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26 Mechanical loads on substation apparatuses

An equivalent static load

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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 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...) .

1.Introduction

Short-circuit currents mechanical effects is nowadays a key factor for the design of open-air substations, especially what concerns flexible connections (bus-bars, droppers, switch bay connections, connections to and between apparatuses).

Mechanical effects have been studied inside CIGRE for more than 15 years. Actual IEC recommendations 865 (TC73) help the designer to take these effects into account.

The aim of these recommendations is to give access to some maximal loading during short-circuit (namely f.e. pinch effect, swing out maximum, falling down maximum)

These maximum instantaneous loads are well evaluated by IEC formulas in classical disposition for span length lower than 60 meters. Of course the help of advanced computations (finite element) like [1] can help the designer in more complex situations or even to get a better evaluation than simplified approach.

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 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).

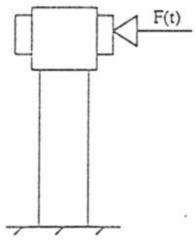
There is no reason to design on the peak instantaneous load, if the basic frequency of the structure on which the load is applied, is as low as a few hertz (like 420 kV insulators, isolators, measuring transformers, surge arresters, bushing, etc...)

The aim of this paper is to point out a simple way to take into account both the dynamic aspects of the load and its interaction with the dynamics of the structure. As a first trial we will apply the theory on a triangular impulse. Future work will be discussed inside actual CIGRE task force on the effect of short-circuit, attached to working group 23-11.

2. 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 (Fig. 1) 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 fig 1; Clearly point out the big difference in the time domain between top load and bottom bending moment : that is because of inertial forces which are distributed along the apparatus. If the frequency of the load had been very small the top and the bottom curves would be the same (with a scale factor) but it is not at all the case for high frequency loads, like impulse and pinch effect.



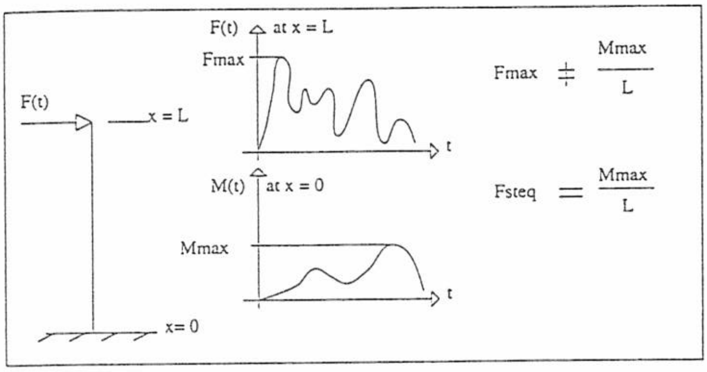


Fig. 1 typical substation apparatus submitted to dynamic loading F(t) (at the top of the device) and corresponding design value M(t) located at the bottom of the device.

There are two ways for the design : either apply advanced computation method, which is sometimes very cumbersome and need many data's and appropriate software, either to find out a simple method which include the dynamic aspects of the load, in relation with he structure. The designer have already similar method for earthquake analysis, f.e.

3. The method

To be of some interest for the designer, we need a certain level of generality.

We decided to split the problem in two parts :

1) analysis of the load itself, hoping to be generalised to envelop curves for typical loads (one for all kind of impulse, another one for all kind of pinch, for example).

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

2) analysis of the structure itself, hoping to be generalised in such a way to be available for any kind of 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", as shown on fig. 2.

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

The next step is to define converters A and B (fig. 4)

4. The converters for load and structure

As we would like to develop simple method, we will suppose the behaviour of the structure to be linear So that the basic development is coming for the theory of modal analysis and superposition.

The reader will find many books of such mathematical development [3 f.e.]. Lets remember that it is possible to study the time behaviour of structure by two ways, either by time integration or by modal superposition.

The second starts by the separation of the response in two parts : the geometrical response which is not time dependent and a time response which is not geometrically dependent. The superposition of appropriate contributions (so-called mode) will give access to the global time response. Each mode has its own frequency and geometrical shape. It is remarkable to point out that each mode is independent of each other and can be studied separately from the other ones. It means that the mathematical system of initially coupled equations between the displacement of each point of the structure has been transformed to another one (unknown are no more nodes but well so called "mode shape"), so that each mode "i" has its own scalar equation, with its own mass ("generalised mass of mode i"), its own damping ("generalised damping of mode i"), its own stiffness ("generalised stiffness of mode "i") and its own load ("generalised load for mode i").

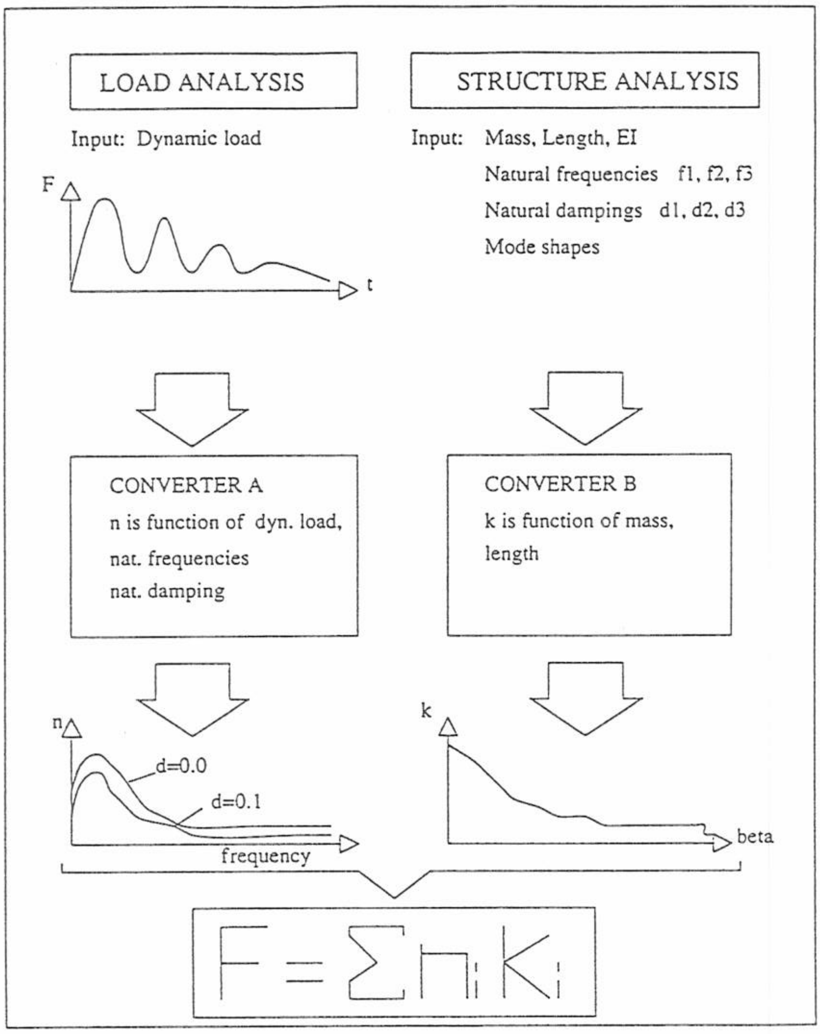


Fig. 4 The steps to find out the static equivalent load.

For example, the classical second order equation which describe the behaviour of a beam is governed by the partial differential equation :

$$\frac{\partial^2}{\partial x^2}\left[EI\,\frac{\partial^2 y}{\partial x^2}\right] + m\frac{\partial^2 y}{\partial t^2} = p(x,t) \qquad (1)$$

After discretisation (using f.e. finite element) we can get the discretised equation :

$$K\,y + M\ddot{y} = p(x,t) \qquad (2)$$

where **K,M** are consistent matrix and y the vector of generalised displacements

The unknowns are the nodal displacements and rotations (nodes are coming from discretisation). All the matrix are consistent (means not diagonal). This system can be solved by time integration. This system has a finite number of degrees of freedom (DOF), say N.

If we use the modal decomposition, we get a set of N scalar equations, one for each frequency ω_i obtained after treatment of the left hand side (and including damping) of equation (2).

let :

$$y(x,t) = \sum_{i=1}^{N} y_i(x)\,.g_i(t) \qquad (3)$$

$$\ddot{g}_i(t) + 2\,\xi_i\omega_i\,\dot{g}_i(t) + \omega_i^2(t)\,g_i(t) = \frac{1}{\mu_i}\,\phi_i(t) \qquad (4)$$

and for a simple clamped-free beam with a mass M at the top and a distributed mass m along the insulator, we can get :

modal frequencies (rad/s) :

$$\omega_i = \lambda_i^2 \cdot \sqrt{\frac{EI}{mL^4}} \quad (5)$$

modal shape ($\eta = x/L$) :

$$y_i(x) = sh(\lambda_i\eta) - \sin(\lambda_i\eta) - C_i\left(ch(\lambda_i\eta) - \cos(\lambda_i\eta)\right) \quad (6)$$

where :

$$C_i = \frac{\sin(\lambda_i) + sh(\lambda_i)}{\cos(\lambda_i) + ch(\lambda_i)} \quad (7)$$

and λ_i are given by the solutions of :

$$1 + \cos(\lambda).ch(\lambda) - \beta\lambda.\left[\sin(\lambda).ch(\lambda) - sh(\lambda).\cos(\lambda)\right] = 0 \quad (8)$$

where $\beta = M/mL$

the modal generalised mass is given by :

$$\mu_i = M \cdot y_i^2(L) + m.\int_0^L y_i^2(x)\,dx \quad (9)$$

the modal generalised load is given by (load only applied at the top in our case)

$$\Phi_i(t) = f(t) \cdot p(L) \cdot y_i(L) \quad (10)$$

finally ξ_i is the modal percentage of critical damping, following Clough [3]

the next figures detail the mode shape for the three first modes, with $\beta = 0$ (means $\lambda_1 = 1.875$, $\lambda_2 = 4.694$ and $\lambda_3 = 7.855$) and $\beta = 1.29$ (means $\lambda 1 = 1.184$, $\lambda 2 = 4.01$ and $\lambda 3 = 7.12$)

As the mass at the top increase, top point has more limited movement for higher modes.

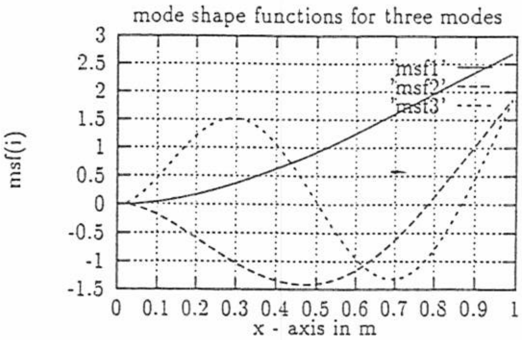


fig. 3 modal shape of clamped free beam with no local mass at the top (like insulator support) (f2 = 6.3 f1 and f3 = 17.6 f1)

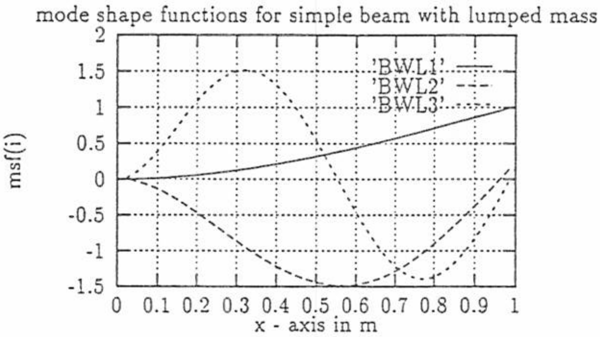


fig. 4 modal shape of clamped-free beam with a big mass at the top. (like measuring transformers) (f2 = 11.5 f1 and f3 = 36.2 f1)

The solution of each scalar equation is easily find out by the so-called Duhamel Integral ,following f.e. Bathe [3].

We will give only the expression when no initial conditions exists and when damping is small (which is the case for substation apparatuses) So that the displacement of the structure can be given by :

$$y(x,t) = \sum_{i=1}^{3} y_i(x) \cdot g_i(t) \quad (11)$$

where $y_i(x)$ is given by (6) and $g_i(t)$ by : (using (5) to (10))

$$g_i(t) = \frac{p(L) \cdot y_i(L)}{\omega_i \cdot \mu_i} \int_0^t f(\tau) \cdot e^{-\xi_i \omega_i (t-\tau)} \cdot \sin(\omega_i (t-\tau)) \cdot d\tau \quad (12)$$

The bending moment is obviously deduced from the second derivative to x.

The maximum of which will give access to the maximum strain in the structure, together with its location.

If we suppose that the maximum is located at the base of the structure, the maximum bending moment is given by the same expression when $\eta = 0$ ($\eta = x/L$)

which would corresponds to a bending moment caused by a STATIC force applied at the top of the beam, with the following value :

$$F_{i,\ stat.eq.} = \frac{EI}{L} y_i''(0) \cdot [g_i(t)]_{max} \quad (13)$$

This is the equivalent static load , contribution for the ith mode.

From this expression it is clearly point out that we can split the expression in two parts (using (6) to (9)) :

the structural participation factor k_i (Converter B) :

$$k_i = (-2).\frac{\lambda_i^2 \cdot y_i(L)}{\int_0^1 \left(\frac{d^2 y_i}{d^2\eta}\right)^2 d\eta} = f(\beta, \text{mode shape}) \quad (14)$$

the load participation factor n_i (Converter A) :

$$n_i = p(L).\ \omega_i \left[\int_0^t f(\tau) \cdot e^{-\xi_i \omega (t-\tau)} \cdot \sin(\omega_i(t-\tau)) \cdot d\tau\right]_{max} \quad (15)$$

k_i is only a function of β parameter, the ratio between the mass at the top a the beam and the mass of the insulator, and of the modal shape

n_i is only a function of the applied dynamic load(peak value p(L), shape f(t) , duration of its application), ω_i and ξ_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 , as for earthquake analysis this curves will be given for different damping values, which are always in the range 1 to 10% of critical damping.

Due to our kind of problems and excitations, we can limit the approach to the three first modes of the structure.

5. Application

We will apply the theory to a typical dropper stretch. This kind of load looks like a triangular impulse. Based on some tests performed in Laborelec in Belgium , we define the excitation as follows :

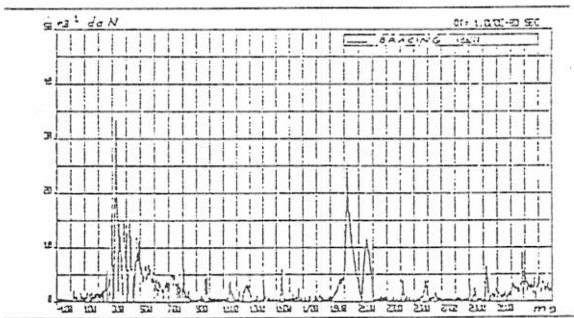


Fig.5 Time history for dropper stretch [4]

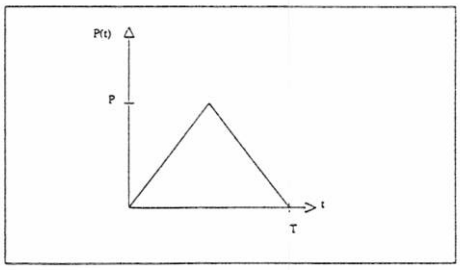


Fig. 6 Synthetic load for dropper stretch (Laborelec tests)

The maximum peak load is taken as 1000 N , just for example (because n_i is proportional to the peak value), the duration of the impulse (0.07s) is in connection with observed results

during full scale tests during a 30 kA test on a 40 m span length with two droppers.
The structure at the bottom of the dropper is defined by the following data's : clamped-free beam with 1000 kg at the top and 1000 kg distributed along the 3 m insulator. (this is typical f.e. for a 420 kV current transformer) : static stiffness 2.5 10^5 N/m, first frequency : 6 Hz , damping 4%; second frequency : 50 Hz, damping 1% ;third frequency : 100 Hz, damping 0.5%.

The true response can be obtained, for purpose of comparisons, by any time integration method and is given below :

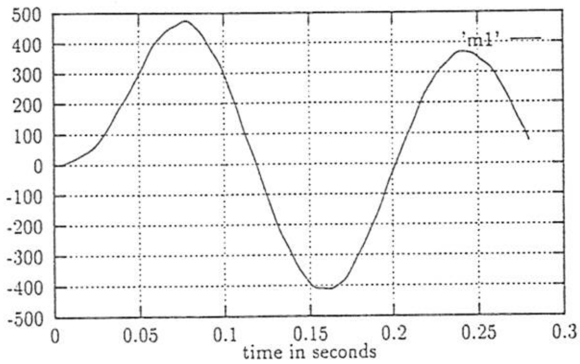


fig. 7 full time response of clamped-free beam during and after a triangular impulse. bending moment at the bottom.

The design maximum bending moment is 470 Nm, which corresponds to equivalent static load of 470/3 = 157 N.

This is an exact method.Now what about our proposal to evaluate the static equivalent load ?

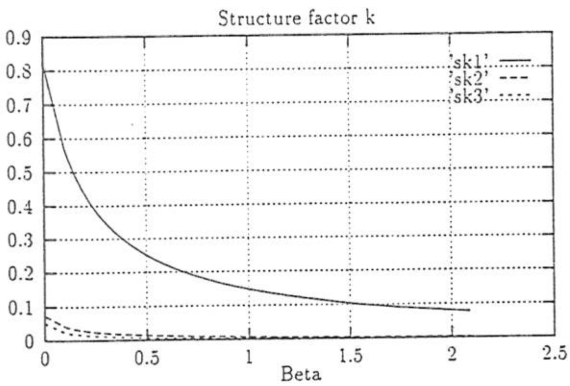


Fig.8 structural k factor for typical substation apparatuses. Abscissa is the ratio between the mass at the top and the distributed mass along the insulator. For example : β is 0 for supporting insulator and around 1 for measuring transformers.

k factor is given here above ,we can deduce :

k1=0.147; k2=0.008 and k3 =0.004

n factor is given here under (the damping influence is very low). In order to generalise the n factor, we have changed a little bit the ordinates (which is now n/p(L)) and the abscissa (which is now the product of a frequency by the duration of the impulse). In such a way that this figure is now valid for any triangular impulse of any peak value and any duration :

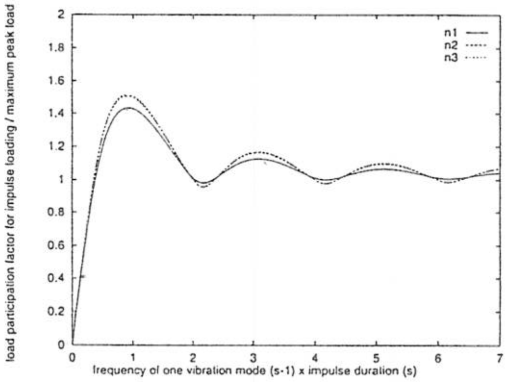


Fig. 9 : load participation factor for any kind of triangular impulse. Ordinates is n_i/peak load and abscissa is the product of impulse duration and a frequency (Hz) of the structure. For example our impulse is 0.07 s duration, which give abscissa of 6x0.07=0.42 for the first mode, 50x0.07=3.5 for the second one, etc...

ordinates : n1 = 1.076 ; n2 = 1.117 and n3 = 1.072 which have to be multiplied by the peak load (1000N) to obtain the load participation factor.

Finally we deduce very easily

the equivalent static force :

$$F_{stat.\ eq.} = n_1 . k_1 + n_2 . k_2 + n_3 . k_3$$

which is equal to 170 N (with a dominant contribution of mode 1)

<u>As a summary :</u>

maximum peak instantaneous load :
1000 N
exact equivalent static load :
157 N
approximate equivalent static load :
170 N

The new method design value save more than 80% in the design value and is in the security border, compare to the exact result.

It is remarkable to point out that the mass located at the top of the structure has a very sensible effect on the load : the same structure without mass at the top would have had more than four times higher equivalent static load. This is obviously a dynamic effect.

6. Conclusion

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.

We suggest a simple method to evaluate the equivalent static load. The theory is developed in the paper but the user only need the resultant curves.

Example is detailed on impulse loading, typical for dropper stretch. But the same method is applicable to any kind of loading (we are working on pinch effect).

A test campaign will then be necessary to get confidence in such a method, to be sure that the dynamics and the simplification to simple beam model has not too much affected the results. For example a clarification of dynamic concentration factor [5] has to be tested and could easily be added to this simple theory.

This is a new trends for design in substation to save time and money for the designers. The simple method can easily be applied in a very short time (some minutes) including the possibility of the effects of some uncertainties in the available data's (frequencies, damping, modal shape).

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 on main busbars (including droppers). 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.

Last, the knowledge of dynamic behaviour of substations apparatuses is a must for the future design of substations. Manufacturers must be sensible to this fact. Structural factor could be directly given by manufacturers after vibration test. A comparison with suggested very simple structural factor could validate or infirm the hypothesis for getting mode shapes, but the method remains valid even if it is not the case, only structural factor would have to be adapted to real world.

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