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Article

Analysis of Transient Phenomena Due to a Direct Lightning Strike on a Wind Energy System

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Abstract: This paper is concerned with the protection of wind energy systems against the direct effects of lightning. As wind power generation undergoes rapid growth, lightning damages involving wind turbines have come to be regarded as a serious problem. Nevertheless, very few studies exist yet in Portugal regarding lightning protection of wind energy systems using numerical codes. A new case study is presented in this paper, based on a wind turbine with an interconnecting transformer, for the analysis of transient phenomena due to a direct lightning strike to the blade. Comprehensive simulation results are provided by using models of the Restructured Version of the Electro-Magnetic Transients Program (EMTP), and conclusions are duly drawn.

Keywords: wind turbines; lightning; transients; overvoltages 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. Wind power is considered as one of the most promising renewable energy sources after its rapid expansion all over the World during the last decades [1,2].

Wind power generation is a priority for Portugal's energy strategy. The new wind power capacity target is 5500 MW by 2012, and 8500 MW by 2020, increasing considerably the role that wind power will play in the power generation mix. As wind power generation undergoes rapid growth, lightning damages involving wind turbines have come to be regarded with more attention. The incidence of lightning strokes is a very serious problem, as it can produce dangerous overvoltages [3]. Hence, lightning studies are of major importance. Lightning protection of wind energy systems 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 more than 150 m in height;
- wind turbines are frequently placed at locations very exposed to lightning;
- 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.

Modern wind turbines are characterized not only by greater heights, but also by the presence of ever-increasing amounts of 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, very few studies exist yet in Portugal regarding lightning protection of wind energy systems using models of the Electro-Magnetic Transients Program (EMTP). Also, surge propagation during lightning strikes at wind farms located in Portugal is still far from being clearly understood, given that the Portuguese Lightning Location System (LLS) has only been in operation since 2003, thus much work remains to be done in this area.

Direct and indirect lightning strokes can produce damages to electrical and electronic systems [7], as well as of mechanical components such as blades and bearings [8]. Damage statistics of wind turbine components have been analyzed in the literature [9], as well as the risk analysis [10].

Concerning mechanical components, blades and bearings are the most involved parts. In particular, lightning-damages produced on bearings positioned at the mechanical interface between rotating parts of the wind turbine can result in high maintenance costs, considering the difficulties involved in the replacement of such components [11]. 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 in wind turbine equipment (more than 50%) 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 have been

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 [12].

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 [13].

Usually, converter units and boost transformers are installed very close to 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 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 wind turbines, but also in adjacent wind turbines 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 energy systems.

Scale models of electrical systems have been a popular tool, especially in the past, to predict power system transients after different types of perturbations [14]. 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 [15] for experimental and analytical studies of lightning overvoltages. However, in recent years scale models have been progressively replaced by numerical codes, capable of describing the transient behaviour of power systems in an accurate way, such as the EMTP used in or the EMTP-RV that designates the Restructured Version of the EMTP [16].

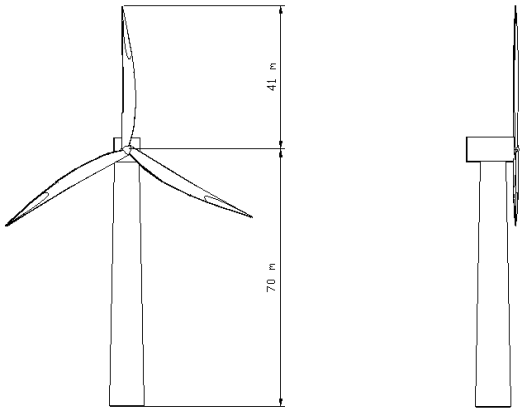
A new case study is presented in this paper, based on a wind turbine with an interconnecting transformer, for the analysis of lightning surges. The blade is considered to be directly stroked by lightning. Comprehensive simulation results obtained by using the EMTP-RV are presented, and conclusions are duly drawn.

2. Wind Turbine Description

A wind turbine with 2 MW of rated power is considered. The hub height varies between 70 m and 138 m. The rotor diameter is about 82 m. 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 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. The output voltage and frequency change with the speed, implying the need for electronic frequency conversion in order to make a connection to the electric grid. 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. The wind turbine shown in Figure 1 was modeled in 3D with AutoCAD [7].

Figure 1. Dimensions of the wind turbine [7].



Ensuring proper power feed from the wind turbine into the grid requires grid connection monitoring, shown in Figure 2 [7].

Figure 2. Grid connection monitoring on the wind turbine [7].

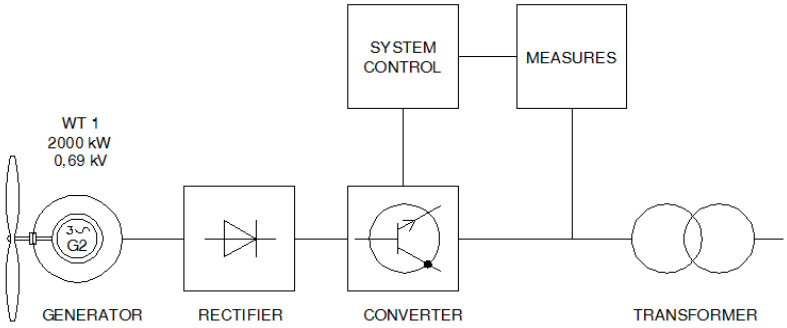
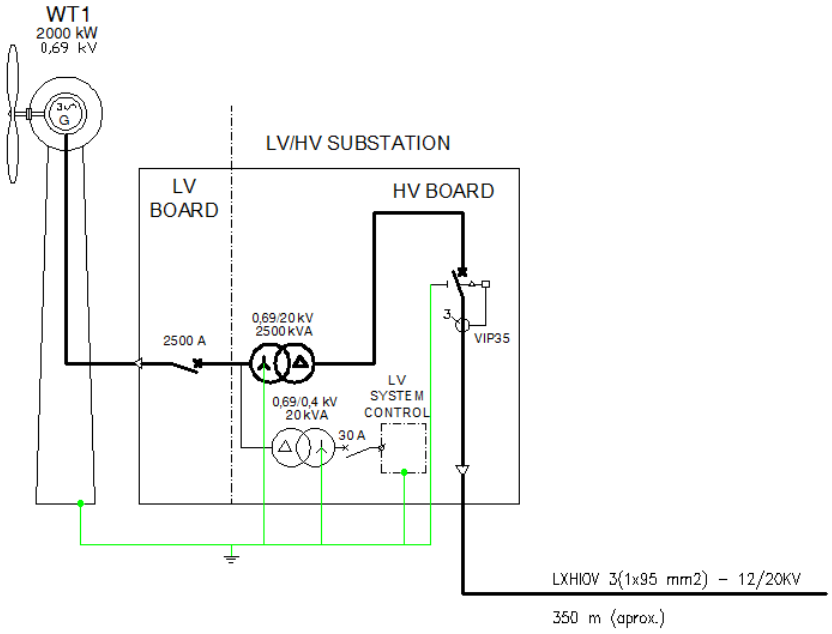


Figure 3 shows the electric schema of a LV/HV substation near the wind turbine [7].

Figure 3. LV/HV substation near the wind turbine [7].



The wind turbine model is characterized by:

- a 690 V synchronous generator, sufficiently stable at 50 Hz, is considered;
- a 690 V/20 kV boost transformer is placed inside the wind turbine or installed rather close to the wind turbine; joint grounding of the primary and secondary side is assumed;
- the transformer model considers only electromagnetic transfer, considering surges only with relatively long periods exceeding 100 μs; the static transfer is ignored;
- the 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 1 Ω.

In addition, a standard lightning current waveform is considered with wave front duration of 10 μs, wave-tail duration of 350 μs, and a peak value of 10 kA. According to reference [17], the Portuguese lightning activity shows that 80% of first CG strokes have a peak current lower than about 8–10 kA. This is the reason for choosing the peak current of 10 kA for the first CG stroke. As long as we are dealing with the first return stroke we chose the 10/350 μs, defined by IEC61312-1 to be the waveform for first lightning stroke.

Lightning strikes at the tip of the wind turbine blade, and then the surge current flows through the grounding wire placed inside the blades, nacelle and the turbine itself towards 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, a discussion of blade damage and insulation faults in electric devices caused by a direct lightning stroke is omitted.

3. System Modeling

EMTP has been used to study transients in large scale power systems or in arbitrary electrical networks. In this paper the most recent version, 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.

3.1. 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 this model and the reasoning behind the provided analytical representation of the current shape can be found in [16].

3.2. Wind Turbine Structure

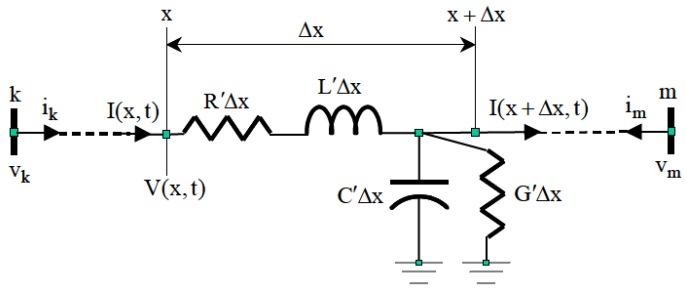
To model the blade and the tower of a wind turbine, the Constant Parameter (CP) line is used, which is a frequency independent transmission line model. For the purpose of this paper, the CP line model can be successfully used. The frequency dependence of the parameters was also not considered in [18], because the authors concluded that it has scarce influence on the transient responses of the tower system. Besides, the same remark is provided in [19], where the frequency dependence of the parameters is again not considered, since some studies have shown that the skin effect has little influence on the lightning transient response.

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

$$\frac{dV(x,t)}{dx} = -R'I(x,t) - L'\frac{dI(x,t)}{dt} \quad (1)$$

$$\frac{dI(x,t)}{dx} = -G'V(x,t) - C'\frac{dV(x,t)}{dt} \quad (2)$$

Figure 4. Distributed parameter line model.



The CP line parameters are calculated at a given frequency, which is better to take it above 1 MHz [15], and that is why it is labeled as frequency independent. The CP line parameters are calculated taking into account technical information from the manufacturer, such as, material characteristics and dimensions of components.

3.3. Ground Electrode

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 [20]. These phenomena might have mutually opposing effects since the soil ionization effectively improves the grounding performance, while frequency-dependent inductive behavior impairs it. In the case of lightning, the current that is injected in the grounding electrodes is a fast-changing 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.

The ground electrode model used in this paper is very often used with lightning simulation purposes for HV transmission lines and towers [16]. It considers a nonlinear resistance using controlled resistance and admittance. The presence of the current source provides an option for creating a piecewise linear resistance function. Any segment k of such a function can be represented by the Norton circuit equivalent:

$$i_k = Y_k\, v_k + I_k \quad (3)$$

The term Y_k is the partial derivative at the operating point k:

$$Y_k = \frac{\partial i_k}{\partial v_k} \tag{4}$$

when using the same ground electrode for safety and service purposes, the Portuguese regulation requires a maximum value for earth resistance of 1 Ω. This value is assumed in the absence of lightning current flowing through it.

3.4. Surge Arrester

The basic arrester model equation is given by (5), where i_a is the arrester current and v_a is the arrester voltage [21]:

$$i_a = k\, v_a^{\alpha} \tag{5}$$

for silicon carbide (SiC) arresters the value of α is between 2 and 6. For metal oxide (MO) arresters the value is $10 \leq \alpha \leq 60$. The k parameter is a constant used in fitting the arrester characteristic. At page 5 the lightning current considered was characterized. In these conditions, the SPD have to fit these parameters. The main function of SPD is that it reduces the overvoltage to a sustainable value for electric equipment (2.5 kV) and electronic equipment (1.5 kV). Due to the large energy associated to the lightning discharge and the low overvoltage value allowed for electronic devices it is usual to mount in cascade two different SPD technologies.

3.5. Transformers

Transformers in operation are subject to various kinds of overvoltages caused by lightning strikes. Two different voltage transformers are used. The YD_2 transformer raises the voltage to 20 kVrms, reducing losses in energy transportation. This transformer is modeled by a three phase EMTP-RV model with separated coils and magnetization current consideration. The configuration YD reduces the propagation of overvoltages through the HV grid. The DY_1 transformer adapts the LV voltage to the LV control equipment. This transformer is also modeled by a three phase EMTP-RV model with separated coils and magnetization current consideration. The configuration DY is necessary to create the neutral used for mono phase equipment. A detailed surge transfer model of a transformer has been developed in [22].

3.6. Capacitive Coupling

The capacitive effect between the tower and the cable inside or the LV/HV transformer has been considered because the lightning current flowing through the tower will increase radically its potential. In these circumstances disruptions could occur and consequently dangerous overvoltages to the equipment. The values used for capacitances in this model are theoretical.

3.7. Nonlinear Load

The nonlinear load at the circuit model represents a LV control system. The values used for nonlinear resistances in this model are also theoretical.

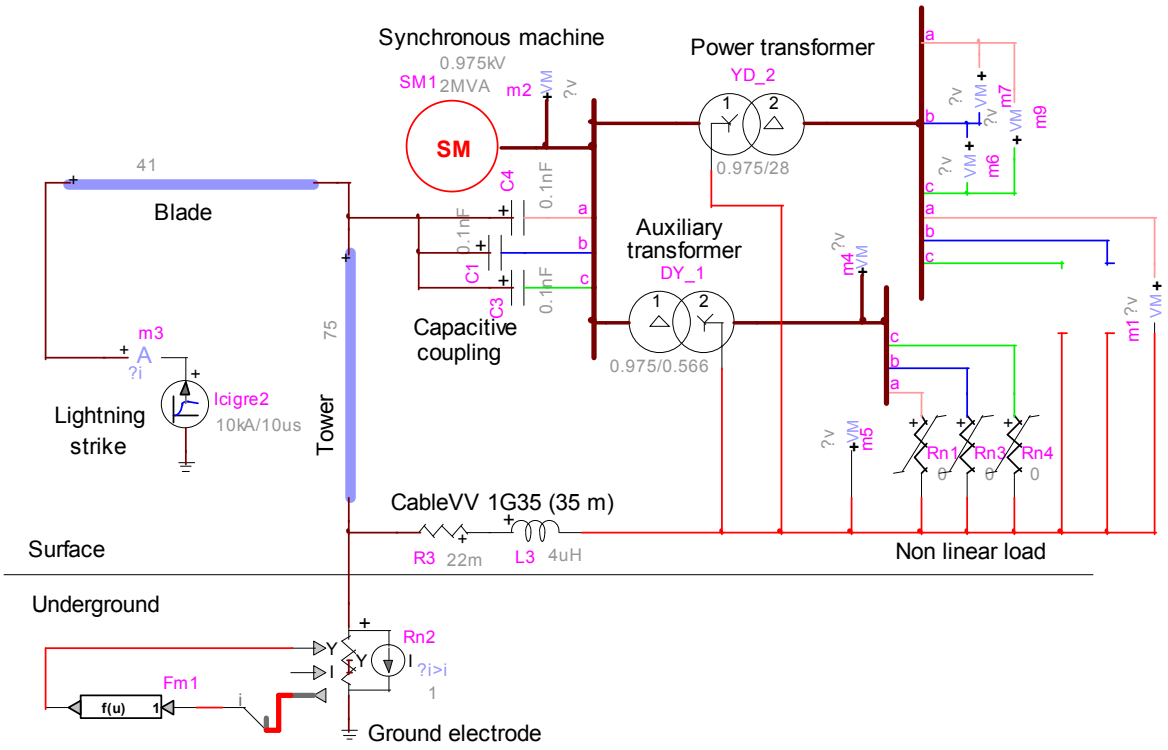
3.8. Cable Model

For the purpose of this paper, the LV cable between the generator and the LV/HV transformer has been considered as an ideal cable due to its small length. To model the cable inside the tower of a wind turbine, the CP line could be used. The model must take into account the cable data (geometry, insulation thickness, *etc*.), as indicated in [23].

4. Simulation Results

It is assumed that the blade tip of a wind turbine is struck by lightning (ICIGRE). The lightning current flows through the metallic wires (CP) placed into blades, nacelle and the turbine itself, towards the ground electrode, shown in Figure 5, and creating an overvoltage.

Figure 5. EMTP-RV circuit without SPD.



Inside the wind turbine a 690 VRMS generator (SM) produces electrical energy which is delivered to the main power transformer (YD_2) and to the adapter transformer (DY_1). The DY_1 transformer feeds electronic control equipment (Rn1, Rn3 and Rn4). Figure 6 presents the shape of the overvoltage that the turbine and blades have to support. The peak value of overvoltage reaches 1.2 MV.

Figure 6. Overvoltage at the primary side of transformers.

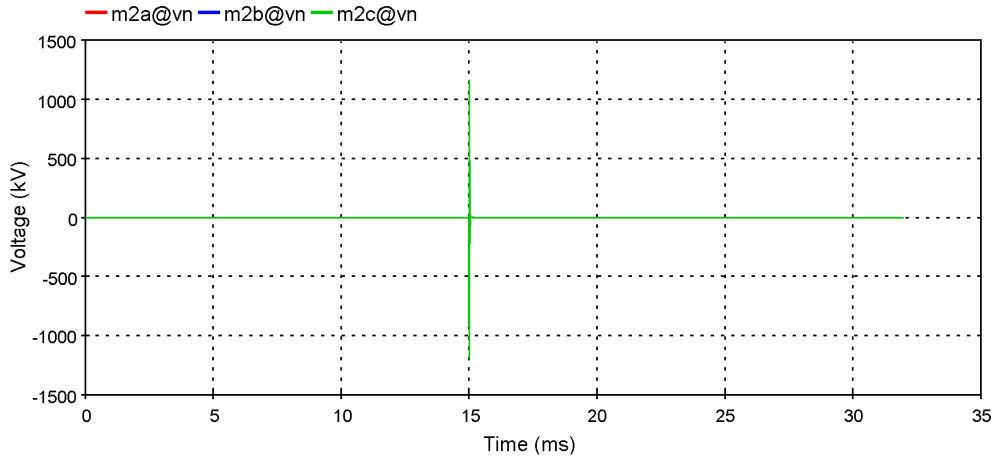


Figure 7 presents the shape of the overvoltage at the secondary side of the main power transformer. The peak value of overvoltage reaches 80 kV.

Figure 7. Overvoltage at the secondary side of the main power transformer.

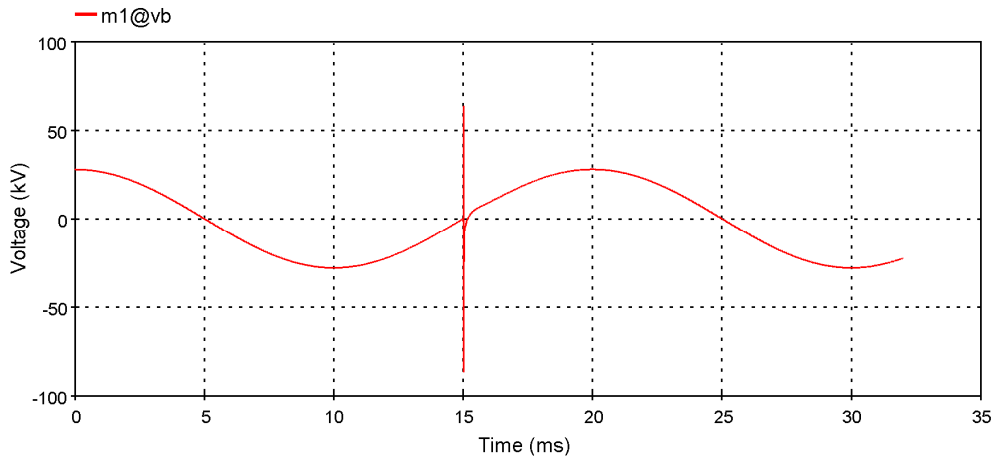
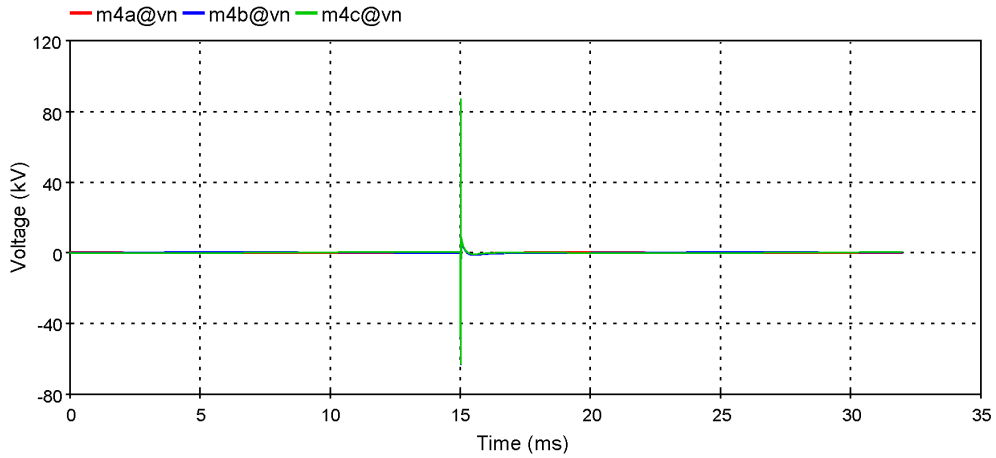


Figure 8 presents the shape of the overvoltage at the electronic control equipment. The peak value of overvoltage reaches almost 80 kV, which is much more than this kind of equipment can support.

Figure 8. Overvoltage at the secondary side of the auxiliary transformer.



In these conditions, an adequate surge protective device (SPD) is necessary to limit the voltage below 1500 V, as shown in Figure 9.

Figure 9. EMTP-RV circuit with SPD.

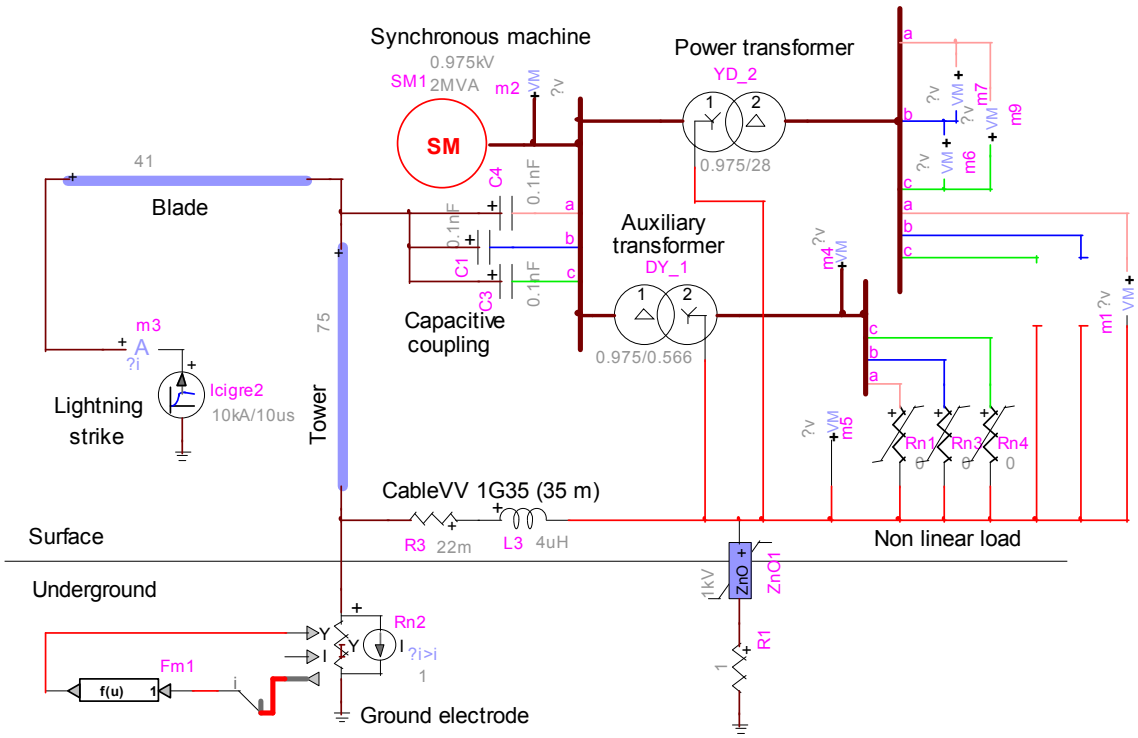


Figure 10 presents the shape of the overvoltage at the secondary side of the main power transformer with SPD. The peak value of overvoltage is now negligible due to SPD action.

Figure 10. Limited overvoltage at the secondary side of the main power transformer with SPD.

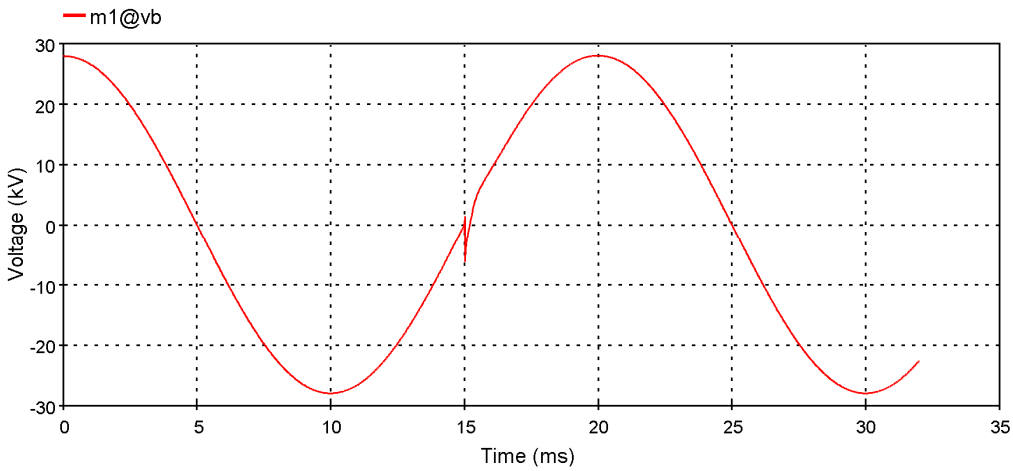
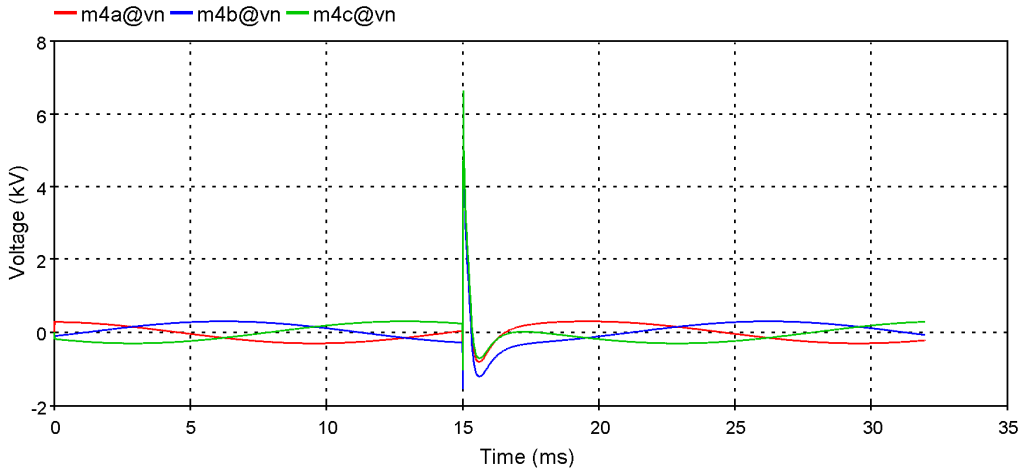


Figure 11 presents the shape of the overvoltages at the electronic control equipment with SPD. The peak value of overvoltage reaches 6 kV, which is still more than this kind of equipment can support. Thus, additional protection measures are needed to keep overvoltages under the maximum value supported by the electronic control equipment.

Figure 11. Overvoltage at the secondary side of the auxiliary transformer with SPD.



The EMTP-RV circuit with SPD ideally connected is shown in Figure 12.

Figure 12. EMTP-RV circuit with SPD ideally connected.

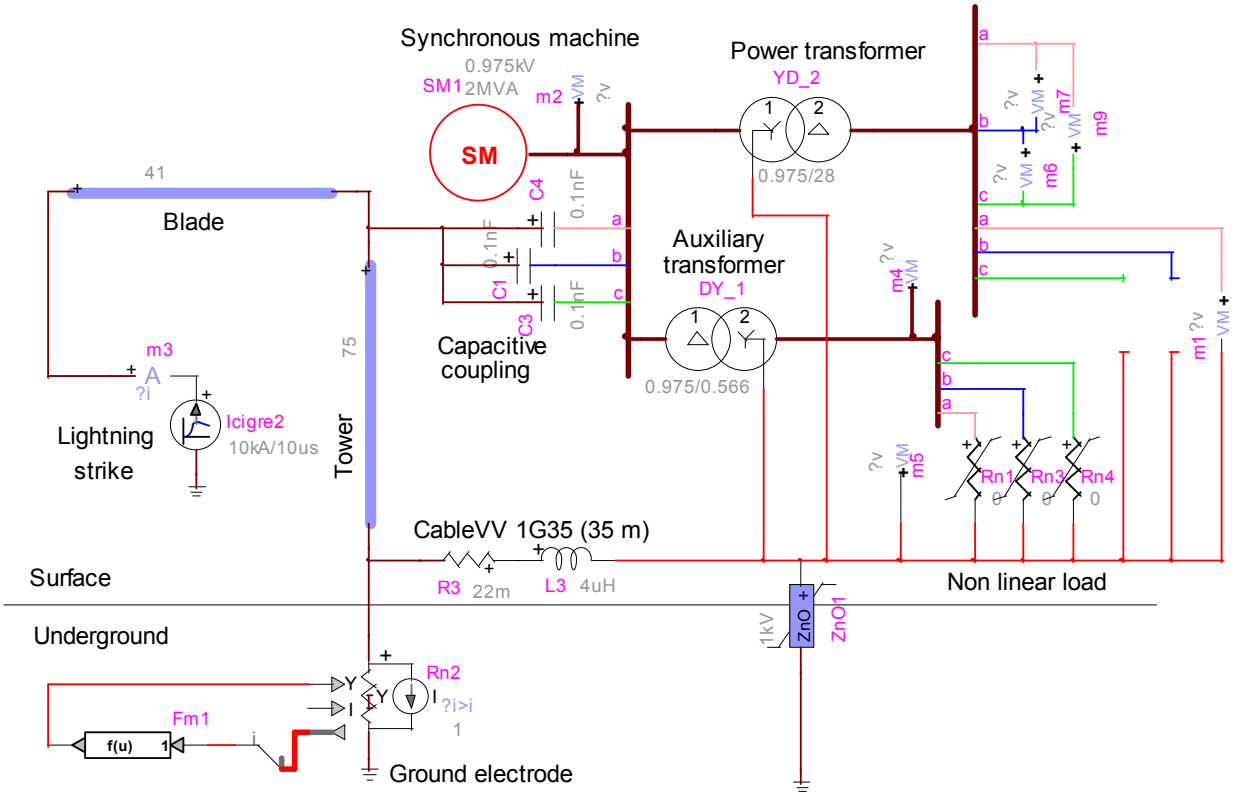
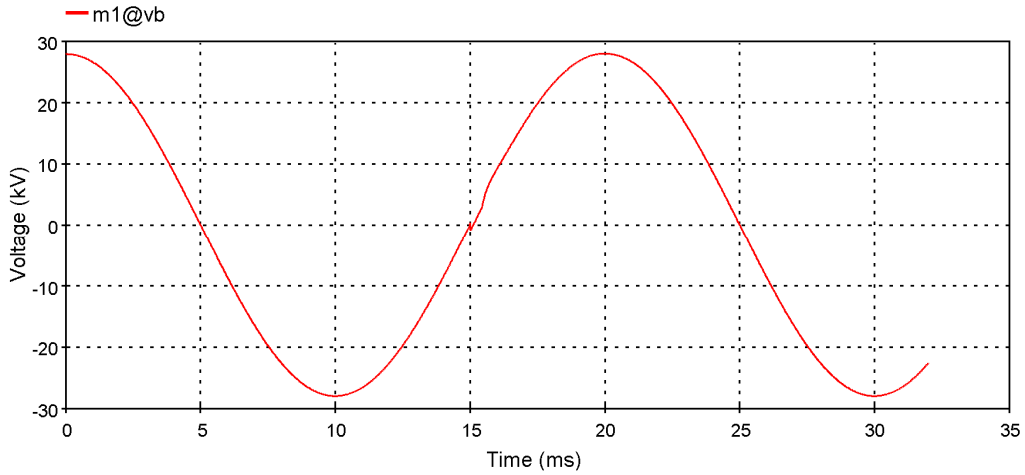


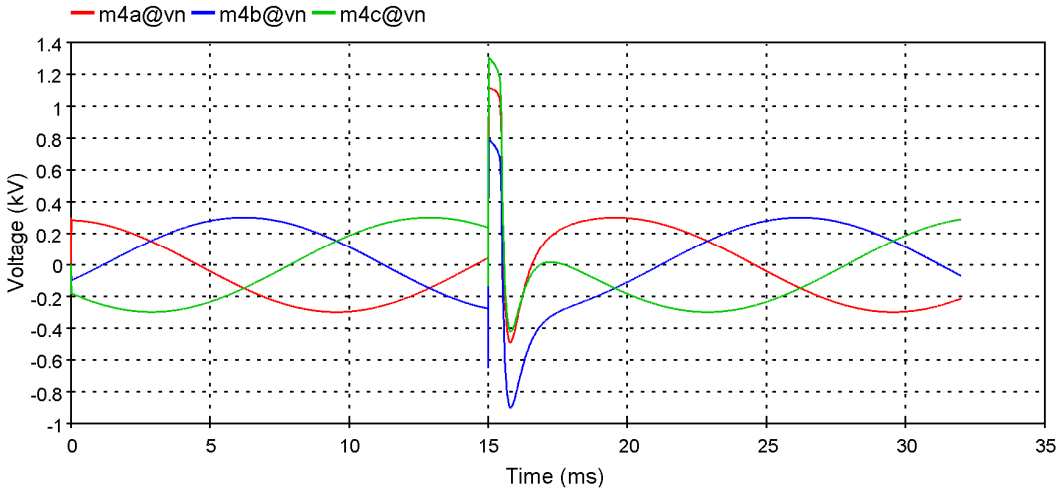
Figure 13 presents the shape of the overvoltage at the secondary side of the main power transformer with SPD ideally connected. The peak value of overvoltage is negligible due to SPD action.

Figure 13. Limited overvoltage at the secondary side of the main power transformer with SPD ideally connected.



Finally, Figure 14 presents the shape of the overvoltages at the electronic control equipment with SPD ideally connected. The peak value of overvoltage now remains below 1.4 kV.

Figure 14. Limited overvoltage at the secondary side of the auxiliary transformer with SPD ideally connected.



These results confirm the need of having the lowest ground impedance possible. To achieve that in soils with high resistivity the most practical ground electrode could be established into the concrete foundations. The use of appropriate SPD is crucial in order to protect the vulnerable electronic equipment, since the wind tower is a natural lightning captor and thus a source of overvoltages. In certain circumstances it would be necessary to connect SPD in differential and common mode.

5. Conclusions

This paper presents a new case study, based on a wind turbine with an interconnecting transformer, for the analysis of transient phenomena due to a direct lightning strike to the blade. The most recent international standards have been used in this work. Also, comprehensive simulation results are

obtained by using EMTP-RV, the most recent EMTP version. A lightning current with 10 kA of peak value has been considered. This CG lightning current strikes the tip of the blade. The peak value of the overvoltage reaches 6 kV at the electronic control equipment, even with a SPD installed. This occurs because the connection of SPD to ground is not ideal. Only an SPD ideally connected in common mode would allow limiting the overvoltage at the secondary side of the auxiliary transformer to 1.4 kV. Nevertheless, the SPD is sufficient to reduce the overvoltage at the high-voltage branch of the main power transformer. The analysis carried out is very helpful on finding which are the most adequate protection measures, and where they must be located, thus avoiding downtime production and saving money.

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