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 the proposed 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.

Based on 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 behavior of angle arrangement during lightning stroke needs to be solved using structural dynamics. Structural eigenfrequencies of such arrangement, depending of length, mass, moment of inertia and elasticity modulus is typically in the range 20 - 200 Hz.
Compared to that frequency, the lightning stroke is just like an impulse load with a peak value after only 20 microseconds.
Due to angle configuration, the load is mainly acting close to the angle 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. So that 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 lightning inception. For the same reason very large forces will try to extract the rods from the angle clamps, causing slipping in case of inadequate tightening.
Bending moment at the other side of the rods is also of importance and will be studied.
Heating of the rods can also be taken into account, but generally causing limited effects (in our case heating of the steel rod is about 40 C).
In this paper, we have adopted a full non-linear model (large displacement beam model) to perform evaluation of angle arrangement under lightning stroke for the configuration given in fig. 1 and for three different kind of material (steel, copper and aluminum). Partial tests confrontation will be carried out. Finally recommendation for 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.

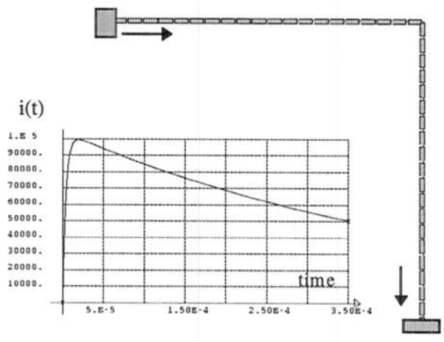

Fig. 1 geometrical configuration used for lightning stroke tests. Each part of the angle has a rod length = 0.5 m. Outside diameter of 8 mm. Lightning impulse 100 kA(20/350)

2. Modelization

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, Nederland, Switzerland and some in USA ,Canada and Argentina.
The sub-module MECANO [4] 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 electrodynamic effects on beam and cable elements as explained in [3], noticeably

electrodynamic forces are obtained owing to the integration (fully consistent with the developed finite element approach) of Biot-Savart law, heating effects are included . The modelization used in this paper is made of non-linear beam element [2]. There were 20 elements on each part of the angle arrangement. The lightning stroke has been added in the data base of current wave shape. Damping was chosen equal to 2 percents (of critical value) on frequency of 146 Hz. Computation have been performed on 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).

3. Case study

As typical output from the time response analysis, fig. 2 and 3 show a general view of the rod at the short beginning after the stroke start (fig. 2) and when maximum displacement occur at mid-span (fig. 3).

Fig. 2.

Fig. 3

Fig. 2 and 3 : Configuration of the angle arrangement during lightning stroke. Fig 2 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 3 after 2.2 milliseconds with scaling factor 10.

Structure	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 N.m 24 N.m	1.75 0.3	support corner	20 N.m
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	time (ms)		
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 N.m 17.5 N.m	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	time (ms)		
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 N.m 22 N.m	2 0.2	support corner	20 N.m
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.

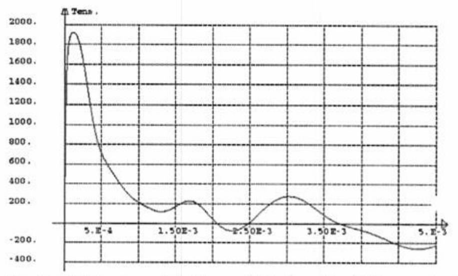

Fig. 4 tensile load (Newtons) in the rod during 5 milliseconds.(maximum 1900 N after 200 microseconds)

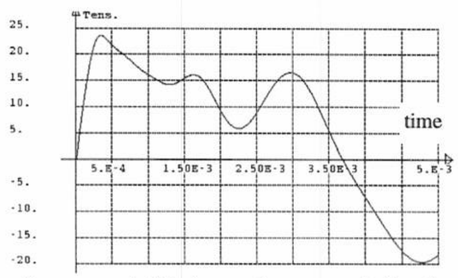

Fig. 5 Bending moment (N.m) near the corner during 5 milliseconds (maximum about 24 N.m after 0.3 milliseconds)

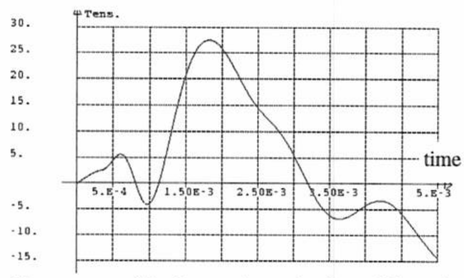

Fig. 6 Bending moment (N.m) near the anchoring of the rod. (maximum about 27 N.m after 1.75 milliseconds)

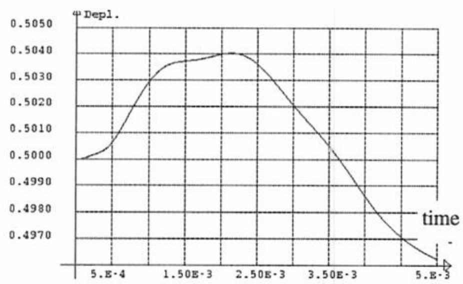

Fig. 7 Transverse displacement (m) on the mid-span of the rod during 5 milliseconds (0.5 m is the initial position of the node in our model, so that the reader have only to consider the relative value which is about 4 mm after 2 milliseconds)

4. Comments.

4.1 stresses.

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

In all cases the stresses are larger than the yield point (537 N/mm^2 for steel, 378 for aluminum, 517 for copper). So that the confrontation with experiment is very difficult. In fact our model has been limited to elastic behavior (if the stress is too large, it means that the design has to be reviewed). And the displacement measured during tests have been made after the test, means after plastic deformations. Moreover, it seems that some slipping occur during tests (as explained in the introduction) so that some disymmetry happens in the tests between the displacement of the two rods.

And even with such limitations, the confrontation is quite good !!

4.2 slipping

We have also evaluated the maximum slipping by giving free longitudinal movement for one rod, 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.

Based on the results, it is clearly emphasized that corner shape is a very bad shape which imposed drastic stresses on the clamp. So that we tested some other shapes.

Design values (for the given lightning stroke of 100 kA) for the clamp in the configuration with the two steel rods (Basic case , as referred in table 1) :

tensile load (in the direction of the rod) :

N = 1900 N

bending moment at the location of the clamp :

M = 24 N.m

Shear force at the clamp location :

T = 1300 N

4.3.1. the corner clamp is replaced by a small length of cable with two clamps to fix it on the rods.

N = 1200 N

M = 0 N.m

T = 450 N

4.3.2. the corner clamp is replaced by a curve rod (tangent to the two initial rods, with a radius of 10 cm) and two end clamps.

N = 2700 N

M = 7 N.m

T = 235 N

Of course design values for the rods are also available !

5. Tests or computations

The interest to use computation instead of tests are the following :

- very reduced cost and no need of large installation
- all details available (displacement, bending moment, tensile load) everywhere in the structure
- any short-circuit wave shape can be tested with no limitation of peak current.
- if some design mistake exists, there are no breaking of component, simply restart the computation with new datas.
- 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 which 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 non-linear beam model.

6. Equivalent mechanical test for clamp design.

The suggestion is made to perform pure mechanical tests for clamp design.

The first step is a computational evaluation of the M,N,T moment and forces obtained on the actual datas of the lightning stroke and structural datas. 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 the computed maximum N.

The bending moment and the shear force can be applied to the clamp as steady loads with computed maximum values. Some series of tests could validate this approach and fix a safety factor which will be probably very close to 1.

7. Conclusions

A new approach for clamp design against lightning stroke has been presented. It no more needs any high current laboratory tests. Only equivalent mechanical tests are proposed for clamp design. This method is based on sophisticated mathematical development (including non-linear beam) actually commercialized in worldwide known software, like SAMCEF (MECANO-CABLE module)[4].

8. References

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[4] SAMCEF - MECANO. Software distributed by SAMTECH S.A., Bd Frère Orban, 25, B4000 Liège.Belgium. (contact M. Defourny)

Jean-Louis Lilien was born in Liège (Belgium) on may 24th, 1953. He received his degree in Electrical and Mechanical Engineering from Liège University in 1976. He received his PhD. degree from the same university in 1984. He is presently professor at the same University, department of « Transmission and Distribution of Electrical Energy » His main activity is based on short-circuit mechanical effects and overhead lines vibrations (galloping). He is the chairman of CIGRE task force on the effects of short-circuit in substation (belonging to working group 23-11). He is expert of CIGRE task force on galloping (belonging to working group 22-11). He has published over 60 technical papers and participated to many symposia and international conferences. He received the International price « George Montefiore » in 1986.

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