# Protection of wind energy systems against the indirect effects of lightning

R.B. Rodrigues [a], V.M.F. Mendes [a], J.P.S. Catalão [b,c,]*

[a] Departmental Area of Electrical Engineering and Automation, Instituto Superior de Engenharia de Lisboa, R. Conselheiro Emídio Navarro, 1950-062 Lisbon, Portugal
[b] Department of Electromechanical Engineering, University of Beira Interior, R. Fonte do Lameiro, 6201-001 Covilha, Portugal
[c] Center for Innovation in Electrical and Energy Engineering, Instituto Superior Técnico, Technical University of Lisbon, Av. Rovisco Pais, 1049-001 Lisbon, Portugal

**Abstract**

This paper is concerned with the protection of wind energy systems against the indirect effects of lightning. As wind energy is gaining increasing importance throughout the world, lightning damages involving wind energy systems have come to be regarded with more attention. Nevertheless, there are still very few studies in Portugal regarding lightning protection of wind energy systems using models of the Electro-Magnetic Transients Program (EMTP). Hence, a new case study is presented in this paper, based on a wind turbine with an interconnecting transformer, considering that lightning strikes the soil near the tower at a distance such that galvanic coupling occurs through the grounding electrode. Computer simulations obtained by using EMTP-RV are presented and conclusions are duly drawn.

## 1. Introduction

Renewable energy sources, especially wind energy, are widely applied as a mean to reach emission reduction [1]. Hence, it is expected that wind energy will turn out to be an important part of the future energy policy for Portugal [2,3], increasing significantly the share of renewable energy sources in the overall generation mix at the expense of the conventional fossil energies [4].

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. 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 [5,6].

As wind power generation undergoes rapid growth, lightning damages involving wind energy systems have come to be regarded with more attention [7-10].

* Corresponding author at: Department of Electromechanical Engineering, University of Beira Interior, R. Fonte do Lameiro, 6201-001 Covilha, Portugal. Tel.: +351 275 329914; fax: +351 275 329972.
*E-mail address:* catalao@ubi.pt (J.P.S. Catalão).

Lightning is in fact a tremendous phenomenon of nature, as beautiful as dangerous. Fig. 1 shows Lisbon under a storm in 2009. The incidence of lightning strokes is a very serious problem [11], as it can produce dangerous overvoltages [12].

"See Fig. 1 at the end of the manuscript".

Lightning protection of wind energy systems presents problems that are not normally seen with other structures. These problems are a result of the following [13]:

• 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.

When lightning hits a wind energy system without the proper protection, damages are often severe. Fig. 2 shows a wind turbine in Portugal damaged by lightning [14].

"See Fig. 2 at the end of the manuscript".

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 [15]. 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 [16]. Nevertheless, there are still very few studies 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) is in operation only since 2003, thus much work remains to be done in this area.

Direct and indirect lightning strokes can produce damages on electrical and electronic systems, as well as of mechanical components such as blades and bearings [17]. 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 [18]. Thus, an effective lightning protection system should protect not only against the direct effects of lightning, but also against its indirect effects. The possible damages due to overvoltage transients induced by indirect lightning strikes are thoroughly studied in this paper, which is a new contribution to earlier studies.

Scale models of electrical systems have been a popular tool, especially in the past, to predict power system transients after different types of perturbations [19]. For instance, a 3/100-scale model of an actual wind energy system that has blades with a length of 25 m and a turbine that is 50 m high was considered in [20, 21] 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 EMTP, while RV stands for Restructured Version [22].

A new case study is presented in this paper, based on a wind turbine with an interconnecting transformer, considering that lightning strikes the soil near the tower at a distance such that galvanic coupling occurs through the grounding electrode. Computer simulations obtained by using EMTP-RV are presented and conclusions are duly drawn.

This paper is organized as follows. Section 2 presents the description of the wind turbine. Section 3 explains the EMTP models. Section 4 presents the case study and the simulation results. Finally, concluding remarks are given in Section 5.

## 2. Wind turbine description

A wind turbine with 2 MW of rated power is considered. 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. The wind turbine shown in Fig. 3 was modeled in 3D with AutoCAD.

"See Fig. 3 at the end of the manuscript".

Ensuring proper power feed from the wind turbine into the grid requires grid connection monitoring, shown in Fig. 4.

"See Fig. 4 at the end of the manuscript".

Fig. 5 shows the electric schema of a LV/HV substation near the wind turbine.

"See Fig. 5 at the end of the manuscript".

The following assumptions are made for the wind turbine model:

• the 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 is placed inside the wind turbine or installed rather close to the wind 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;

• as a first approach, 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. This will allow evaluating afterwards its real need;

• 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 $\Omega$.

In addition, a standard lightning current waveform is assumed with wave front duration of 10 μs, wave-tail duration of 350 μs, and a peak value of 10 kA. This is because, in Portugal, 80% of lightning strikes have a peak current higher than 8-10 kA [3]. Lightning strikes the soil near the tower at a distance such that galvanic coupling occurs through the grounding electrode.

## 3. 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, 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 is an EMTP-RV model that 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 [22], from where the following equations were taken.

The current front of the first stroke is given by:

$$I = At + Bt^n \tag{1}$$

where:

$$A = \frac{1}{n-1}\left(0.9n\frac{I_{max}}{t_n} - S_m\right) \tag{2}$$

$$B = \frac{1}{t_n^n(n-1)}\left(S_m t_n - 0.9I_{max}\right) \tag{3}$$

The current tail equation is given by:

$$I = I_1 e^{\frac{-(t-t_n)}{t_1}} - I_2 e^{\frac{-(t-t_n)}{t_2}} \tag{4}$$

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

*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 [23], because the authors concluded that it has scarce influence on the transient responses of the tower system. Besides, the same remark is provided in [24], 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 are:

$$\frac{dV(x,t)}{dx} = -R'I(x,t) - L'\frac{dI(x,t)}{dt} \tag{5}$$

$$\frac{dI(x,t)}{dx} = -G'V(x,t) - C'\frac{dV(x,t)}{dt} \tag{6}$$

The CP line parameters are calculated at a given frequency, which is better to take it above 1MHz [20,21], and that is why it is labeled as frequency independent. The CP line parameters were 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. 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-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.

The ground electrode model used in this paper is very often used with lightning simulation purposes for HV transmission lines and towers. 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:

$$i_k = Y_k \, v_k + I_k \tag{7}$$

The $Y_k$ is actually the derivative at the operating point k:

$$Y_k = \frac{\partial i_k}{\partial v_k} \tag{8}$$

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

*3.4 Surge arrester*

The basic arrester model equation [22] is given by (9), where $i_a$ is the arrester current and $v_a$ is the arrester voltage:

$$i_a = k \, v_a^{\alpha} \tag{9}$$

For SiC (Silicon Carbide) arresters the value of $\alpha$ is between 2 to 6. For MO (Metal Oxide) arresters the value is $10 \leq \alpha \leq 60$. The k parameter is a constant used in fitting the arrester characteristic.

## 4. Simulation results

In a first approach, the EMTP-RV circuit is considered without SPD, as shown in Fig. 6. 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 auxiliary transformer (DY_1). The DY_1 transformer feeds electronic control equipment (Rn1, Rn3 and Rn4).

"See Fig. 6 at the end of the manuscript".

Lightning strikes the soil near the tower. Fig. 7 presents the shape of the overvoltage at the primary side of transformers, where "m" stands for measure and "a, b, c" stands for phases L1, L2 and L3. The peak value of overvoltage surpasses 10 kV.

"See Fig. 7 at the end of the manuscript".

Fig. 8 presents the shape of the overvoltage at the secondary side of the main power transformer.

"See Fig. 8 at the end of the manuscript".

Fig. 9 presents the shape of the overvoltages at the electronic control equipment. The peak value of overvoltage reaches almost 10 kV, which is more than this kind of equipment can support.

"See Fig. 9 at the end of the manuscript".

In these conditions, an adequate surge protective device (SPD) is necessary to limit the voltage below 1500 V, as shown in Fig. 10.

"See Fig. 10 at the end of the manuscript".

Fig. 11 presents the shape of the overvoltage at the primary side of transformers with a SPD installed. The peak value of overvoltage decreases to approximately 5 kV.

"See Fig. 11 at the end of the manuscript".

Fig. 12 presents the shape of the overvoltage at the secondary side of the main power transformer. The peak value of overvoltage is inferior, but still noticeable.

"See Fig. 12 at the end of the manuscript".

Fig. 13 presents the shape of the overvoltages at the electronic control equipment with SPD. The peak value of overvoltage reaches almost 6 kV, which is still more than this kind of equipment can support.

"See Fig. 13 at the end of the manuscript".

Only with a perfect SPD connection the overvoltage could remain below the upper limit supported by the control equipment, as will be shown hereafter.

The EMTP-RV circuit with SPD ideally connected is shown in Fig. 14.

"See Fig. 14 at the end of the manuscript".

Fig. 15 presents the shape of the overvoltage at the primary side of transformers with SPD ideally connected. The peak value of overvoltage decreases to less than 4 kV.

"See Fig. 15 at the end of the manuscript".

Fig. 16 presents the shape of the overvoltage at the secondary side of the main power transformer. The peak value of overvoltage is now negligible.

"See Fig. 16 at the end of the manuscript".

Finally, Fig. 17 presents the shape of the overvoltages at the electronic control equipment with SPD ideally connected. The peak value of overvoltage is now below 1500 V, so the control equipment is safe.

"See Fig. 17 at the end of the manuscript".

## 5. Conclusions

This paper presents a case study, based on a wind turbine with an interconnecting transformer, for the analysis of lightning surges. The most recent international standards have been used in this work. Also, computer simulations are obtained by using the most recent EMTP version, the EMTP-RV. Reference values of international standards have been adapted to Portuguese reality. Nevertheless, results are also true for other countries. A lightning current with 10 kA of peak value has been considered stroking the ground near the tower. The peak value of the overvoltage reaches almost 6 kV at the electronic control equipment, even with a SPD installed. This occurs because the connection of SPD to ground is not ideal. To reduce the overvoltage to an acceptable value, SPD in differential mode could be installed. Nevertheless, the SPD considered is sufficient to reduce the overvoltage at the high-voltage branch of the main power

transformer. The computer simulations have proven to be very helpful on finding which are the most adequate protection measures, and where they must be located, thus avoiding downtime production and saving money.

**Acknowledgements**

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**Figure captions**



Fig. 1. Lightning over Lisbon in 2009.



Fig. 2. Wind turbine in Portugal damaged by lightning.
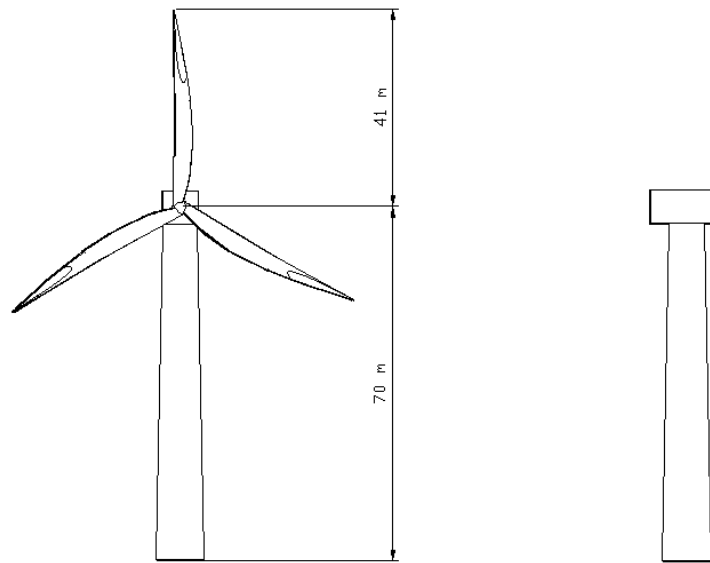
Fig. 3. Dimensions of the wind turbine.
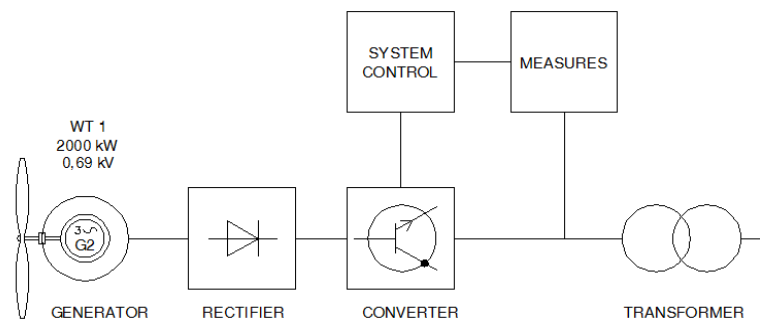


Fig. 4. Grid connection monitoring on the wind turbine.
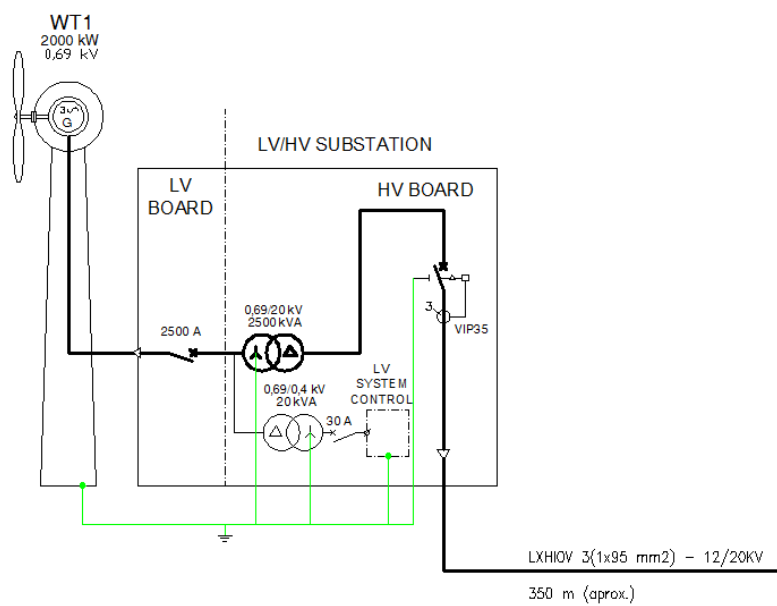


Fig. 5. LV/HV substation near the wind turbine.
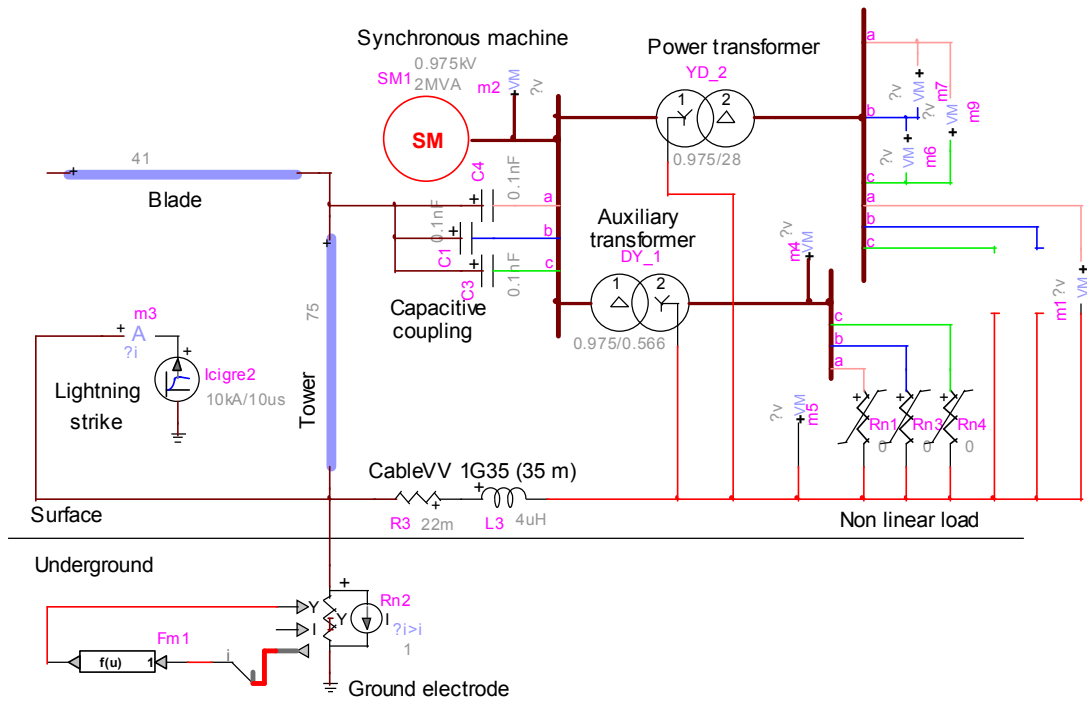
Fig. 6. EMTP-RV circuit without SPD.
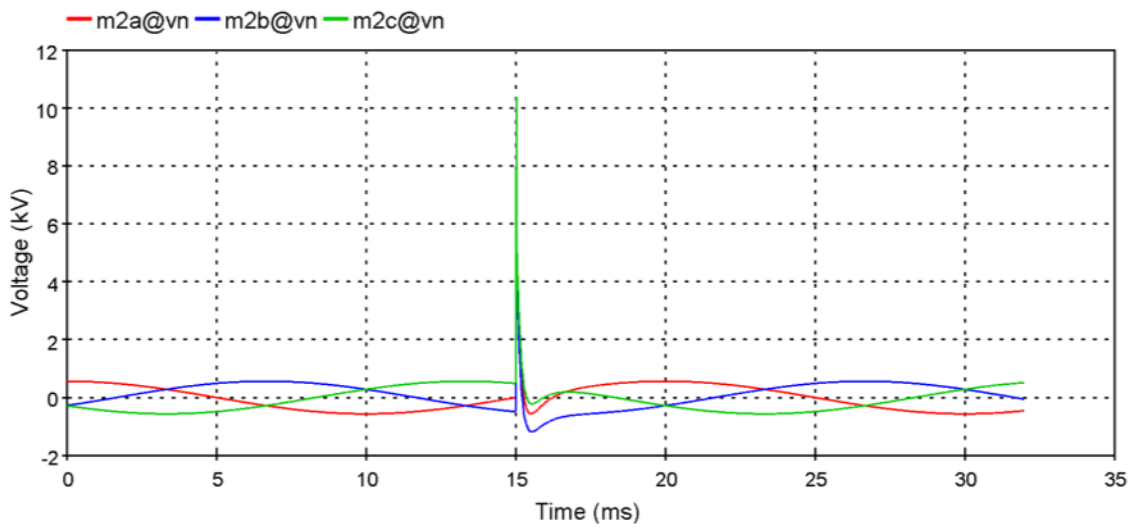


Fig. 7. Overvoltage at the primary side of transformers. m2a@vn, m2b@vn e m2c@vn states for voltages output (scope) from node to ground
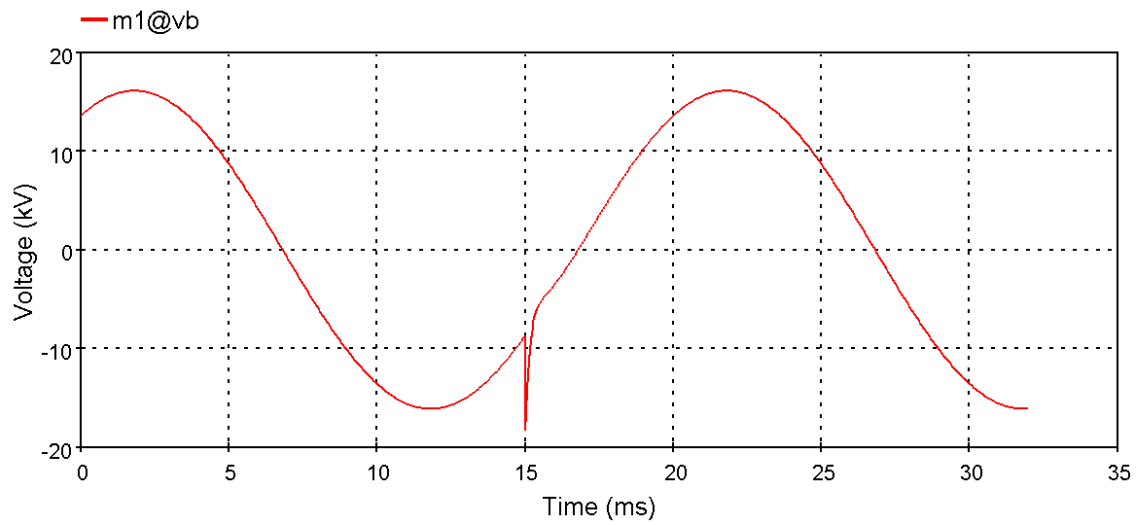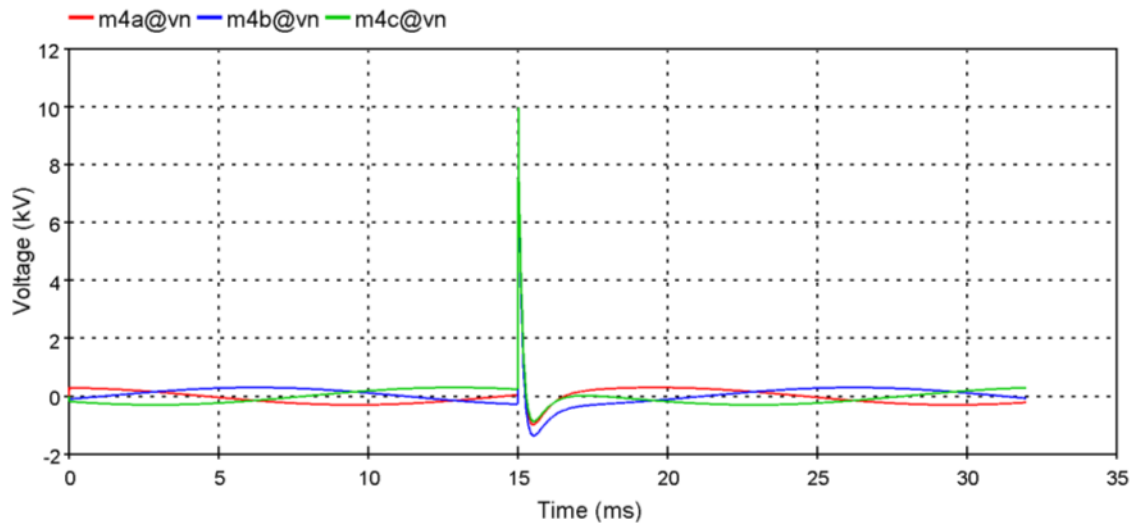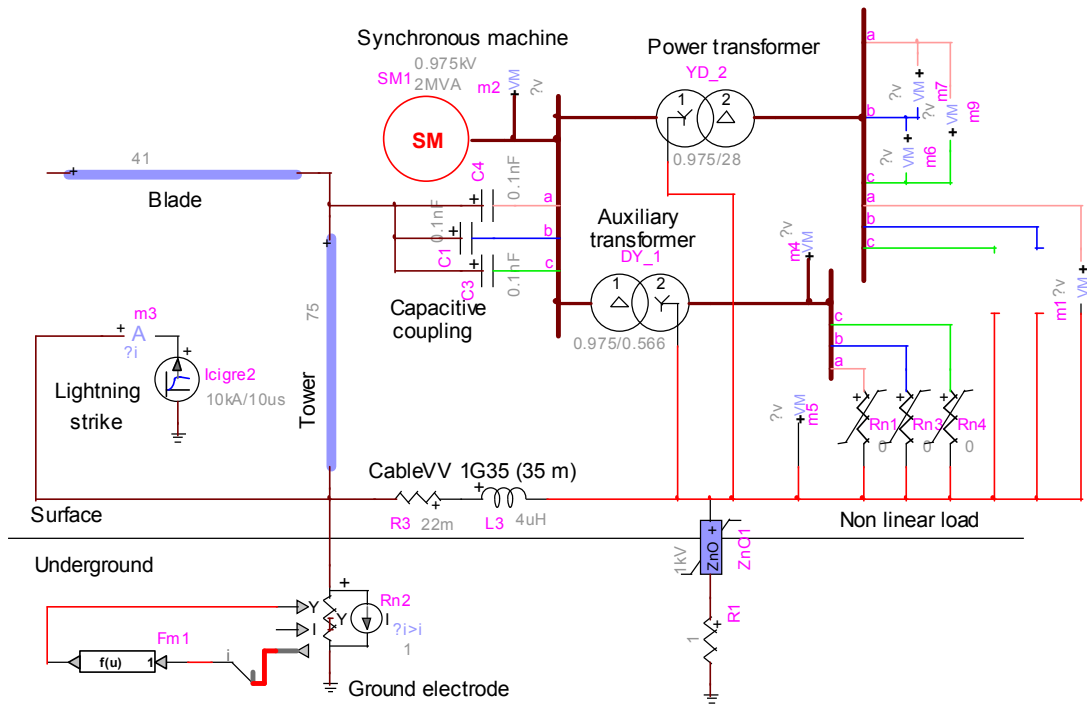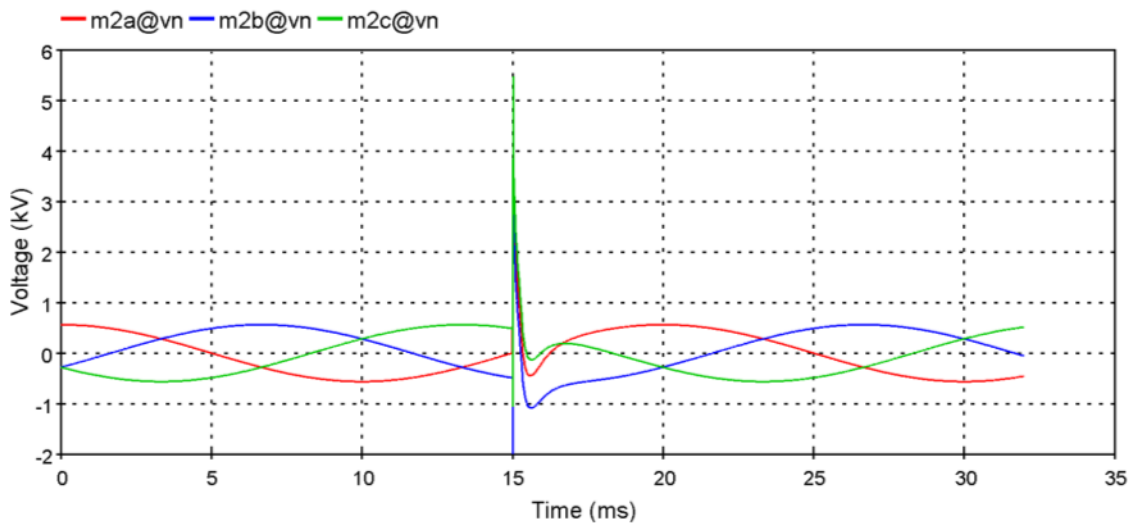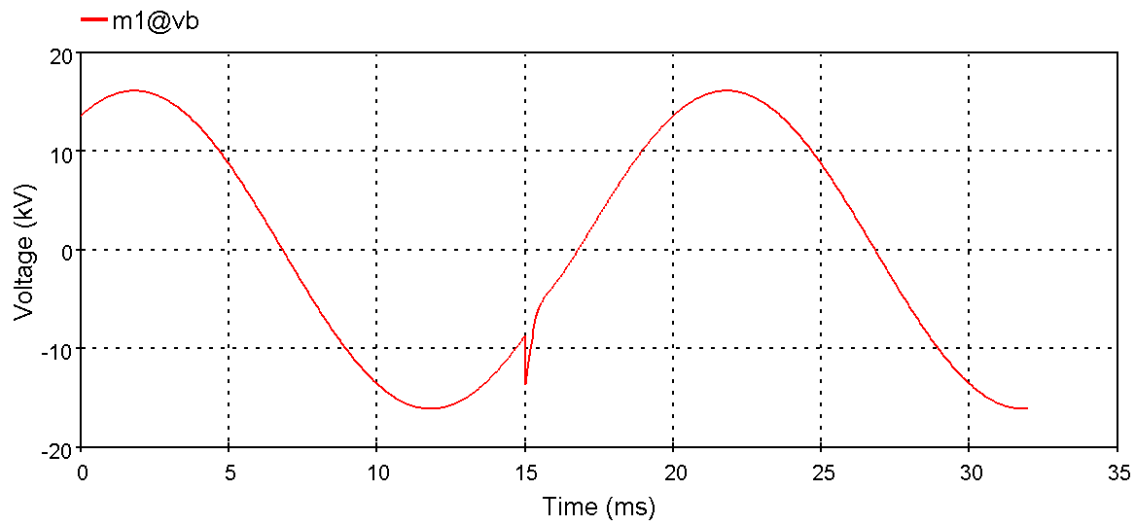
Fig. 8. Overvoltage at the secondary side of the main power transformer. m1@vb states for voltage output (phase a) from node to ground
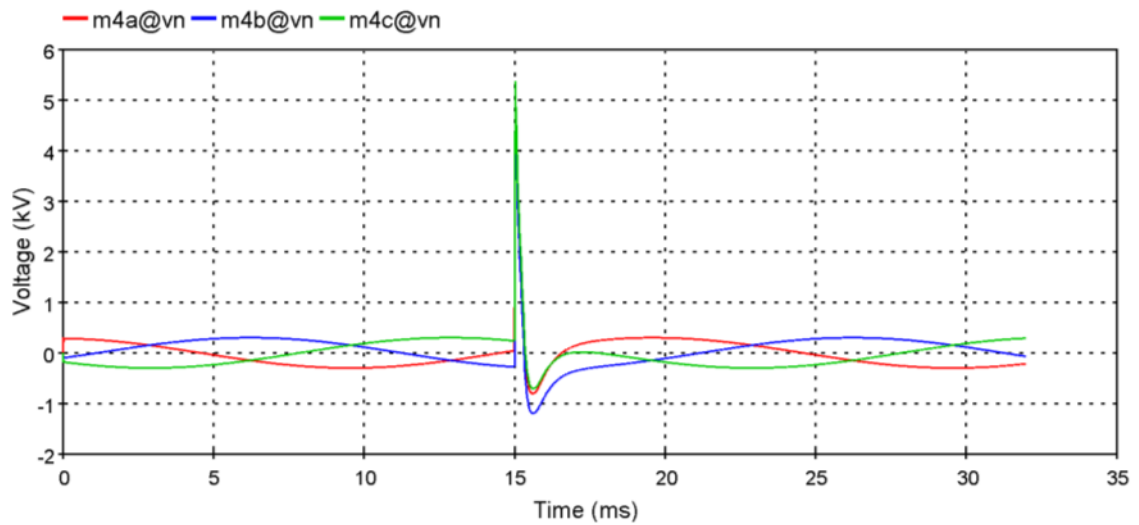


Fig. 9. Overvoltage at the secondary side of the auxiliary transformer. m4a@vn, m4b@vn e m4c@vn states for
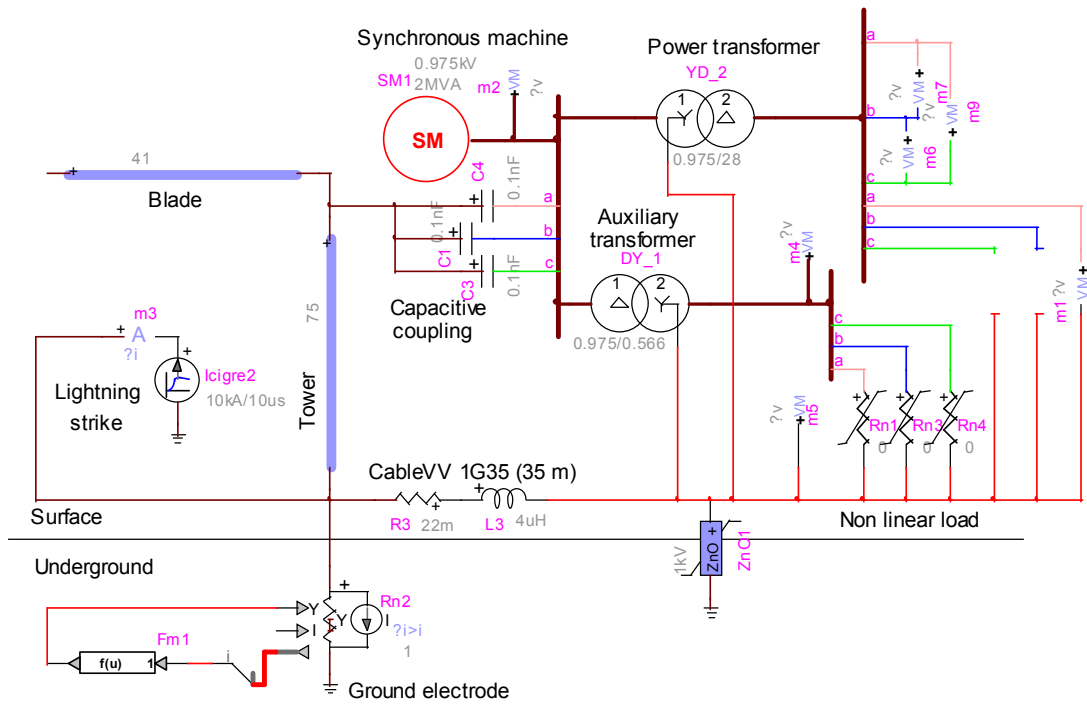
voltages output (scope) from node to ground

Fig. 10. EMTP-RV circuit with SPD



Fig. 11. Overvoltage at the primary side of transformers with SPD. m2a@vn, m2b@vn e m2c@vn states for voltages

output (scope) from node to ground

Fig. 12. Limited overvoltage at the secondary side of the main power transformer with SPD. m1@vb states for

voltage output (phase a) from node to ground



Fig. 13. Overvoltage at the secondary side of the auxiliary transformer with SPD. m4a@vn, m4b@vn e m4c@vn

states for voltages output (scope) from node to ground
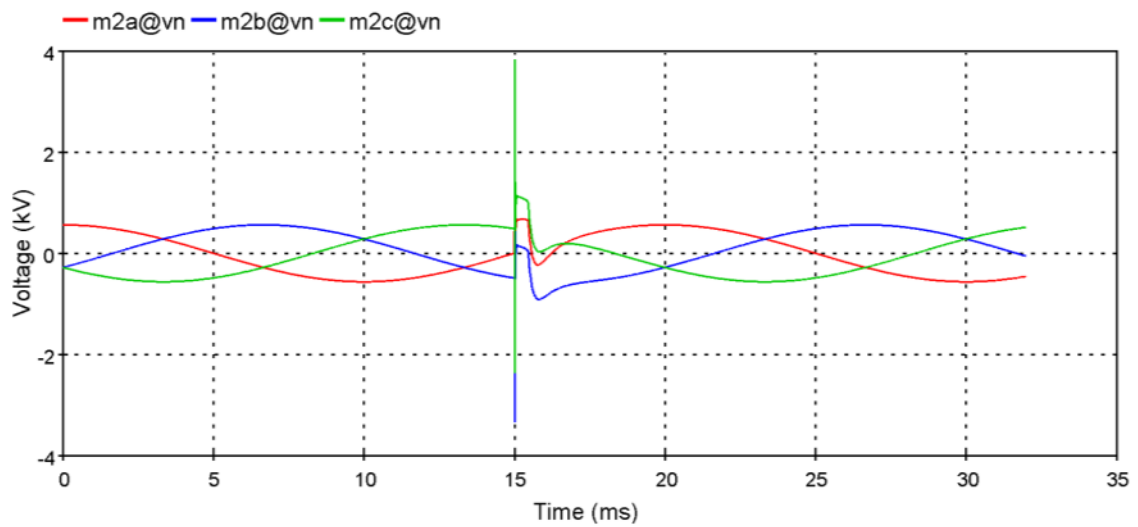
Fig. 14. EMTP-RV circuit with SPD ideally connected.



Fig. 15. Overvoltage at the primary side of transformers with SPD ideally connected. m2a@vn, m2b@vn e m2c@vn

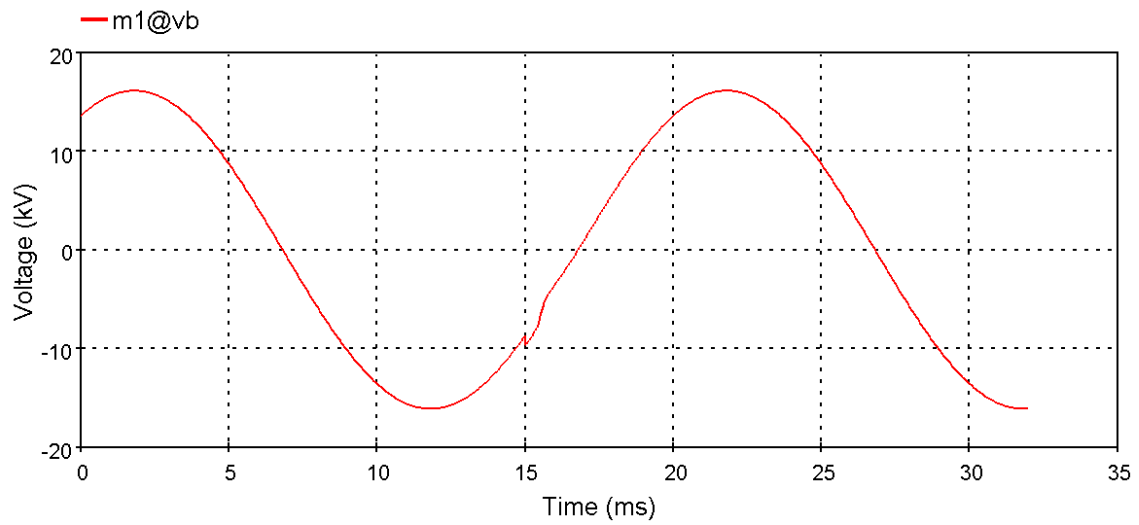states for voltages output (scope) from node to ground

Fig. 16. Limited overvoltage at the secondary side of the main power transformer with SPD ideally connected.

m1@vb states for voltage output (phase a) from node to ground
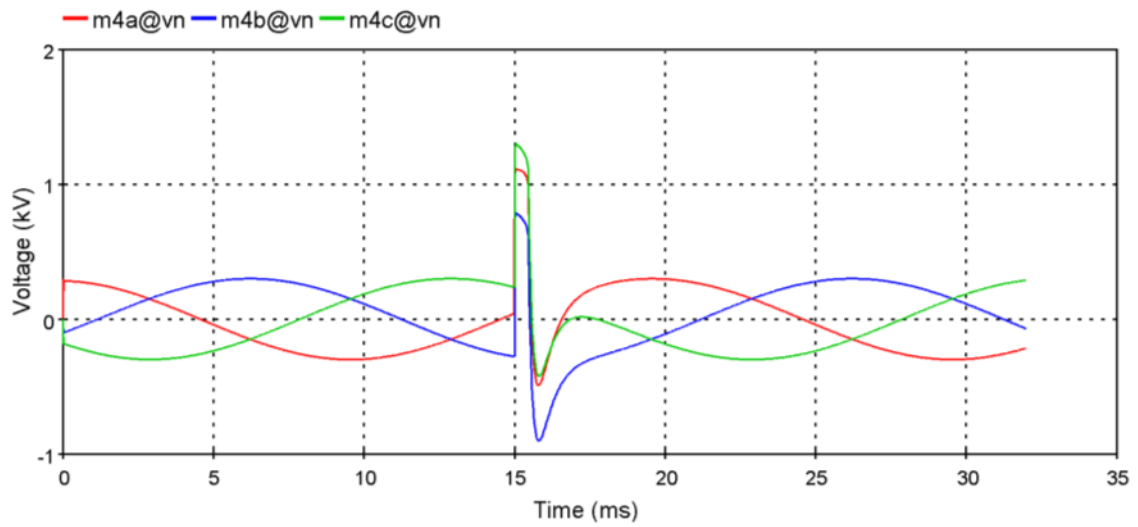


Fig. 17. Overvoltage at the secondary side of the auxiliary transformer with SPD ideally connected. m4a@vn,

m4b@vn e m4c@vn states for voltages output (scope) from node to ground