DYNAMIC LOADS CAUSED BY LIGHTNING STROKE IN A CONDUCTOR ANGLE ARRANGEMENT

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Abstract. In an outside lightning protection scheme it is common to have lightning conductors joined in an angle arrangement. The joining hardware consists normally of a bolted type clamp. Practical experience has shown that it is difficult to perform related realistic tests in the laboratory and for this reason it would be advisable to develop suitable calculation methods to study this phenomenon. Such a method is developed and presented in this paper.

The conductor angle arrangement is modeled using large displacement, small deformation, non linear beam elements. The electromagnetic forces caused by the lightning current are evaluated using a numerical integration of the Laplace formula and not the formula of Ballus [1], commonly used.

Considering the above, a time analysis of the system is performed and the maximum instantaneous stress in the conductor is evaluated. The results of the calculation are used to facilitate the design of suitable clamping hardware in the corner and to recommend equivalent mechanical tests for this hardware.

1. Introduction

The components comprising the external and the internal system of a Lightning Protection Installation (LPI) should be able to sustain the lightning stress as well as the environmental erosions. These components earn these properties from the material they are made of, such as steel, copper, aluminum and their alloys, and from their dimensions, which are determined either by standards or by long experience.

This practice is considered to be satisfactory, the design of these components being done mainly from the safety point of view and thus leading to their satisfactory operational behavior. It can even be stated, that they are sometimes overdimensioned; in spite of this, they are offered at a comparably low cost.

Marketing reasons call for standards for testing these components, in order to give to the manufacturers the freedom to design other types of similar components satisfying the minimum acceptable safety requirements, and so to offer to the users a safe product at a low cost.

Due to the above facts, the tests should also be of a low cost with no need of sophisticated and expensive devices and rare test facilities.

The expected lightning current, causing the stress on the heavy duty components in the external system of the LPI, according the CENELEC draft standard prENV50164-1, does not exceed a surge current with parameters of I_{peak}=100 kA, W/R=2,5 MJ/Ω, and Q=50 As.

In this paper we shall analyze and compute the effects of such a lightning current passing through an arrangement consisting of two conductors connected in 90° angle with a clamp, fig. 1. This type of connection is often met in the LPI as indicated by the arrows in fig. 2.

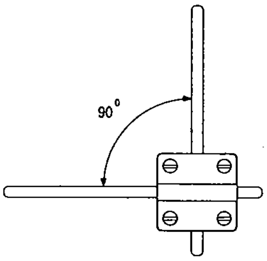

Fig. 1: Connection of LPI conductors at 90°

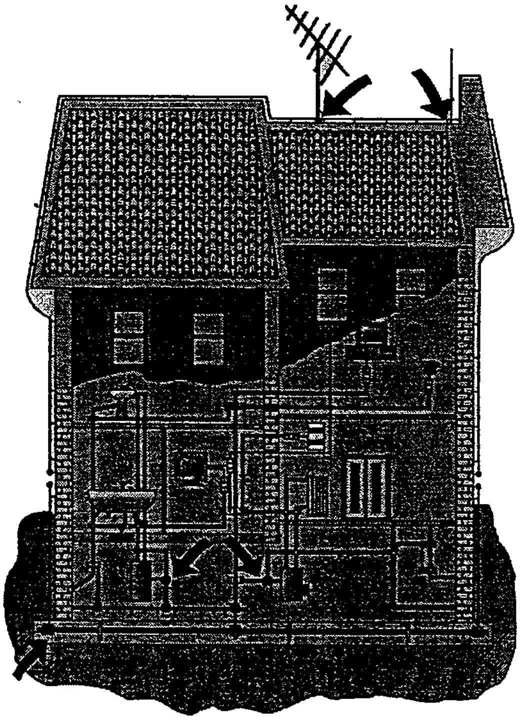

Fig. 2: A complete Lightning Protection Installation (LPI)

The behavior of this angle arrangement during a lightning stroke needs to be solved using structural dynamics. Structural eigenfrequencies of such an arrangement, depend on length, mass, moment of inertia and elasticity modulus and are typically in the range 20 - 200 Hz.

Compared to that frequency, the normalized lightning stroke mentioned above, is just like an impulse load with a peak value after approximately only 20 microseconds.

Due to the angle configuration, the load is mainly acting close to the corner and a typical lightning stroke of 100 kA peak gives a maximum peak force close to 800 N/cm (Newtons per centimeters) on the two first centimeters near the angle, going down to less than 200 N/cm at 4 cm far from the corner. For this reason a transient response of the whole structure will be first a transverse wave propagation from the angle to the end parts, causing large bending near the angle very shortly after the lightning inception. For the same reason very large axial forces will try to extract the rods from the angle clamps, causing slipping in case of inadequate tightening.

The bending moment at the other side of the rods is naturally of major importance and will also be studied.

Heating of the rods can also be taken into account, but is generally causing limited effects (in our case heating of the steel rod is about 40° C). Nevertheless the thermal effects of the lightning on these components can be significant when the ohmic resistance of the connection point is relative high such as for conductors made of steel and stainless steel. In contrary the thermal effects are not so important for connections made of copper or aluminum.

In this paper, we have adopted a full non-linear model (large displacement beam model) to perform the evaluation of an angle arrangement under lightning stroke for the configuration given in fig. 3 and for three different kinds of material (steel, copper and aluminum). A partial comparison with tests will also be carried out. Finally recommendations for the clamp design are deduced, and the computation method used can be adopted as a general tool for evaluation of forces, displacements and constrains in any configuration using cable and beam element during any event of electrodynamic loading. The same software is nowadays used for substation busbars design during short-circuit events.

2. Modelling

The University of Liège has developed for the last 30 years a worldwide known software « SAMCEF » nowadays used by more than 200 licensees in France, Germany, Belgium, Italy, Netherlands, Switzerland and some in USA ,Canada and Argentina.

The sub-module MECANO [2] is able to perform dynamic and transient analysis of nonlinear structures. It has been completed by the authors of the same University to take into account for electrodynamic effects on beam and cable elements as explained in [3]. Noticeably electrodynamic forces are obtained by integration (fully consistent with the developed finite element approach) of the Biot-Savart law and heating effects are also included. The modelling used in this paper is made of non-linear beam elements [4]. There are 20 elements on each part of the angle arrangement. The lightning stroke has been added in the data base of current wave shapes. Damping was chosen equal to 2 per cent (of critical value) at the frequency of 146 Hz. The computations have been performed on a SUN SPARC20 workstation in about 13 minutes CPU time per case (time integration during 5 milliseconds using time steps of 1 microsecond for the 2 first milliseconds and time steps of 6 microseconds afterwards).

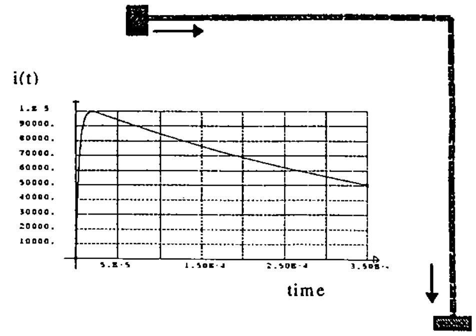

Fig. 3: Geometrical configuration used for lightning stroke tests. Each part of the angle has a rod length of 0.5 m and an outside diameter of 8 mm. Lightning impulse i(t) is100 kA (10/350) as normalized in IEC

3. Case study

As typical output from the time response analysis, fig. 4 and fig. 5 show a general view of the rod at a short beginning after the stroke start (fig. 4) and when maximum displacement occurs at mid-span (fig. 5).

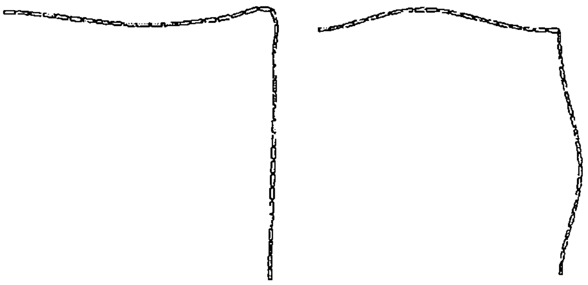

Fig. 4. Fig. 5

Fig. 4 and 5: Deformation of the angle arrangement during lightning stroke. Fig 4 after 20 microseconds, with scaling factor of 1000 (effect of gravity is emphasized on the horizontal rod due to scaling factor) large deformation near the angle is clearly visible. Fig 5 after 2.2 milliseconds (when maximum displacement occurs) with scaling factor of 10

Parameter	Steel	time(ms)	Location	Test
Excited Mode	146 Hz			
Temperature	42 C	2		
Young Modulus	21 10^{10} N/m^2			
Specific mass	7800 kg/m^3			
Tensile load in the rod	1900 N	0.2	corner	
Bending Moment	27 Nm 24 Nm	1.75 0.3	support corner	20 Nm
Shear Stress	1300 N	0.2	corner	
Vertical Displacement	4.2 mm	2	mid-span	0 mm
Horizontal Displacement	4.2 mm	2	mid-span	
Vertical Displacement	0.1 mm		corner	
Horizontal Displacement	0.1 mm		corner	
	Copper			
Excited Mode	96 Hz			
Temperature	4.5 C	2		
Young Modulus	10^{11} N/m^2			
Specific mass	8900 kg/m^3			
Tensile load in the rod	1750 N	0.2	support	
Bending Moment	19 Nm 17.5 Nm	2.6 0.5	support corner	
Shear Stress	1050 N	0.2	corner	
Vertical Displacement	5.7 mm	3	mid-span	10 mm
Horizontal Displacement	5.7 mm	3	mid-span	
Vertical Displacement	0.2 mm		corner	
Horizontal Displacement	0.2 mm		corner	
	Aluminum			
Excited Mode	136 Hz			
Temperature	12.5 C	2		
Young Modulus	6 10^{10} N/m^2			
Specific mass	2700 kg/m^3			
Tensile load in the rod	1900 N	0.2	corner	
Bending Moment	26 Nm 22 Nm	2 0.2	support corner	20 Nm
Shear Stress	1220 N	0.2	corner	
Vertical Displacement	13 mm	2.2	mid-span	15 mm
Horizontal Displacement	13 mm	2.2	mid-span	25 mm
Vertical Displacement	0.4 mm		corner	
Horizontal Displacement	0.4 mm		corner	

Table 1: Results of simulation (maxima), time of occurrence, location of corresponding values and available tests values (displacement after plastic deformation)

The next figures reproduce the time response of displacement, tensile load and bending moment in the steel rod.

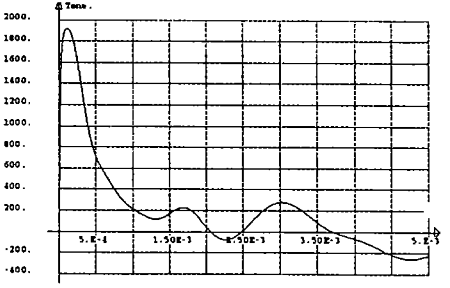

Fig. 6: Tensile load (Newtons) in the rod during 5 milliseconds (maximum 1900 N after 200 microseconds)

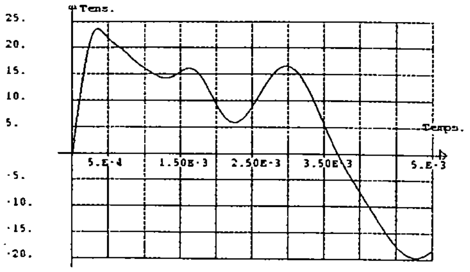

Fig. 7: Bending moment (Nm) near the corner during 5 milliseconds (maximum about 24 Nm after 0.3 milliseconds)

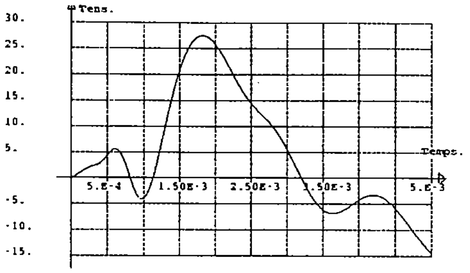

Fig. 8: Bending moment (Nm) near the anchoring of the rod. (maximum about 27 Nm after 1.75 milliseconds)

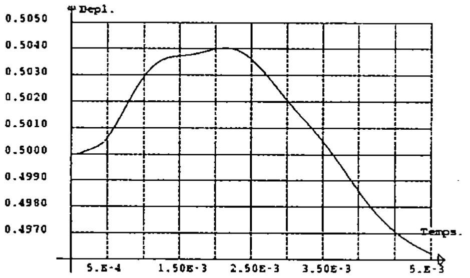

Fig. 9: Transverse displacement (m) on the mid-span of the rod during 5 milliseconds (0.5 m is the initial position of the node in the model, so that only the relative value which is about 4 mm after 2 milliseconds has to be considered)

4. Comments

4.1 Stresses

We have considered a general yield point (250 N/mm^2 for steel, 100 for aluminum and 200 for copper).

In all cases the computed stresses (537 N/mm^2 for steel, 378 for aluminum, 517 for copper) are larger than the yield point. For this reason the comparison with experimental data is very difficult. In fact our model has been limited to elastic behavior, while the displacements have been made measured after the test, that means after plastic deformations. Moreover, it seems that some slipping occurred during the tests (as explained in the introduction) so that a certain disymmetry is found in the tests between the displacement of the two rods.

Even with such limitations, the comparison between computed and measured values is quite good, see table 1.

4.2 Slipping

We have also evaluated the maximum slipping by giving free longitudinal movement to one rod while keeping fixed rotation for the clamps. We obtained 14 mm for the steel configuration compared to 7 mm measured, with of course restricted movement due to tightening of the clamp.

4.3 Proposal for other shapes

Considering the results, it is evident that the 90° corner shape is a very bad shape, which imposes drastic stresses on the clamp. For this reason we tested some other shapes for the clamp in the configuration with the two steel rods and for the given lightning stroke of 100 kA, which is the basic case and has resulted to the following design values, as shown in table 1:
Tensile load (in the direction of the rod):
N = 1900 N
Bending moment at the location of the clamp:
M = 24 Nm
Shear force at the clamp location:
T = 1300 N

4.3.1. Corner clamp is replaced by a small length of cable with two clamps to fix it on the rods. Calculation results:
N = 1200 N
M= 0 Nm
T = 450 N

4.3.2. Corner clamp is replaced by a curved rod (tangent to the two initial rods, with a radius of 10 cm) and two end clamps. Calculation results:
N = 2700 N
M= 7 Nm
T = 235 N

5. Tests or computations

The interest to use computation instead of tests is there because of the following:

- very reduced cost and no need of large installation
- all details available (displacement, bending moment, tensile load) everywhere in the structure.
- any current wave shape can be tested with no limitation of peak current.
- if some design mistake exists, there is no breaking of components, simply restart the computation with new data.
- any risk of slipping can be evaluated and give access to appropriate tightening of the clamps.
- any geometrical changes can be quickly evaluated.
- it gives access to time response of some important data that are of use for clamp design, so that pure mechanical tests can be easily defined to impose similar constrains.
- validation of the method is excellent with the non-linear beam model.

6. Equivalent mechanical test for clamp design

The suggestion is made here to perform pure mechanical tests for clamp design.
The first step is a computational evaluation of M, N, T, that is the moment and forces obtained with the actual data of the lightning stroke and the structural data. The second step is to apply the computed values to the clamp using pure mechanical tests as following :
- the tensile force on the clamp can be applied with its computed maximum.
- the bending moment and the shear force can be applied to the clamp as steady loads with their computed maximum values.

A preliminary series of tests could validate this approach and fix a transformation factor between tests and computations, that will be probably very close to one.

7. Conclusions

A new approach for clamp design against lightning stroke has been presented. It does not anymore require regular high current laboratory tests. Only equivalent mechanical tests of low cost are proposed for the clamp design. This method is based on sophisticated mathematical developments (including non-linear beam models) actually commercialized in worldwide known software packages like SAMCEF (MECANO-CABLE module),[2].

8. References

[1] H. Ballus « Ein Beitrag zur Berechnung elektromagnetischer Kräfte zwischen stromführenden Leitern » ETZ-A, 90, Jg, 1969, pp 539-544.
[2] SAMCEF - MECANO. Software distributed by SAMTECH S.A., Bd. Frère Orban 25, B4000 Liège, Belgium (contact M. Defourny).
[3] J.L. Lilien « Contraintes et conséquences électromécaniques liées au passage d'une intensité de coumat dans les structures en câbles » Ph.D. thesis, University of Liège, Montefiore Electrical Institute, Collection des publications de la Faculté des Sciences Appliquées, N°87, 1983.
[4] A. Cardona « An integrated approach to mechanism analysis » Ph.D. thesis, University of Liège, Collection des publications de la Faculté des Sciences Appliquées, N°127, 1989.

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