Surge Protection against Indirect Lightning Strike for Wind Electrical Power Energy Systems

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***Abstract*-Wind power does not pollute and is recyclable. Wind energy as a clean/green resource offers manyadvantages. Wind power is one of the fastest-growing energy sources in the world. The supply of wind power is unlimited and cannot be depleted. In order to reach the highest efficiency, the wind turbines are usually installed on the hills and flat areas. Therefore, they are subjected to the direct and indirect lightning strikes. Direct and Indirect lightening strokes can produce damages on electrical and electronic systems as well as of mechanical components such as blades and bearings. This paper aims to model all parts of wind turbine involved in this transient phenomena such as tower, blade, coaxial cable, control system and considering accurate and frequency-dependent model for the ground system. 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). The influence of over voltages resulting from indirect surges on control systems as the most sensitive part has been deeply investigated.**

***Keywords*-component; wind turbine; EMTP; lightning; protection; frequency-dependent ground model; indirect strike**

I. INTRODUCTION

The need to control climate change and the increasing environmental pollution as well as the alternating price of fossil fuels, encourage the international community to pay more attention to the renewable energy. The rising consumption of fossil fuels, together with increasing greenhouse gas emission, threatens our secure energy supply. Facing the exhaustion of energy and petroleum resources, the development of new energy has been an inevitable topic for humans, including solar energy, wind energy, biomass energy, oceanic tides, etc. Therefore, there is a need for alternative energy sources which can provide as energy in a sustainable manner. The obvious choice of a clean energy source, which is abundant and could provide security for the future development and growth, is the Wind's energy. Wind turbines need to install in the areas with highest wind density such as hills, seas, seashore, flats, etc. Wind turbines depended on their power capacity could acquire up to 43-*m* blades and 78-*m* tower, totalling 121-*m*. These high height structures are a proper target for lighting; consequently, it is very important to protect them against it [3-6]. Lightning protection of wind electrical energy generation systems are more difficult and complicated than the other structures and buildings due to the following reasons [7-9]:

1. Wind turbines are usually installed in windy places that are often hilly land or mountain or sea beach and therefore, there are no tall buildings in the adjacent.

2. New wind turbines are taller than 150 meters.

3. Windy areas are often places that are most threatened by lightning.

4. Blades and nacelle's coating built of composite materials, which have a high potential to hit by lightning.

4. In the wind turbines, there are electronic and control equipment that are very vulnerable against the overvoltage caused by lightning.

According to IEC/TR 61400-24, 4% to 8% of wind turbines that have been installed in northern Europe are injured seriously because of lightning per year. The damaged parts giving rise to the lightning have been reported as follows: 51% for the control systems, 20% for the electricity generation system, 10% for the blades and 19% for the other parts of the wind turbine. The lighting could be either direct strike or indirect strike. The later refers to the striking the ground next to the wind turbine or the other turbines adjacent. Indirect strike induces high voltage and transient surge in the different parts of wind turbine [10]. Although the possibility of an indirect lightning strike to the ground next to the wind turbine is less than the other, the appropriate wind turbine protection system must be able to reduce all overvoltage caused by both direct and indirect lightning strike.

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). The influence of protection system on the overvoltage's resulting from the indirect strikes in those parts specially in control system has been investigated.

II. EMTP BASED TRANISENT MODEL OF WIND TURBINE

In order to simulate the transient over voltages caused by lightning strikes, the transient simulation software "EMTP-RV" is used in this paper. This Section is devoted to present the transient model of different parts of wind turbine and over voltages caused by indirect strike of lightning.

1. Lightning Current Model:

Natural lightning is attributed with different wave shapes. This paper uses a popular exponential model, i.e., a current source in parallel with a 400-ohm resistor [11]. The standard waveform of lightning, 24-*kA*, 8/20 μs , has been employed in

this paper [2]. The I_CIGRE box in the EMTP-*RV* could address the model.

2. Blades Model:

In order to model blades of wind turbine, the constant parameter (CP) line has been employed. CP line is a frequency independent transmission line model. In fact, it represents the conductor inside the blades. The required parameters for CP line are calculated based on the material of conductor and dimensions [12].

3. Slip Ring Model:

Slip rings are made of carbon coal that can be modeled with a 5-ohm resistor.

4. Nacelle and Electrical Power Generation Unit Model:

This paper considers an asynchronous generator (690V/2.5 MVA) that connected to a three-phase bus. The bus is connected to the top of the tower, which is modeled by three 0.1-*nF* capacitors. These capacitors represent dispersion capacitor between tower and nacelle. To supply control systems, a 690*V*/566*V* internal transformer is used. It is connected to this bus. This part is installed in the bottom of the tower or near the tower in a cabin.

5. Tower and Control Cable Model:

Wind turbine tower are made of several parts with different radii (See Fig. 1). The tower can be considered approximately as a hollow cone. For the sake of simplicity, an average radius (*rTower*) could be taken into account via (1). To increase the accuracy of model, the tower is divided into several parts (in this paper ten-part [13]) with an inductance (*LTower*) series with a resistance (*RTower*). The inductance and resistance have been calculated using (2) and (3), respectively [11].

$$r_{tower} = \frac{\left(r_1 h_1 + r_2 H + r_3 h_1\right)}{2H} \quad (1)$$

where *H* is the tower height, *r1* is the radius of the upper, *r2* and *r3* are the radius of the middle and lower part of the wind turbine, respectively and *h1, h2* are the height of the upper to the middle and the middle to the lower parts of the wind turbine tower, respectively (See Fig. 1).

$$L_{tower} = \frac{\mu_0 H}{2\pi}\left(\ln\frac{2H}{r_{tower}} - 1 - \frac{\mu}{\mu_0}\ln c\right)(H) \quad (2)$$

where*H* is the tower height of the wind turbine, *rTower* is the average radius of the tower cross-sectional area, *c* is the ratio

of the inner and outer radii of the tower, *ȝ0* is the absolute permeability, *ȝ* is the relative permeability.

$$R_{tower} = \rho \frac{H}{A} (\Omega) \quad (3)$$

Where ρ is the resistivity of the tower material, *A* is the conducting area of the tower.

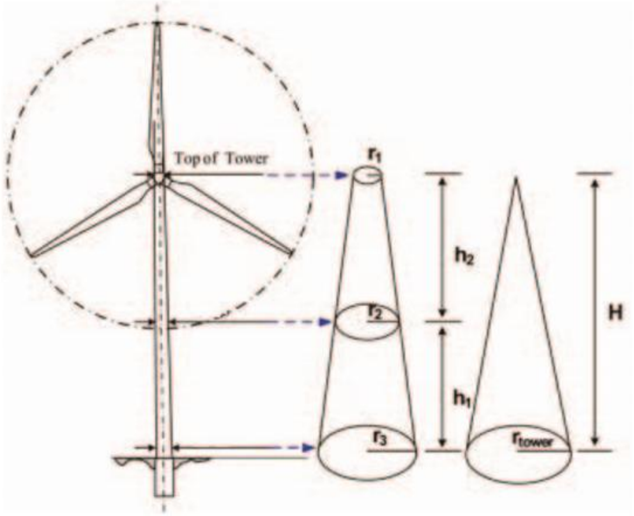

Fig. 1. Dimensions of the wind turbine tower for modeling.

The RG58A/U coaxial cable is widely used in the control section of wind turbines. The cable is installed from top to the bottom of the tower into control system at a distance around 25-*cm* from the tower's body. The cable is consistent of a covering layer, shielding layer, insulator layer, and a conductor from the outside to the inside. In order to simulate the transient behavior of the cable, it is essential to consider the resistance, an inductance of the conductor and shielding layer, as well as the capacitance between conductor and shielding layer. The maximum DC resistance of the conductor, *RCable* is 37.3 */km*; the inductance value of the conductor is calculated using (4).
The maximum resistance of shielding layer is 21Ÿ/km and its inductance is calculated by (4). To calculate the distribution capacitance between the conductor and shielding layer of the coaxial cable (*C23*), we can use the equation (5) [9]. Coaxial cable, such as the tower is conventionally divided into ten-equal part (See Fig. 2).

$$L = \frac{\mu}{2\pi}\ln\left(\frac{D_{12}}{.7788\times r}\right)(H/m) \quad (4)$$

where*D12* is the distance between the conductor and shield layer and r is the radius of the conductor.

$$C_{23} = \frac{0.02413\varepsilon}{\log_{10}\frac{D}{d}}(\mu F/\text{km}) \quad (5)$$

where*D* is the outer radius of insulation and *d* is radius of conductor.

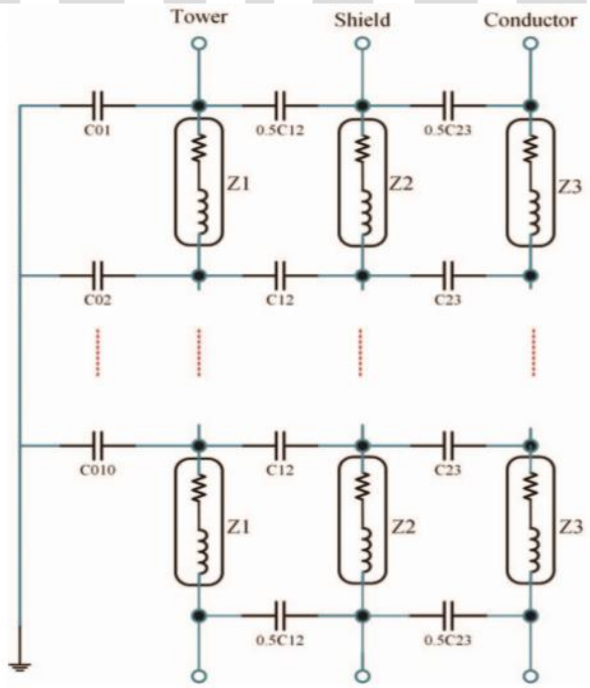

Fig. 2. Schematic of modeling used for the tower and control cable.

In order to determine the transient voltages on different parts of the turbine caused by lightning strikes, calculating the dispersion capacitor is essential. The capacitors between tower and ground (*C0*) are calculated by (6) and the dispersion capacitor between tower and shield of coaxial cable (*C12*) is obtained from (7) [11].

$$C_0 = \frac{2\pi\varepsilon l}{\ln\left(\frac{2l}{r_{tower}}\right)}(F) \tag{6}$$

$$C_{12} = \frac{2\pi}{\cosh^{-1}\left(\frac{r^2_{tower} + r^2_{cable} - D^2_{23}}{2r_{tower}r_{cable}}\right)}(F/m) \tag{7}$$

where*l* is the average length of each part of wind turbine (distance between middle of each ten sections to ground), and *D23* is the distance between the cable and the tower.

6. The Control System Modeling:

A high resistance in a large number of reaches has modeled control system. However, it could not provide sufficient accuracy. The model of control systems is dependent on the type of those. Reference [14] presents a general model for low voltage systems used in the distributed generators. It is included a five *microH* inductor series with 100 *nF* capacitor.

7. Ground Model:

Overvoltages caused by lightning has a wide frequency range from DC to several MHz. Using typical resistance as the ground model that measured in frequency of 120 Hz cannot properly show the transient behavior of ground system [15]. In fact, suitable model for ground system need to attribute the effects of soil ionization and be frequency-depended [16].

The behavior of ground impedance in low-frequency is almost resistive, however the high-frequency increases the nonlinearity and changes the impedance phase, as well [16],

[17]. This paper uses the earth-transmission-line theory for the ground model. Fig. 3 presents the transmission line model used in this paper; more information about this theory is available in [18]. The value of parameters has been selected based on information available in [15]-[18].

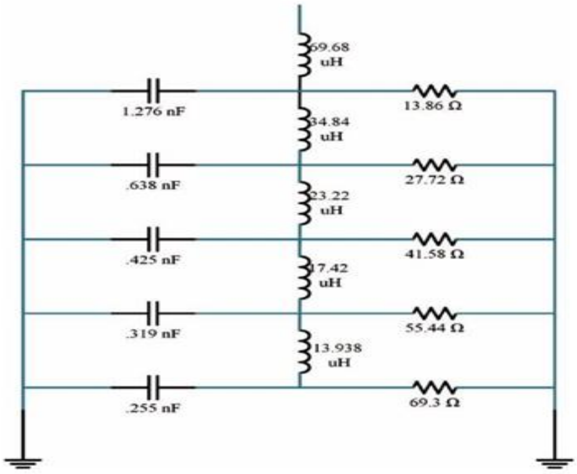

Fig. 3.Schematic model of the earth system.

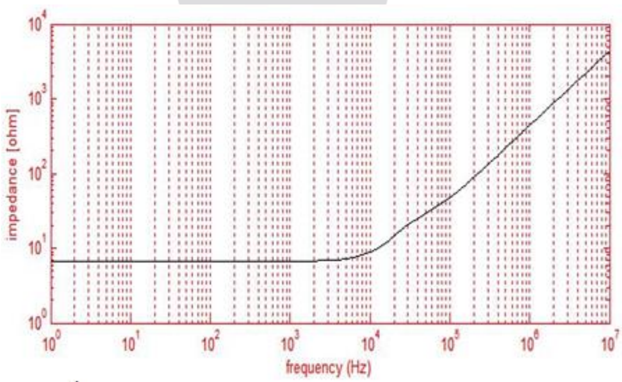

Fig. 4.The frequency response of the earth system model.

The frequency response for this model is shown in Fig. 4. As it can be seen, the model could track the transient behavior of ground. The trend shown in Fig. 4 is compatible with the measurements presented in [13].

III.SIMULATION RESULTS

The all parts affected by lighting overvoltage have been modelled in EMTP-*RV* based on the explanations provided in Section II. Indirect strike means that lightning strike hits the ground nearby a wind turbine that a galvanic coupling between flash of lightning and ground system occurs. The schematic of this event shows in Fig. 5.

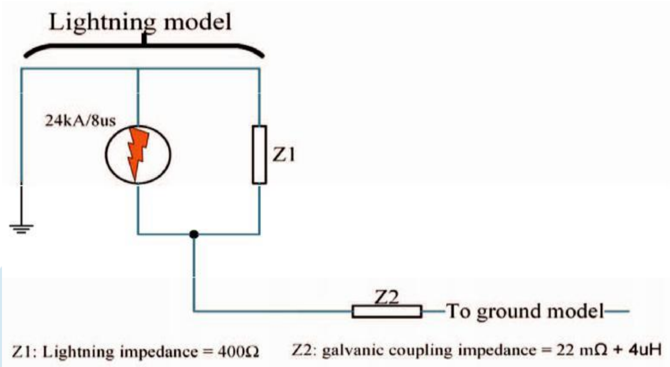

Fig. 5.Model of indirect strike.

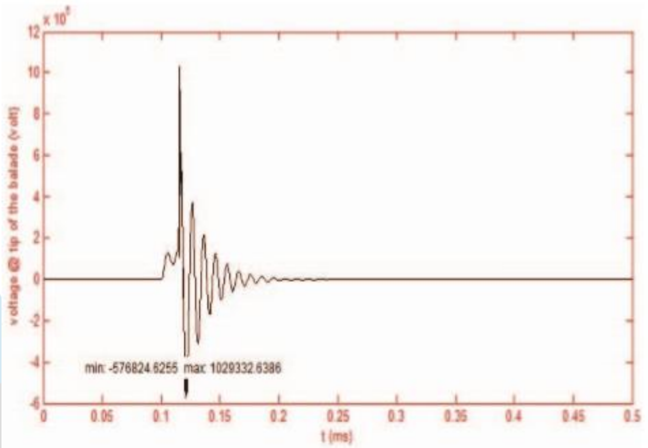

Fig. 6.Overvoltage caused by indirect lightning strikes the tip.

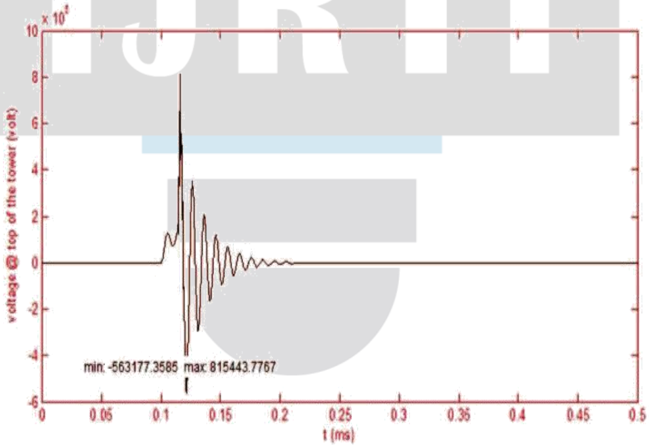

Fig. 7.Overvoltage caused by indirect lightning strikes at top of tower.

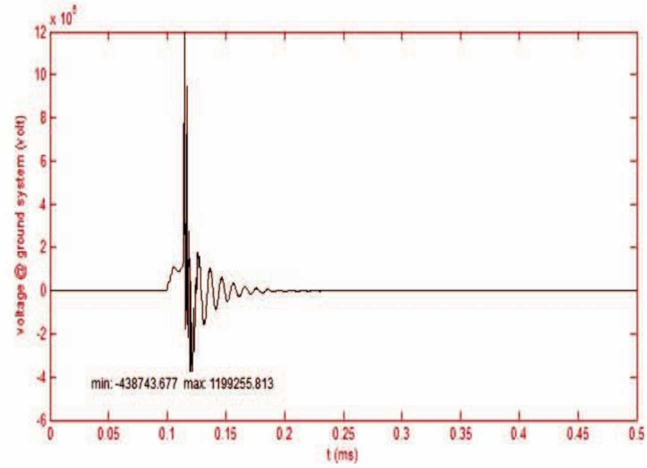

Fig. 8.Overvoltage caused by indirect lightning strike at ground system.

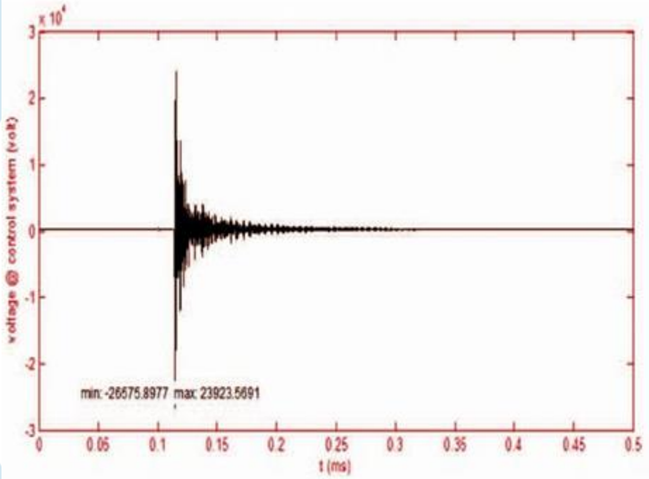

Fig. 9.Overvoltage caused by indirect lightning strikes in the phase to neutral control system.

The results caused by indirect lightning strike are shown in Figs. 6-9. According to the simulations, during an indirect lightning collision, overvoltages occur in different parts of a wind turbine with the significant maximum for a few microseconds. In the case that the wind turbine intended without protection system, the maximum amount of overvoltage on the tip of the blades is 1029.3 *kV*, top of the tower is 815.4 *kV*, in the ground system is 1192.4 *kV* and in the phase to neutral of control system is 26.5 *kV*. The indirect strike could rise the potential of ground system.

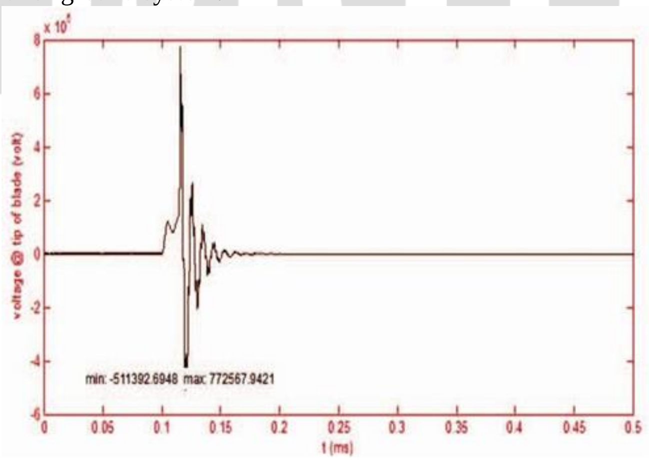

Fig. 10.Overvoltage in the tip with protection.

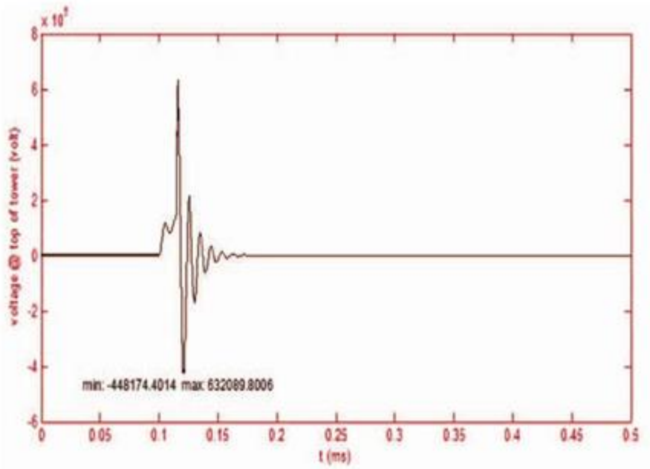

Fig. 11.Overvoltage at top of tower with protection

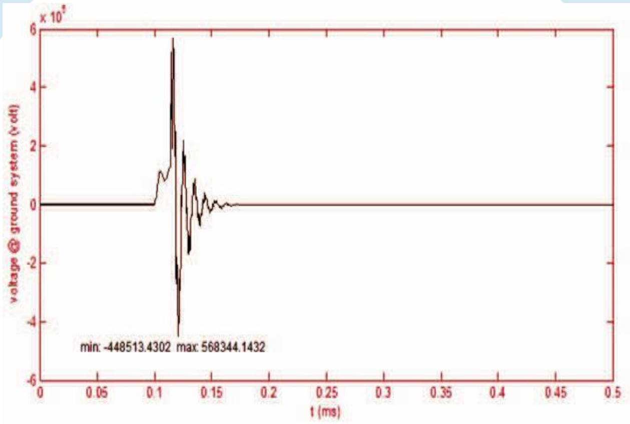

Fig. 12.Overvoltage at ground system with protection.

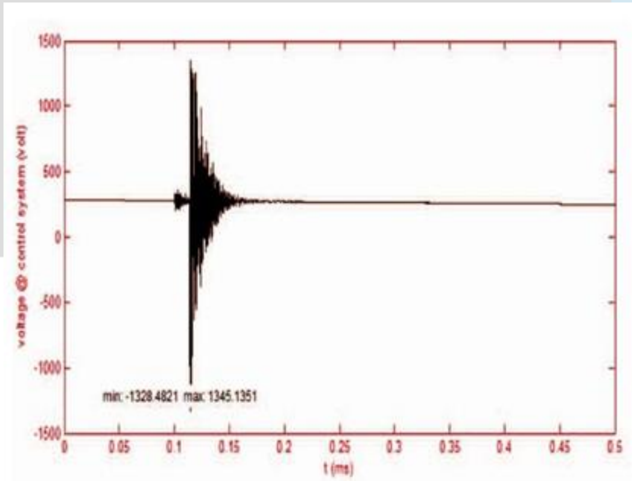

Fig. 13.Overvoltage in the phase to neutral control system with protection.

These overvoltages can create serious damage for the electronic and control systems. The maximum tolerable voltage of control systems is reported to be 1500 V [9]. The impacts of overvoltages could be reduced through using protection scheme such as using a protective low impedance wire from top of the tower to ground system, using a low impedance conductor with high conductivity in the blades, and using appropriate surge protections device (SPDs) in the phases to neutral of control system.

The results of impacts of application of this protection scheme in EMTP-RV are shown in Figs. 10-13. The results indicate that the amplitude and damping time of overvoltage significantly reduces via protections systems. The reduction of overvoltage peak is 300 *kV* for the blade tip, 200 *kV* for top of the tower, and 500 *kV* for the ground system. Overvoltages for the control system have been reached less than the maximum allowed, i.e. 1345 *V*.

Table I presents the peak of overvoltages for various parts of wind turbine. As it can be seen, the amplitude has been reduced substantially by using protection system. In present condition, the control system can tolerate the voltage. It is worth to mention that the protection system have the greatest effect on control system in comparison the other parts of wind turbine. The precise model of control parts and shielding results in to set a proper protection system for wind turbine control-system against indirect lighting strikes.

Table I. COMPARISON BETWEEN OVERVOLATGES RESULTED FORM INDIRECT LIGHTINING SURGES.

Different parts of wind turbine	Overvoltage without protection (*kV*)	Overvoltage with protection (*kV*)
Tip of blade	1029.3	772.5
Top of tower	815.4	632.1
Ground system	1192.2	568.3
Phase to neutral of control system	26.575	1.345

IV. CONCLUSION

Nowadays, wind turbines have obtained the significant portion of the production of electrical energy. Wind turbines are threatened by both direct and indirect lightning strike. It is necessary to review and simulate the lightning protection process before installation to reach adequate assurance. Indirect strike means that lightning flash hits the ground nearby the wind turbine. Indirect lightning strike propagates transient surge into wind turbine structure and causes overvoltage in different parts such as blade, tower, control system and the like. Among them, the control system included the sensitive electrical equipment is the main target for the overvoltage caused by indirect lightning. This paper provided a comprehensive and precise transient model guideline using EMTP-RV against this phenomenon. The proposed model considered all practical issues such as high frequency model of ground system and parasitic capacitance in the control system in one framework. According to the results of simulations, the indirect lighting could induce 26 *kV*overvoltages on the control system without protection scheme, while that is much more than its insulation limits, i.e. 1500 *V*. The overvoltage peak could reach to 1345 *V* (acceptable value) once surge protection device is used in the phase to neutral of control system.

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