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Electromagnetic Transients Analysis of Lightning Overvoltages on Wind Power Plants

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Abstract – *As wind power generation undergoes rapid growth, lightning and overvoltage incidents involving wind power plants have come to be regarded as a serious problem. Firstly, lightning location systems are discussed, as well as important parameters regarding lightning protection. Also, this paper presents a case study, based on a wind turbine with an interconnecting transformer, for the study of adequate lightning and overvoltage protection measures. The electromagnetic transients circuit under study is described, and computational results are presented.* ***Copyright © 2010 Praise Worthy Prize S.r.l. - All rights reserved.***

Keywords*: Electromagnetic Transients, Lightning, Overvoltages, Protection, Wind Power Plants*

Nomenclature

O_1	Virtual origin
I	Peak current
T_1	Front time
T_2	Time to half value
T_{long}	Duration time
Q_{long}	Long stroke charge
U	Peak voltage
Z_0	Impulsive impedance of the line
k	Correction factor for the peak current
t	Time
τ_1	Front time constant
τ_2	Tail time constant

I. Introduction

The need to control climate changes and the increase in fossil-fuel costs stimulate the ever-growing use of renewable energies worldwide [1].

Concerning renewable energies, wind power is a priority for Portugal's energy strategy. In Portugal, 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. This value has recently been raised to 5100 MW, by the most recent governmental goals for the wind sector [2]. 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.

As wind power generation undergoes rapid growth, lightning incidents involving wind power plants have come to be regarded as a serious problem [3]. Lightning protection of wind power plants presents problems that are not normally seen with other structures. These problems are a result of the following [4]:

- wind turbines are tall structures of up to more than 150 m in height;
- wind turbines are frequently placed at locations very exposed to lightning strokes;
- the most exposed wind turbine components such as blades and nacelle cover are often made of composite materials incapable of sustaining direct lightning stroke or of conducting lightning current;
- the blades and nacelle are rotating;
- the lightning current has to be conducted through the wind turbine structure to the ground, whereby significant parts of the lightning current will pass through or near to practically all wind turbine components;
- wind turbines in wind farms are electrically interconnected and often placed at locations with poor earthing conditions.

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].

The future development of wind power generation and the construction of more wind farms will necessitate intensified discussion of lightning protection and the insulation design of such facilities [6].

Nevertheless, no known studies exist yet in Portugal regarding lightning protection of wind power plants. Also, surge propagation during lightning strikes at wind farms is still far from being clearly understood. Thus, much work remains to be done in this area.

Direct and indirect lightning strokes can produce damages of electrical and electronic systems [7], as well as of mechanical components such as blades and bearings [8].

Damages statistics of wind power plant components has been analyzed in the literature, as well as the risk

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analysis [9].

Concerning mechanical components, blades and bearings are the most involved parts. In particular, lightning-damages produced at bearings positioned at the mechanical interface between rotating parts of the wind turbine, can result in high costs of maintenance, considering the difficulties involved in the replacement of such components [10].

Apart from serious damage to blades and bearings, breakdown of low-voltage and control circuits have frequently occurred in many wind farms throughout the world.

According to IEC TR61400-24 [4], the most frequent failures, more than 50%, in wind power plant equipment are those occurring in low-voltage, control and communication circuits.

Indeed, many dielectric breakdowns of low-voltage circuits and burnout accidents of surge arresters in wind power plants are reported.

Such frequent problems in the low-voltage circuits may cause a deterioration of the utilization rate and consequently cause increases in the cost of power generation.

The events on low-voltage circuits are not triggered by only direct lightning strikes but also induced lightning and back-flow surges propagating around wind farms just after lightning strikes on other wind power generators [11].

Usually, converter units and boost transformers are installed very close to wind power plants or inside windmill towers. In addition, lightning arresters are often installed on the high-voltage side (power grid side) and grounded jointly with the low-voltage side in order to decrease the grounding resistance and to protect against winter lightning.

Therefore, when the grounding potential rises around transformers due to a lightning stroke, lightning arresters may operate in the opposite direction from ground to line, causing a lightning surge that flows toward the distribution line. In actual lightning accidents at wind farms, insulation breakdown often occurs not only in lightning-stricken windmills but also in adjacent windmills or even relatively distant ones [6].

Such reverse surges flowing from the low-voltage side to the high-voltage side should be studied in the case of lightning strikes on windmill towers and wind farms.

Scale replicas of electrical systems have been a popular tool, especially in the past, to predict power system transients after different types of perturbations [12]. For instance, a 3/100-scale replica of an actual wind turbine generation system that has blades with a length of 25 m and a tower that is 50 m high was considered in [13] for experimental and analytical studies of lightning overvoltages.

However, in recent years, scale replicas have been progressively replaced by sophisticated numerical codes, capable of describing the transient behavior of power systems in an accurate way, such as the EMTP-RV, which designates the latest version of the Electro-Magnetic Transients Program and RV stands for Restructured Version [14].

In this paper, lightning location systems are discussed, as well as important parameters regarding lightning protection. Also, a case study is presented, based on a wind turbine with an interconnecting transformer, for the analysis of electromagnetic transients. The EMTP circuit is described, and computational results are presented.

II. Lightning Location Systems

Several methods and systems have been developed to detect and locate Cloud-Ground (CG) strikes. These systems are useful to characterize lightning activity of regions, to trace and predict the direction of thunderstorms and to measure their intensity. The characterization of lightning activity allows the construction of Ground Flash Density (GFD) maps used in risk analysis and helping the design of the most adequate protection measures. The information of lightning location systems are used by meteorologists as additional information to improve predictions based on data of meteorological radars and satellite images.

The Direction Finders (DF) system operates in the range of 1 to 500 kHz (VLF and LF). It was designed to intercept signals from CG return strokes and each detector is able to cover 500 km around it [15]. The electric field is also detected to determine polarity and the peak current is estimated as a function of the magnitude of magnetic field. The location of the point of impact can be achieved by triangulation as shown in Fig. 1.

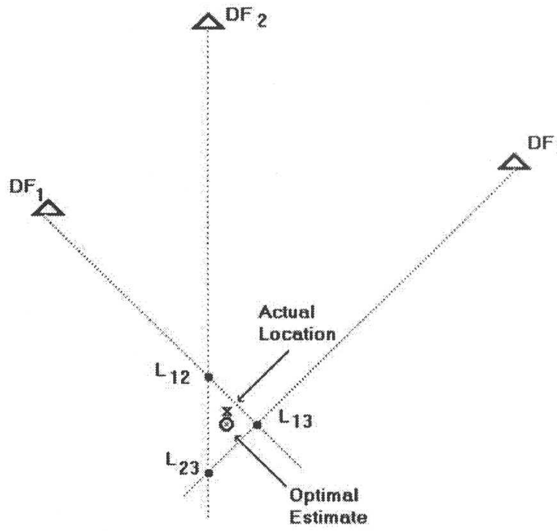

Fig. 1. Optimal scenario for DF system [15]

The DF system has difficulties when the lightning strike occurs in line between two detectors and those two are the only to detect it.

The Time-Of-Arrival (TOA) system was developed by Lewis et al [16]. This system requires precision clocks on each detector, precisely synchronized, to measure the instant of detection. Being known the speed of electromagnetic waves on the air a constant difference in the arrival time at two stations defines a hyperbola, and multiple stations provide multiple hyperbolas whose intersections define a source location. This technique is illustrated in Fig. 2.

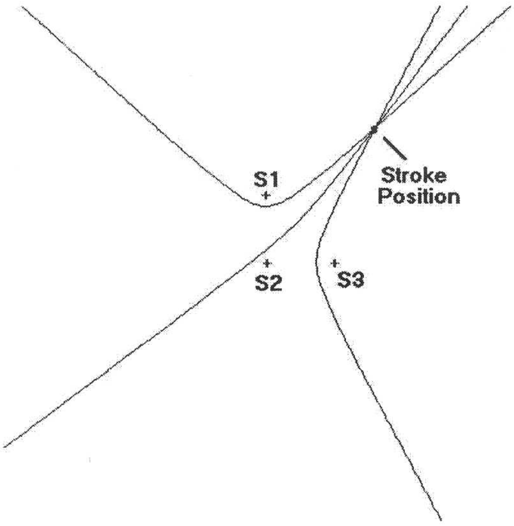

Fig. 2. Optimal scenario for TOA system [16]

Under some geometrical conditions, curves produced from only three detectors will result in two intersections, leading to an ambiguous location as shown in Fig. 3. This problem is avoided if four detectors detect the lightning strike.

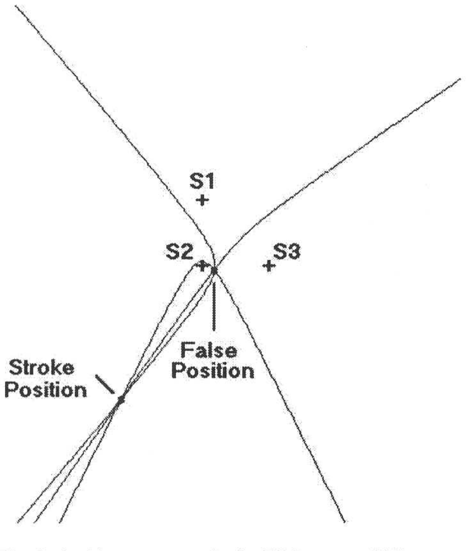

Fig. 3. Ambiguous scenario for TOA system [16]

TOA systems can provide accurate locations at long ranges [17], and if the antennas are properly sited, the systematic errors are minimal.

Casper and Bent [18] have developed a wideband TOA receiver, the Lightning Position and Tracking System (LPATS) that is suitable for locating lightning sources at medium and long ranges using the hyperbolic method.

More recently the Global Atmospherics Inc. developed the so-called Improved Accuracy Using Combined Technology (IMPACT) system. The IMPACT system combines the DF and TOA techniques.

This methodology assures redundant information allowing a more precise detection even in adverse geometric situations. Fig. 4 shows an example of location with 3 IMPACT detectors and 2 LPATS TOA.

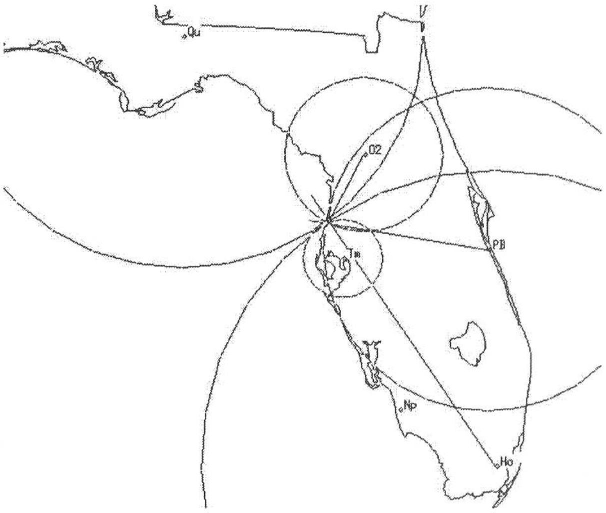

Fig. 4. Example of location with IMPACT system [16]

In Fig. 4 the direction measurements are shown as straight-line vectors, and range circles centred on each detector represent the TOA measurements.

III. Lightning Surge Parameters

From the electrical point of view lightning is regarded as a current source. The lightning current consists in one or more return strokes which can combine in some different ways as shown in Fig. 5.

The IEC 62305 series are a set of standards that provides the general principles to be followed in the protection against lightning of:

- Structures (installations and contents) and persons;
- Services entering a structure.

The following cases are outside the object of this standard: railway systems; vehicles, ships, aircraft, offshore installations; underground high pressure pipelines. Usually these systems are under special regulations made by various specific authorities.

The definitions of short and long stroke parameters are given in Fig. 6 and Fig. 7, respectively.

When lightning strikes a structure, the current wave propagates through the structure to the ground and generates a corresponding voltage surge which will be a function of the current wave and the characteristic impulsive impedance of the structure.

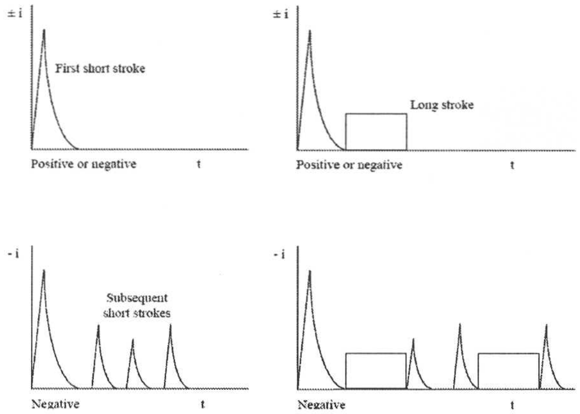

Fig. 5. Possible components of downward flashes (Typical in flat territory and to lower structures) [19]

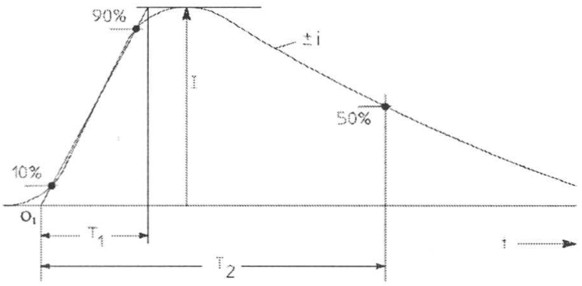

Fig. 6. Definitions of short stroke parameters (usually $T_2 < 2$ ms) [19]

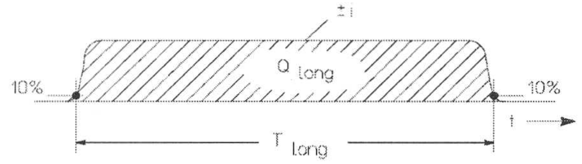

Fig. 7. Definitions of long stroke parameters (usually 2 ms$<T_{long}<$1 s) [19]

If the structure stroked is an electrical line it causes two voltage surges which will propagate at about 1/3 the speed of light along the line in both directions. When the voltage wave arrives to the first pole the voltage rise and if it exceeds the supported voltage by the insulators the back flashover happen. Fig. 8 represents this case, in which:

$$U = \frac{I}{2} \cdot Z_0 \tag{1}$$

The current wave shapes of the first short stroke 10/350 μs and the subsequent short strokes 0,25/100 μs may be defined [19] as:

$$i = \frac{I}{k} \cdot \frac{(t/\tau_1)^{10}}{1+(t/\tau_1)^{10}} \cdot exp(-t/\tau_2) \tag{2}$$

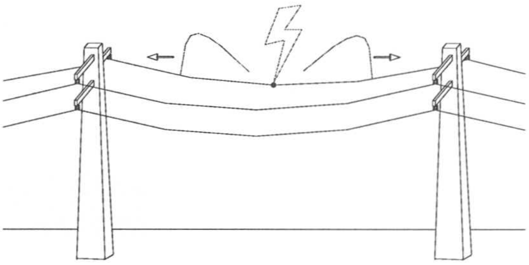

Fig. 8. Propagation of voltage surges along a line

IV. Protection Issues in Wind Power Plants

Damage events are registered in the databases as turbine faults caused directly or indirectly by lightning. A summary of these faults is shown in Table I for Germany, Denmark and Sweden. The lightning caused faults vary from 3.9 to 8 events per 100 turbine years. Restated, in Northern Europe one would expect that 4 to 8 turbines of every 100 would be damaged by lightning in a given year.

TABLE I
LIGHTNING DAMAGE FREQUENCY

Country	Period	Turbines in Database	Capacity in MW	Faults per 100 Turbine Year
Germany	1991-1998	1498	352	8.0
Denmark	1990-1998	2839	698	3.9
Sweden	1992-1998	428	178	5.8

When lightning hits a wind power plant without the proper protection, damages are often severe. Fig. 9 shows a wind turbine in Portugal damaged by lightning.

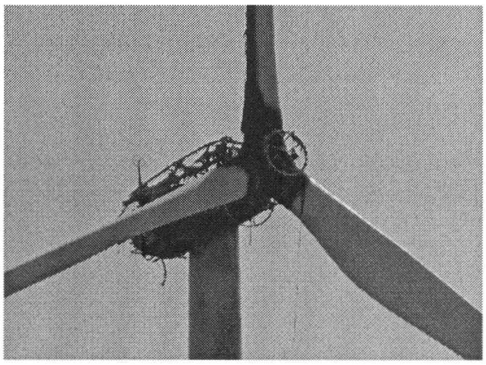

Fig. 9. Wind turbine in Portugal damaged by lightning

V. Wind Power Plant Description

The wind turbine considered has 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 vary 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 turbine is manufactured in several individual turbine sections connected using stress reducing L-flanges.

The LV/HV transformer is placed at the bottom of the turbine. It has 2500 kVA of rated power and has a special design to fit the reduced dimensions and working conditions of the turbine. In Fig. 10 a wind turbine is represented.

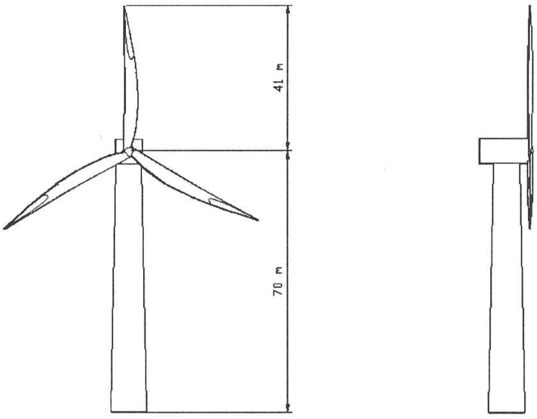

Fig. 10. Dimensions of the wind turbine

The following assumptions are made for the wind power plant:

- The gearbox, wind power generator, rectifier, and inverter (power conditioner) are treated as a unit, specifically, as a 690 V synchronous generator that is sufficiently stable at 50 Hz;
- A 690 V / 20 kV boost transformer (Y–Δ connection) is placed inside the wind power plant or installed rather close to the turbine. In addition, joint grounding of the primary and secondary side is assumed;
- In the transformer, only electromagnetic transfer is considered, and static transfer is ignored. This is because we assume surges with relatively long periods exceeding 100 μs;
- No lightning arresters to protect control circuits are connected to the primary side (low-voltage side) or secondary side (high-voltage side, power grid side) of the boost transformer;
- Interconnection to the power grid is through a 20/60 kV transformer;
- The grounding resistance considered for the electrode in the absence of lightning currents is 5 Ω.

In addition, we assume a standard lightning waveform with wave front duration of 1.2 μs, wave-tail duration of 50 μs, and a peak value of 10 kA. This is because in [20] 80% of lightning strikes have at least 10 kA of peak value.

VI. Electromagnetic Transients

The EMTP has been used to study transients in large scale power systems or in arbitrary electrical networks. In this paper the most recent version, the EMTP-RV, is applied. The complete software is also named EMTP/EMTPWorks, where EMTP designates the computational engine. The following explains briefly the most important concepts used in this paper.

VI.1. Lightning Current Source

The ICIGRE device was chosen to simulate the current lightning source. This device is used for accurate calculations of the lightning performance of equipment. A complete description of the reasoning behind the provided analytical representation of the current shape can be found in [21].

VI.2. Wind Turbine Structure

The Constant Parameter (CP) line is used to model the structure of a wind turbine. The CP is classified as a frequency independent transmission line model. Its main advantage is computational speed. It is less precise than frequency dependent line, but it can be successfully used in analysis of problems with limited frequency dispersion. The CP line parameters are calculated at a given frequency and that is why it is labeled as a frequency independent line.

VI.3. Ground Electrode

The dynamic performance of grounding electrodes under lightning currents must take into account both the time-dependent nonlinear soil ionization and the frequency-dependent phenomena. These phenomena might have mutually opposing effects since the soil ionization effectively improves, while frequency-dependent inductive behavior impairs, the grounding performance.

In this paper, we will use a circuit approach valid in the low-frequency domain, which leads to the well-known formulas for the grounding resistance.

VII. Circuit and Results

It is assumed that the blade tip of a wind turbine is stroked by lightning (ICIGRE). The lightning current flows through the metallic wires (CP) placed into blades, nacelle and the turbine itself, towards the ground electrode (R1, L1, C1) and creating an overvoltage. Inside the wind turbine a 690 V RMS generator (AC1) produces electrical energy which is delivered to the main power transformer (DD_1) and to the adapter transformer (DY_1), which feeds electronic control equipment (RL1).

Fig. 11 represents the described circuit.

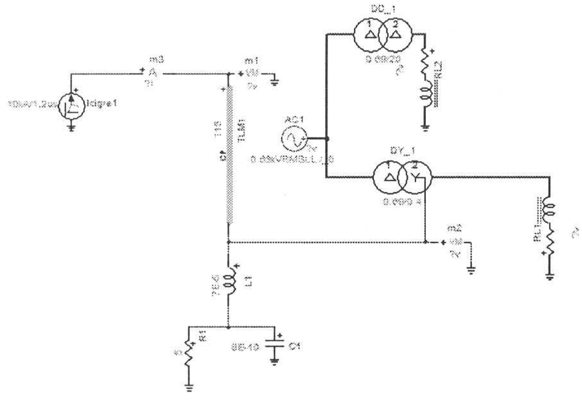

Fig. 11. EMTP-RV circuit

Fig. 12 presents the shape of the 1.2/50 lightning current with 10 kA of peak value using the source Icigre1 of EMTP-RV results.

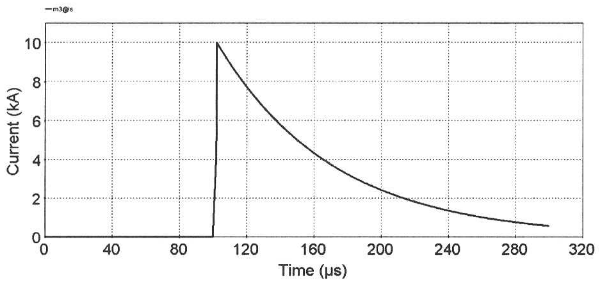

Fig. 12. Lightning current produced by source Icigre1

Fig. 13 presents the shape of the overvoltage that the turbine and blades have to support. The peak value of overvoltage reaches 1.2 MV.

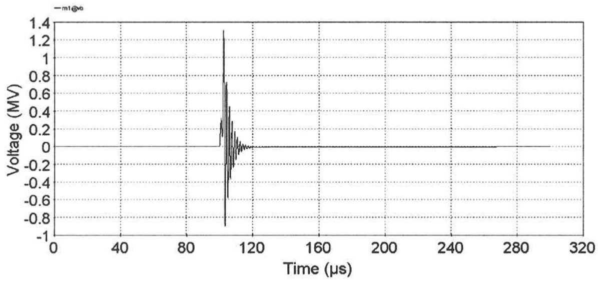

Fig. 13. Overvoltage at the wind turbine

Fig. 14 presents the shape of the overvoltages at the control electronic equipment. The overvoltage produced by lightning reaches almost 5 kV, which is much more than this kind of equipment can support.

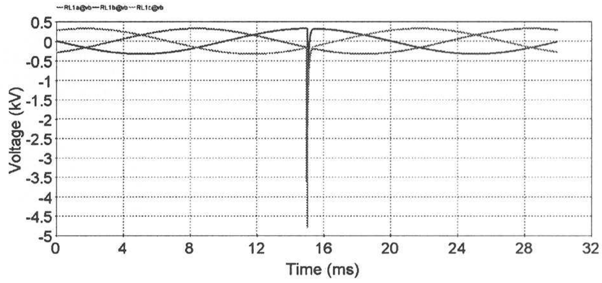

Fig. 14. Overvoltages at the electronic equipment

In these conditions, an adequate surge protective device (SPD) is necessary to limit the voltage below 1500 V.

VIII. Conclusion

This paper is concerned with lightning and overvoltage protection of wind power plants. The lightning location systems have been discussed, as well as the lightning surge parameters. Also, computational results have been obtained by using the latest version of EMTP-RV. The most recent national and international standards have been used in this work. When lightning hits a wind power plant without the proper protection, damages are often severe. Computational results allow determining the most adequate protection measures, avoiding downtime production and saving money. Accordingly, an adequate surge protective device may be necessary to limit the voltage.

References

[1] R.M. Ciric, N.L.J. Rajakovic, On the performance of low voltage network with small scale synchronous generators, *International Review of Electrical Engineering-IREE*, *vol. 4 n. 5*, September-October 2009, pp. 1025-1034.

[2] R. Melício, V.M.F. Mendes, J.P.S. Catalão, Modeling, control and simulation of full-power converter wind turbines equipped with permanent magnet synchronous generator *International Review of Electrical Engineering-IREE*, *vol. 5 n. 2*, March-April 2010, pp. 397-408.

[3] R.B. Rodrigues, V.M.F. Mendes, J.P.S. Catalão, Estimation of lightning vulnerability points on wind power plants using the rolling sphere method, *J. Electrost.*, *vol. 67 n. 5*, September 2009, pp. 774-780.

[4] IEC, Wind turbine generation system—24: Lightning protection, Tech. Rep. TR61400-24, 2002.

[5] F. Rachidi, M. Rubinstein, J. Montanyà, J.-L. Bermúdez, R.R. Sola, G. Solà, N. Korovkin, A review of current issues in lightning protection of new-generation wind-turbine blades, *IEEE Trans. Industrial Electronics*, *vol. 55 n. 6*, June 2008, pp. 2489-2496.

[6] Y. Yasuda, T. Hara, T. Funabashi, Analysis of lightning surge propagation in wind farm, *Electrical Engineering in Japan*, *vol. 162 n. 2*, January 2008, pp. 30-38.

[7] M. A. Omidiora, M. Lehtonen, Protection of lightning disturbances on MV underground cable, *International Review of Electrical Engineering-IREE, vol. 5 n. 1,* January-February 2010, pp. 317-326.

[8] I. Cotton, N. Jenkins, K. Pandiaraj, Lightning protection for wind turbine blades and bearings, *Wind Energy, vol. 4 n. 1*, January-March 2001, pp. 23-37.

[9] A. Kern, F. Krichel, Considerations about the lightning protection system of mains independent renewable energy hybrid-systems—practical experiences, *J. Electrost., vol. 60 n. 2-4*, March 2004, pp. 257-263.

[10] M. Paolone, F. Napolitano, A. Borghetti, C. A. Nucci, M. Marzinotto, F. Fiamingo, C. Mazzetti, H. Dellago, Models of wind-turbine main shaft bearings for the development of specific lightning protection systems, *Proc. IEEE Power Tech Conf.*, Lausanne, Switzerland, 2007.

[11] Y. Yasuda, T. Funabashi, Transient analysis on wind farm suffered from lightning, *Proc. 39th Int. Univ. Power Eng. Conf.*, 2004, pp. 202-206.

[12] A. Piantini, J.M. Janiszewski, A. Borghetti, C.A. Nucci, M. Paolone, A scale model for the study of the LEMP response of complex power distribution networks, *IEEE Trans. Power Delivery, vol. 22 n. 1*, January 2007, pp. 710-720.

[13] K. Yamamoto, T. Noda, S. Yokoyama, A. Ametani, An experimental study of lightning overvoltages in wind turbine generation systems using a reduced-size model, *Electrical Engineering in Japan, vol. 158 n. 4*, March 2007, pp. 22-30.

[14] J. Mahseredjian, C. Dewhurst, Using EMTP Tutorials and Reference, 2003-2008.

[15] E.P. Krider, R.C. Noggle, A.E. Pifer, D.L. Vance, Lightning direction finding systems for forest fire detection, *Bulletin of the American Meteorological Society, vol. 61 n. 9*, 1980, pp. 980-986.

[16] E.A. Lewis, R.B. Harvey, J.E. Rasmussen, Hyperbolic direction finding with sferics of transatlantic origin, *Journal of Geophysical Research, vol. 65 n. 7*, 1960, pp. 1879-1905.

[17] A.C.L. Lee, Ground truth confirmation and theoretical limits of an experimental VLF arrival time difference lightning flash locating system, *Quart J. Roy. Meteor. Soc., vol. 115*, 1989, pp. 1147-1166.

[18] P.W. Casper, R.B. Bent, Results from the LPATS USA national lightning detection and tracking system for the 1991 lightning season, *Proc. 21st Int. Conf. on Lightning Protection*, Berlin, 1992.

[19] IEC, Protection of structures against lightning—Part 1: General principles, 62305-1, 2006.

[20] R.B. Rodrigues, V.M.F. Mendes, J.P.S. Catalão, Lightning data observed with lightning location system in Portugal, *IEEE Trans. Power Delivery, vol. 25 n. 2*, April 2010, pp. 870-875.

[21] CIGRÉ WG 33.01, Guide to procedures for estimating the lightning performance of transmission lines CIGRÉ technical brochure, 1991.

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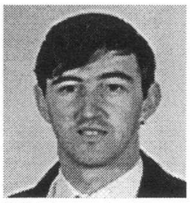

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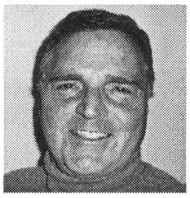

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