Estimation of lightning vulnerability points on wind power plants using the rolling sphere method

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Abstract

The escalating number of wind power plants in many countries makes their reliability and safety of crucial importance. One of the main causes of damages for wind power plants is constituted by lightning. Hence, appropriate tools for the lightning protection of wind power plants are required. We have developed a new computer program in Visual Basic, LPS 2008, which runs over AutoCAD and is able to perform risk assessment on a structure or on service due to lightning flashes to ground. Computer simulations obtained by using LPS 2008 are presented, and conclusions are duly drawn.

Keywords: Lightning protection; risk assessment; wind energy

1. Introduction

Effective lightning protection for wind power plants is increasingly important nowadays, since areas of favorable locations for wind power plants often coincide with areas of significant thunderstorm activity. Moreover, the escalating number of wind power plants in many countries makes their reliability and safety of crucial importance [1].

In Portugal, the first wind turbine was installed in 1985. Since then, the total installed capacity increased drastically, reaching 2556 MW in July 2008. The wind power goal foreseen for 2010 was established by the government as 3750 MW and that will constitute some 25% of the total installed capacity by 2010 [2]. This value has recently been raised to 5100 MW, by the most recent governmental goals for the wind sector. Hence, Portugal has one of the most ambitious goals in terms of wind power, and in 2006 was the second country in Europe with the highest wind power growth.

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One of the main causes of damages of wind power plants is certainly constituted by lightning [3]. Lightning damage is the single largest cause of unplanned downtime in wind turbines, and that downtime is responsible for the loss of countless megawatts of power generation [4]. Modern wind turbines are characterized not only by greater heights but also by the presence of ever-increasing control and processing electronics. Consequently, the design of the lightning protection of modern wind turbines will be a challenging problem [5].

Damages statistics of wind turbine components have been analyzed in the literature. In Germany, 14 % of the wind turbines in the mountain areas in the south are damaged by lightning [6]. Japan, especially suffers from frequent and heavy lightning strikes, the notorious “winter lightning” [7], which puts damage at 36% as reported by CRIEPI. Additionally, risk analysis procedures have been reported in the literature, as to whether lightning protection is needed or not. A risk analysis for lightning protection purposes is a fairly new approach, but its importance increases considerably [8]. However, there is currently no international standard specifically written for the lightning protection of wind power plants. The closest document of the International Electrotechnical Commission (IEC), IEC TR 61400-24 [9], is purely informative and is not to be regarded as an international standard, but it should be regarded as a significant breakthrough.

In January 2006, a new four parts standard document has appeared, IEC 62305-1 to 62305-4 [10–13], providing the general principles of protection against lightning. However, standards IEC 62305 are not specifically developed for the lightning protection of wind power plants, since no account is taken of the peculiarities of wind turbines. In fact, wind turbines are tall structures often placed in regions very exposed to lightning. Additionally, they are composed of conductive parts in relative movement, what complicates the application of standard lightning protection systems principles [3]. The need for protection, the economic benefits of installing protection measures and the selection of adequate protection measures should be determined in the terms of risk management [14]. The identification of the most vulnerable points on a given structure to be struck by lightning is an important issue on the design of a reliable lightning protection system (LPS) [15].

The risk management method reported in IEC 62305-2 [11] entails a significant number of input data and mathematical processing worthy of being supported by a new computer program for a friendly practical application. The lightning strike model considered in IEC 62305 is the rolling sphere method (RSM).

Hence, we have developed a new computer program in Visual Basic, LPS 2008, which runs over AutoCAD and is able to perform risk assessment on a structure or on service due to lightning flashes to ground. Our program is a three dimensional one and is based on the RSM. LPS 2008 marks the vulnerable points on a structure, taking into account the most recent international standards.

Although the LPS 2008 computer program was specially developed for the lightning protection of wind power plants, it is sufficiently general to be applied to other structures or services. Hence, two case studies are presented in this paper to illustrate what can be done with LPS 2008: a church and a wind power plant. Computer simulations obtained by using LPS 2008 are presented, and conclusions are duly drawn.

2. Method for risk assessment

The method used in this paper for risk assessment on a structure or on a service due to lightning flashes to ground is based in IEC 62305-2 [11]. Once an upper tolerable limit for the risk has been ascertained, this method allows the selection of appropriate protection measures in order to reduce the risk at or below the tolerable limit.

Lightning flashes influencing a structure or a service are considered sources of damage and are divided into:

- S1 - flashes striking the structure;
- S2 - flashes striking near the structure and/or near the connected services (power, telecom lines, other services);
- S3 - flashes striking the service;
- S4 - flashes striking near the service or direct to a structure connected to the service.

Lightning flashes can be hazardous to life, to structures and to services, and the following damages are considered:

- D1 - injuries of living beings in or close to the structure;
- D2 - damages to the structure and to its contents;
- D3 - failures of associated electrical and electronic systems.

Source of damage S1 and S3 may cause damages of type D1, D2 and D3. Source of damage S2 and S4 may cause damages of type D3. Moreover, failures caused by lightning overvoltages in users' installations and in power supply lines may also generate switching type overvoltages in the installations.

Each type of damage, alone or in combination with others, may produce a different consequent loss in the object to be protected. The type of loss that may appear depends on the characteristics of the structure itself and its content. The following types of losses are into account:

- L1 - Loss of human life;
- L2 - Loss of service to the public;
- L3 - Loss of cultural heritage;
- L4 - Loss of economic value (structure and its content, service and loss of activity).

Protection measures may be required to reduce the loss due to lightning. Whether they are needed, and to what extent, should be properly determined by risk assessment. The risk, defined in [11] as the average annual loss on a structure or on a service due to lightning flashes to ground, depends on:

- the annual number of lightning flashes influencing the structure and/or the service;
- the probability of damage by one of the influencing lightning flashes;
- the average amount of the consequent loss.

The number of lightning flashes influencing the structure or the service depends on their: dimensions and characteristics; environment characteristics; as well as on the lightning ground flash density in the region. The probability of lightning damages depends on the structure, the service and the lightning current characteristics, as well as on the kind and efficiency of applied protection measures. The annual average amount of the consequential loss depends on the extent of damages and the consequential effects, which may occur as a result of a lightning flash. The effect of protection measures results from the features of each protection measure and allows for a reduction of the damage probability and the amount of consequential loss.

The mathematical expression to assess the risk value is given by:

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

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 per strike; and t is the period under evaluation, which is usually considered one year.

Since $N P t << 1$, Eq. (1) becomes:

$$R = N P L t \qquad (2)$$

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

- **R**1 - Risk of loss of human life;
- **R**2 - Risk of loss of service to the public;
- **R**3 - Risk of loss of cultural heritage;
- **R**4 - 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) are 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 $\mathbf{R}_T$. Representative values of $\mathbf{R}_T$, where lightning flashes involve loss of human life or loss of social or cultural values, are reported in Table 1.

"See Table 1 at the end of the manuscript".

The procedure to evaluate the need of protection measures considers the following steps:

- identification of the components $\mathbf{R}_i$ which make up the risk;
- computation of the identified risk components $\mathbf{R}_i$;
- computation of the total risk **R**;
- identification of the tolerable risk $\mathbf{R}_T$;
- comparison of the risk **R** with $\mathbf{R}_T$.

If $\mathbf{R} \leq \mathbf{R}_T$, protection measures are not necessary. If $\mathbf{R} > \mathbf{R}_T$, protection measures must be adopted in order to reduce **R** until $\mathbf{R} \leq \mathbf{R}_T$ for all risks considered.

The method used in LPS 2008 to find the vulnerable points in a structure due to lightning flashes to ground is the RSM, which is also adopted in IEC 62305. The RSM appeared in the early 1970s [16] and was developed by Ralph H. Lee in 1977 for shielding buildings and industrial plants and extended by J.T. Orrell for use in substation design. The RSM was built on basic principles and theories from Whitehead and the electrogeometric model. It uses an imaginary sphere of radius ***r*** which rolls up and over the surface of a structure. A piece of equipment or structure is said to be protected from a direct stroke if it remains below the curved surface of the sphere. The other parts of equipment or structure in contact with the sphere are vulnerable points to direct strokes and should be protected by lightning masts, shield wires and other grounded metallic objects that can provide lightning shielding. The radius of the rolling sphere is a function of the lightning current. In an IEEE working group report, Estimating Lightning Performance of Transmission Lines II [17], the experimental relation is given by:

$$r = 10 I^{0.65} \tag{3}$$

The standard sphere radius (20, 30, 45, and 60 m) is chosen depending on the lightning protection level [10]. The RSM based on the electrogeometric model is convenient to detect the possible striking points at a protected structure [18]. So far it is the best model we have to work in an international standard [14]. The evaluation of the vulnerable points over a structure is essential to design an efficient LPS against lightning flashes to ground.

3. Computer program

The method for risk assessment on a structure or on a service due to lightning flashes to ground, based on IEC 62305-2, requires a great number of input data and computation. The following tasks concerning relevant data and characteristics are necessary:

- for the building itself and its surroundings (Table 2);

"See Table 2 at the end of the manuscript".

- for internal electrical systems, relevant incoming power line and internal electronic systems (Table 3);

"See Table 3 at the end of the manuscript".

The definition of zones in the structure and their characteristics are also necessary, taking into account:

- type of soil outside and inside the structure;
- risk of fire;
- existence of spatial shields;
- existence of sensitive electronic systems;
- type of losses.

Characteristics of defined zones are reported in Table 4.

"See Table 4 at the end of the manuscript".

Once these tasks are completed, mathematical computation and comparisons must be done before the output of results can be achieved. Many engineers and technicians consider the method proposed in IEC 62305-2 to be unpractical, because they need: three dimensional (3D) reduced scale buildings; and some values of areas obtained by drawing complex shapes, which are not easy to draw. Hence, they spent a lot of time obtaining reduced scale buildings, which is a burdensome task, and at the end they know that they have to protect the building but they do not know how to do it.

Due to the previous facts, it is recommended to use a computer to manage it all, reducing errors and avoiding the burdensome task. The IEC understood the problem and developed a computer program, simplified IEC risk assessment calculator, which is referred to in [11].

The simplified IEC risk assessment calculator speeds up time and is able to avoid human computation errors. However, it cannot help the designer during the drawing and calculation of the necessary areas of influence, referred to in [11], and it cannot perform the simulation of the RSM to find the vulnerable points on a structure.

To overcome these difficulties, a new computer program has been developed in Visual Basic, LPS 2008, which runs over AutoCAD and is able to perform risk assessment on a structure or on services due to lightning flashes to ground.

The salient advantages of LPS 2008 are:

- Completely adapted to the new IEC standard (IEC 62305), which is used for risk assessment.
- Allows also risk assessment with IEC 61662 and BS 6651. The BS 6651 uses a faster assessment method because it considers fewer characterization factors than IEC 61662 or IEC 62305-2. The risk value assessed by BS 6651 can drive the designer of a LPS to a non clear situation about what protection measures could be used and even if they are needed or not. The IEC 61662 is the Technical Report that was used by IEC as a basis for the development of IEC 62305-2. Both use the same method but it was improved with years of experience in IEC 62305-2.
- Runs over any version of AutoCAD (since AutoCAD 2000), making it easier to model 3D structures (like buildings, telecom antennas, wind turbines, etc.) and to draw/compute 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 IEC 62305-2.

In Fig. 1, a display of the LPS 2008 running over AutoCAD is shown.

"See Fig. 1 at the end of the manuscript".

LPS 2008 easily extracts numeric values from objects drawn in the space model, like areas, lengths, coordinates, etc., with a simple click on a command button, and then selecting the object on the screen.

In Fig. 2, a display of the RSM is shown.

"See Fig. 2 at the end of the manuscript".

After the risk assessment is completed, the user knows which level of protection must be used for the structure under study. The appropriate selection is made in the display shown in Fig. 2. In this display, the user can define the resolution for the simulation. However, the higher is the resolution the larger is the computation time. The dimensional information of the structure is given by the 3D model. The user only has to select two points on screen, to define a rectangle which involves the structure, and the highest point of the structure. The point’s coordinates are extracted to LPS 2008, then the RSM simulation is started, and during this simulation some layers and 3D objects are created automatically.

One problem normally faced is due to the dimension of the structure, or set of structures: if the dimensions are considerable, then the computer can run out of memory during program execution, because hundreds of thousands of points will be checked. To avoid this problem, LPS 2008 divides those dimensions in smaller parts and saves the result at the end of each computation. This new procedure allows the simulation of those structures without requiring special PC features. The structures have to be modeled with solids and not with meshes as required by LPS 2008.

4. Case studies

The LPS 2008 computer program was specially developed for the lightning protection of wind power plants, but is sufficiently general to be applied to other structures or services. Hence, two case studies are presented in this paper to illustrate what can be done with LPS 2008: a church and a wind power plant.

Risk assessment for the Pastorinhos Church, at Alverca do Ribatejo, Portugal, has shown the need of additional protection measures: protection with metallic captors, to reduce damages due to direct lightning strikes; and installation of surge protective devices into the electrical boards, to reduce damages due to transient overvoltages caused by lightning [19].

Fig. 3 shows a 3D model in perspective drawn by AutoCAD of the referred church.

"See Fig. 3 at the end of the manuscript".

In Fig. 4 the result of the RSM simulation with LPS 2008 shows all points touched by the rolling sphere for the protection level I [11] (efficiency of 98%). The sphere also touches the ground and a contour line is drawn as shown. 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 struck by lightning. On the other hand, if someone is in LPZ 0B he cannot be struck directly by lightning, but still has no protection against electromagnetic disturbance. LPZ 0B is inside the contour line while LPZ 0A is outside this line.

"See Fig. 4 at the end of the manuscript".

In Fig. 5 the LPS natural and artificial metallic elements were drawn using AutoCAD controls.

"See Fig. 5 at the end of the manuscript".

It is a common practice, when allowed, to physically connect metallic elements of the structure, called natural elements, represented with continuous line in dark blue color, to other metallic captors, called artificial elements, represented with dashed line in red color. With this procedure an equipotencial bonding is achieved avoiding the risk of sparks. Of course all these elements have to be connected to the ground electrode, represented with dash-dot line in light blue colour. In this case, a ring electrode was constructed because the building was almost ready when the LPS were installed.

Once local data have been collected and depending on the experience with AutoCAD, 2 man-h are enough to draw the 3D model of the church, 1/2 man-h to input data, assess the risk value and chose the most adequate protection measures. The computer simulation of the RSM takes about ten minutes. Finally, 1 man-h more is needed to produce the final drawings.

The wind power plant under study has 25 wind turbines each 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.

Risk assessment for the wind power plant has also shown the need of additional protection measures: protection in order to reduce damages due to direct lightning strikes; and installation of surge protective devices into the electrical boards, to reduce damages due to transient overvoltages caused by lightning [19].

In Fig. 6 a wind turbine is represented. The wind turbines were also modeled in 3D with AutoCAD.

"See Fig. 6 at the end of the manuscript".

Ensuring proper power feed from wind turbines into the grid requires grid connection monitoring, shown in Fig. 7.

"See Fig. 7 at the end of the manuscript".

The 25 wind turbines are arranged in groups of 5 with distance among towers around 350 m. Fig. 8 shows the electric schema of a LV/HV substation near the tower.

"See Fig. 8 at the end of the manuscript".

Cables connecting these groups enter into the main substation. Taking into account that the type of soil is different outside and inside the building, two zones are defined: Z_1 (outside the building) and Z_2 (inside the building), as shown in Fig. 9. Also, this figure shows the collection area (A_d) for flashes to an isolated structure [11].

"See Fig. 9 at the end of the manuscript".

In Fig. 10 the result of the RSM simulation with LPS 2008 shows all points touched by the rolling sphere for the protection level I (efficiency of 98%) and for the protection level IV (efficiency of 80%) [11]. A contour line on the ground is shown, limiting the LPZ 0A and LPZ 0B.

"See Fig. 10 at the end of the manuscript".

Fig. 11 shows the electric schema of the external part main substation with surge protective devices installed.

"See Fig. 11 at the end of the manuscript".

Concerning the time spent to find a solution for this second case, it was similar to the previous case.

Our LPS 2008 computer program has shown in all case studies that it is an efficient and useful tool for risk assessment due to lightning flashes to ground. Additionally, RSM simulation done by LPS 2008 avoids the need of reduced scale buildings, which is a burdensome task.

5. Conclusions

The increased wind power penetration leads to new challenges related to the design and installation of appropriate lightning protection measures. Computer simulations obtained by using a new computer program, LPS 2008, are presented in this paper. Our computer program is based on the most recent standards of IEC, namely IEC 62305-2. LPS 2008 has shown that it is an efficient and useful tool for risk assessment due to lightning flashes to ground, creating an AutoCAD drawing in 3D with the vulnerable points marked on the structure. Additionally, RSM simulation done by LPS 2008 avoids the need of reduced scale buildings, which is a burdensome task.

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Figure captions

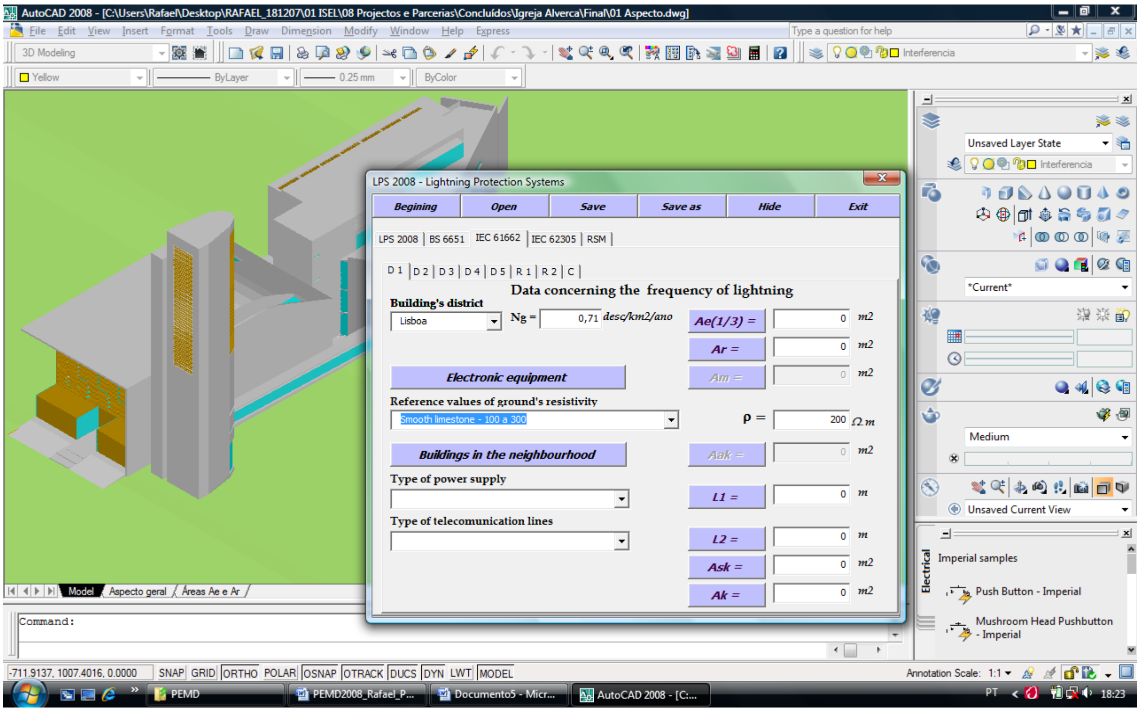

Fig. 1. LPS 2008 running over AutoCAD.

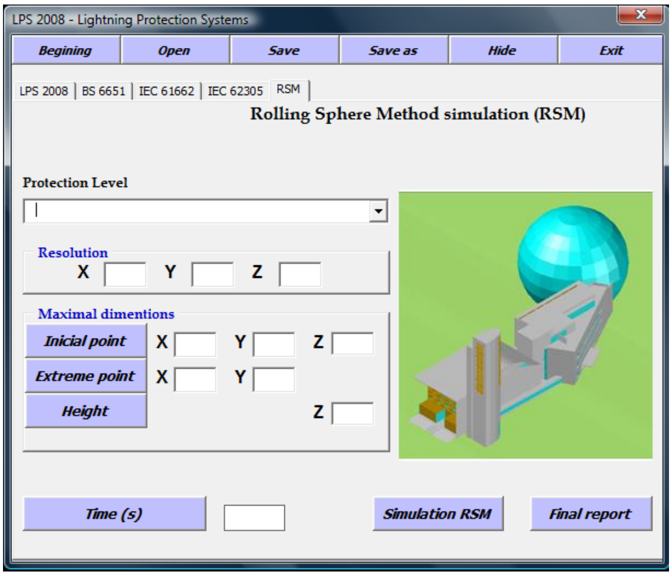

Fig. 2. RSM display of LPS 2008.

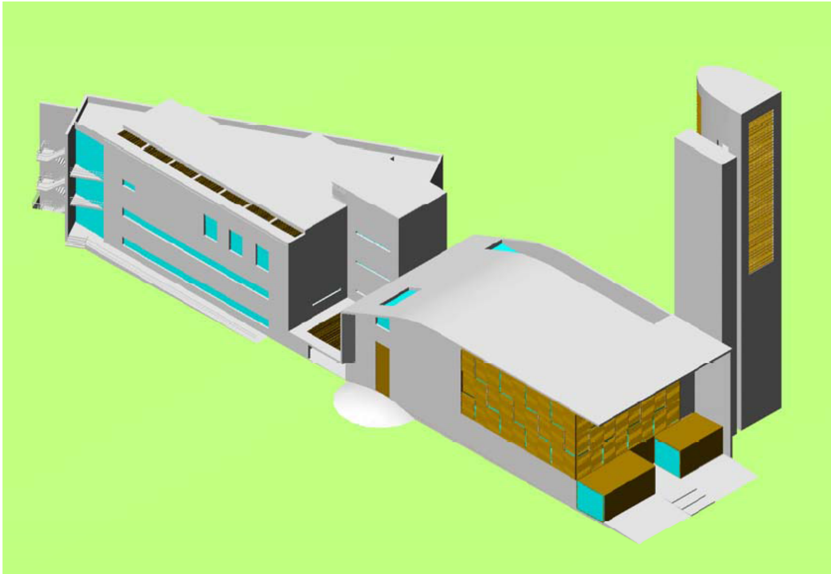

Fig. 3. 3D model of Pastorinhos Church.

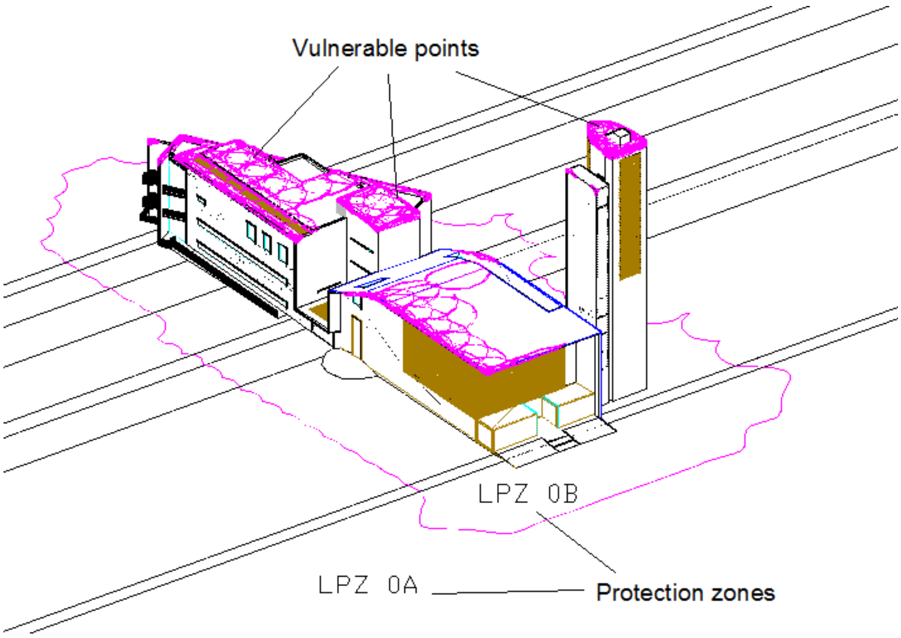

Fig. 4. Result of RSM simulation with LPS 2008 for the protection level I. LPZ 0B is inside the contour line while LPZ 0A is outside this line.

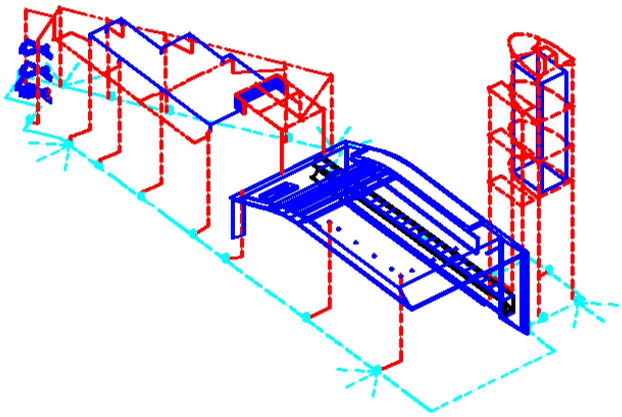

Fig. 5. LPS natural metallic elements (continuous line in dark blue colour) and artificial metallic elements (dashed line in red colour) connecting to the ground electrode (dash-dot line in light blue colour).

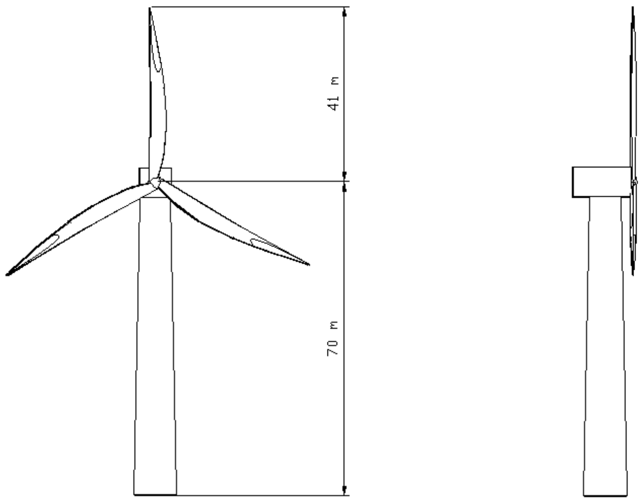

Fig. 6. 3D model and dimensions of a wind turbine.

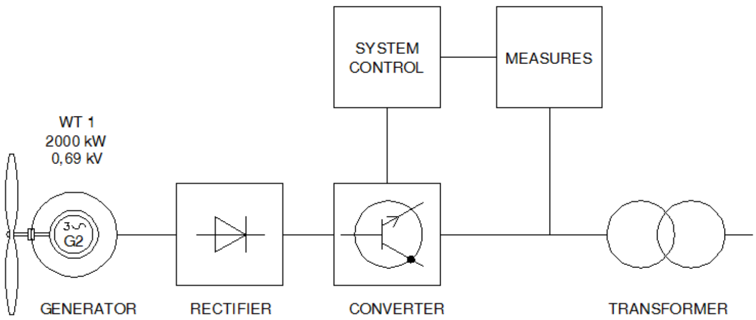

Fig. 7. Grid connection monitoring on wind turbines.

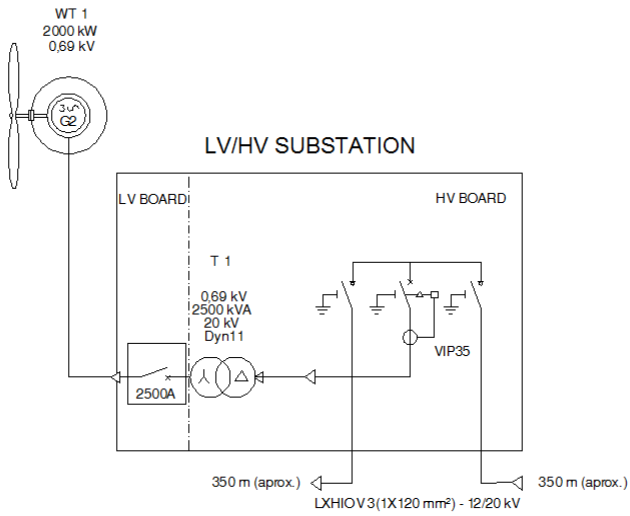

Fig. 8. LV/HV substation near the tower.

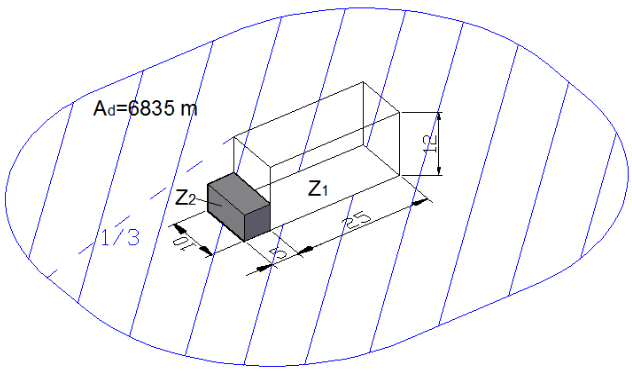

Fig. 9. Main substation at wind power plant: Z_1 is the zone outside the building; Z_2 is the zone inside the building.

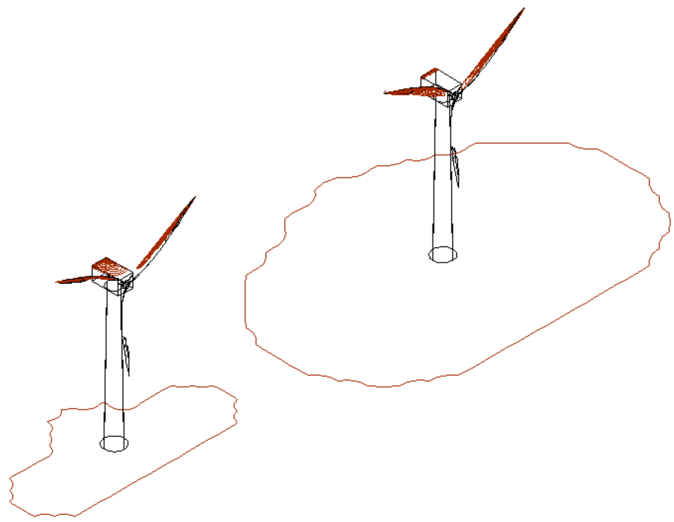

Fig. 10. Result of RSM simulation with LPS 2008 for level of protection I and IV.

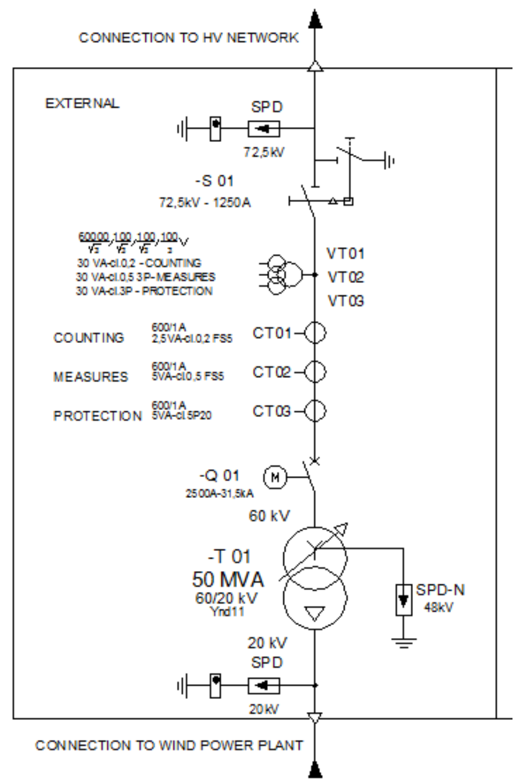

Fig. 11. Electric schema of the external part main substation with surge protective devices.

Tables

Table 1

Typical values of tolerable risk $\mathbf{R}_T$

Case	$\mathbf{R}_T$
Loss of human life	10^{-5}
Loss of service to the public	10^{-3}
Loss of cultural heritage	10^{-3}

Table 2

Structure characteristics

Parameter	Symbol
Dimensions (m)	(L.W.Hb)
Location factor	C_d
LPS	P_B
LPS shied	K_{S1}
Lightning flash density	N_g

Table 3

Internal power system, relevant incoming power line characteristics, internal telecom system and relevant incoming telecom line characteristics

Parameter	Symbol
Length (m)	L_c
Aerial	-
Height (m)	-
HV/LV Trafo	C_t
Line location factor	C_d
Line environment factor	C_e
Line shielding	P_{LD} P_{LI}
Internal wiring precaution	K_{S3}
Equipment withstand voltage Uw	K_{S4}
SPD set	P_{SPD}
End “a” line structure dimensions (m)	(L·W·Ha)
Structure “a” location factor	C_{da}

Table 4

Characteristics of zones Zx considered

Parameter	Symbol
Soil type	r_a
Risk of fire	r
Special hazard	h
Fire protection	r_f
Shock protection	P_A
Spatial shield	K_{S2}
Internal systems	-
Loss by touch and step voltages	L_t
Loss by physical damages	L_f
Loss by failure of internal systems	L_o