Lightning Surges on Wind Power Systems: Study of Electromagnetic Transients

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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. Nevertheless, no known studies exist yet in Portugal regarding lightning protection of wind turbines. In this paper we present an overview of Electro-Magnetic Transients Program (EMTP) models for the analysis of lightning surges.

Key words

Lightning surge, wind turbines, transient analysis, protection.

1. Introduction

The need to control climate changes and the increase in fossil-fuel costs stimulate the ever-growing use of renewable energies worldwide. 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 [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. These problems are a result of the following [3]:

1) wind turbines are tall structures of up to more than 150 m in height;
2) wind turbines are frequently placed at locations very exposed to lightning strokes;
3) 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;
4) the blades and nacelle are rotating;
5) 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;
6) 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 [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, no known studies exist yet in Portugal 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 [7], as well as the risk analysis [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 [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]. 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 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 [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 tower that is 50 m high was considered in [12,13] 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 behaviour of power systems in an accurate way, such as the Electro-Magnetic Transients Program (EMTP) [14].

In this paper we present an overview of EMTP models for the analysis of lightning surges.

2. Wind Farm Description

The wind power plant under study has five 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 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 tower is 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. 1 a wind turbine is represented. The wind turbines were modelled in 3D with AutoCAD.

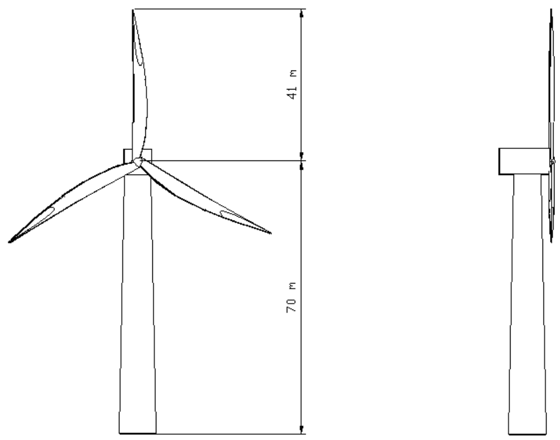

Fig. 1. Dimensions of a wind turbine.

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

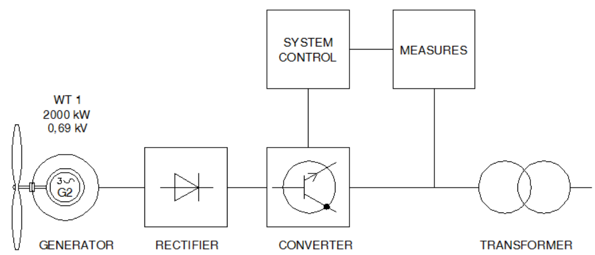

Fig. 2. Grid connection monitoring on wind turbine.

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

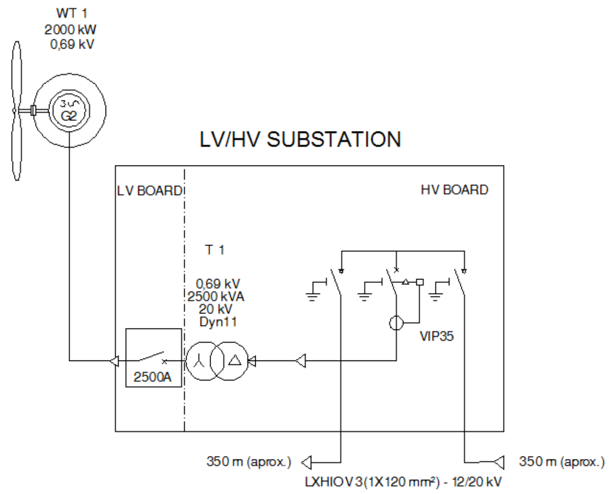

Fig. 3. LV/HV substation near the tower.

Fig. 4 shows the electric schema of the external part main substation with surge protective devices (SPD) installed.

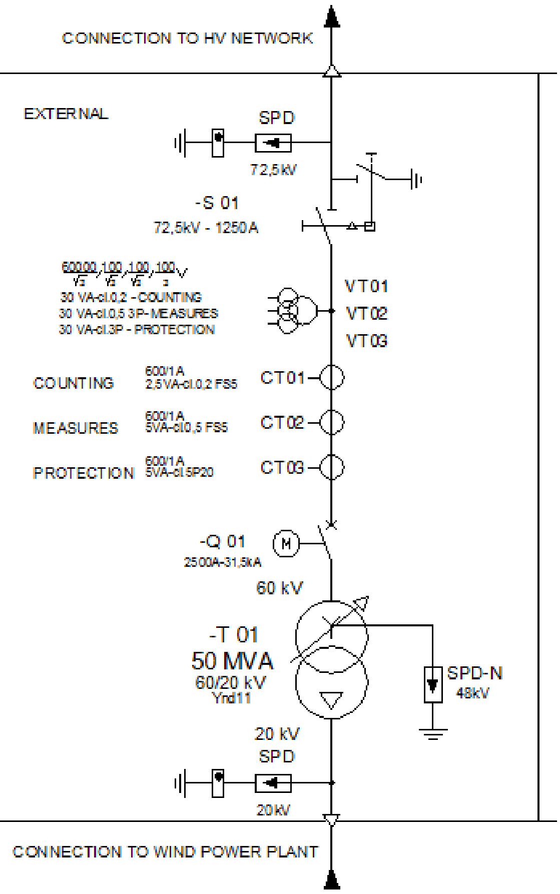

Fig. 4. Electric schema of the external part main substation with SPD installed.

The following assumptions are made for the wind farm model:

1) 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;
2) a 690 V / 20 kV boost transformer (Y–Δ connection) is placed inside the windmill tower or installed rather close to the tower. In addition, joint grounding of the primary and secondary side is assumed;
3) in the transformer model, only electromagnetic transfer is considered, and static transfer is ignored. This is because surges with relatively long periods exceeding 100 μs are assumed;
4) no lightning arresters to protect control circuits are connected to the primary side (low-voltage side, windmill side) or secondary side (high-voltage side, power grid side) of the boost transformer;
5) interconnection to the power grid is through a 20/60 kV transformer;

For the grounding resistance around the windmill tower, two cases may be considered: 10 Ω and 2 Ω.

The value of 10 Ω is somewhat greater than the normal grounding resistance of real wind turbines. However, the widely used ring grounding often has an inductive component, and in penetration by high-frequency surges, such as lightning surges, the resistance can become higher than usual. Thus, 10 Ω is considered as well.

In addition, it is assumed: a standard ramp lightning waveform with a wavefront duration of 1.2 μs, a wave-tail duration of 50 μs, and a peak value of 20 kA. This lightning strikes at the tip of a windmill blade, and then the surge propagates directly to the grounding electrode via the grounding wire.

The ultimate goal of this study will be the comprehension of surge propagation in a wind farm, and of insulation breakdown in non-stricken windmills. Only surge propagation inside the wind farm will be considered. A discussion of blade damage and insulation faults in electric devices caused by a direct lightning stroke will be omitted.

3. EMTP Models

A. Lightning Current Impulse

The lightning current impulse is modelled on a current source, EMTP module type 15. The parameters are chosen to achieve a current wave shape of 1.2/50 and current amplitude of 20 kA – a value, which will occur in the system with a probability of 50 % [15].

B. Metal-Oxide Arresters

The metal-oxide arresters (MOA) are modelled by EMTP module type 92, extended by inductances and stray-capacitances as shown in Fig. 5 [16]. Of course, this model is empirical and not an exact physical representation of an arrester; but it reflects its performance under lightning current impulse stress with sufficient accuracy.

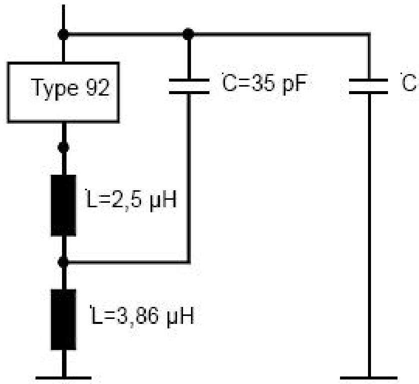

Fig. 5. EMTP model of the MOA.

C. Core-Type Distribution Transformers

A transient simulation model of core-type distribution transformers is adopted [17]. The model takes into account the following effects:

1) winding-to-winding and winding-to-enclosure capacitance;
2) skin effects of winding conductors and an iron core (eddy current losses);
3) multiple resonance due to the combination of winding inductance and turn-to-turn capacitance.

Each effect is represented by a circuit block and added to the fundamental equivalent circuit of transformer that consists of an ideal transformer, winding resistance, leakage inductance, magnetizing conductance, and inductance.

Thus, the model can reproduce not only the impedance characteristics seen from each terminal, but also the transfer characteristics between the primary and secondary sides from the power frequency to a few megahertz. At the same time, the model agrees to the fundamental equivalent circuit of transformer at the power frequency.

The parameters of the model are determined by frequency-characteristic measurements using an impedance analyzer. The saturation and hysteresis effects of an iron core are usually ignored in lightning-surge studies. But those effects can be introduced by the methods proposed in [18].

A 2500-kVA transformer should be modelled by the proposed method, and various transient calculations may then be carried out by EMTP.

For the accurate modelling of core-type distribution transformers, the following effects should be taken into account:

1) winding-to-winding and winding-to-enclosure capacitance;
2) skin effects of winding conductors and an iron core;
3) multiple resonance due to the combination of winding inductance and turn-to-turn capacitance;
4) saturation and hysteresis effects of an iron core.

Fig. 6 is the equivalent circuit, and it consists of the fundamental equivalent circuit of transformer and circuit blocks representing the effects 1–4 [17].

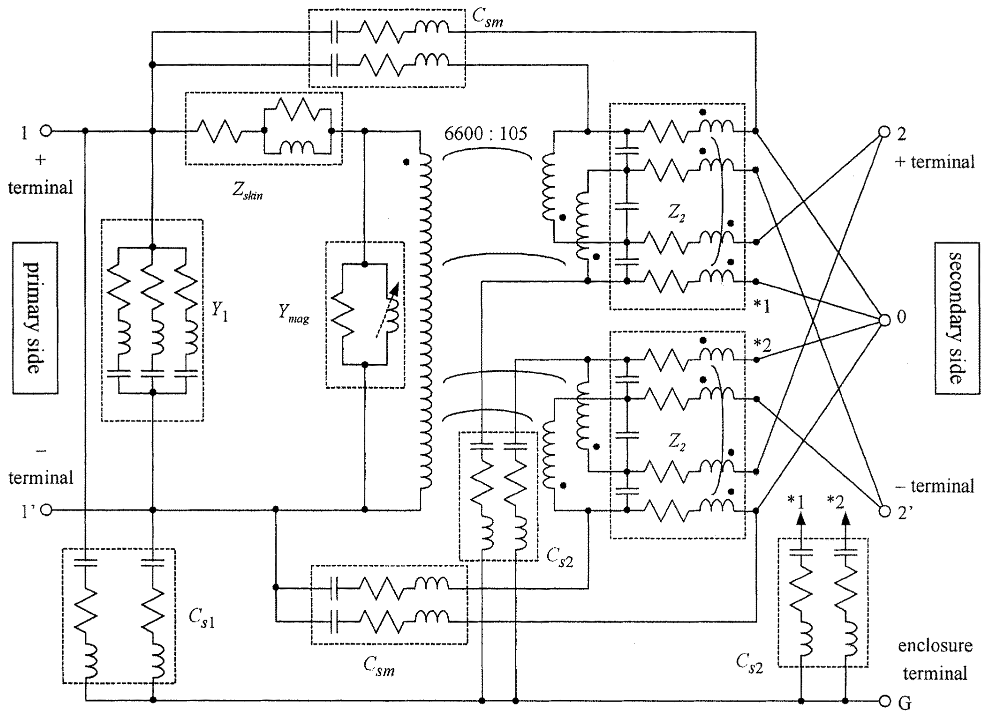

Fig. 6. Equivalent circuit. (1) Winding-to-winding and winding-to-enclosure capacitance: C_{S1}, C_{S2}, C_{Sm}. (2) Skin effects of winding conductors and an iron core: Z_{Skin}. (3) Multiple resonance due to the combination of winding inductance and turn-to-turn capacitance: Y_1, Z_2. (4) Saturation and hysteresis effects of an iron core: Y_{mag} [17].

One is represented by capacitors C_{S1}, C_{S2} and C_{Sm}, and their parasitic resistance and inductance, and two is by circuit block Z_{Skin}.

As for number three, the multiple resonance of the primary side is represented by circuit block Y_1 and that of the secondary by Z_2.

Number four is usually not considered in lightning-surge studies, where magnetic flux cannot penetrate into an iron core due to its skin effect, and most current flows through turn-to-turn capacitance. CIGRE WG 33.02 also suggests that four can be ignored for the lightning-surge studies. However, number four can be incorporated in the proposed model by modifying the inductor of the magnetizing circuit Y_{mag}., and possibly also the resistor, to be nonlinear as proposed in [18].

It should also be noted that the proposed model agrees to the fundamental equivalent circuit of transformer at a power frequency, and that the model can be applied to transients starting from a steady state.

4. Conclusion

In this paper we present an overview of Electro-Magnetic Transients Program (EMTP) models for the analysis of lightning surges. Lightning protection of wind turbines will be of ever-increasing importance, as wind power generation undergoes rapid growth. Future work will present simulation results in order to show the accuracy of the proposed model.

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