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Safety of Wind Farm Grounding Systems under Fault and Lightning Currents

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***Abstract*— This article discusses the safety issues related to wind farm grounding systems. Two different cases are considered. The first case treats a wind turbine subjected to a single phase to ground fault while the second case treats a wind turbine hit by lightning. In the first case, a detailed analysis of the fault current distribution for various scenarios, is presented. A comparative study of the touch and step voltages has demonstrated that the fault conditions on HV side leads to dangerous touch and step voltages. A focus is made on the human safety regarding lightning surges. In this regard, the transient currents flowing through the legs and body are computed for two different lightning waveforms. A comparative study of these currents for the cases of a single and two turbines reveals the non-validity of one of the design criterion established in international standards.**

Keywords-component; wind power plant, grounding, fault current, lightning, touch voltages.

I. Introduction

The critical need for green energy production has resulted to a very rapid growth of wind turbines technology. Due to the increasing number and size of wind turbines, the probability of lightning strikes to wind farms is rising, while wind turbines are vulnerable to lightning stroke. As lightning is a high transient current, significant voltages induced between any two points of the grounding grid may cause damage to equipment and may be dangerous to personnel working nearby [1]-[2].

When a fault occurs on the grounding network, it is necessary to keep touch and step voltages and ground potential rises of the installation at a level which does not affect the people safety until the outbreak of the protective equipment and the interruption of the flow of fault current.

According to IEC 61400-24:2010 [1], the global grounding system shall ensure people safety and equipment integrity regarding two different aggressions: 50 Hz fault conditions, and lightning strikes. For both cases, safety performance concerns the capability of the grounding system to maintain touch and step voltages below the tolerable values as defined per the applicable standards such as IEEE Std 80-2000 [2].

Thus, in the general specifications of independent producer of renewable energy, it is mentioned that the grounding system of the wind power plant shall be able to carry currents to earth under normal, fault and transient conditions. This current transfer must be achieved without exceeding the operating limits of the equipment, electrical, thermal and mechanical properties of the materials constituting it, neither affecting the continuity of service of the wind power plant. Various works have been dedicated to safety of wind turbines under fault conditions without a full analysis of the fault current distribution [3]-[7]. Nevertheless, the grounding systems of wind turbines hit by lightning are facing transient, high-current electric discharges. It is also mandatory that the grounding system quickly disperses lightning currents without dangerous heating or electrodynamics effects. Therefore, they must avoid damages to the facility for very adverse conditions.

A number of paper have been devoted to the transient performance of wind turbine grounding systems hit by lightning [5]-[7], but few of them has considered the human safety issue. As the main specificity of wind turbines is their accessibility to public entities, a safety performance evaluation of their grounding systems during direct lightning strikes is primordial. Contrary to the fault conditions, the determination of the safety limits for wind turbines hit by lightning is complex. According to related international standards [1], the grounding system of a wind turbine with a resistance lower than 10 Ω might be adequate for lightning protection purposes. But safety limits for touch and step potentials are not defined clearly.

Indeed, we propose in this article a demonstration of non-validity of this design criterion with regard to safety issues. To this end, the full wave analysis method of CDEGS (Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis) software package [9] is utilized for the determination of the induced transient current by lightning. The method uses a solution of the electric field integral equation by the Method of Moment (MoM), and is applicable to complex structures including networks of wires and metallic surfaces. The presence of a multilayer soil can also be taken account. The design methodology introduced aims to integrate the various phenomena affecting the performance of earthing systems with appropriate numerical calculations. We address in this article two main issues:

- How to take into account the worst fault location?
- How to demonstrate that ventricular fibrillation thresholds are met during lightning strikes?

Accordingly, the paper is organized as follows. In section II, the system under study is presented in detail. In section 3, the safety issues for different scenarios of fault conditions at low frequency, will be examined. Section IV is dedicated to the safety issues of wind turbine hit by lightning.

II. Description of the System

Wind turbines farm grounding system consists in a network of many small earth-termination systems distributed in a wide area with various soil types and characteristics. The earth-termination systems of each wind turbine are generally interconnected to form a wide network spread across the wind power plant.

A. Wind Power Plant characteristics

Located closed to Paris in France, the wind farm power plant is situated on a land with an approximately area of 5 km^2 and consists of ten wind turbines. The wind farm delivers its generated power to a high voltage 63 kV grid that is connected to the 20 kV collector network through a 75 MVA transformer located in the substation.

Figure 1. represents a schematic of the system during the fault conditions scenario at one of the wind turbines.

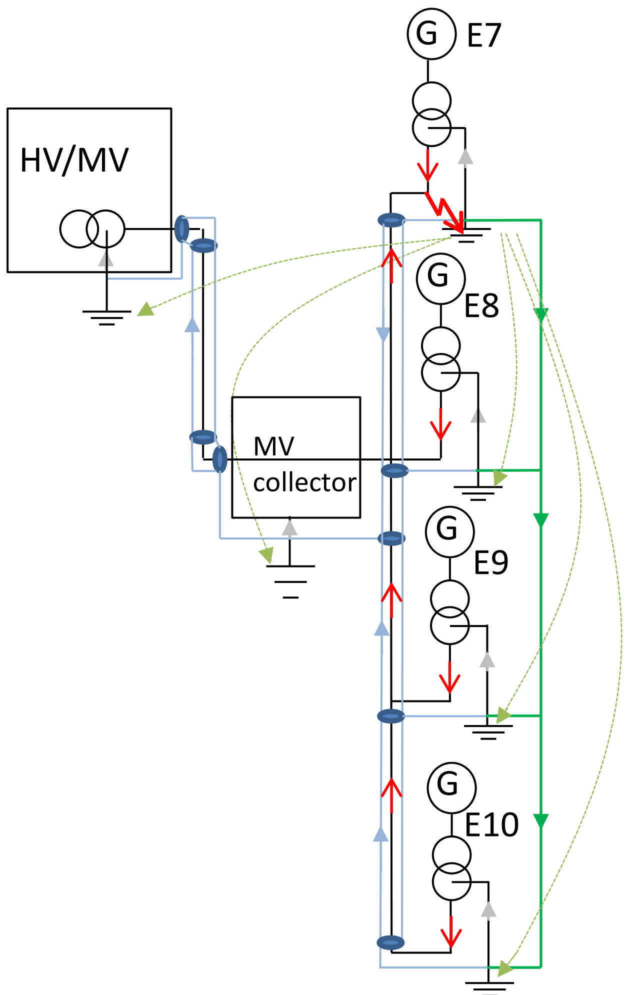

Figure 1. Schematic of the problem under study

In this paper, the analysis is restricted to a system including four wind turbines and one collecting substation as described in Figure 1. In addition, the collecting substation is connected to a high voltage substation located 2 km away. All wind turbines are interconnected through underground cables to the MV collector without any transformer.

B. Computer modeling

The system under study is examined when a fault occurs in an area close to the substations or the wind farm collector systems. It is also assumed that the system is subjected to a single phase to ground fault. The main purpose of the simulation is to estimate the worst ground potential rise at the locations of wind turbines and the substation.

To this end, the construction of a simplified but realistic 3D model of the entire wind farm including the substations, and a uniform soil model is needed.

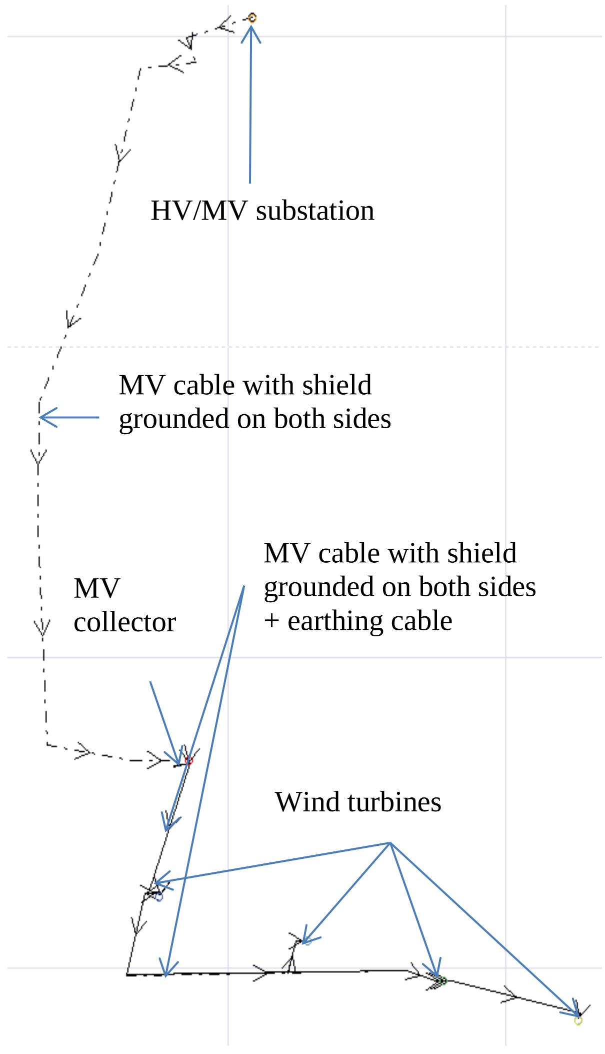

Figure 2. Global earthing network model

Accordingly, the HIFREQ module of CDEGS software package [9] is used as computing engine to simulate the electromagnetic behavior of topography described by Figure 2. The method uses a solution of the electric field integral equation by the Method of Moment (MoM), and is applicable to complex structures including networks of wires and metallic surfaces.

For the simulation purpose, a network of underground conductors is built. The reinforcement steel rebars of foundation are connected to the grounding mesh electrode. They are modeled as steel conductors coated with a 5 cm thick, 300 Ω.m resistivity material and bare buried conductors, respectively.

Figure 3. presents a perspective view of the model of each wind turbine foundation.

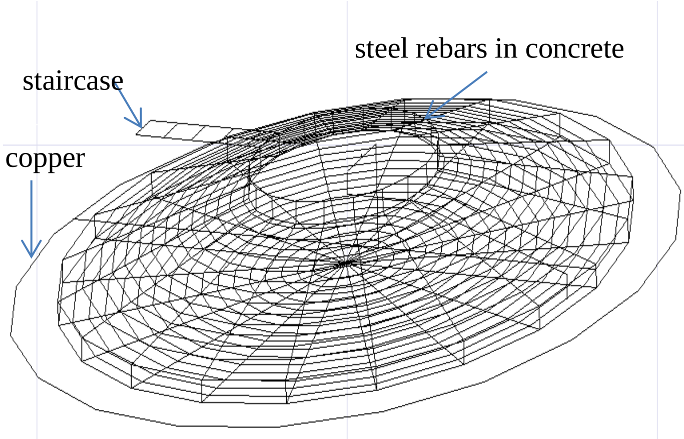

Figure 3. Perspective view of the wind turbine foundation model

C. Soil resistivity measurements and interpretation

Indeed, the soil resistivity varies throughout the year, with both moisture content and soil temperature. Thus, the soil resistivity measurements were made during the summer for each wind turbine and the collector in order to consider the "worst" case for simulation purpose. Five measurements with a maximum spacing of 20 m and 8 m were carried out using the 4-pins Wenner method. In principle, soil resistivity measurements should be made up to a spacing (between the current and adjacent potential electrodes) which is at least on the same order as the maximum extent (or diagonal length) of the grounding system under study. The RESAP module of CDEGS software package is used for the transformation of soil resistivity measurements into a layered soil model that can be used by HIFREQ.

First, an average resistivity value of 2500 Ω-m is obtained from measurements. Then a soil model is built for each wind turbine in order to assess safety performances of the grounding systems.

III. Fault Conditions

In this section we present a detailed analysis of the fault current distribution in order to determine the most conservative scenario. The main objective is to evaluate the consequences of transferred potentials from HV (High Voltage) side to MV (Medium Voltage) side.

A. Assessment of wind turbines grounding resistances

The grounding resistance of each wind turbine is determined from the methodology described in previous chapter. TABLE I. depicts the value of computed grounding resistances for locations E7 to E10, and the MV collector.

TABLE I. Grounding Resistances

Location	Grounding resistance
E7	1.7 Ω
E8	1.64 Ω
E9	1.8 Ω
E10	1.76 Ω
MV collector	5.1 Ω

These values can be used in a global system to take into account for local soil conditions.

B. Fault current distribution analysis

Previously, we mentioned that the turbines are electrically interconnected to each other via a buried bare copper conductor. If a fault occurs on a wind turbine, this conductor will participate to the fault current distribution which will then be distributed in all ground systems. In addition, an interconnection between the HV/MV substation and the MV collector via the MV cables screens has to be considered. Hence, a fault occurring both on the HV side or MV side of substation can spread to the MV collector and thus probably to each turbine. The fault conditions on HV side will affect the transferred potentials which depend to the soil resistivity, the distance between facilities, connections of the transformers and the nature of the connecting cables.

A total of 6 different fault cases were examined, one on the 63 kV substation side and five on the 20 kV side at each wind turbine site and MV collector. For each scenario, the GPR (Ground Potential Rises) is observed at all wind turbines sites and at the MV collector location. In this paper, first a MV fault occurring at the MV collector is analyzed.

TABLE II. 300 A Fault at MV collector

	MV collector	E7	E8	E9	E10
Maximum GPR (V)	102.2	19.1	37.7	58.8	57.4
Maximum current (A)	20	29.7	12.7	8.7	8.1

Then an HV fault occurring at the MV collector is considered. Table II and Table III depict the maximum GPR and current of each wind turbine when a 300 A fault and a 12 kA fault occur at MV collector, respectively.

TABLE III. 12 kA Fault at MV collector

	MV collector	E7	E8	E9	E10
Maximum GPR (V)	594.2	286.3	116.3	85.7	77.0
Maximum current (A)	116.5	168.4	70.9	47.6	43.8

A comparison between TABLE II. and TABLE III. shows that the most restrictive case happens for a HV fault as the GPR is about six times higher.

C. *Tolerable body current limit*

Touch and step voltages thresholds are determined without taking into account the personal protective equipment (gloves, shoes). These values are determined from the IEC 60479-1 by considering the following assumptions:

- hand to foot current paths,
- probability of ventricular fibrillation 5%,
- surface layer of gravel or asphalt not taken into account.

The fault current duration is set at 0.8 s for a HV fault and 0.2 s for a MV fault. TABLE IV. presents safety criteria for several cases.

TABLE IV. SAFETY CRITERIA

Threshold values		Touch voltage	Step voltage
MV collector	*HV side*	46.9 V	57.1 V
	MV side	190.5 V	246.5 V

D. *Safety performances*

In this section, a comparison between computed results and threshold values is performed for both faults scenarios from the 63 kV and 20 kV substation sides. Safety near the MV collector site is evaluated based on the worst case of GPR values.

Figure 4. and Figure 5. show the distribution of the touch voltage one meter away from any metallic structures for the HV fault and MV faults, respectively.

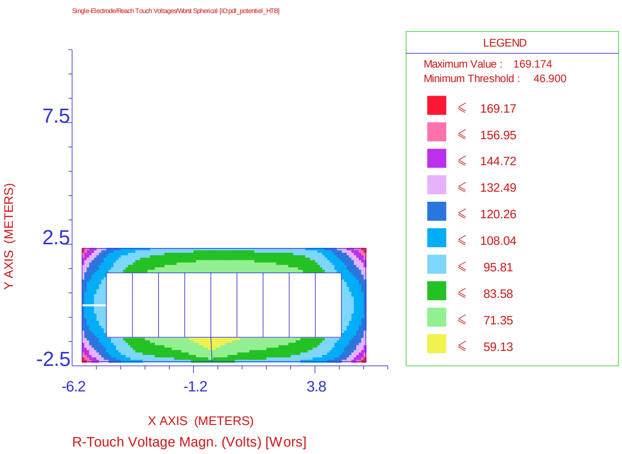

Figure 4. Touch voltage distribution - HV fault

For the case of HV fault, the maximum touch voltage is about 169.1 V which is above the threshold value of 46.9 V. The maximum touch voltage is about 65.5 V for the case of MV fault which is below the threshold value of 190.5 V.

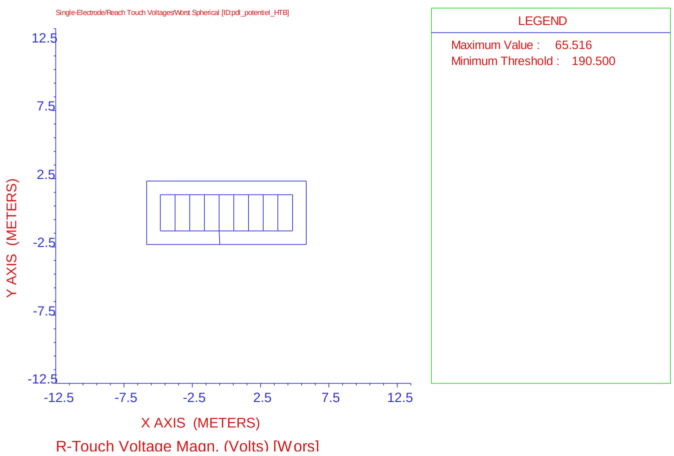

Figure 5. Touch voltage distribution - MV fault

Figure 6. and Figure 7. show the distribution of the step voltage for a one meter inter feet spacing for the same fault scenarios. As seen in these figures, the maximum step voltage for HV fault is about 113.7 V which is above the threshold value of 57.1 V. While, the maximum step voltage is about 19.5 V for MV fault which is below the threshold value of 246.5 V.

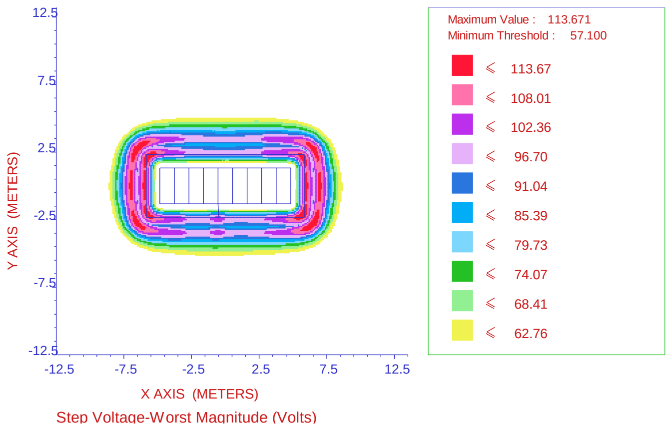

Figure 6. Step voltage distribution - HV fault

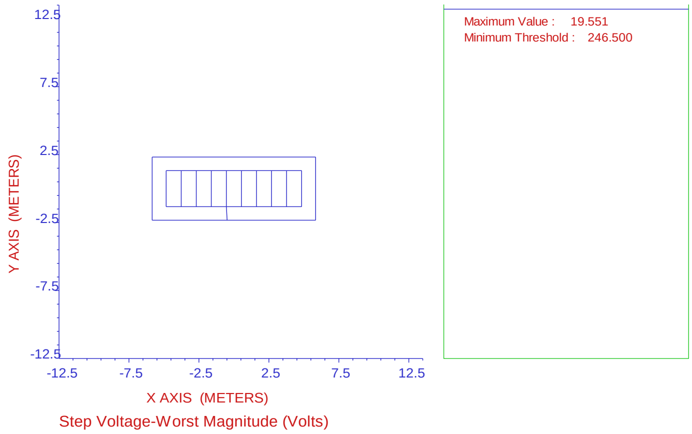

Figure 7. Step voltage distribution - MV fault

The performed analysis highlights the need to investigate the worst fault scenario. Indeed, it was shown that the HV fault leads to dangerous touch and step voltages whereas the MV fault case does not exhibit unsafe issues.

IV. Wind Turbines Hit By Lightning

Lightning strike to a wind turbine with a large grounding resistance creates very high ground potential rises (GPR), which may lead to intolerable touch and step voltages. Furthermore, a large differential voltages between power cables phase conductors and their sheaths, power transformers phase conductors and their grounded parts can be expected [6].

Unlike designing grounding system for a fault at industrial frequency, a more complex model of wind turbine that can take into account all lightning-related phenomena, is needed.

Previous studies have shown that the earth impedance and corresponding GPR are much higher at high frequencies when accounting for the tower structure [8]. Their results also indicate that it is necessary to account for the above-ground structure for more accurate prediction of voltages developed at the turbine base. In the following, we are going to use the capabilities of HIFREQ to perform the full wave analysis of a wind turbine hit by lightning. Due to transient behavior of lightning, the FFTSES module of CDEGS software package is also utilized for the transient analysis. To this end, first a frequency decomposition of the transient (lightning waveforms) is performed, and then the time-domain response of the system under study is reconstituted by a multiple frequency analysis of the structure using HIFREQ. Figure 8 depicts the wire grid model of the wind turbine and its grounding system, which is used in HIFREQ.

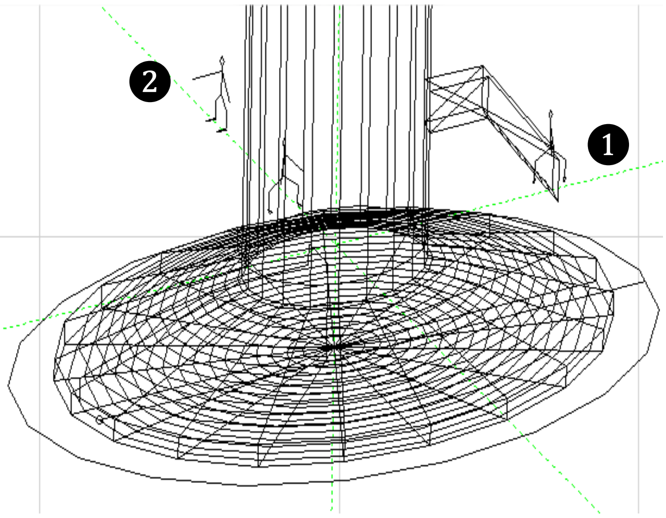

Figure 8. Perspective view of the wind turbine model – zoom on foundation

The building structure is assumed to have been struck by a standard double-exponential lightning waveform. The lightning strike is modeled by injecting a current surge at the top of the highest blade. The direct lightning strike ***i(t)*** is simulated by an ideal current source.

A. Tolerable body current limit

The objective is to estimate the people hazards levels generated by lightning surges. This requires knowledge of the effects of surges on human beings and animals. In accordance with IEC 60749-2, to determine the hazard threshold we use, as parameter, the lower specific energy limits.

1) Determination of specific fibrillating energy F_e

IEC Standard 60479-2 deals with the effects of current on human beings and livestock due to unidirectional single impulse currents of short durations. The standards of the IEC 60479 series combine two variables for evaluating the effect on the human body:

- specific energy: F_e in A^2.s,
- charge: Q in A.s

The specific energy is used because it represents the energy dissipated by the lightning current in a unit resistance as shown in Equation 1.

$$E(j) = Z(\Omega) * F_e(A^2 s) \quad (1)$$

Where E is the electric energy in Joule, and Z is the impedance of current path (we consider later in the study a body impedance value of 500 Ω and a legs impedance value of 1000 Ω)

The specific fibrillating energy for rectangular impulses is determined by:

$$F_e = I_{DC}^2 \times t_i \text{ with } I_{DC} = \frac{I_{C(p)}}{\sqrt{6}}. \quad (2)$$

Where t_i is the shock duration in second and $I_{c(p)}$ is the peak current.

A comparison of the current magnitudes for rectangular and sinusoidal impulses and for a capacitor discharge with the time constant T having the same specific fibrillating energy Fe and the same shock-duration t_i is performed in Figure 17 of IEC Standard 60479-2.

2) Threshold of ventricular fibrillation

The threshold of intensities as a function of pulse duration leading to avoid any risk of ventricular fibrillation is indicated in the Figure 20 of IEC Standard 60479-2. These are the effects associated with unidirectional current pulse of short duration. The curves indicate the probability of fibrillation risk for current flowing through the body from the left hand to both feet. For other current paths, see 5.9 in IEC 60479-1.

Insofar as the pulse duration identified in the human body may be less than 0.1 ms, we have to extrapolate the curve C1 though this pushes us outside the scope of the standard. Indeed, the IEC 60479-2 standard deals with the biological effects of an electric pulse with a duration of 100 µs to 10 µs for a unidirectional current [10]. Despite standardization available for the evaluation of allowable values in the lightning field we use the curve C1. It is therefore more appropriate to rely on the geometric mean for a peak pulse. Hence, by considering the area below C1, we get the following condition to avoid any fibrillation risk due to touch voltage:

$$I_B^{1.4} \times t_i \leq 1.5 \times 10^{-3}\ A^{1.4}.s. \qquad (3)$$

Where I_B is the current flowing through the body.

Regarding step voltages, we retain a current factor F of 0.04. It leads to the following condition:

$$I_L^{1.4} \times t_i \leq 0.137\ A^{1.4}.s. \qquad (4)$$

Where I_L is the current flowing through the legs.

B. Safety performances

In the following, assessment of human safety is investigated for several configurations and two different waveforms.

First, we consider a conservative case including only one wind turbine. Lightning currents are based on LPL I (lightning protection level 1), two different waveforms, have been used for simulation purpose. They are characterized by their peak values (200 kA and 50 kA), front time (10 µs and 0.25 µs) and time to half value (350 µs and 100 µs). Figure 9. shows the influence of the lightning waveforms on the transient current flowing through the body of someone touching the staircases.

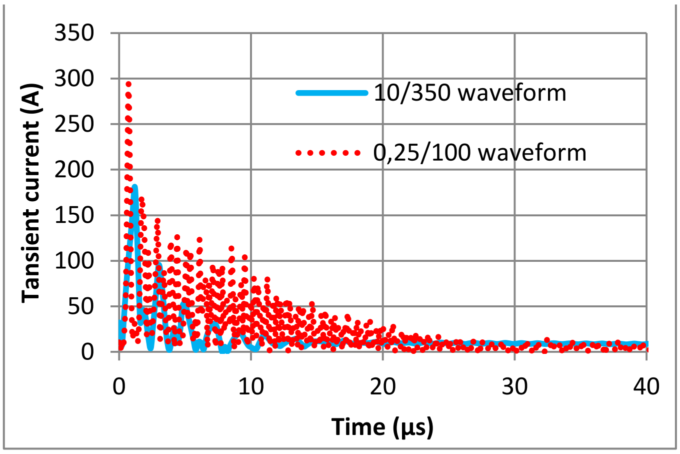

Figure 9. Current flowing through the body as a function of time

Due to the grounding system reactance, current peak values are larger for high frequency excitation currents.

Some authors have studied the effect of interconnections [5], [8]. It appears that the contribution of interconnections to the reduction of maximum GPR is limited by their effective length. Thus, in this paragraph, a comparison between configurations with one or two turbines is made. Figure 10. Figure 13. present the currents flowing through the body and the legs respectively for both lightning current waveforms. A comparison is performed between cases including only one turbine and two turbines.

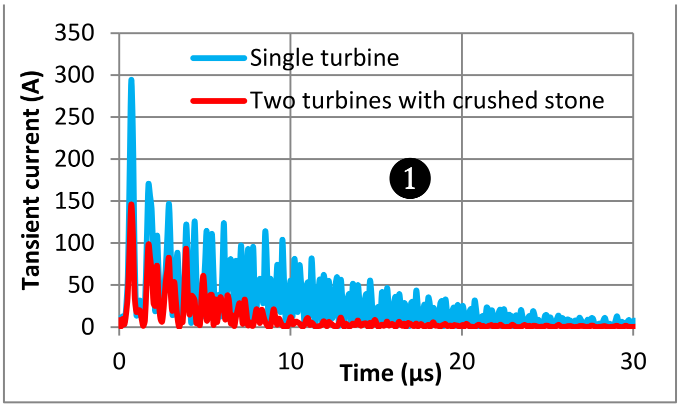

Figure 10. Current flowing through the body as a function of time – 0,25/100 µs waveform

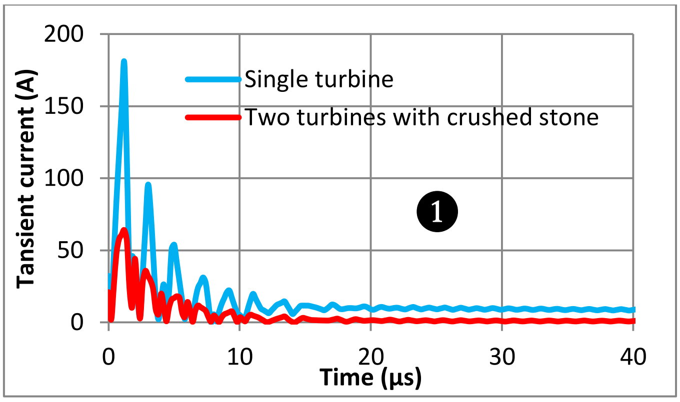

Figure 11. Current flowing through the body as a function of time – 10/350 µs waveform

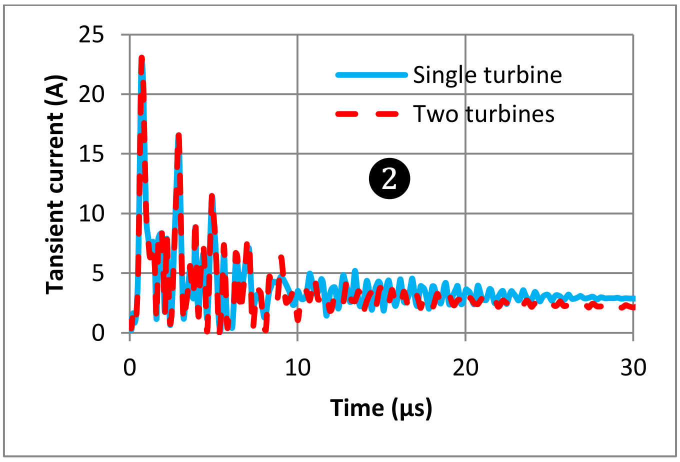

Figure 12. Current flowing through the legs as a function of time – 0,25/100 µs waveform

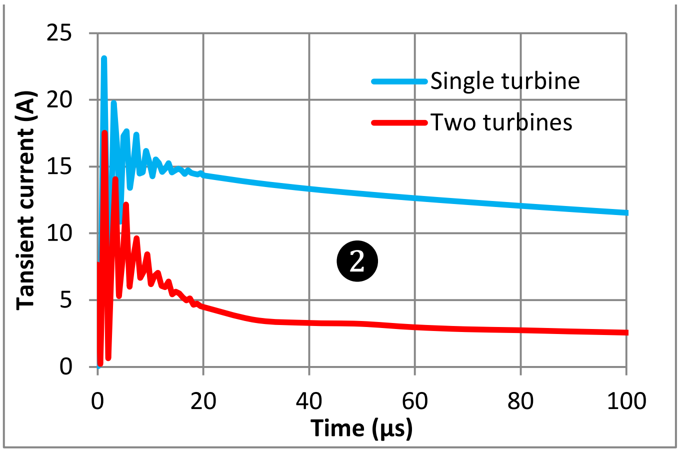

Figure 13. Current flowing through the legs as a function of time – 10/350 µs waveform

C. *Results and discussion*

A synthesis of previously presented results is made here. A comparison between simulation results and tolerable values is performed.

TABLE V. RESULTS FOR A SINGLE TURBINE

Case	Peak current	RMS current	t_i	$I_B^{1,4}*t_i$	Safety
❶ 0.25/100 µs	293	119.6	2.3E-5	1,86E-2	NO
❶ 10/350 µs	180.4	75.1	4.4E-5	1.64E-2	NO
❷ 0.25/100 µs	22.9	9.3	6.2E-5	1.4E-3	YES
❷ 10/350 µs	23.1	9.4	4,35E-4	1E-2	YES

As safety criteria are satisfied for step voltages (❷), a crushed stone layer is added for touch voltages (❶). TABLE VI. presents touch voltage results for two turbines interconnected.

TABLE VI. RESULTS FOR TWO TURBINES

Case	Peak current	RMS current	t_i	$I_B^{1,4}*t_i$	Safety
❶ 0.25/100 µs	145.9	59.5	4.5E-6	1.37E-3	OUI
❶ 10/350 µs	67.2	27.4	1.30E-6	1.34E-4	OUI

According to Figure 10. Figure 13. one can make the following comments:

- interconnections between wind turbines generally reduces current peak values and energy passing through the body,
- interconnections do not provide the same effect according to the lightning current waveform, faster rise time waveform are less sensitive to interconnections, this is due to the grounding system reactance,
- safety criteria can be satisfied independently to the wind turbine grounding resistance but depends on the resistivity and thickness of the surface layer installed.

V. CONCLUSIONS

Full-wave analysis of wind turbines grounding system has been presented to verify its ability to provide a safe response to 50 Hz fault and lightning current.

It was established that, for low frequency currents, the magnitude of GPR and hence touch voltages are significantly higher when the HV fault is taken into account. Depending on the soil resistivity, distance between facilities and type of connections, some transferred potentials can occur. This is why specific studies shall be performed for each project.

Regarding the lightning, human safety is examined in terms of energy and current transferred to a person subjected to step and touch potential mechanisms. The influence of the current waveform and interconnections between individual wind turbines grounding systems were evaluated. It has been shown that, even with an individual wind turbine grounding resistance as low as 1.7 **Ω**, dangerous touch and step voltages can exist. We strongly recommend this methodology to limit the risks as far as possible since no risk at all in lightning protection does not exist.

As perspective, future work will be performed to show that lightning energy can be successfully dispersed into the ground in spite of individual wind turbines grounding system resistance larger than 10 **Ω**.

ACKNOWLEDGMENT

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