Wind Turbine Power Electronics and Electrical Machines: On Lightning Protection Simulation

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***Abstract*-This paper presents an overview of wind energy in Portugal and briefly describes the Portuguese Lightning Location System. Some aspects of lightning activity in Portugal are discussed. The method for risk assessment due to lightning flashes to earth is performed by the computer program LPS 2008 developed in Visual Basic by the authors. LPS 2008 is based on well established standards and on the Rolling Sphere Method. LPS 2008 draws in 3D the most vulnerable points to lightning of a structure. A case study is presented to illustrate the protection measures resulting from this methodology, reducing damages due to lightning effects in power electronics and electrical machines to acceptable levels.**

I. INTRODUCTION

One of the main causes of damage on wind turbines is lightning [1]. Areas of favorable location for wind turbines often coincide with areas of strong lightning activity. Hence, it is expected that the increasing number of wind turbines and the increasing height of the towers will result in an incidence of lightning damages greater than anticipated with significant repair costs, particularly in electronic equipment and electrical machines.

The influence of lightning faults on operational reliability becomes a concern as the capacity of individual wind turbines increases. In a study completed in 2002 [2] it is expected that up to 8 out of 100 wind turbines could be damaged by one direct lightning strike every year. Between 1992 and 1995 Germany alone reported 393 accidents with damages due to lightning: 124 direct strikes to the turbine, and the remainder through the electrical network [3].

The wind turbine has an outside structure: blades, nacelle and tower, which are affected by direct effects of lightning. Inside this structure is the electrical installation. The electrical installation has power electronics equipment: servo-mechanisms, rectifiers and inverters, and electronic control systems; electrical machines: power generator, LV/HV transformer; cables, which can be damaged by indirect effects due to overvoltage. Hence, in order to face these hazardous it is crucial to install an efficient lightning protection system (LPS) on wind power plants whenever the risk is above the acceptable limit.

This paper presents an overview of wind energy in Portugal and briefly describes the Portuguese Lightning Location System. Some aspects of lightning activity in Portugal are discussed. The method for risk assessment due to lightning flashes to earth is performed by the computer program LPS 2008 developed in Visual Basic by the authors. LPS 2008 is based on well established standards and on the Rolling Sphere Method. LPS 2008 draws in 3D the most vulnerable points to lightning of a structure. A case study is presented to illustrate the protection measures resulting from this methodology, reducing damages due to lightning effects in power electronics and electrical machines to acceptable levels.

II. WIND ENERGY IN PORTUGAL

The first wind turbine in Portugal was installed at Lourel, in 1985. This wind turbine was an Aeroman 12/20 model with 20 kW, and during the next thirteen years a few more wind turbines were connected to the electrical grid. But, since 1998 the wind energy capacity increased exponentially, as shown in Fig. 1. The general situation of wind power in Portugal until September 2007 can be observed in Table I and Fig. 2.

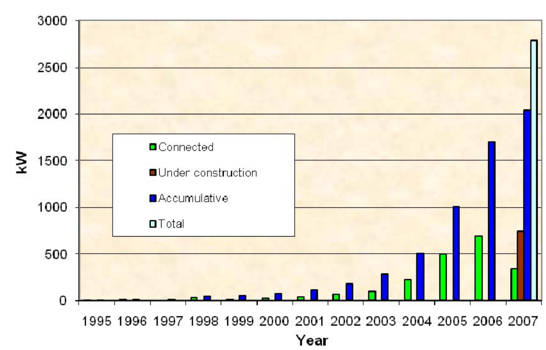

Fig. 1. Portugal wind power (source INEGI), from 1995 to 2007.

TABLE I
PORTUGAL GENERAL DATA OF WIND POWER FOR THE CONTINENTAL AREA (SOURCE: INEGI).

Estimated sustainable wind potential onshore(MW)	4800
Total capacity in operation in Sept. 2007(MW)	2037
Total capacity under construction in Sept. 2007 (MW)	746

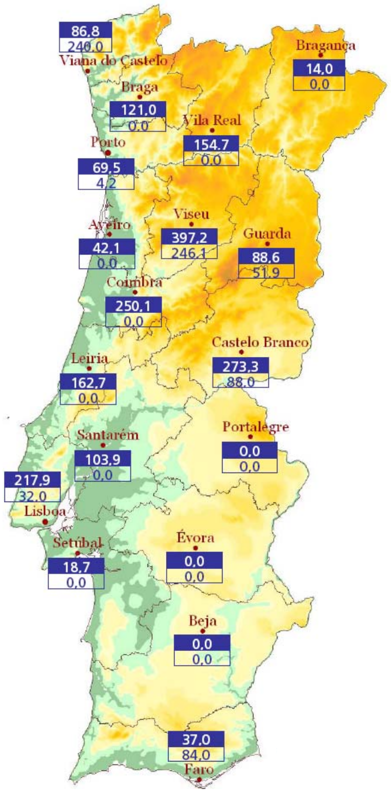

Fig. 2. Portugal wind power capacity in MW: top - connected; bottom - under construction (source INEGI).

III. PORTUGUESE LIGHTNING LOCATION SYSTEM

The first LLS is working in Portugal since June 2002 and is operated by the national Institute of Meteorology (IM). In December of the same year Portugal began sharing its data with Spain. The system has now eighteen IMPACT sensors: four in Portugal and fourteen in Spain, of which Portugal share information with the nearest five (Fig. 3).

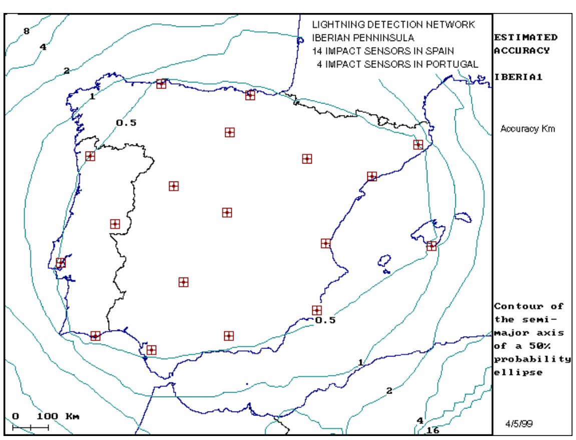

Fig. 3. Location and accuracy of the LLS operated by IM (source: IM).

Three methods are used to find the geographical location of lightning in latitude and longitude: magnetic direction, time-of-arrival, and a combination of the two. Furthermore, the system allows the measurement of the peak current and identifies the return stroke measured. The software manufacturer announces an error in spatial location, over the continental area of Portugal, which is less than 500 m for the semi major axis of a 50 % probability ellipse (Fig. 3). The manufacturer also assures efficiency higher than 90 % for strokes with peak current greater than 5 kA, and for the same area. The appearance of an installed IMPACT sensor is shown in Fig. 4.

Fig. 4. Appearance of the IMPACT sensor (source: IM).

But, before the installation of this system, Portugal had only a Thunderstorm Days (T_d) map (Fig. 5). A T_d map is drawn with the number of days which observers can hear at least one thunder.

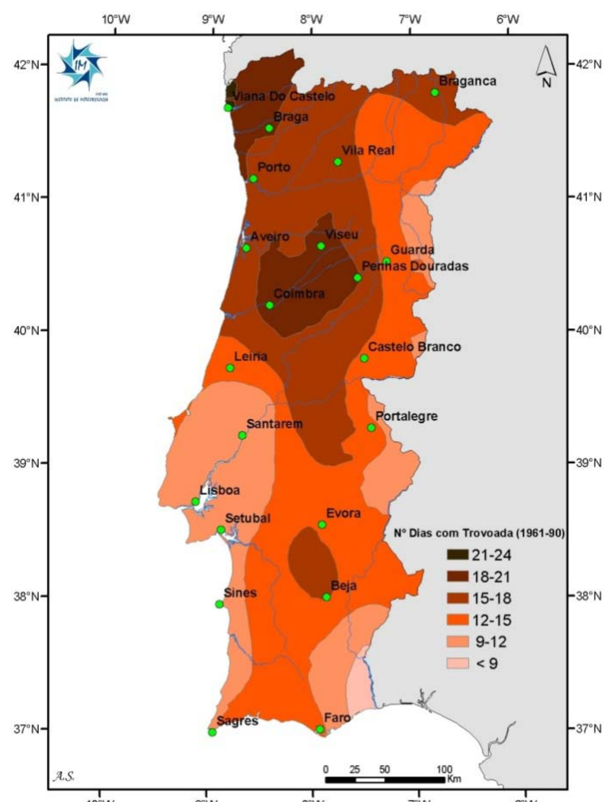

Fig. 5. Thunderstorm day's map of Portugal, from 1961 to 1990 (source: IM).

IV. Some aspects of Lightning Activity in Portugal

The collected information after validation is recorded by the system in an ASCII file. This information is then analyzed with database software resulting in probabilistic characterization.

The results presented [4] are from July of 2002, when the system became operational, until June of 2007, which is the last month of data on evaluation in this paper.

A spatial characterization by latitude and longitude was carried out and two years of this characterization are shown in Figs. 6 and 7, as an example, because similar results were obtained for the other years. Fig. 6 shows a decrease of positive cloud-ground (CG) strikes with the increase of latitude. Fig. 7 shows that the relative polarity distribution of positive strikes is about 35 %, between -12.5º and -9.5º (Atlantic Ocean). It is about 23 %, between -9.5º and -5.5º (Portugal) and is about 10% between -5.5º and -2.5º (Spain). International standards, like IEC 62305-1, assume a polarity ratio of 10 % for positive CG strikes and 90 % for negative ones, if no local information is available.

The high ratio of positive CG strikes observed in Portugal is probably due to its boundary condition between the Atlantic Ocean and the European Continent. Fig. 8 shows the relative polarity distribution by month for 2004. Relative distribution values have a steady behaviour over the years, as shown in Fig. 8. Positive CG strikes are more frequent in winter months (October to March), reaching 40 %, while negative CG strikes are more frequent in summer months (April to September), reaching 90 %.

The accumulative probability of the peak current was also computed and compared with the curve accepted by IEC [5] (Fig. 9). Along the five years under study, all curves overlap quite well, but they do not match so well the IEC curve. According to the IEC curve, 80 % of CG strikes have a peak current lower than 20 kA. However, for the Portuguese situation 80 % of CG strikes have a peak current lower than about 10 kA.

The overall flash density in Portugal between 2003 and 2006 can be observed in Fig. 10.

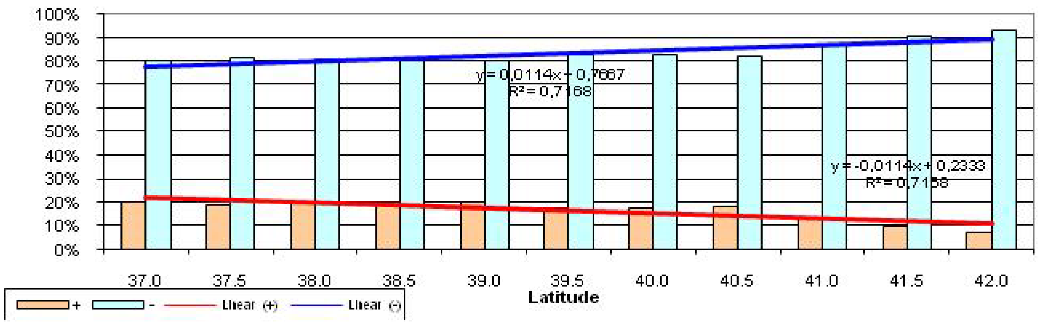

Fig. 6. Relative distribution of CG strikes by latitude for 2004.

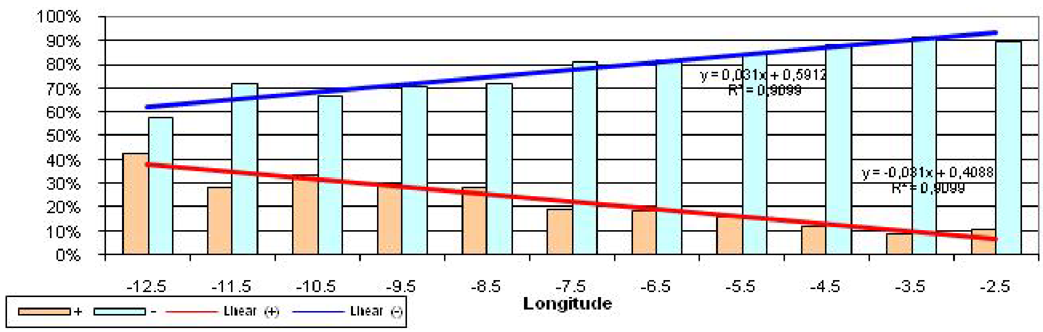

Fig. 7. Relative distribution of CG strikes by longitude for 2003.

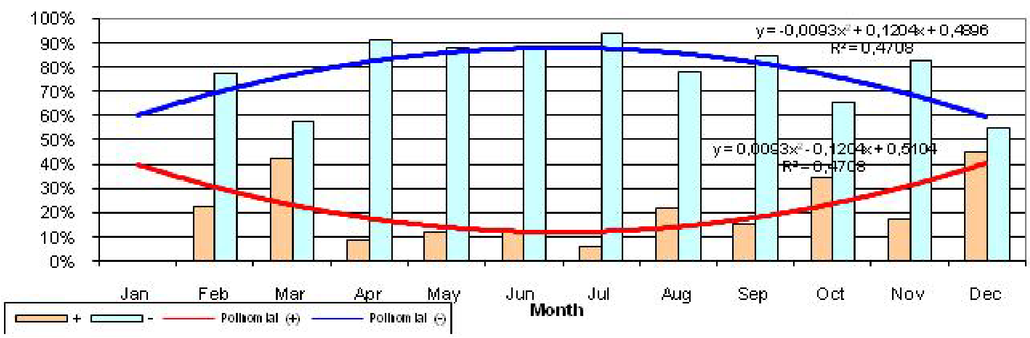

Fig. 8. Relative polarity distribution by month over Portugal for 2004.

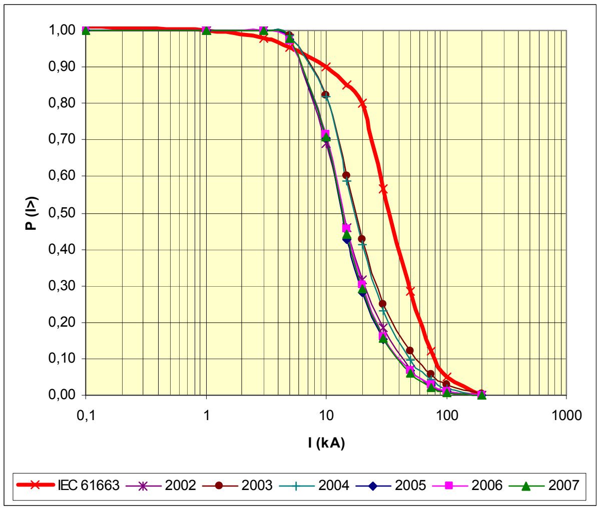

Fig. 9. Accumulative probability of the peak current.

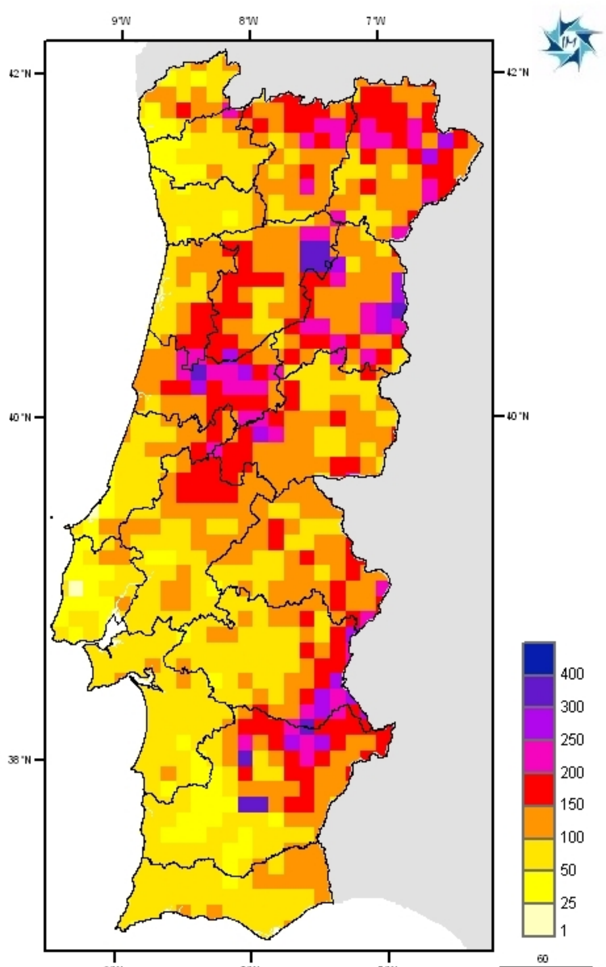

Fig. 10. Overall flash density between 2003 and 2006.

V. Methodology

The method used in this paper for risk assessment on a structure or on a service due to lightning flashes to earth is based on IEC 62305 part 2 [6]. The scope of this part of IEC 62305 is to provide a procedure for the evaluation of such a risk. Once an upper tolerable limit for the risk has been ascertained, this procedure allows the selection of appropriate protection measures to be adopted, in order to reduce the risk at or below the tolerable limit.

The assessment of the risk due to all possible effects of lightning flashes to structures or services presented in IEC 62305-2 is a revised version of IEC 61662: 1995-04 and A1: 1996-05 TR 2, Ed. The mathematical expression used on [6] to assess the risk value is given by

$$R = (1 - e^{-N\,P\,t})\,L\;. \tag{1}$$

where N is the number of lightning flashes influencing the structure and/or the service; P is the probability of damage by one of the influencing lightning flashes; L is the consequent mean amount of loss; and t is the period under evaluation, which is usually considered one year. As the product N P t is N P t << 1, the expression (1) becomes

$$R = N\,P\,L\,t\;. \tag{2}$$

The risk R is the measure of a loss. For each type of loss, L1 to L4, the relevant risk shall be evaluated. The risks to be evaluated in a structure may be:

- R1 - Risk of loss of human life;
- R2 - Risk of loss of service to the public;
- R3 - Risk of loss of cultural heritage;
- R4 - Risk of loss of economic value.

The risks to be evaluated in a service may be:

- R’1 - Risk of loss of human life;
- R’2 - Risk of loss of service to the public;
- R’4 - Risk of loss of economic value.

To evaluate R the relevant risk components (partial risks depending on the source and on the type of damage) shall be defined and calculated. R is the sum of its risk components which may be grouped according to the source of damage and the type of damage. It is the responsibility of the national authority having jurisdiction to identify the value of tolerable risk R_T. Representative values of R_T, where lightning flashes involve loss of human life or loss of social or cultural values, are reported in Table II. For more details on the background of these values reference can be made to BS 6651-1985 and to publications relevant to fatal accident rate.

TABLE II
Typical Values of Tolerable Risk R_T.

Loss of human life	10^{-5}
Loss of service to the public	10^{-3}
Loss of cultural heritage	10^{-3}

The LPS 2008 computer program has been developed, using Visual Basic for AutoCAD. The LPS 2008 is a new computer program [7] which takes advantage from the experience achieved with two other programs: SPDA and SPDA 2002.

Some advantages of LPS 2008 are:

- adapted to the new IEC standard (IEC 62305), which is used for risk assessment;
- allows also the risk assessment with BS 6651 and IEC 61662;
- runs over any version of AutoCAD (since AutoCAD 2000), making easier to model 3D structures (like buildings, telecommunication antennas, wind turbines, etc.) and consequently the drawing and calculation of the necessary areas of influence;
- performs the RSM simulation, marking all vulnerable points on a structure, or set of structures, for the selected protection level according to [6].

In Fig. 11 one display of the LPS 2008 is shown.

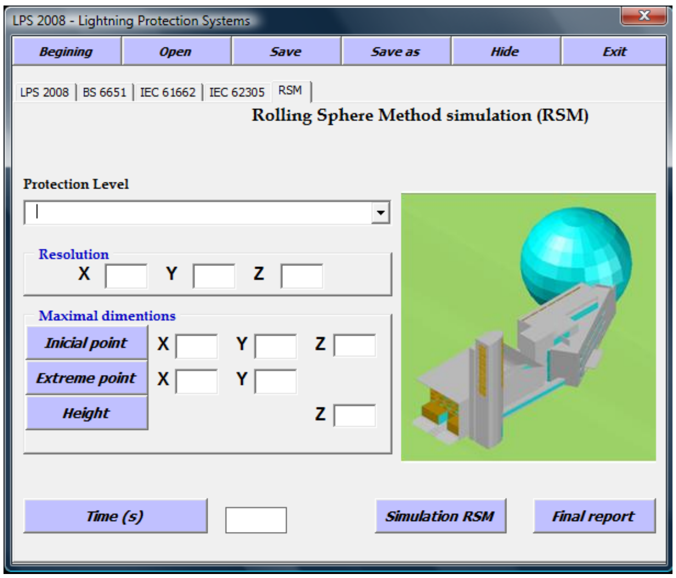

Fig. 11. RSM display of LPS 2008.

In Fig. 12 the result of the RSM simulation with LPS 2008 shows all points touched by the rolling sphere for the protection level I [6] (efficiency of 98%). The sphere also touches the ground and a contour line is drawn as shown.

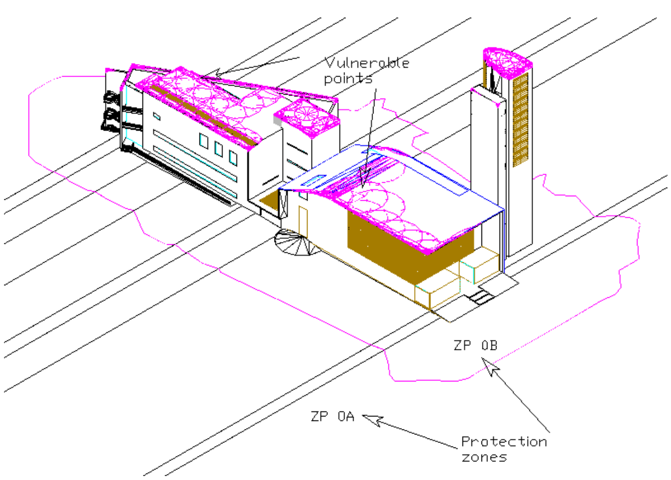

Fig. 12. Result of RSM simulation with LPS 2008 over Pastorinhos church at Alverca do Ribatejo in Portugal.

According to the concept of Lightning Protection Zones (LPZ), someone in LPZ 0A has no protection against electromagnetic disturbance caused by lightning and can be stroked by lightning. On the other hand, if someone is in LPZ 0B cannot be stroked directly by lightning, but still has no protection against electromagnetic disturbance.

VI. Application and Results on a Case Study

The wind power plant under study has 25 wind turbines with 2 MW of rated power. Rotor blades are manufactured using the so-called sandwich method. Glass fibre mats placed in the mould are vacuum-impregnated with resin via a pump and a hose system. The rotor diameter is about 82 m. The rotor hub and annular generator are directly connected to each other as a fixed unit without gears. The rotor unit is mounted on a fixed axle. The drive system has only two slow-moving roller bearings due to the low speed of the direct drive. The annular generator is a low-speed synchronous generator with no direct grid coupling. Hence, the output voltage and frequency varies with the speed, implying the need for a converter via a DC link in order to make a connection to the electric grid. The hub height varies between 70 to 138 m. The tubular steel towers are manufactured in several individual tower sections connected using stress reducing L-flanges. The LV/HV transformer is placed at the bottom of the tower. It has 2500 kVA of rated power and has a special design to fit the reduced dimensions and working conditions of the tower. In Fig. 13 a wind turbine is represented. The wind turbines were modelled in 3D with AutoCAD.

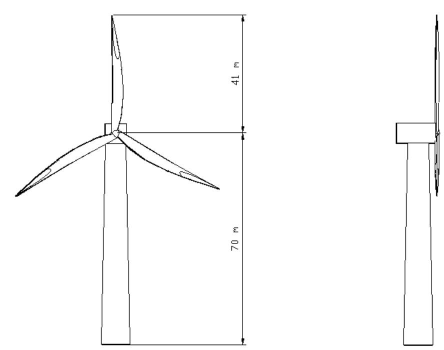

Fig. 13. Dimensions of a wind turbine.

Ensuring proper power feed from wind turbines into the grid requires grid connection monitoring, shown in Fig.14.

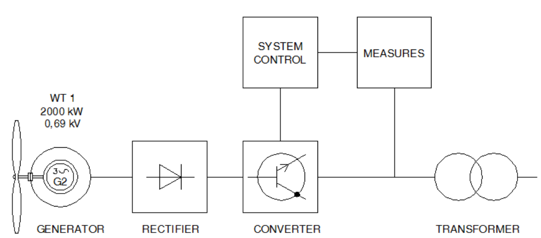

Fig. 14. Grid connection monitoring on wind turbines.

The 25 wind turbines are arranged in groups of 5 with distance among towers around 350 m. Fig. 15 shows the electric schema of a LV/HV substation near the tower.

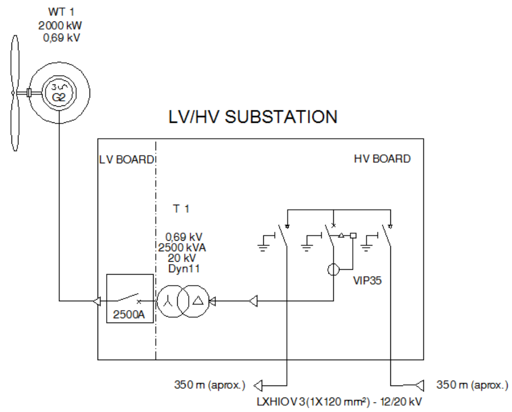

Fig. 15. LV/HV substation near the tower.

Cables connecting these groups enter in the main substation, which has an external part, Z1, and an internal part Z2 as shown in Fig. 16. Also, this figure shows the collection area (Ad) for flashes to an isolated structure [6].

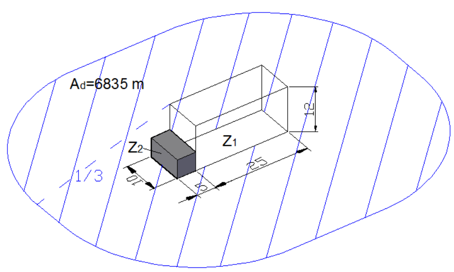

Fig. 16. Main substation at wind power plant.

Results show a risk value R higher than tolerable risk R_T for L1 - Loss of human life and for L2 - Loss of service to the public (see Table II). In order to reduce the value of R the main substation must be protected with a Class I LPS and surge protective devices (SPD) must be installed. Fig. 17 shows the result of RSM simulation, applied to a wind turbine, done by LPS 2008. Fig. 18 shows the electric schema of the external part main substation with SPD installed.

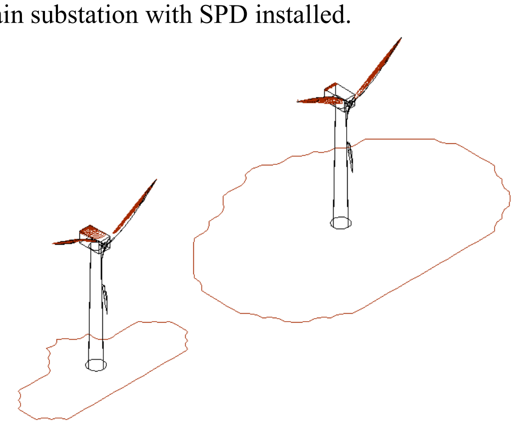

Fig. 17. Result of RSM simulation with LPS 2008 for Class I and IV.

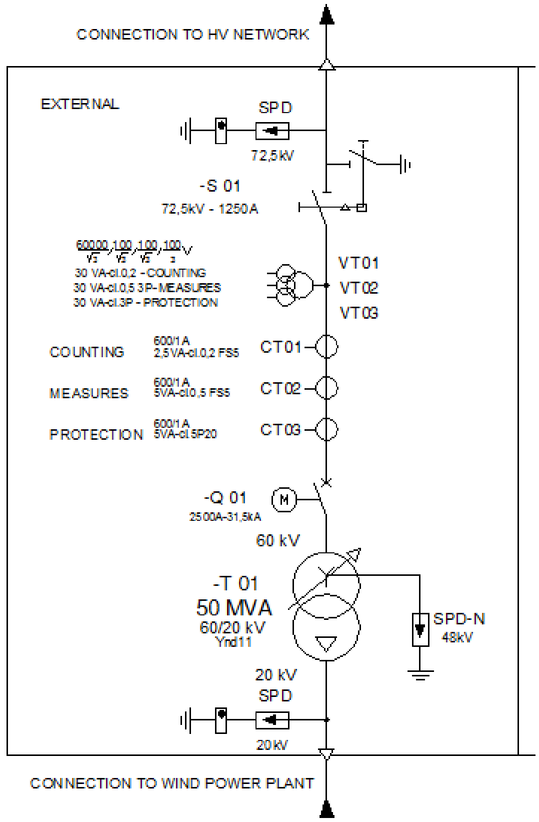

Fig. 18. Electric schema of the external part main substation with SPD.

VII. Conclusion

An overview of wind energy in Portugal and a brief description of the Portuguese Lightning Location System were made. Some aspects of lightning activity in Portugal were also discussed. The paper enhances the importance of having a well established knowledge of the lightning activity on the regions chosen for wind power plants, combined with projects based on the most recent international standards and well established methods. The LPS 2008 have been proved to be a useful tool able to save time during the project stage.

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