Investigation of direct lightning strikes to wind turbine blades

Nina Stipetić, Božidar Filipović-Grčić, Ivo Uglešić, Amir Tokić

***Abstract*—Lightning discharge is a serious cause of damage to wind turbines. Because of their height, they are exposed to direct lightning strikes which can damage the blades, mechanical parts or the electrical and control systems. According to the lightning protection zone concept, only the external parts are subjected to direct lightning strikes. The internal parts are subjected to indirect effects of lightning, but they are sensible because of their low insulation level. This paper elaborates the wind turbine exposure to lightning strikes and presents the EMTP-RV simulation of a direct strike to a wind turbine blade, identifying the overvoltages at the generator and the low voltage side of the step-up transformer, the ground potential rise and the energy absorbed by the surge protective devices, depending on the grounding resistance.**

***Keywords*—lightning location system, direct lightning strike, wind turbine, surge protective device**

I. Introduction

With a rapid growth of the wind power capacity in the world, the damages caused by lightning activity received more attention, especially in the regions with intense lightning activity. The statistic analysis of the reported wind turbine damages caused by lightning in the early growth in the wind turbine installations showed that the blade damage is the most expensive and damage of low voltage electrical equipment and control system within the tower was the most frequent [1]. Following the world's trend, the wind power capacity in Croatia is in the ascent, with 576 MW currently installed and 11 % share in total power generation; and with plans to reach 1328 MW until 2021 and 2193 MW until 2028 [2]. As a Mediterranean country, Croatia has a relatively high keraunic level, especially on the coast and in the hilly regions close to the coast. This is exactly where the wind potential is significant and where all the Croatian Wind Power Plants (WPPs) are installed. Recent experiences of both blade damages and low voltage equipment failure in Croatia were the motivation for the research and analysis of the wind turbine exposure to lightning discharges and the transient phenomena due to a direct lightning strike to a wind turbine blade.

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A. Lightning activity observation at the Wind Power Plant location

The data collected by the lightning location system (LLS) can be used to get the insight in the lightning activity at WPP locations. Such analysis was done in [3], where the authors analyzed the lightning data before and after the wind turbines' installations, adapting the definition for the wind turbine attraction area from the IEC 61400-24 [4]. Since the wind turbines, as very tall, isolated structures attract lightning, the expected increase in the lightning strike density after the wind turbine installation was confirmed. The same analysis was done using the data from Croatian LLS. The lightning activity on the WPP micro-locations was observed before and after the wind turbine installations.

The following example presents the lightning activity change on the location of two WPPs which consist of 14 wind turbines. The rated power of each wind turbine is 3 MW, the towers are 80 m high and the blades are 49 m long. Figure 1 shows the lightning strike density map of the WPP location before and after the installation of wind turbines in 2013. The map on the left considers lightning data recorded 2009-2012 and the map on the right the data recorded 2013-2017. The most significant change is observed in the impact area of wind turbine WT1-4, where the strike density after the wind turbine installation is 141.6 strikes/(km^{2}year), including all first and subsequent strikes, which is a 5.25 times increase [5]. Due to the geographic characteristic of the location, the relative difference between the lowest and highest wind turbine position is 485 m. As expected, the most exposed WT1-4 is also the most elevated of all observed wind turbines.

However, the data from the lightning location systems does not give a total insight into wind turbine exposure to lightning strikes. The reason are the upward strikes initiated from the blades, whose initiation mechanism is still not understood completely. Unlike in downward lightning, upward strikes always have the initial continuous current (ICC), which lasts relatively long and has low amplitudes (tens to hundreds of milliseconds and 100 A to a few kA) [6]. If there is no superimposed fast rising and high peak current impulse, the lightning is categorized as ICC$_{only}$. ICC$_{only}$ events are not detected by the lightning location systems due to their very low frequency electromagnetic fields and their weak peak current amplitude [3], [6], [7]. According to measurements done in the world, approximately 50 % of upward lightning strikes are of the ICC$_{only}$ type [6], [7], [8]. The portion is not negligible, moreover the emphasis should be given to the

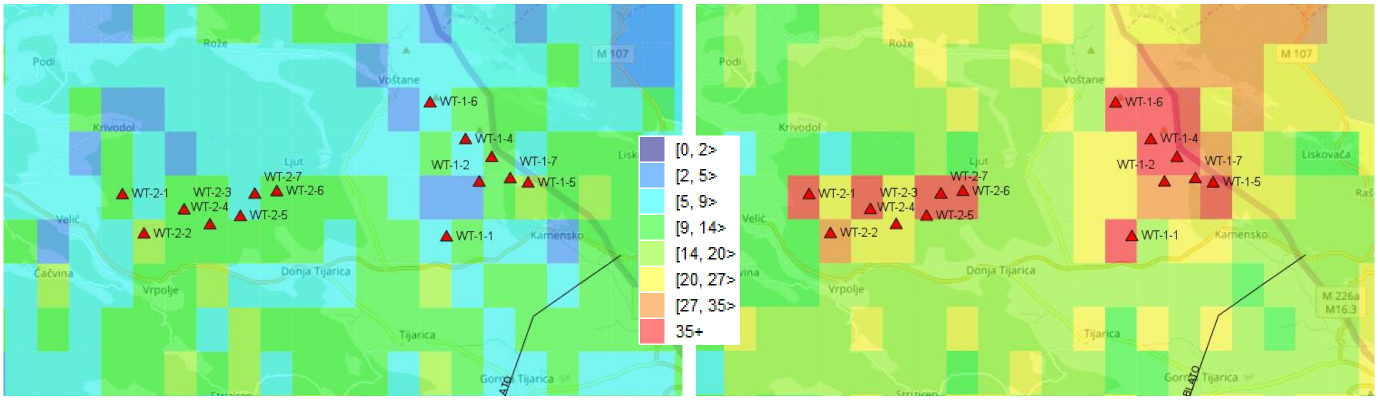

Fig. 1. Lightning strike density maps [strikes/(km^{2}year)] of the WPP location before (left) and after the installation of wind turbines (right)

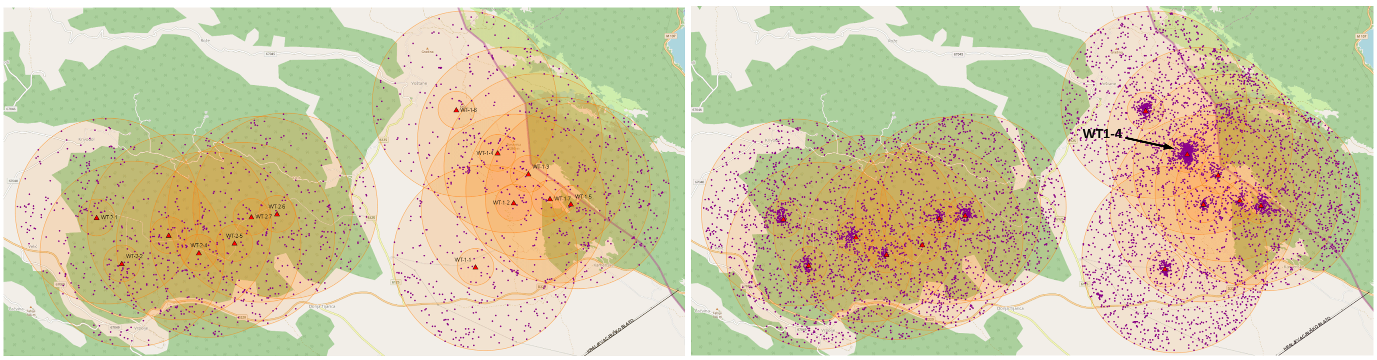

Fig. 2. Map of the WPP location with visible strikes before (left) and after the wind turbines installation (right)

detection of upward strikes since it was recognized that they are a dominant cause of wind turbine damages [1], [8]. Aside from inability to detect the ICC$_{only}$ events, the uncertainty of the LLS data also rises from the radius of the attraction area and the location accuracy of the LLS. The attraction areas are shown in Figure 2. Circles with a smaller radius around each wind turbine are the equivalent attraction areas as defined in IEC 61400-24. Larger circles have the radius which is the radius of the attraction area compensated with the LLS location error. It can be observed how some of the adjacent attraction zones overlap, hence it is not sure at which wind turbine the strike occurred. In addition, lightning observations in one WPP in Japan showed that about 30 % of the recorded direct strikes simultaneously hit on two or more wind turbines [9].

II. Simulation of a direct lightning strike to a Wind turbine blade

The simulations of lightning strikes to wind turbines are performed to clarify the transition phenomena and identify the impact of the grounding parameters and lightning current wave shape on the overvoltages and the SPD energy absorption. This paper presents the EMTP-RV simulation results of wind turbine blade stroked by 8/20 μs and 10/350 μs lightning test wave-shapes, with 100 kA amplitude. The grounding resistance was varied and the energy absorbed by the SPDs was considered. In addition, a case of an ICC with superimposed lightning impulses was simulated.

A. Description of the EMTP-RV model

The EMTP-RV model of a direct lightning strike to a wind turbine blade is shown in Figure 3. A single wind turbine was modeled which includes the lightning current model, blade and tower model, grounding model, 3 MVA, 690 V synchronous machine model connected with cable to a 0.69/22 kV step-up transformer, which is further cable connected through a 22/110 kV substation transformer to a transmission network equivalent. SPDs were modeled and placed at the low voltage side of a step-up transformer and at generator terminals. Wind turbine blades and towers conduct the lightning current and have similar physical characteristics as some high voltage transmission lines and structures. As such, they have been modeled as constant parameter (CP) lines. The surge impedances of a blade and a tower were approximated from conical and cylindrical equations established from electromagnetic field theory as follows:

$$Z_b = 60 * ln(\frac{2B}{r_b}) \tag{1}$$

$$Z_t = 60 * ln(\frac{T_h\sqrt{2}}{r_t}), \tag{2}$$

where B and r_b represent the length and radius of the blade and T_h and r_t represent the height and radius of the base of the tower [10]. The blade length is 49 m and the tower height

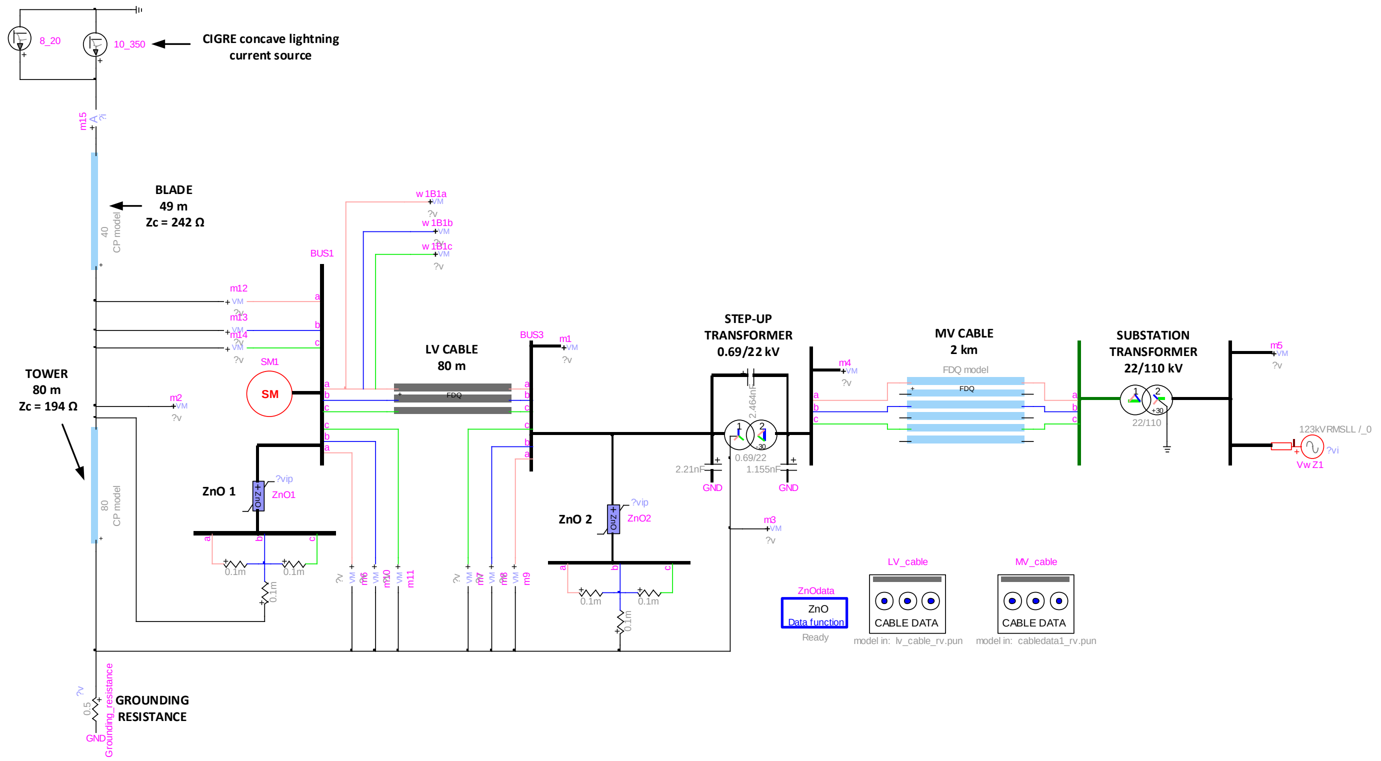

Fig. 3. EMTP-RV model of a lightning strike to a wind turbine blade

80 m with the base radius of 4.5 m. The propagation speed is set to the speed of light.

A detailed model of the wind turbine grounding should include both time-dependant nonlinear soil ionization and the frequency dependant impedance. The soil ionization improves the grounding performance and the frequency dependant inductive behaviour, which is rather complex to model [11], hinders it. Because of the opposing effects of mentioned phenomena, the grounding was modeled simply as a resistance. The grounding resistance in the simulations was varied from 0.5 Ω, to 10 Ω and 25 Ω. The LV cable is modeled as frequency-dependant and 80 m long, which equals the tower height. The 3 MVA, 0.69/22 kV, step-up transformer was represented as low-frequency model with added winding to ground and interwinding capacitances since the capacitances have a significant impact when simulating high frequency phenomena such as lightning. A LV SPD, intended for nominal AC voltage of 690 V [12], was modeled and placed in each phase at the generator terminals and at the LV side of the step-up transformer. The SPDs protecting the generator are connected between the generator terminals and the tower grounding system. The SPDs at the LV side of the transformer are connected between each phase and the grounding.

III. Results

A. Simulation of 8/20 μs, 100 kA strike without and with SPD protection

Firstly, the simulation of a 8/20 μs, 100 kA strike was performed without SPDs. The grounding resistance was set to 0.5 Ω. The overvoltage on the generator without protection reaches peak value of over 2 MV (Figure 4), and over 22.5 kV at the LV side of the step-up transformer. When the SPDs are included in the simulation, these overvoltages reduce to 3.3 kV at generator terminals (Figure 5) and 2.2 kV at the LV side of the transformer.

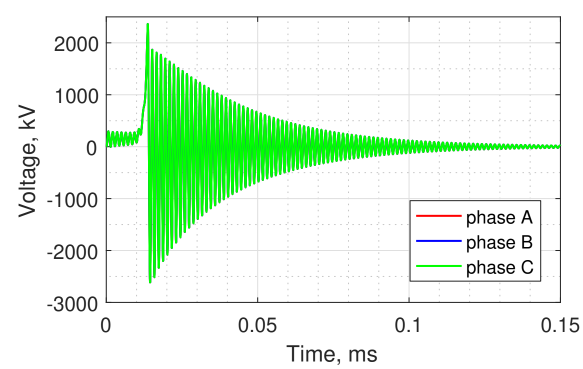

Fig. 4. Voltage at the generator without the SPD protection, U_{max} = -2703 kV

B. Comparison of the results for different grounding resistance values and SPD energy absorption in case of 10/350 μs, 100 kA strike

Simulation results for 8/20 μs strike for different grounding resistances was observed. Firstly, transient grounding potential rise was observed. The grounding potential rise with no SPDs included in the simulation reaches peak value of 55 kV. With

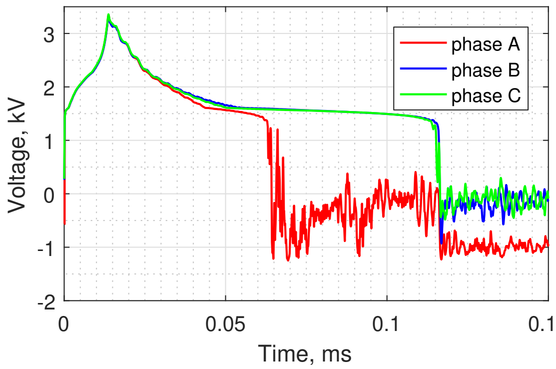

Fig. 5. Voltage at the generator with SPD protection, U_{max} = 3.3 kV

the SPDs included and 0.5 Ω grounding resistance, it reduces to 27 kV. However, for higher values of grounding resistance it increases significantly. In case when the grounding resistance was set to 10 Ω the peak value of transient potential rise is 288 kV, and for 25 Ω grounding resistance it reaches 412 kV as show in Figure 6. The ground potential rise can not be

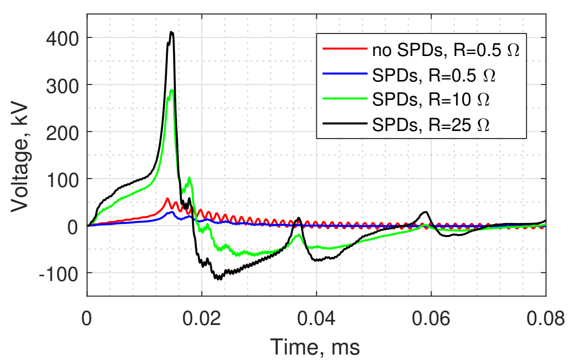

Fig. 6. Transient ground potential rise comparison in case of 8/20 μs, 100 kA strike, for grounding resistances 0.5 Ω, 10 Ω and 25 Ω

avoided and despite the very high peak voltage values, it does not endanger the equipment since the potential difference is what is relevant and not the potential only at the grounding side. The comparison of overvoltages at the generator and at the LV transformer side in case of 8/20 μs, 100 kA strike for different grounding resistances are shown in Figure 7 and Figure 8. The comparison is conducted for phase C since the highest overvoltages and currents through SPDs occurred in phase C due to the phase angle of the generator voltage at the instant of the lightning strike.

The overvoltage peak at the generator is higher when the grounding resistance is higher. However, this is not the case for the overvoltage at the LV transformer side, which has more complex wave-shape due to reflections in the grounding system, and highest overvoltage peak in case of 0.5 Ω grounding resistance. The comparison of the currents conducted by the SPDs in phase C is shown in Figure 9 and Figure 10.

For the SPD at the generator, the peak current is higher for higher grounding resistance. The current through SPD at

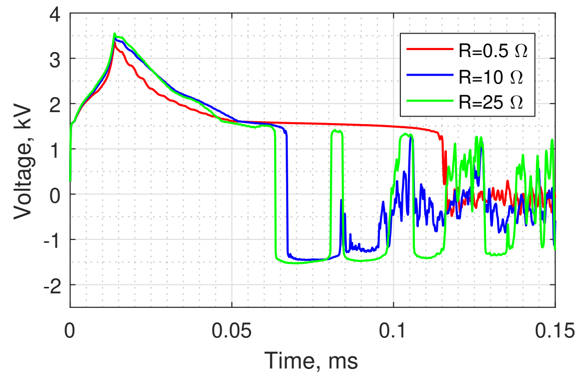

Fig. 7. Comparison of the overvoltages at the generator in phase C, in case of 8/20 μs strike, for grounding resistances 0.5 Ω, 10 Ω and 25 Ω

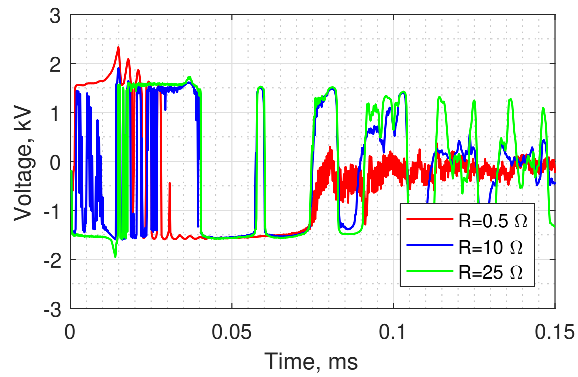

Fig. 8. Comparison of the overvoltages at the LV transformer side in phase C, in case of 8/20 μs strike, for grounding resistances 0.5 Ω, 10 Ω and 25 Ω

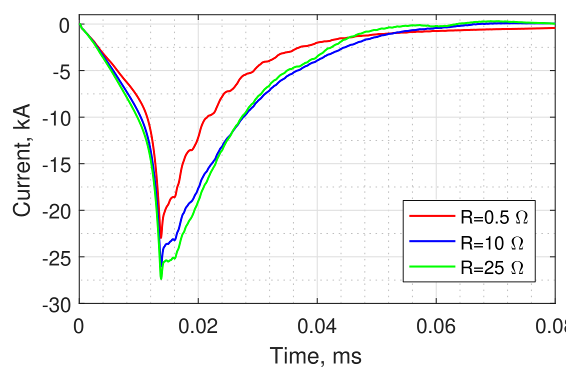

Fig. 9. Comparison of currents conducted by the SPD in phase C at generator terminals, for grounding resistances 0.5 Ω, 10 Ω and 25 Ω

the LV transformer side shows more complex wave-shape. For the higher grounding resistances, the first peak of the current conducted by the SPD is negative. This means that the SPDs firstly conducted in reverse, allowing the back-flow of the current to the LV circuit.

Finally, the energy absorption of the SPDs was observed. Comparison of energy absorption for 8/20 μs and 10/350 μs strikes and for different grounding resistances is shown in Figure 11 and Figure 12.

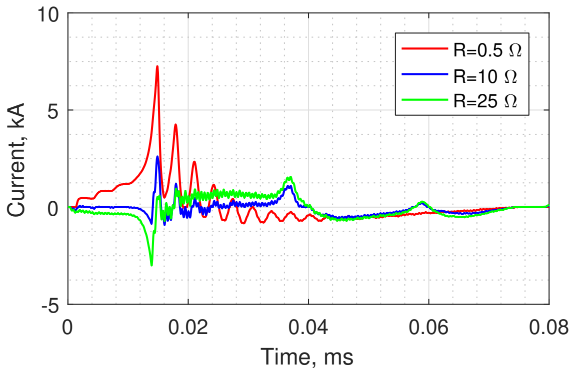

Fig. 10. Comparison of currents conducted by the SPD in phase C at the LV transformer side, for grounding resistances 0.5 Ω, 10 Ω and 25 Ω

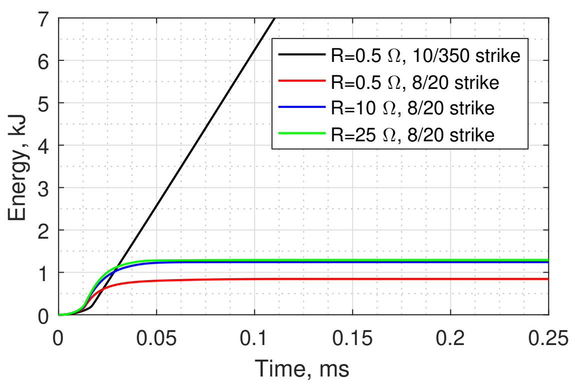

Fig. 11. Energy absorption of the SPD in phase C at generator terminals, for 8/20 μs and 10/350 μs strikes and grounding resistances 0.5 Ω, 10 Ω and 25 Ω

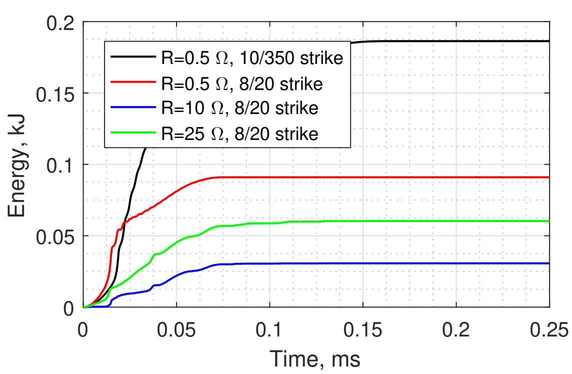

Fig. 12. Energy absorption of the SPD in phase C at the LV side of the transformer, for 8/20 μs and 10/350 μs lightning wave-shapes and grounding resistances 0.5 Ω, 10 Ω and 25 Ω

The energy absorption of the SPDs protecting the generator increases with the grounding resistance increase. For the SPDs at the LV transformer side, the highest energy is absorbed in case of 0.5 Ω grounding resistance, which agrees with highest voltage and current peaks from Figure 8 and Figure 10. Generally, the energy absorption in the SPDs at generator terminals is higher than the energy absorption in the SPDs at the LV transformer side. The worst case of energy absorption (SPD at generator terminals in phase C in case of 10/350 μs strike) is observed from Figure 11. In the first 0.25 ms there is a steep rise, and the final energy value, which can not be observed from Figure 11, is 35.5 kJ. For comparison, the energy capability of SPDs intended for nominal AC voltage of 690 V is 4.5 kJ. However, this does not mean that this SPD is not suitable for use, since the 10/350 μs is a wave-shape for testing Class I SPDs, and it should be regarded as an extremity with a very low probability scenario. Normally, lightning strikes have shorter times to half and accordingly, the associated energy absorption is then lower. This is confirmed in case of 8/20 μs strike, when the energy absorbed reached 1.3 kJ, which can be observed from the same figure. However, in reality, multiple flashes occur often and accumulated energy of each subsequent strike will stress the SPD. Exceeding the energy capability of an SPD will depend on the number and parameters of each subsequent strike. In the end, the energy absorption change is shown with respect to the grounding resistance increase. The results, shown in Figure 13, are chosen for the worst case of energy absorption from conducted simulations, which is in case of the 10/350 μs strike, for SPD in phase C at generator terminals. It can be observed that the energy absorption stabilizes at around 40.5 kJ as the grounding resistance exceeds 10 Ω.

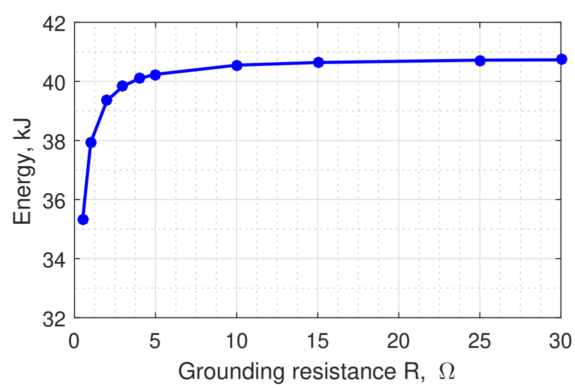

Fig. 13. Energy absorption of the SPD in phase C at generator terminals, in case of 10/350 μs strike, with respect to grounding resistance

C. Simulation of an ICC and superimposed impulses lightning strike

As mentioned in the introduction, ICC$_{only}$ lightning events are important cause of wind turbine damages. However, having very low amplitudes, ICC$_{only}$ should not over-stress the SPDs. They are primarily a threat for receptor melting which leads to further blade damage. The damage effect is cumulative and the detection of ICCs could serve for adjusting the maintenance timing for the Lightning Protection System. For observation of SPD's energy absorption, it is more interesting to consider a combined lightning current which consists of ICC and subsequent strokes. One recorded lightning current of this type given in [6] was used for the simulation on the model described in this paper. The lightning current consists of an ICC with 2 kA amplitude, lasting for about 270 ms, one superimposed impulse close to the end of the ICC, with -8 kA amplitude, and four return strikes with amplitudes of -13 kA,

-10 kA, -12 kA and -11 kA respectively. Energy consumption of the SPDs at generator terminals and LV transformer side are shown in Figure 14 and Figure 15 respectively.

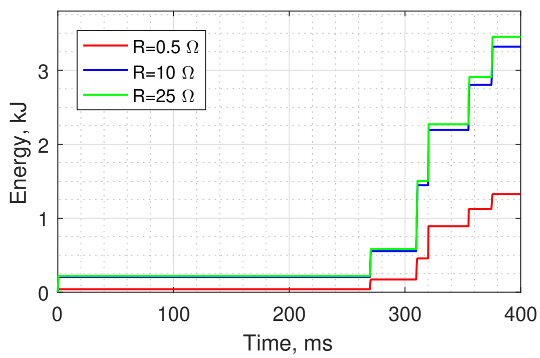

Fig. 14. Energy absorption of the SPD in phase C at generator terminals, in case of combined ICC and subsequent lightning strikes

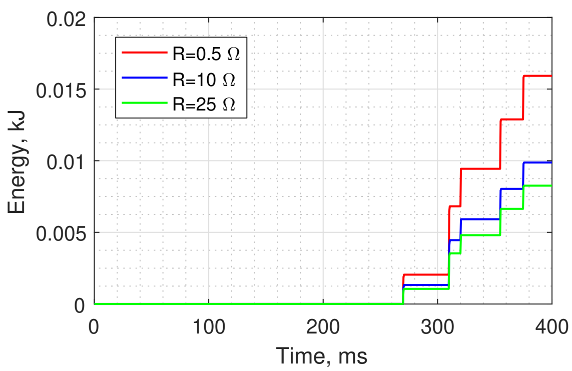

Fig. 15. Energy absorption of the SPD in phase C at generator terminals LV side of the step-up transformer in case of combined ICC and subsequent lightning strikes

From Figure 14 and Figure 15, a cascade can be observed, with 5 steps, each for one subsequent strike. It is again confirmed that the energy consumption of the SPD at the LV transformer side is higher for lower grounding resistances, but all energy values for this SPD are lower than 0.017 kJ which is negligible. However, for the SPD protecting the generator, energy absorption is higher, reaching 3.5 kJ in case of 25 Ω grounding resistance. Hence, aside to the grounding parameters, the energy absorption of the SPDs greatly depends on lightning flash multiplicity and each subsequent strike characteristics.

IV. Conclusion

The paper elaborates the exposure of wind turbines to direct lightning strikes. A change in lightning activity based on the Croatian LLS data is presented for the location of two closely installed WPPs. The results show the general increase of the lightning strike density after the installation of wind turbines. The greatest lightning strike density is at the micro-location of the most elevated wind turbine. The transient phenomena due to a direct lightning strike to a wind turbine blade was analyzed in the paper based on the EMTP-RV model of a single wind turbine. The overvoltages at the generator and at the LV transformer side, the ground potential rise, the currents conducted by the SPDs and their energy absorption were observed with respect to the grounding resistance change. Higher peak overvoltages, higher peaks of currents conducted by SPDs and higher energy absorption of the SPDs are associated with higher value of grounding resistance. However, the simulation showed oscillations due to reflections at the grounding system in case of the lowest grounding resistance of 0.5 Ω. Consequently, the overvoltage at the LV transformer side, current conducted and energy absorbed by the SPD at the LV transformer side are the highest for that case. This was not the case at generator terminals since there is the tower impedance between the SPD and the grounding. For grounding resistances 10 Ω and 25 Ω, back-flow of the current and reversed conduction of the SPDs at LV transformer side was observed. When the energy absorption is concerned, it was shown that the SPDs at the generator terminals are subjected to higher energy absorption. Accordingly, the SPDs protecting the generator should be chosen to withstand higher energy stresses. It was confirmed that high values of SPD's energy absorption is related to long lightning current wave-tails and lightning flash multiplicity.

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