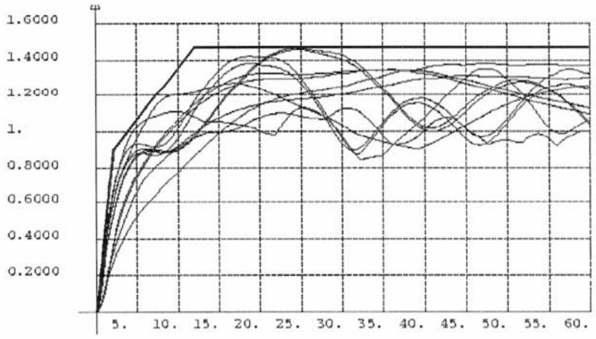

Fig. 3 : load participation factor for many kind of dropper stretch. Ordinates is $n_i$/peak load. The straight lines is the proposed simplified curve to be used in all cases.

We can easily evaluate the ESL knowing approximate frequency of the apparatus (if unknown, range indicated in table 1 can be used) and using synthetic curve of n (straigth line on fig 3) and k factor detailed here above.

In appendix, the way used to compare exact ESL with approximate ESL is given, by comparison with the use of advanced finite element method including the apparatuses in the simulation. The simulation gives access to maximum bending moment in the apparatuses from which equivalent static load is simply obtained by dividing the bending moment by the part of the length remaining from top of apparatus (where the load is applied) to the location where bending moment has been evaluated.

The next figure reproduces such comparisons.

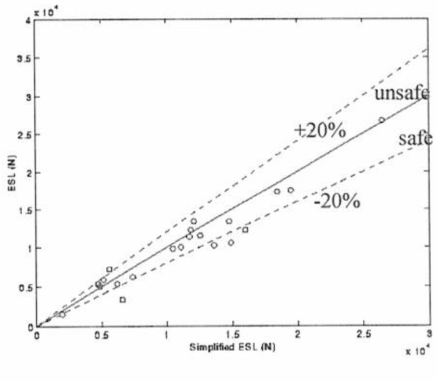

Fig.4: Comparison between ESL values calculated using synthetic curve n and ESL evaluated with bending moments

It is remarkable to see that most of the cases are in the ran,ge of ± 20% around exact value and generally in the safe side. Moreover it is also remarkable that some dropper stretch in typical existing substations could be as high as 2000 daN, which overpass typical manufacturer cantilever stretngth.

The Fig. 5 details the relation between ESL and maximum instantaneous peak. It is remarkable to point out that most of ESL are higher than instantaneous peak horizontal load. which is opposite to the result presented in [3] which was probably a very specific case. This fact is in relation with the time during which the increase of the stress occurs compared to the period of oscillation of the fisrt mode of the apparatus.

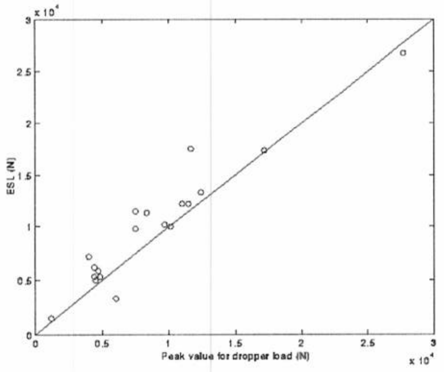

Fig.5: Comparison between calculted peak value of dropper load and ESL calculted with n and k factor.

The cases which have been computed or obtained from tests are detailed in table 2, including he peak load on apparatus (Fmax), the exact ESL (Freal) obtained by advanced finite element method and the ESL(Feq) evaluated by the method described in this paper. The kind of apparatus could be 1 (for 123kV), 2 (for 245 kV) and 3 (for 420 kV), without (β=0) or with (β =1) a big mass at the top, data detailed on table 3.

| N° | Span (m) | d (m) | S (mm²) | $I_{rms}$ (kA) | Ap | n | $F_{max}$ (daN) | Freal (daN) | Feq (daN) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 40 |  | 1267 | 40 | 1 | 1.47 | 441 | 620 | 738 |
| 2 | 40 | 4 | 1267 | 63 | 2 | 1.236 | 834 | 1133 | 1173 |
| 3 | 60 | 6 | 1267 | 63 | 3 | 0.944 | 450 | 500 | 484 |
| 4 | 40 | 2.5 | 1267 | 40 | 4 | 1.353 | 400 | 720 | 558 |
| 5 | 40 | 4 | 1267 | 63 | 5 | 1.061 | 1010 | 1000 | 1108 |
| 6 | 60 | 6 | 1267 | 63 | 6 | 0.944 | 485 | 533 | 472 |
| 7 | 40 | 2.5 | 1140 | 40 | 1 | 1.47 | 1166 | 1750 | 1950 |
| 8 | 40 | 4 | 1140 | 40 | 2 | 1.236 | 968 | 1020 | 1361 |
| 9 | 60 | 6 | 1140 | 63 | 3 | 0.944 | 1717 | 1734 | 1843 |
| 10 | 40 | 2.5 | 1140 | 40 | 4 | 1.353 | 1146 | 1220 | 1599 |
| 11 | 40 | 4 | 1140 | 40 | 5 | 1.061 | 603 | 333 | 660 |
| 12 | 60 | 6 | 1140 | 63 | 6 | 0.944 | 2722 | 2670 | 2647 |
| 13 | 40 | 2.5 | 570 | 40 | 1 | 1.47 | 750 | 1150 | 1254 |
| 14 | 40 | 4 | 570 | 40 | 2 | 1.236 | 440 | 533 | 619 |
| 15 | 60 | 6 | 570 | 63 | 3 | 0.944 | 1100 | 1222 | 1181 |
| 16 | 40 | 2.5 | 570 | 40 | 4 | 1.353 | 750 | 980 | 1046 |
| 17 | 40 | 4 | 570 | 40 | 5 | 1.061 | 470 | 587 | 514 |
| 18 | 60 | 6 | 570 | 63 | 6 | 0.944 | 1240 | 1333 | 1207 |
| 19 | 40 | 2.5 | 570 | 30 | 1 | 1.47 | 118 | 150 | 197 |

table 2- 19 cases computed to evaluate dropper stretch and corresponding ESL. d is the distance between phases, S the equivalent cross section of one phase, Ap is the number of apparatus used , the characteristics of which is detailed in table 3.

*Apparatuses characteristics*

| Type | L (m) | K (N/m) | m (kg/m) | Freq .(Hz) | $\beta$ |
|---|---|---|---|---|---|
| 1 | 1 | 1.5 $10^6$ | 62.5 | 50 | 0<br>(k=1.138) |
| 2 | 3 | 1 $10^5$ | 34.4 | 8 | 0<br>(k=1.138) |
| 3 | 4.5 | 5 $10^4$ | 143 | 2.85 | 0<br>(k=1.138) |
| 4 | 1 | 1.5 $10^6$ | 324 | 10 | 1<br>(k=1.031) |
| 5 | 3 | 8 $10^5$ | 230 | 4.85 | 1<br>(k=1.031) |
| 6 | 4.5 | 5 $10^5$ | 235 |  | 1<br>(k=1.031) |

table 3- typical apparatuses used for simulation. Type 1 and 4 are for 123 kV, 2 and 5 for 245kV, 3 and 6 for 420 kV. 1,2 and 3 are typical post insulators, whereas 4,5 and 6 are typical current transformers. L is the total height of the apparatus, K its stiffness, m its mass per unit length for the insulating body and freq the first eigenfrequency of the apparatus.

Typical dropper stretch, evaluated on classical substation lay out with short-circuit level of 40 and 63 kA point out typical range of ESL (design load to be used for cantilever strength) up to 3000 daN.

ESL can be very high in some cases, generally with long span and a few dropper per span. The actual forces on apparatuses is very dependent of the span length of the main bus, the electromagnetic loading (short-circuit current and distance between phases) and its ratio with main bus weight per unit length, the number of droppers in the span, etc...

Actual manufactured typical supporting insulator at 420 kV can hardy withstand cantilever failing load greater than 1700 daN which needs appropriate bus-bars lay out.

## Future work

Actually the method is based on the knowledge of maximum instantaneous load during dropper stretch. This can easily be obtained by advanced computation method. Next step will be to evaluate such maxima by a simple method, which is under consideration.

The same method will be applied also for other dynamic loading, like bundle pinch effect.

## Conclusions

To take into account the dynamic aspects of the load is a must for the design of substation apparatuses, especially for pinch effect and dropper stretch. This paper is dealing with dropper stretch and its effect on the design of apparatuses.

We suggest a simple method to evaluate the equivalent static load. The theory is developed in a former paper summarised in this one.

This is a new trends for design in substation to save time for the designers. The method can easily be applied in a very short including the possibility of the effects of some uncertainties in the available data's.

We can hope , after completion of this study, to introduce similar method into IEC recommendations.

The suggested method could also be applied as post processor of advanced computations method, which is the case for [1]. It is in fact well known that the substations apparatuses has very limited dynamic effects on the loads apply on it (static effects can easily be taken into account by a simple spring). So we can save many time of data entrance and computation time by neglecting their presence in the sophisticated computations used for bus-bars response. Therefore, the advanced computations can be used for evaluation of dropper stretch and bundle pinch, which can easily be treated afterwards, as input signal for the suggested simple method.

## References

[1] Samcef-Mecano (partim CABLE). A finite element software distributed by Samtech S.A., Bd Frère Orban 25, B4000 Liège Belgium.
[2] R.W. Clough. *Dynamic of structures*. Mc Graw Hill, New York, 1975.
[3] J.L. Lilien, U. Schön. *Mechanical loads on substation apparatuses- Equivalent static load* présenté au "VIth Symposium on short-circuit in Power Systems" , proceedings, session 2. report 2.6. Liège, sept 1994
[4] The mechanical effects of short-circuit currents in open-air substations (rigid or flexible bus-bars). Brochure from CIGRE SC 23. Paris 1996.

## Acknowledgement

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## Appendix :

Example of evaluation of exact ESL from advanced calculation method [1].

The datas corresponds to case 19 of table 2. and fig. A.1

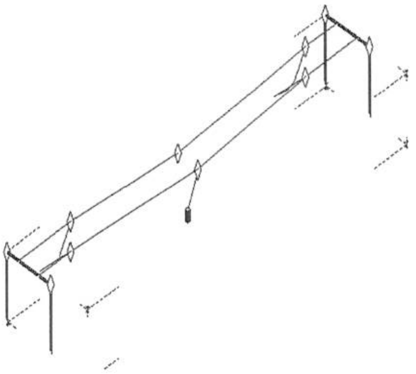

fig. A.1 Bus-bars lay out for 123 kV level used for computation of dropper stretch. Short-circuit level : 30 kA during 0.8 s., sections of cables : 570 mm$^2$. - 2.5 m between phases. Three droppers on one phase.

The next figures are the computation results.

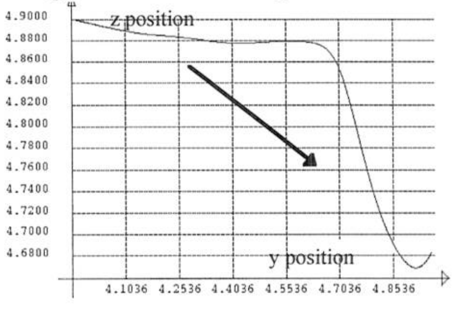

Fig. A.2 Movement of the main bus in a vertical plane perpendicular to the bus at mid-span. The cable must go down due to dropper action.

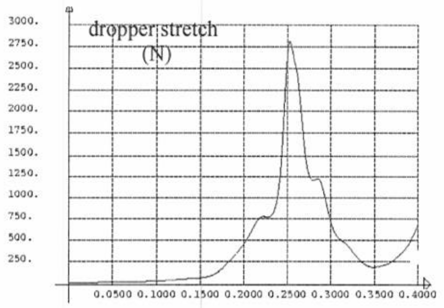

Fig. A.3 Dropper stretch (time evolution of the tension in the dropper during the movement of the main bus).

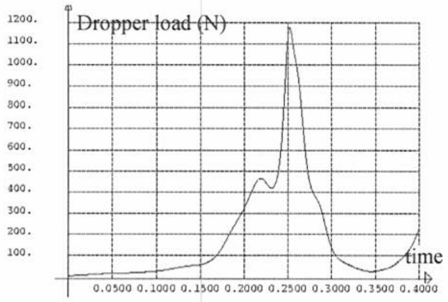

Fig. A.4 Horizontal reaction force on the apparatus at the bottom of the dropper located near the middle of the span.

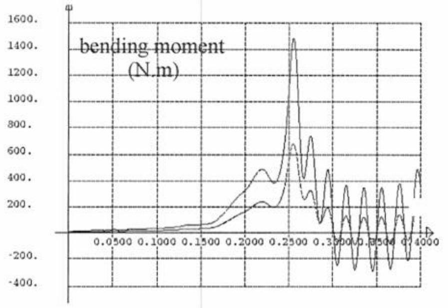

Fig. A.5 Bending moment in the support of the dropper, taken as an insulator support of 1 m height with first eigenfrequency equal to 50 Hz. (the two curves are for middle and bottom location)

The same maximum bending moment could be induced by a static load of :
1400 N for the curve at the middle height of insulator.
1500 N for the curve at the bottom of insulator.

Exact ESL is thus 1500 N as represented on fig. 4 ( first point left)

Evaluated ESL based on the reaction force (which is the same if we include or not include the apparatus in the simulation) is given by :
k1 = 1.138 because of the insulator support configuration.
n1 = 1.47 deduce from synthetic curve detailed on fig 2, because first eigenfrequency of the insulator is 50 Hz.
Maximum reaction force : Fmax = 1180 N

ESL obtained by simplified approach :
ESL = n1 x k1x Fmax = 1974 N.

(this point is first left point on the fig.4)
In this case actual ESL (1500 N) is overestimate by the simple method up to 1974 N (+24%) and is unfortunately sensibly higher (+20%) than the maximum instantaneous peak value of the cantilever load applied at the top of the apparatus (1180 N).