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EVALUATION OF THE DAMAGES CAUSED BY LIGHTNING  
CURRENT FLOWING THROUGH BEARINGS

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ABSTRACT

A laboratory for lightning current tests has been set up at CESI allowing the generation of the lightning currents foreseen by the Standards. Lightning tests are carried out on different objects, aircraft materials and components, evaluating the direct and indirect effects of lightning. Recently a research has been carried out to evaluate the effects of the lightning current flow through bearings with special reference to wind power generator applications.

For this purpose, lightning currents of different amplitude have been applied to bearings in different test conditions and the damages caused by the lightning current flow have been analysed.

The influence of the load acting on the bearing, the presence of lubricant and the bearing rotation have been studied.

INTRODUCTION

The peculiar structure of the wind power generators and often the weather conditions typical of the areas where the eolic plants are installed, increase the probability for a generator to be struck by a lightning flash. If a lightning flash happens to hit a wind power generator, the lightning current path to earth can involve the shaft and the bearing (Fig.1). Similar problems may arise, for example, if a lightning flash hits the blades of an helicopter.

The flow of the lightning current can damage bearing rolling elements and raceways, with a possible consequent reduction of the reliability of the structure where the bearing is installed.

The evaluation of the effects produced by the lightning current flow through bearings is important both to evaluate the efficiency of the structure and to identify possible protection systems. For this purpose, lightning currents of different amplitude have been applied to bearings in different test conditions and the damages caused by the lightning current flow have been analysed.

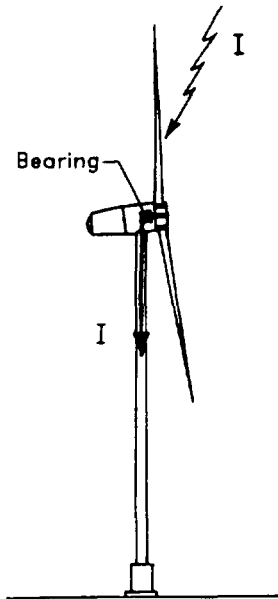


Fig. 1 - Schematic view of the lightning path in a wind power generator, with involvement of the generator bearings.

For the evaluation of the effects produced by the lightning current flow through bearings, the contact conditions among the rolling elements and the raceways are of special interest.

In the loaded zones of the bearings the rolling elements are in contact with the raceways, while in the unloaded zones the rolling elements are not in contact with the raceways and small gaps are formed.

The lightning current interests the contact areas between the rolling elements and the raceways.

The number of rolling elements in contact with the raceways is a function of the mechanical load (the number of rolling elements in contact increases when the mechanical load is increased); in the limit case only one rolling element can be in contact.

The extension of the contact area for each rolling element is also a function of the load.

The lightning current may interest the small gaps between the raceways and the rolling elements in the bearing zones not in contact. The electric strength of the gap depends on the kind and the characteristics of the insulating media.

The performance of the bearing under lightning can be finally influenced by its rotation.

It is evident that the phenomenon is very complex.

In order to try to understand the mechanism of damage, the tests were designed to analyse separately the influence of the parameters mentioned above.

In particular, the effect of the mechanical load and of the lightning current amplitude was analysed on a simplified configuration (single couple

of rollers), while the influence of rotation, lubrication and lightning current flow through the different rolling elements was analysed on complete bearings.

#### TEST OBJECT

The systematic research was performed on self-aligning roller bearings, with double order of rollers, having the following main characteristics: external diameter of 160 mm, internal diameter of 90 mm and dynamic load coefficient of 322 kN. The raceways and rollers of the bearings were made of high-chrome steel.

The following test configurations were examined, as shown in fig. 2:

- a) simplified configuration with single couple of rollers (see fig. 2a) to analyse the effects of the lightning current flow through single rollers.

To this purpose all the rollers, except the two under investigation, were taken out from the bearing and substituted by an insulating ring having the function to maintain the bearing geometry. In this way the lightning current was forced to flow exclusively in the couple of rollers.

The bearing was tested in still condition, without lubricant.

- b) complete bearings (see fig. 2b), to study their lightning performance in different conditions. Namely the bearings were tested without oil both in still and rotating conditions and finally in rotation with oil.

A rotation of 300 rpm was maintained through a motor mounted on the shaft. The lubricant was housed in a box under the bearing and transported through the rolling elements by the rotation itself.

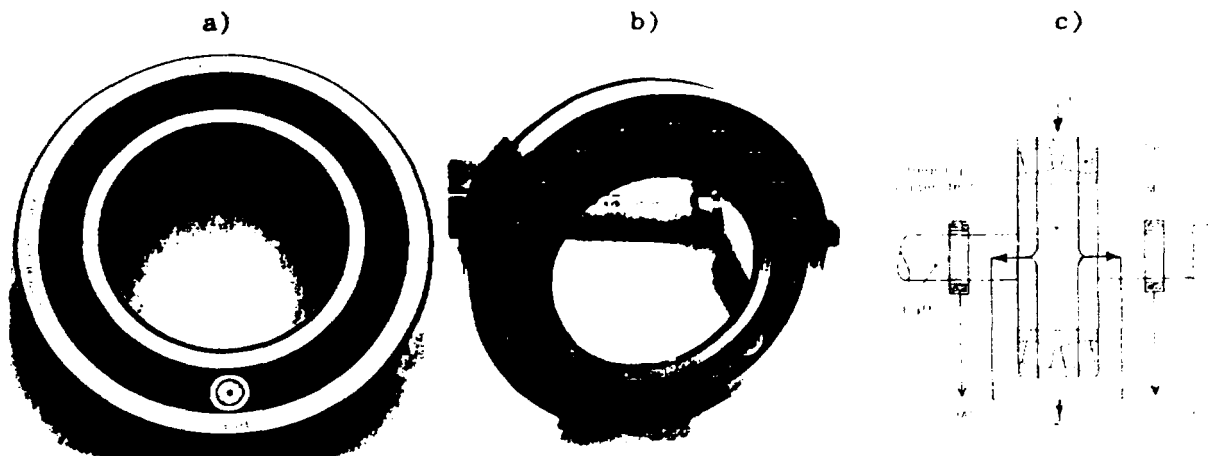


Fig. 2 - Test objects and test set up  
a) picture of the simplified configuration (with single couple of roller)  
b) picture of complete bearing  
c) scheme of the test set up.

## TEST CONDITIONS

### MECHANICAL STRESSES

Radial mechanical loads were applied to the bearings under test; the load was applied symmetrically on the shaft (see fig. 2c).

The load was varied up to 10 kN in the tests on single couple of rollers to vary the contact area.

The relation between the contact areas on a single roller (S) (in the bearing under test, the contact areas are ellipses) and the load acting on the bearing is reported in Fig.3, where the curves relevant to inner and outer raceways are given [1].

A constant load of 5 kN was applied on the complete bearings. Mechanical calculations [1] indicate that in this case only 5 couples of rollers are in contact with the raceways. The calculation also permits to evaluate the load distribution among the different rollers and thus the contact areas. The extension of the single roller contact area results of 1.8 mm<sup>2</sup> for the most loaded rollers decreasing to 1.3 and 0.3 mm<sup>2</sup> for adjacent rollers (see fig. 8b).

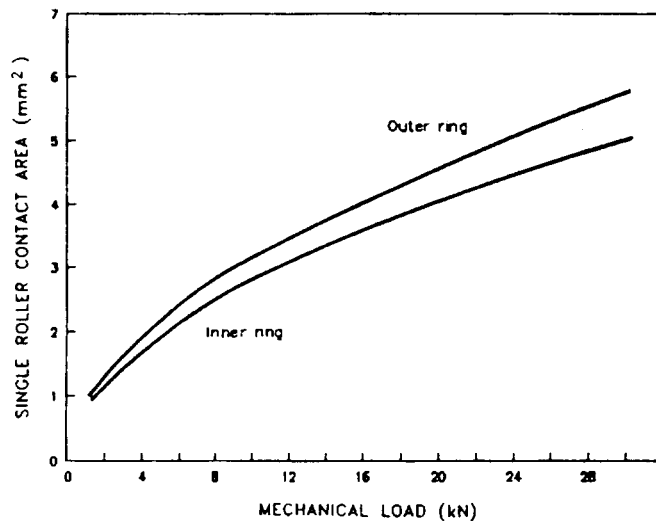


Fig. 3 - Mechanical calculations. Inner and outer ring contact areas of a single roller as a function of the mechanical load applied to the bearing simplified model, with only one couple of rollers.

### CURRENT STRESSES

In all the above mentioned cases, the lightning current was injected in the outer ring of the bearing through an additional metallic ring externally clamped to the bearing itself.

The lightning current was flowing from the outer ring to the inner one through the rolling elements and then to earth through the shaft (see Fig.2 c).

The lightning current was generated by means of the test circuit shown in fig. 4; the circuit allows the generation of the current waveforms A,B,C and D foreseen by the Standards [2] both as single pulses and as a combined waveforms. It is composed by three current generators and a filter with blocking capacitors and inductances; the main characteristics of the current generators are described in the followings.

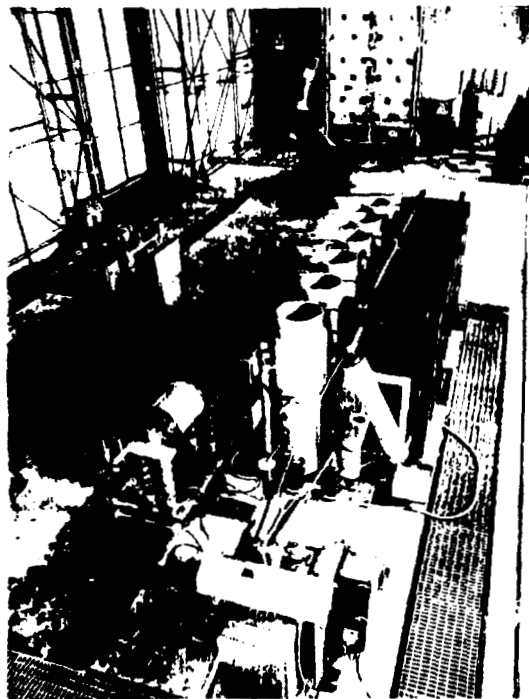


Fig. 4 - Test circuit to generate current components as in [2].

The A/D current generator consists of a 100 kV, 24  $\mu$ F, 120 kJ capacitor bank; the capacitors can be charged in both positive and negative polarity. Damped oscillating waves with peak values up to 200 kA, action integral up to  $2 \cdot 10^6$  A<sup>2</sup>\*s and rise times between 8  $\mu$ s and 20  $\mu$ s can be achieved with load inductances up to some  $\mu$ H.

The B current generator is a 12 LC cell, 20 kV, 90 kJ generator. The cells can be charged both in positive and negative polarity. Currents with peak values up to 2.5 kA and duration of few ms can be generated.

The C current generator consists in a DC generator and a smoothing capacitor bank. Continuous currents up to 250 A with time durations up to 1 s can be generated.

Plasma gaps are used to switch the different lightning current components.

The systematic research was carried out injecting the A current component, while only few checks were made with B and C components.

The lower amplitude and rate of rise of the B & C lightning currents with respect to the A component, the longer time duration and the speed rotation of the bearing seem to be the most important parameters in determining the damage mechanism with this kind of current components. Further tests are foreseen in order to better analyse the influence of the different lightning components on the damage mechanism and extension.

In the following the results obtained with the A current component will be given.

Tests with current peak values in the range from 1 kA up to 100 kA and an action integral<sup>(1)</sup> in the range from 18 A<sup>2</sup>\*s up to 1.2\*10<sup>6</sup> A<sup>2</sup>\*s were applied to the simplified configuration with the single couple of rollers to determine the minimum current leading to damage (damage threshold) and study the relationship between current and damages.

A current impulse with a peak value of 100 kA and an action integral of 1.2\*10<sup>6</sup> A<sup>2</sup>\*s was applied to complete bearings under test.

## TEST RESULTS

### LIGHTNING TESTS ON SIMPLIFIED CONFIGURATIONS

Damages were observed both on the inner and the outer raceways and correspondingly on the rollers of the bearing.

The damage-threshold-peak-value of the injected current (I<sub>pt</sub>) and the corresponding action integral (E<sub>t</sub>) are reported in fig. 5 as a function of the load acting on the couple of rollers: the threshold peak current increases when the load is increased.

By combining the data of fig. 3 and fig. 5, the threshold values of the current density I<sub>pt</sub>/S and of the action integral density E<sub>t</sub>/S were determined. The damage-threshold peak current-density was found approximately constant (about 4 kA/mm<sup>2</sup>) independently of the mechanical

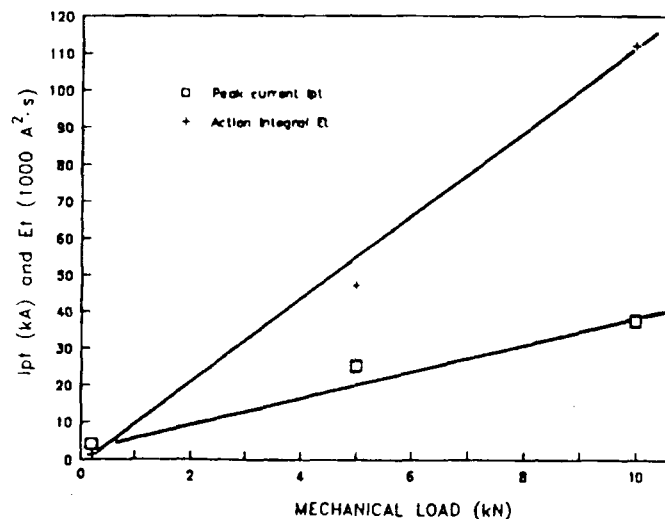


Fig. 5 - Tests on the simplified configuration with one single couple of rollers: damage- threshold current values as a function of the mechanical load applied to the bearing.

I<sub>pt</sub>= peak current value

E<sub>t</sub>= action integral value

(1) The Action Integral E represents the energy per unit resistance transferred by the lightning current and is defined as:  $E = \int_T i^2 dt$ , where T is the duration of the current waveshape.

load. The damage threshold action integral density varied from  $190 \text{ A}^2 \cdot \text{s}/\text{mm}^2$  to  $6.000 \text{ A}^2 \cdot \text{s}/\text{mm}^2$  when varying the mechanical load in the examined range.

The type and size of damage varied with current and mechanical load value. At low current values, craters (see fig. 6a) were observed when very low mechanical loads were applied, while flutes (as shown in Fig. 6b) were observed for higher loads.

For higher current values the type of damage remained similar. However, bigger surfaces of the rollers and raceways were damaged and melted materials appeared at the flute extremities.

The damages caused by the flow of the lightning current to the bearing rollers and raceways were estimated, in a preliminary way, by evaluating the extension of the damaged surface, independently of the damage type. Other more precise evaluation of damages in terms of depth, volume, type and so on are undergoing. Metallographic exams will be also made in order to detect possible changes of the metal characteristics in the damaged areas.



Fig. 6 - Tests on the simplified configuration with one single couple of rollers: damages observed:

- a) craters
- b) flutes

Fig. 7 reports the maximum values of the damaged area (independently of the type of damage), at one of the contact side of each roller, as a function of the peak value of the injected current for the three mechanical load conditions examined; the contact area of a single roller for the three different loads are also reported. The figure shows that the damage extension increases when the load is decreased and, for a given load, increases with the increase of the lightning current amplitude. Comparing the damaged areas with the estimated contact areas, it appears clearly that while for low current values the damaged surface is close to the contact area size, for higher currents it is much larger.

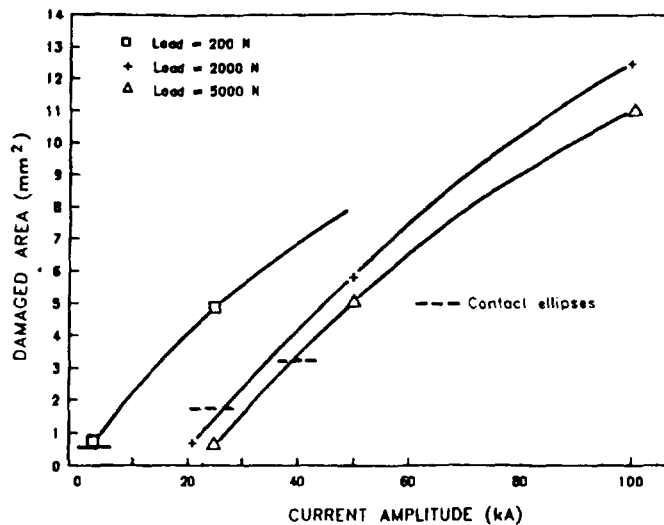


Fig. 7 - Tests on the simplified configuration with one single couple of rollers. Maximum values of the damaged surfaces as a function of the peak value of the lightning current for different load conditions.

#### TESTS ON COMPLETE BEARINGS

Also in the case of complete bearings, a rough estimation of the damages has been made. The damaged surfaces, independently of the damage type, are reported in Fig. 8 where the maximum values of the damaged areas are given in correspondence of each couple of rollers. For sake of simplicity only the cases of still bearing without lubricant and rotating bearing with lubricant are considered in the Figure.

A qualitative analysis of the damages observed on complete bearings was made.

In the case of bearings in still condition without oil, craters and burns were observed on the raceways and correspondingly on the rollers in the whole unloaded zone of the bearing, while very limited damages were observed in the loaded areas (small craters): a part of the lightning current had passed through the unloaded area, where air gaps were present.

For rotating bearings without lubricant, the damages were bigger than in the previous condition. Moreover abrasions were observed on the raceways. This may be explained considering that, owing to the rotations, the melted materials had been squashed around the damaged area and transported around the bearing causing abrasions on the bearing raceways.

In the case of rotating bearing with lubricant, craters were present in the unloaded zone only at the extremities of the loaded area, where the smallest gaps between rollers and raceways were present, while in the loaded zone, the size of the damages was higher than in the previous cases. Abrasions were more limited with respect to the case without lubricant. This can be explained considering that the presence of lubricant, acting as



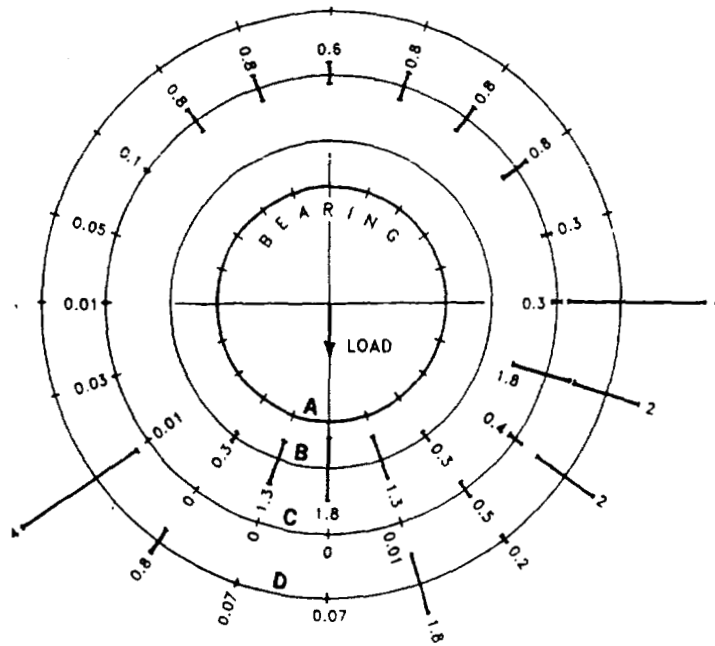


Fig. 8 - Tests on complete bearings. Contact areas and damage extension at each radial location (extension given in  $\text{mm}^2$ ).

- A) Radial position of the rollers
- B) Contact areas
- C) Damages for bearing in still conditions without lubricant
- D) Damages for bearing in rotating condition with lubricant

a dielectric medium (with a higher dielectric strength than air), plays an important role in the prevention of the occurrence of localised discharge in the gaps and also in the reduction of the abrasions.

If the larger part of the lightning current would flow through the rollers in contact and it would distribute among them according to the contact areas, a theoretical peak current density of about  $10 \text{ kA/mm}^2$  could be evaluated in the examined case of an injected peak current value of  $100 \text{ kA}$ . This value is more than twice the threshold value determined in the tests on the simplified configuration with one single couple of rollers and would imply damages of loaded zones. Actually the test results generally indicate a very limited damage in the loaded zone. This can imply that a large part of the current flows in the unloaded zone.

### CONCLUSIONS

Lightning tests have been made on rolling bearings applying the A current component of the Standards and the damages caused by the lightning current flow have been analysed.

The damage mechanism and extension depend on current values and on the mechanical load condition, which determines the area of contact between roller and raceway.

When the lightning current flows through the contact areas, a consequent enhancement of the local temperature occurs. The high temperatures in the contact area can lead to local melting of the material, with a consequent formation of flutes.

The lightning current density (which is a function of the load and the current intensity) and the current energy content play an important role in this kind of damage mechanism.

Test in simplified conditions indicate that for areas in contact a peak current density of 4 kA/mm<sup>2</sup> resulted sufficient to initiate the damage.

The lightning current may also interest the zone where rollers are not in contact with the raceways (unloaded zones). In fact, owing to the high di/dt associated with the A lightning current component, voltages are induced across the small gaps. These voltages can lead to the breakdown of the gaps; once the gap has been broken, the lightning current can flow through it and the resulting arc leads to the formation of craters and burns. The extension of the damages produced by the arc root can be bigger than that corresponding to the current conduction damages.

The research is going on and further tests will be made on bearings of different dimensions, with different lightning current components and in different test conditions, in order to better understand the lightning performance of rolling bearings, obtain statistical data on the different kinds of damage and finally define an electrical-mechanical model able to describe the lightning behaviour of bearings in different operating conditions.

#### ACKNOWLEDGEMENTS

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#### REFERENCES

- [1] Orlandini and Beretta-SKF-Torino-Italy. Private communication.
- [2] SAE AE-4L "Lightning Tests Waveforms and Techniques for Aerospace Vehicles and Hardware" 1978.