Electromagnetic Transients due to Lightning Strikes on Wind Turbines: A Case Study

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Abstract—The lightning discharge is one of the two natural sources of electromagnetic interference. Electric and magnetic fields generated by lightning represent a serious hazard to various systems, particularly those containing sensitive electronics. As wind power generation undergoes rapid growth, lightning damages involving wind turbines have come to be regarded with more attention. This paper is concerned with lightning surge propagation in wind turbines. We present a case study, based on a wind turbine with an interconnecting transformer, for the analysis of lightning surges. Computer simulations obtained by using the EMTP-RV code are presented, and conclusions are duly drawn.

I. INTRODUCTION

The very rapid growth in Denmark and Germany, up to around 2003/4, has now slowed, but Portugal, Spain, India, China and the United States are forging ahead and there are plans for further capacity in Canada, the Middle East, the Far East and South America. If the current growth rate continues, there may be about 150 GW of wind by 2010 [1].

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 [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.

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

- 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 grounding conditions.

Also, 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].

Direct and indirect lightning effects can produce severe damages on electrical and electronic systems, as well as on mechanical components such as blades and bearings [7]. Damages statistics of wind turbine components can be seen in the literature [4], as well as the risk analysis [4] and [8].

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 [9]. 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 turbine 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 turbine 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 [3]. 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 [10].

Usually, converter units and boost transformers are installed very close to wind turbines or inside wind turbines. 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 wind turbines and wind farms.

Scale models of electrical systems have been a popular tool, especially in the past, to predict power system transients after different types of perturbations [11]. For instance, a 3/100-scale model of an actual wind turbine generation system that has blades with a length of 25 m and a turbine that is 50 m high was considered in [12] and [13] for experimental and analytical studies of lightning overvoltages. However, in recent years, scale models 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 ElectroMagnetic Transients Program and RV stands for Restructured Version [14].

The paper is structured as follows. Section II describes the wind turbine. Section III presents some EMTP models. Section IV illustrates the results obtained by using the EMTP-RV code. Finally, in Section V conclusions are duly drawn.

II. WIND TURBINE DESCRIPTION

The wind turbine considered has a wind turbine 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 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. 1 a wind turbine is represented.

Figure 1. Dimensions of the wind turbine.

Ensuring proper power feed from wind turbines into the grid requires grid connection monitoring, shown in Fig. 2.

Figure 2. Grid connection monitoring on wind turbine.

Fig. 3 shows the electric schema of a LV/HV substation near the turbine. Distance among turbines is about 350 m.

Figure 3. LV/HV substation near the turbine.

The following assumptions are made for the wind turbine model:

- 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 turbine or installed rather close to the turbine. In addition, joint grounding of the primary and secondary side is assumed;

• In the transformer model, 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 [15] 80% of lightning strokes have at least 10 kA of peak value.

Lightning strikes at the tip of a windmill blade and then the surge current propagates through the grounding wire placed inside blades, nacelle and turbine to the grounding electrode.

Since the purpose of this study is comprehension of surge propagation in a wind turbine and insulation breakdown of the components inside wind turbines, we omit a discussion of blade damage and insulation faults in electric devices caused by a direct lightning stroke.

III. EMTP MODELS

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 models used in this paper.

A 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 this model and the reasoning behind the provided analytical representation of the current shape can be found in [16], from where the following equations were taken.

The current front of the first stroke is given by:

\[ I = At + B t^n \]  \hspace{1cm} (1)

where:

\[ A = \frac{1}{n-1} \left( 0.9n \frac{I_{\text{max}}}{t_n} - S_m \right) \]  \hspace{1cm} (2)

\[ B = \frac{1}{t_n^{n-1}} \left( S_m t_n - 0.9 I_{\text{max}} \right) \]  \hspace{1cm} (3)

The current tail equation is given by:

\[ I = I_t e^{-\frac{t-t_n}{t_0}} - I_{e} e^{-\frac{t-t_n}{t_0}} \]  \hspace{1cm} (4)

Equation (4) is used when EMTP enters the tail zone at \( t \geq t_n + t_{\text{start}} \).

B Wind turbine structure

To model the structure of a wind turbine, the Constant Parameter (CP) line is used. 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 and cable models, 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.

The CP line is a distributed parameter model. The basic frequency domain equations of the single phase distributed parameter line, shown in Fig. 4, are:

\[ \frac{dV(x,t)}{dx} = - R' I(x,t) - L' \frac{dI(x,t)}{dt} \]  \hspace{1cm} (5)

\[ \frac{dI(x,t)}{dx} = - G' V(x,t) - C' \frac{dV(x,t)}{dt} \]  \hspace{1cm} (6)

Figure 4. Distributed parameter line model.

The forward and backward traveling wave concept is interpreted using the illustration in Fig. 5 for the waveform \( V^\circ(x-vt) \). The traveling wave is first shown at \( t = 0 \) where at \( x = a \) it has a value of \( V^\circ(a) \). At any subsequent time \( t_x \) it has the same value at \( x = a + v t_x \) (distortion is neglected) as it formerly had at \( x = a \). It means that the voltage distribution has moved in the direction of positive x. A similar explanation is used for \( V^\circ(x+vt) \) which is traveling in the negative x direction.

Figure 5. The traveling wave function at \( t = 0 \) and \( t = t_x \)
Precise modeling of the dynamic performance of grounding electrodes under lightning currents must include 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 the case of lightning, the current that is injected in the grounding electrodes is a fast-varying current pulse with high peak values. The dynamic response of the grounding electrodes subjected to such current pulses is predominantly influenced by:

• the soil ionization in the immediate proximity of the grounding electrode, which is related to the current pulse intensity;

• the lightning pulse propagation along the grounding electrode, which is related to the current pulse front time.

However, 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 $R$. Therefore, for the horizontal electrode, according to Sunde [17]:

$$R = \frac{\rho}{\pi \ell} \left[ \ln \left( \frac{2 \ell}{\sqrt{2ad}} \right) - 1 \right]$$

(7)

where $\rho = 100 \ \Omega \cdot m$ is resistivity of the earth, $\ell = 40 \ m$ is grounding electrode length, $a = 4.10^{-3} \ m$ is radius, and $d = 1 \ m$ is depth of burial of horizontal electrode, assuming $\ell \gg a$ and $\ell \gg d$. $R$ in (7) is derived by applying the static image method. A simple lumped-circuit high-frequency model suggested by Rudenberg [18] is used. $R$ is computed by (7) and the grounding capacitance $C$ is computed based on the relationship [17]:

$$C = \frac{\rho \varepsilon}{R}$$

(8)

where $\varepsilon = 4.10^{-11} \ F/m$ is permittivity of the a quartz soil.

As mentioned in [17], the inductance $L$ of a horizontal wire reduces slightly as the depth of the wire is increased. Therefore, for horizontal “wires at ordinary depths, the inductances are substantially the same as for wires at the surface” [17], given as:

$$L = \frac{\mu \ell}{2\pi} \left[ \ln \left( \frac{2 \ell}{a} \right) - 1 \right]$$

(9)

where $\mu = 1.26.10^{-6} \ H/m$ is permeability of the soil, which is usually assumed to be equal to the permeability of vacuum.

**Surge arrester**

The basic arrester model equation is given by (9) [14]. Where $i_a$ is the arrester current and $v_a$ is the arrester voltage. For SiC (Silicon Carbide) arresters the value of $\alpha$ is between 2 to 6. For MO (Metal Oxide) arresters we have $10 \leq \alpha \leq 60$. The $k$ parameter is a constant used in fitting the arrester characteristic.

$$i_a = kv_a^\alpha$$

(10)

**IV. 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 VRMS generator (AC1) produces electrical energy which is delivered to the main power transformer (DD_1) and to the adapter transformer (DY_1). The DY_1 transformer feeds electronic control equipment (RL1). Fig. 6 represents the described circuit.
Fig. 9 presents the shape of the overvoltage at the ground electrode placed into the foundation of wind turbine. The peak value of overvoltage reaches 400 kV.

![Figure 9. Overvoltage at the ground electrode](image)

Fig. 10 presents the shape of the voltages at the synchronous generator. The overvoltage produced by lightning did not affect the generator.

![Figure 10. Output voltages of the synchronous generator](image)

Fig. 11 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.

![Figure 11. Overvoltages at the electronic equipment](image)

In these conditions, an adequate surge protective device (SPD) is necessary to limit the voltage below 1500 V as shown in Fig. 12.

![Figure 12. EMTP-RV circuit with SPD](image)

The action of the SPD limiting the overvoltage can be observed in Fig. 13.

![Figure 13. Limited overvoltages at the electronic equipment](image)

V. CONCLUSIONS

This paper is concerned with lightning surge propagation on wind turbines. The most recent national and international standards have been used in this work. Also, computer simulations have been obtained by using the latest version of EMTP-RV. Reference values of international standards have been adapted to Portuguese reality. Nevertheless, results are also true for other countries. An accurate risk analysis taking into account the ground flash density of the region where the wind farm would be installed is of the utmost importance. The risk analysis and computer simulations can determine which are the most adequate protection measures, and where they must be installed, avoiding downtime production and saving money. As future work, we intend to use a more precise modeling of the grounding electrodes under lightning currents, including both the time-dependent nonlinear soil ionization and the frequency-dependent phenomena.

REFERENCES


