Detailed EMTP wind turbine model for simulation transient phenomena during lightning strikes

Dominik Miloš, Viktor Milardić, *Member, IEEE,* Amir Tokić, *Member, IEEE*

***Abstract*-- Lightning strikes on wind turbine blades cause significant damage to the wind turbine. This paper presents a detailed description of the EMTP wind turbine model for transient analysis of lightning strikes to wind turbine blades. The main objective of this paper is to develop the EMTP simulation model that can be used to perform simulations and transient analysis of lightning current strikes on wind turbine blades. Another objective of this paper is to identify the waveform of the lightning current that strikes the wind turbine blades by comparing the simulated current waveform with the current waveform obtained from a prototype measurement system at the base of the tower. A prototype measurement system for direct lightning current measurement was developed by a research group at Faculty of Electrical Engineering and Computing, University of Zagreb. Basic functionality of prototype measurement system is described in this paper. In future research it will be possible to determine voltage and current conditions on wind turbine components based on the developed EMTP wind turbine model.**

***Keywords*: EMTP wind turbine model, lightning current waveform, prototype measurement system, simulation results, wave impedance**

NOMENCLATURE

Z_b - wave impedance of blade segment (Ω)
Z_L - wave impedance of bearing system (Ω)
G_U - conductance of earthing strip segment (S/m)
C_U - capacitance of earthing strip (F/m)
L_U - inductance of earthing strip (H/m)
ε_r - dielectric constant of soil
ρ - specific resistance of soil (Ωm)
h - height of blade segment, mean height of bearing system (m)
r - radius of metal strip, radius of earthing Fe/Zn strip (m)
d - diameter of bearing system (m)
l - length of earthing strip (m)

I. INTRODUCTION

WIND energy is one of the most advanced and fastest growing renewable technologies [1]. With the increase in the installed capacity of wind turbines in the world, damages caused by direct lightning strikes to wind turbines are attracting more attention. For quality description and damage analysis, it is necessary to know the basic parameters of lightning current: amplitude (kA), transferred charge (C), specific energy (kJ/Ω) and slope (kA/μs) [2]. To reduce the number of failures of wind turbine (WT) components caused by atmospheric discharges and thus increase their reliability and availability, it is necessary to select a suitable lightning protection system (LPS). Lightning protection systems and surge protection systems are not able to completely reduce the damage to WT caused by lightning strikes. LPS is divided into external and internal, and components are designed according to specific lightning current parameters. The values of the lightning current parameters for dimensioning external and internal LPS components for objects are generally defined in the IEC 62305-1:2010 standard [2]. The norm in question is part of a series of norms related to the protection of buildings from lightning [2]-[5]. Furthermore, the standard IEC 61400- 24:2019 [6] is intended exclusively for WT and relies on parameters defined in IEC 62305-1:2010 [2] according to which LPS is dimensioned.

There are at least two problems when considering maximum amounts of lightning current parameters given in [2]. First, they are based on measurements on tall towers [7], [8] and not on WT. The physical processes of lightning strikes in towers and WT are not the same. Secondly, the distributions are standardized on a global scale and lightning strikes, i.e. current parameters lightning, are primarily a local characteristic phenomenon. In order to obtain the local characteristics and waveforms of lightning currents that strike WT, a prototype measurement system was developed at the Faculty of Electrical Engineering and Computing, University of Zagreb, as part of the DESMe project in the High Voltage Laboratory [9]. The prototype measurement system was installed on the most exposed WT in the wind park in the southeastern part of Croatia. The prototype measurement system is in operation and is continuously monitored remotely. The obtained results and measurement accuracy of the prototype measurement system are compared with the results of the commercial measurement system for measuring lightning current parameters and the LINET system for locating atmospheric discharges [10]. An ultra-fast camera was integrated into the prototype measurement system to confirm the occurrence of lightning strike [11].

In order to analyze the measurement results of the prototype

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D. Miloš is doctoral student at Faculty of Electrical Engineering and Computing, University of Zagreb (e-mail: dominik.milos@fer.unizg.hr).
V. Milardić is with the Faculty of Electrical Engineering and Computing, University of Zagreb (e-mail: viktor.milardic@fer.hr)
A. Tokić is with the Faculty of Electrical Engineering, University of Tuzla (e-mail: amir.tokic@untz.ba)

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measurement system, an EMTP model was created for the transient analysis of a lightning strike in a WT. Simplified WT models have been analyzed in the literature [12] - [16]. EMTP/ATP program was used to model a section of an existing wind farm exposed to different lightning strikes [13]. Simulation of lightning strike to WT blade using simplified EMTP/ATP model was described in [14]. Various calculated models for the transient analysis of lightning strikes in WT were presented in [15]-[16]. The problem of ground potential rise (GPR) in wind farms due to direct lightning strikes was described in [17].

There are many different EMTP WT models in the literature, but they cannot serve the objective of this paper. The main objective of the EMTP model in this paper is to simulate measured lightning strikes registered by the described prototype measurement system and to determine the lightning current waveform that struck WT blades. Based on the developed EMTP WT model, it is possible to determine the voltage and current conditions at any WT components during lightning strikes. In this way, the necessary data is obtained for the possible improvement of the lightning protection system and overvoltage protection to reduce the number of failures on WT [18].

The rest of this document is organized as follows. Section 2 contains a description of the prototype measurement system developed by researchers from the Faculty of Electrical Engineering and Computing, University of Zagreb. A detailed description of EMTP WT model components for transient simulation is presented in Section 3. Section 4 contains the simulation results of the EMTP model compared to the lightning current waveform recorded by prototype measurement system described in Section 2. The corresponding conclusion derived from this research is presented in Section 5.

II. Prototype measurement system

The prototype measurement system for direct lightning current measurement consists of several components: two Rogowski coils with an integrator for measuring lower and higher lightning current frequencies, a module for digitization and signal processing at the output of the integrator, a GPS receiver for direct time synchronization and an industrial computer with a sufficient memory [9].

The entire measuring system can be divided into two functionally independent parts: the measuring part and the control part. The measuring part of the system consists of Rogowski coils and their integrators. The control part consists of the NI cRIO-9055 and its modules: GPS synchronization module NI-9467, fast digitizer NI-9775 and slow digitizer NI-9205.

The aim of the measuring part of the system is to reconstruct a signal that is proportional to the waveform of the lightning current. When a lightning current strikes the WT, the current wave moves in the direction of the grounding system and passes through the Rogowski coils (Figure 1). Since the lightning current wave is time-varying, a time-varying magnetic field is created around it, which generates an induced voltage on the Rogowski coils, according to Faraday's law. The induced voltage is proportional to the derivative of the lightning current with respect to time. The outputs of the Rogowski coils are connected to the inputs of the integrator. Integrators in the measuring circuit are used to achieve proportionality between the amount of induced voltage and the amount of lightning current. The output of the integrator represents the end of the measurement part of the system. Integrator outputs are connected to the inputs of the digitizer, which represent the beginning of the control part of the measurement system. The length of the Rogowski coils is 13.5 m so that they can be installed around the WT tower. The control part of the measurement system consists of a reconfigurable system CompactRIO (cRIO) manufactured by National Instruments (NI). NI cRIO is a robust, reconfigurable embedded system consisting of three main components: a real-time controller, a programmable FPGA chip, and industrial input-output modules (I/O modules). Software support for the prototype measurement system was developed as part of the project. The synchronization of the synchronization module according to GPS time (NI-9467), the triggering of the data acquisition module (NI-9775 and NI-9205), and the recording of the moment of triggering with synchronization according to GPS time have been implemented.

The high-speed camera is integrated into the measurement system to obtain visual recordings of lightning strikes whose current waveforms are recorded with the prototype measurement system. The Phantom VEO 1310L high speed camera is synchronized with GPS time using IRIG-B protocol. With the recording of the lightning strikes it will be possible to determine the point of the lightning strike on the WT and to distinguish between downward and upward strikes [11].

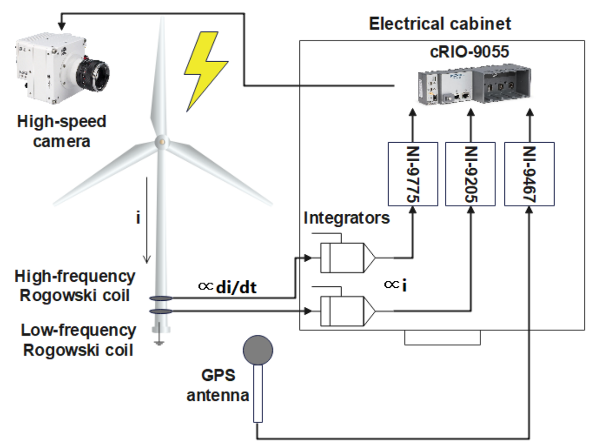

Fig. 1. Prototype measurement system for direct lightning current measurement [9].

III. EMTP model for wind turbine

The EMTP model for the transient analysis of lightning strikes in WT consists of components involved in dissipation of the lightning current wave from the WT blades to the grounding system. The basic WT components modeled for transient analysis during a lightning strike in the WT are blades, bearing system, hub and nacelle, tower and grounding system. The technical data required for the calculation of various electrical values of the WT components in the specified model was obtained from the partner company in the DESMe research project [19].

The main motive behind the development of the EMTP model for transient analysis of lightning strikes is because there is not sufficiently detailed EMTP model in the literature that could be used for the transient analysis of lightning strikes in WT. Using the developed EMTP model, simulations of measured lightning strikes registered by the described prototype measurement system are preformed to obtain the waveform of the lightning current that struck WT blade.

A. Modeling WT components

The modeling of WT components, which are important for the transient analysis of lightning strikes, is based on the wave impedance model in this work. In the literature [20] - [31], the modeling approach is based on the wave impedance model and on the concentrated parameters of the PI model. The two models mentioned have some differences that may affect the results of the transient analysis. The wave impedance model is more effective when it comes to analyzing transient phenomena and reflections at the transition between different components within the system and at high frequencies in the system where the wavelength is comparable to the lengths of the individual components. The PI model with concentrated parameters assumes that the concentrated parameters are constant over the entire length of the component, which can be less accurate at high frequencies, such as those occurring during lightning current strikes in WT. The lightning current that strikes the WT contains high frequencies (in the MHz range) with a large steepness of the lightning current. For these reasons, the development of the EMTP model was started using the wave impedance model when modeling components of the WT.

B. Blades

According to the technical data of the modeled WT, the length of the WT blades is 49 m. Inside the blades there is a metal strip, which is a braid of galvanized copper (30 mm x 5 mm). It serves to divert the lightning current from the receptor of the blade in the direction of the WT grounding system. The radius of the metal strip is calculated using the criterion of equal area. The propagation and reflection of the lightning current wave when it strikes the WT blades was taken into account. The wave impedance of each 3 m length blade segment was calculated. The effectiveness of the WT model for the transient analysis depends on the frequency of the lightning current wave, the wavelength of the wave and the length of the model segments. The λ/10 rule shows that the model is suitable for the transient analysis of current waves up to a frequency of 10 MHz if the length of the WT model segment is less than 3 m. When calculating the wave impedance of the WT blade segments, the positions of all three blades were considered. The probability of a lightning strike is highest at the vertical position of the blade [30]. The wave impedance of the blade components is calculated according to the expression [17]:

$$Z_b = 60 \cdot ln\left(\frac{4h}{r}\right) - 60 \qquad (1)$$

Where: Z_b is wave impedance of blade segment
h is height of the blade segment in relation to reference ground
r is the radius of metal strip (6.91 mm)

Table I show wave impedance values of WT blade segments. The wave impedance value of the blade segment is highest in the highest segment (Z= 614.63 Ω), while it is lowest in the lowest segment (Z= 585.33 Ω). The highest segment of the blade is the furthest away from the reference ground, therefore this segment has the smallest capacitance value, resulting in the highest value of the wave impedance. The WT tower is 78 m high; the height of the hub and nacelle is 3 m and then comes the first blade segment at a height of 81 m.

TABLE I
Wave impedance value by WT blade segments

Height of blade segment in relation to the reference ground (vertical position)	Wave impedance of blade segment Z_b (vertical position)	Height of blade segment in relation to the reference ground (120° and 240° positions)	Wave impedance of blade segment Z_b (120° and 240° positions)
81 m	585.33 Ω	79.5 m	584.21 Ω
84 m	587.51 Ω	78.0 m	583.07 Ω
87 m	589.62 Ω	76.5 m	581.90 Ω
90 m	591.65 Ω	75.0 m	580.71 Ω
93 m	593.62 Ω	73.5 m	579.50 Ω
96 m	595.52 Ω	72.0 m	578.26 Ω
99 m	597.37 Ω	70.5 m	577.00 Ω
102 m	599.16 Ω	69.0 m	575.71 Ω
105 m	600.90 Ω	67.5 m	574.39 Ω
108 m	602.59 Ω	66.0 m	573.04 Ω
111 m	604.24 Ω	64.5 m	571.66 Ω
114 m	605.84 Ω	63.0 m	570.25 Ω
117 m	607.39 Ω	61.5 m	568.81 Ω
120 m	608.91 Ω	60.0 m	567.33 Ω
123 m	610.39 Ω	58.5 m	565.81 Ω
126 m	611.84 Ω	57.0 m	564.25 Ω
129 m	613.25 Ω	56.5 m	563.72 Ω
130 m	613.71 Ω	55.0 m	562.10 Ω

C. Bearing system

The analysis carried out on the WT bearing system shows that the electrical behavior of such a mechanical system in the typical frequency range of lightning currents can be approximated by the resistance and capacitance, which according to experimental measurements is about 8 nF [32]. The propagation and reflection of the current wave through the bearing system were taken into account. The wave impedance for the bearing system of WT was calculated according to the expression [17]:

$$Z_L = 60 \cdot \ln\left(\frac{4\sqrt{2}}{d} \cdot h\right) - 60 \qquad (2)$$

Where: Z_L is the wave impedance of bearing system
h is mean height of bearing system in relation to reference ground (h=79.5 m)
d is the diameter of the bearing system (d=4 m)

The value of bearing system wave impedance is 223.34 Ω.

D. Tower

According to the technical documentation, the height of the WT tower is 78 m. The diameter of the base of the tower at the surface is 4.22 m and 2.7 m at the highest point. For the transient analysis and the calculation of the wave impedance, the WT tower is divided into cylindrical segments of 3 m length. In the calculation, the value of the tower diameter was used as a function of the height of the segment in relation to the reference ground. The wave impedance of the tower segments was calculated according to formula (2). The values of the wave impedance of the tower segments are given in Table II.

Table II
Wave impedance values by WT tower segments

Height of tower segment in relation to the reference ground	Wave impedance of tower segment Z_s	Variable diameter of tower segment
3 m	24.33 Ω	4.161 m
6 m	66.77 Ω	4.103 m
9 m	91.96 Ω	4.044 m
12 m	110.10 Ω	3.986 m
15 m	124.37 Ω	3.927 m
18 m	136.22 Ω	3.869 m
21 m	146.38 Ω	3.810 m
24 m	155.32 Ω	3.752 m
27 m	163.33 Ω	3.693 m
30 m	170.61 Ω	3.635 m
33 m	177.30 Ω	3.576 m
36 m	183.51 Ω	3.518 m
39 m	189.32 Ω	3.459 m
42 m	194.79 Ω	3.401 m
45 m	199.97 Ω	3.342 m
48 m	204.90 Ω	3.284 m
51 m	209.62 Ω	3.225 m
54 m	214.15 Ω	3.167 m
57 m	218.51 Ω	3.108 m
60 m	222.73 Ω	3.050 m
63 m	226.82 Ω	2.991 m
66 m	230.79 Ω	2.933 m
69 m	234.67 Ω	2.874 m
72 m	238.46 Ω	2.816 m
75 m	242.17 Ω	2.757 m
78 m	245.73 Ω	2.700 m

E. Grounding system

In poorly conductive soils, i.e. in soils with a high resistivity, such as the rocky soil on which the WT in Croatia is installed, a lower impulse earth resistance is achieved by installing long earthing strips. Earthing strips in poorly conductive soils can be represented as an overhead line with uniformly distributed parameters [33]: longitudinal resistance R and inductance L, transversal capacitance C and conductance G. In relation to the literature, in which the equivalent scheme of the earthing strip is represented using a π four-pole chain, this paper considers the propagation and reflection of the current wave along the earthing strip. The wave impedance of the earthing strip is used in the model. Longitudinal resistance R does not change the value of the lightning current, nor does it affect the dissipation of the lightning current and is negligible. The dissipation of the lightning current is mainly influenced by the inductance L and the conductance to ground G. In order to calculate the value of wave impedance of the grounding segment (each segment is 3.5 m long), it is necessary to calculate the values of the capacitance, inductance and conductance of the earthing strip segment according to the expressions [33]:

$$G_U = \frac{3{,}1}{\rho} \cdot \frac{1}{ln\frac{l}{r}} \ \ (S/m) \tag{4}$$

$$C_U = 28 \cdot 10^{-12} \cdot (1 + \varepsilon_r) \cdot ln\frac{l}{r} \ \ (F/m) \tag{5}$$

$$L_U = 0{,}2 \cdot 10^{-6} \cdot ln\frac{l}{r} \ \ (H/m) \tag{6}$$

Where: ρ is the specific resistance of soil, l is the length of earthing strip (l= 70 m), r is the radius of earthing Fe/Zn strip (r= 7.14 mm), ε_r is the dielectric constant of soil

The earthing strip can be made of different materials: Cu rope 50 mm^2, stainless steel strip 30 mm x 3,5 mm and Fe/Zn strip 40 mm x 4 mm. The earthing strip on the specified WT were made using Fe/Zn strip 40 mm x 4 mm, and these parameters were used in the calculation of the wave impedance of the grounding system. The radius of the grounding Fe/Zn strip was calculated according to the criterion of equal area. To calculate the specified parameters of the model, it is necessary to know the value of the dielectric constant ε_r. According to [34], high frequencies of lightning currents influence the value of the ground resistance and the dielectric constant of the ground. For a lightning current with a frequency of 1 MHz, the value of the dielectric constant of the soil is approximately 20 [34], which is a result that differs from the value of the dielectric constant of the soil that can be found in the literature [33]. For calculating the values of the mentioned parameters, the value of the specific soil resistance is 2000 Ωm, which is the value characteristic for poorly conductive soils. The value of the inductance of the earthing strip segment is $6{,}434 \cdot 10^{-6}$ H, while the capacitance of the earthing strip segment is $1{,}891 \cdot 10^{-8}$ F. According to the expression for the characteristic wave impedance $Z = \sqrt{\frac{L}{C}}$, the value of wave impedance for grounding segment is 18.44 Ω and the value of segment conductance is $5{,}902 \cdot 10^{-4}$ S. Figure 2. represent overall impedance of grounding system as function of current frequency. Impedance consists of the impedance of grounding mesh and the impedance of earthing strips. According to the graph, with a frequency of 50 Hz value of impedance is 10 Ω. That result correlates to requirements in IEC 61400-24:2019 Wind energy generation systems - Part 24: Lightning protection [6].

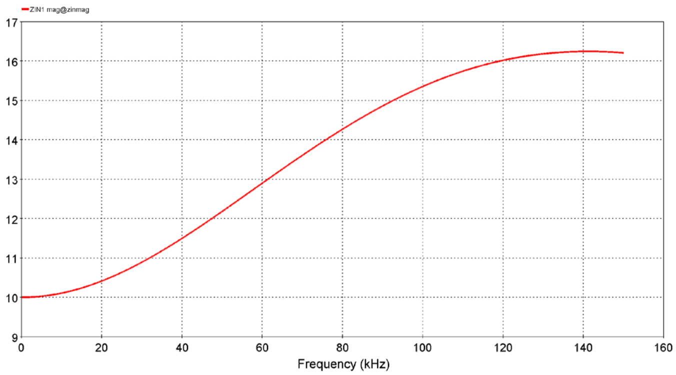

Fig. 2. Overall impedance of grounding system (Ω) as function of current frequency.

IV. Simulation

This section presents the simulation results of the lightning current waveforms recorded by the prototype measurement system and the lightning current waveforms simulated with the EMTP WT model. Signal filtering methods were used to eliminate reflections and noise from the lightning current waveforms recorded by the prototype measurement system at the base of the tower. The filtered lightning current waveforms are used as the current source in the EMTP simulation model. The first waveform, Fig. 3 and 4, represents a negative downward lightning strike, while the second waveform represents a bipolar lightning strike, Fig. 5 and 6. Both strikes were recorded by the prototype measurement system at the base of the tower. Signal filtering methods ("moving average filter method" and "local weighted non-parametric regression fitting using 2nd order polynomial model" [35]) were used to eliminate reflections and noise from the lightning current waveforms recorded by the prototype measurement system. The main objective of the simulation is to determine the waveform of the lightning current that strikes the WT blades, by comparing the simulated current waveform with the current waveform recorded by the prototype measurement system. The simulation results show a high correlation between the lightning current waveforms recorded by the prototype measurement system and the simulated current waveforms, at the base of the tower. If the two signal filtering methods used are compared, the more accurate results are provided by "local weighted non-parametric regression fitting using 2nd order polynomial model".

According to simulation results, it can be concluded that simulated waveforms represent to a high extent actual waveform of the lightning current recorded by prototype measurement system at the base of the tower. It can also be concluded that the filtered lightning current waveforms used as current source in the EMTP simulation model corresponds to the actual lightning current waveforms that strike WT blades.

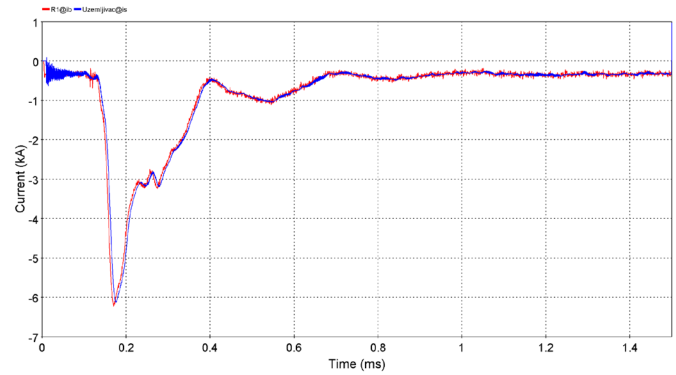

Fig. 3. Comparison of downward lightning waveform measured by the prototype measurement system (red line) and simulated lightning waveform at the base of the tower (blue line) using "moving average filter method" for current source in simulation model.

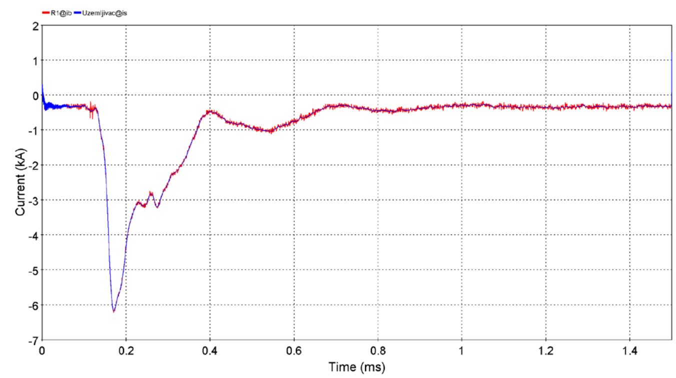

Fig. 4. Comparison of downward lightning waveform measured by prototype measurement system (red line) and simulated lightning waveform at the base of the tower (blue line) using "local weighted non-parametric regression fitting using 2nd order polynomial model" for current source in simulation model.

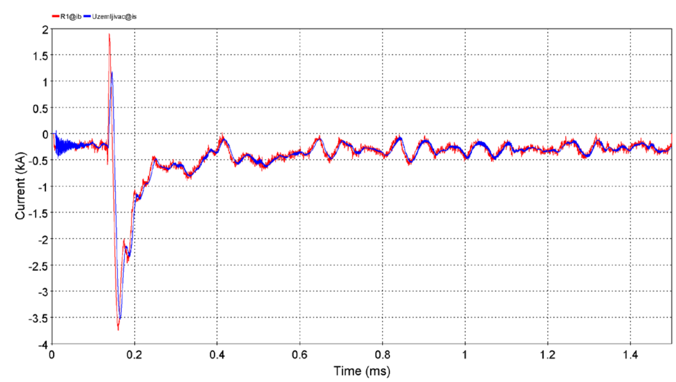

Fig. 5. Comparison of bipolar lightning waveform measured by the prototype measurement system (red line) and simulated lightning waveform at the base of the tower (blue line) using "moving average filter method" for current source in simulation model.

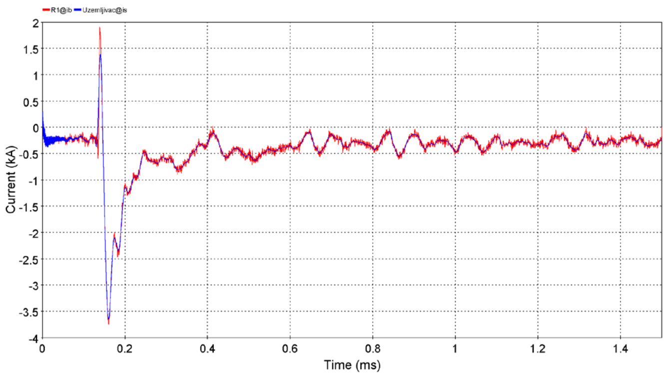

Fig. 6. Comparison of bipolar lightning waveform measured by the prototype measurement system (red line) and simulated lightning waveform at the base of the tower (blue line) using “local weighted non-parametric regression fitting using 2nd order polynomial model” for current source in simulation model.

V. Conclusion

This paper describes the EMTP WT model for the simulation transient phenomena during lightning strikes. The main idea of this paper was to develop an EMTP simulation model that can be used for simulation and transient analysis of lightning strikes on WT blades. The EMTP WT model for the transient analysis of a lightning strike to a WT consists of components involved in the process of discharging the lightning current wave from the WT blades to the grounding system. The basic WT components modeled for the transient analysis are blades, bearing system, hub and nacelle, tower and WT grounding system. All technical data for the WT components were provided by the partner company on the project. In the simulation, two filtered lightning current waveforms recorded by the prototype measurement system were used as the current source. The results were compared between the simulated lightning current waveforms and the lightning current waveforms recorded by the prototype measurement system at the base of the tower. From the simulation results, it can be concluded that the simulated current source waveforms represent to a high extent the actual waveform of the lightning current recorded by prototype measurement system at the base of the tower. It can also be concluded that the filtered lightning current waveforms used as the current source in the simulation model correspond to the actual lightning current waveforms that strike WT blades. Of the two signal filtering methods used, the more accurate results are provided by the “locally weighted nonparametric regression fitting using a 2nd order polynomial model”.

Based on the developed EMTP WT model, it is possible to determine the voltage and current conditions at the WT components during lightning strikes, when it is known the recorded lightning current waveform measured at the base of the WT tower.

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VII. BIOGRAPHIES

Dominik Miloš is born in Osijek, Croatia on April 30, 1996. He graduated in 2020. from the Faculty of Electrical Engineering and Computing, at the University of Zagreb.

His employment experience includes work at scientific DESMe project "Development of an expert system for measuring lightning strike parameters on Wind Turbines" as researcher, company Sigurnost d.o.o. Osijek, as electrical engineer. His special fields of interest include electromagnetic compatibility and interference, electromagnetic transients, communications technology, IT network systems and virtualization, cybersecurity.

Viktor Milardić received his M.Sc. and Ph.D. from the Faculty of Electrical Engineering and Computing in Zagreb (Croatia) in 2001 and 2005, respectively. Currently, he is a Professor at the University of Zagreb. His areas of interest include power system transients, surge protection, lightning protection, grounding, electromagnetic compatibility and high-voltage laboratory testing.
He is the author of many scientific papers and practical projects in the fields.

Amir Tokić received his M.Sc. and Ph.D. degree from the Faculty of Electrical Engineering and Computing in Zagreb (Croatia) in 2001 and 2004, respectively. Currently, he is a Professor at the University of Tuzla, Tuzla, Bosnia and Herzegovina. His areas of interest include power system transients, overvoltage protection, power quality analysis and applied numerical and optimization methods.