ELECTROMAGNETIC TRANSIENTS ANALYSIS ON WIND TURBINES DURING LIGHTNING STRIKES

Rafael B. Rodrigues¹, Victor M.F. Mendes¹, João P.S. Catalão²

Instituto Superior de Engenharia, Lisbon, Portugal, E-mail: rbrodrigues@deea.isel.ipl.pt; vfmendes@isel.pt
University of Beira Interior, Covilhã, Portugal, E-mail: catalao@ubi.pt

Abstract — This paper is concerned with lightning surge propagation on wind turbines. As wind power generation undergoes rapid growth, lightning incidents involving wind turbines have come to be regarded as a serious problem. Hence, simulation studies are of major importance to decide the appropriated protection to prevent damage due to lightning. A case study based on a wind farm model having five wind turbines is presented for the analysis of lightning surges. Simulations carried out by using the EMTP-RV Electromagnetic Transients Program are presented, and conclusions are duly drawn.

Introduction

The need to control climate changes and the dependence in fossil-fuel costs stimulate the ever-growing use of renewable energies worldwide. Concerning renewable energies, wind power is a priority for most countries expressed in their 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 [1]. 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 incidents involving wind turbines have come to be regarded as a serious problem [2]. Lightning protection of wind turbines presents problems that are not normally seen with other structures [3].

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 [4]. 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 [5]. Nevertheless, a lack of studies exists yet regarding lightning protection of wind turbines. 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, as well as of mechanical components such as blades and bearings [6]. Damages statistics of wind turbine components has been analyzed in the literature, as well as the risk analysis [7].

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 [8]. 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 [3], 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 [2]. Events on low-voltage circuits are not triggered only by direct lightning strikes but also induced lightning and backflow surges propagating around wind farms just after lightning strikes on other wind towers [9].
Usually, converter units and boost transformers are installed 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 [5]. 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 models of electrical systems have been a popular tool, especially in the past, to predict power system transients after different types of perturbations [10]. 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 tower that is 50 m high was considered in [11] 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 behaviour of power systems in an accurate way, such as the Electromagnetic Transients Program (EMTP and EMTP-RV) [12].

In this paper, we present a case study, based on a wind farm model with five wind turbines, for the analysis of lightning surges. Computer simulations obtained by using the EMTP-RV code are presented, and conclusions are duly drawn.

**Method and models**

The well known EMTP is used to study transients in large scale power systems or in arbitrary electrical networks. In this paper the version EMTP-RV is applied. EMTP-RV designates the latest version of the EMTP and RV stands for Restructured Version. 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.

**Lightning current source**

The \textit{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 source and the reasoning behind the provided analytical representation of the current shape can be found in [13]. The following equations are taken from [13].

The current front of the first stroke is given by:

\[ I = At + Bt^n \]  

Where:

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

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

The current tail equation is given by:

\[ I = I_1 e^{-\frac{t-t_n}{\tau_1}} - I_2 e^{-\frac{t-t_n}{\tau_2}} \]

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

To model the structure of a wind tower 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 labelled as a frequency independent line.

![Fig. 1 Distributed parameter line model](image)

The CP line is a distributed parameter model. The basic frequency domain equations of the single phase distributed parameter line shown in Figure 1 are:

\[
\frac{dV(x,t)}{dx} = -R' I(x,t) - L' \frac{dI(x,t)}{dt} \\
\frac{dI(x,t)}{dx} = -G' V(x,t) - C' \frac{dV(x,t)}{dt}
\]

(5)

(6)

The forward and backward traveling wave concept is interpreted using the illustration in Figure 2 for the waveform \( V^+(x-vt) \). The traveling wave is first shown at \( t = 0 \) where at \( x = a \) it has a value of \( V^+(a) \). At any subsequent time \( t_x \) it has the same value at \( x = a + vt_x \) (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 \( V^-(x+vt) \) which is traveling in the negative \( x \) direction.

![Fig. 2 The traveling wave function at \( t = 0 \) and \( t = t_x \)](image)

**Ground electrode**

The ground electrode is generally embedded into the circular foundation of the wind tower with the shape of a ring. Assuming that the concrete of the foundation is homogeneous and isotropic, the equation (7) [14] can be used to calculate the ground electrode resistance.
\[ R = 0.355 \frac{\rho}{2\pi r} \left( \log_{10} \frac{16r}{d} + \log_{10} \frac{4r}{h} \right) \]

being \( \rho \) the resistivity of the concrete (150-200 \( \Omega \text{m} \)), \( r \) the radius of the ring (6 m), \( d \) the diameter of the ground electrode wire (0.02 m) and \( h \) the distance of the ground electrode wire from the surface of soil (0.8 m). A small inductance [15] completes the simplified electrode ground model.

**Soil coupling**

Experimental results [15] have been measured the voltage at different distances from the ground electrode after the injection of a lightning current on it. Based on these results and with wind towers separated from nearly 350 m it is assumed that no significant coupling between ground electrodes occurred.

**Surge arrester**

The basic arrester model equation is given by (8). 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 \( 10 \leq \alpha \leq 60 \). The \( k \) parameter is a constant used in fitting the arrester characteristic.

\[ i_a = k v_a^\alpha \]  

(8)

**Circuit and results**

It is assumed that a wind tower in a wind farm plant is stroked by lightning (I_CIGRE). The lightning current flows over the structure of wind tower (CP) towards the ground electrode (R1, L1) and creating an overvoltage. Inside the wind tower a 690 V_{RMS} generator (AC1) produces electrical energy which is delivered to the main power transformer (YD_1) and to the adapter transformer (DY_2). The DY_2 transformer feeds electronic control equipment (RL1). The ground electrode represented by R3, L3 has the same characteristics of R1, L1 and in practice is the same. Figure 3 represents the described circuit.

![Fig. 3 EMTP-RV circuit](image-url)
Figures 4 and 5 present results of EMTP-RV simulation. The first one of Figure 4, $I_{\text{sig}1}$, is the shape of the 1.2/50 lightning current with 10 kA of peak value. It was found that 80% of lightning currents in Portugal have at least 10 kA [16]. TLM1 and m1 are respectively the voltages measured at the wind tower and the ground electrode of it.

![Figure 4: Applied lightning current and measured voltages at wind tower (TLM1) and ground electrode (m1)](image)

Figure 5 presents the measured voltages at three phases feeding the electronic control equipment. At $t = 20$ ms lightning strikes the wind tower. The overvoltage experienced by the ground electrode flow over the connection ground wire to the secondary of the adapter transformer and reaches the load. The electronic control equipment cannot sustain this overvoltage without protection. In these conditions an adequate surge protective device (SPD) is necessary to limit the voltage below 1500 V. The action of the SPD limiting the overvoltage can be observed in Figure 5.

![Figure 5: Measured voltages at three phases load (RL1)](image)
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 Electromagnetic Transients Program. Reference values of international standards have been adapted to Portuguese reality. Nevertheless, results are also true for other countries. It is of utmost importance an accurate risk analysis taking into account the ground flash density of the region where wind farm would be installed. The risk analysis and computer simulations can determine the most adequate protection measures and where they must be mounted, avoiding downtime production and saving money.

References


