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IMPROVEMENT OF MEASUREMENTS OF LIGHTNING CURRENTS CIRCULATING THROUGH THE LINE SURGE ARRESTERS AND TRANSMISSION TOWERS

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Abstract: Due to the improved surge arresters' technology and their low cost and simple installation, there is an increasing number of Line Surge Arresters (LSA) application to the overhead lines installed with the aim to improve the lightning protection of the lines and reduce the outage rate due to the lightning. In order to protect the overhead line from lightning it is advisable to know how does the lightning waveshape look like: what is the peak lightning current; maximum current steepness; charge transfer and specific energy. The experimental system for the measurement of lightning current circulating in line surge arresters and through the transmission line tower was installed on the 110 kV transmission line tower. It is equipped with the real-time monitoring and acquisition system for measuring the amplitude and shape of the currents through surge arresters and the overhead line tower. The newly designed system is based on the state-of-the-art in terms of measuring sensors, communication, and information technologies. The lightning current measuring system is equipped with the custom developed software, which will enable the system to download the data from the measuring device, to process the data and to transfer the data automatically to the cloud. The measuring system's components are chosen according to the specific parameters of the lightning current. The knowledge gained from the measured data will help to define more precisely the procedures to be followed in engineering projects and to specify the phases and towers where line surge arresters have to be installed. On another level, the exploitation of several sources of information simultaneously will help to identify the way to take the maximum possible advantage of the data provided by the lightning detection system.

Keywords: Lightning current, line surge arrester, transient current measurement

INTRODUCTION

As one of the most common geophysical phenomena in nature, lightning has a very wide spatial and temporal distribution. The study of lightning is a challenging task due to its randomness and complex discharge mechanism. Lightning can be defined as a transient electric discharge in air with the length of electric arc measured in kilometres and accompanied by high current that could have values from a few kiloamperes up to tens or hundreds of kiloamperes. The lightning discharge is usually termed a "lightning flash" and the majority of lightning flashes (about three-quarters) do not involve ground. These are termed cloud flashes (discharges) that include intracloud and cloud-to-cloud discharges. Lightning discharges between cloud and earth are relevant for research concerning the power systems, since they can hit objects in the system and threaten the power system reliability. The discharges, i.e. the lightning flashes are usually composed of multiple strokes, and can be downward, or upward when initiated from tall objects.

Lightning protection of renewable energy systems has become a new hotspot and requires further studies. The damage to wind turbines caused by lightning is currently one of the main causes of unplanned downtime responsible for the loss of power generation. Understanding the effects of lightning strikes has become increasingly important as the size and rated power of wind turbines increase. In addition, they are often installed in locations where repair is difficult and costly. Measuring the lightning currents striking wind blades can be helpful for the lightning protection of wind turbines.

Lightning is still one of the main causes of outages on overhead transmission lines. The improvement of lightning protection of overhead transmission lines with the application of the Line Surge Arrester (LSA) is expanding as the technology improves continuously. The use of LSA constitutes a very efficient solution to reduce the number of lightning outages and consequently the number of disturbances to customers and to improve power supply

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availability. LSAs' specification remains challenging because of a lack of precise knowledge regarding lightning current. Typically, lightning current's parameters are estimated based on guidelines and recommendations available in various guidelines.

Although it has been recognized that most of the information contained within is relevant and applicable, it is still possible to improve knowledge using the latest information obtained by the modern lightning location systems installed worldwide. The goal of the developed system for the measurement of lightning current presented in this paper is to contribute help remedy this situation by measuring the lightning current which circulates though the line surge arresters and the body of a transmission tower located in a Croatian region of high lightning activity.

1. REGIONAL EXPERIENCE ON LIGHTNING CURRENT MEASUREMENT SYSTEMS

Nowadays, there are several existing lightning current measurement systems around the world (Japan, Switzerland, Canada, Austria, etc.). Mostly, these systems are installed on high towers, like telecom or broadcasting towers [1]- [6]. The CIGRE brochure 955 published in January 2025 provides with the overview of advanced lightning transient voltage and current measurements for power systems [7].

In this chapter regional experience on different applications of lightning current measurement systems has been described.

1.1. Lightning Activity Monitoring System on a Broadcasting Tower

A monitoring system in real-time for measurement of the direct lightning current was installed on a broadcasting tower in southwestern Montenegro, near the Adriatic coast, on Mount Lovćen, which is of 1749 meters altitude (Figure 1). The lightning current monitoring system was deployed on an 88-meter-high broadcasting tower, which serves as a key telecommunications hub in the area [8]. The selection of this site was based on prior studies and data obtained from a lightning location system (LLS). According to LLS records, Lovćen experiences an exceptionally high lightning density of 1063 strokes per square kilometre annually, exceeding the regional median by over 100 times. The LLS data documented a maximum lightning current amplitude of 500 kA in the observed area [9].

The lightning detection system consists of several components: a sensor module, data recording unit, power supply, central processing system, and user interface. The sensor module, which includes a current transformer, an electric field sensor, and an IP camera, is positioned at the top of the tower.

For current measurement, a 500 kA capacity transformer was used along with a BOLTEK–EFM 100 electric field sensor and a UFG1122 HD IP camera. Data is recorded by an industrial computer via a four-channel acquisition card (8 MSa/s, 15-bit resolution) and synchronized with GPS. Communication with the central server is maintained through Ethernet, with power supplied by AC mains and a low-loss cable featuring a 10:1 voltage attenuator ensuring accurate signal transfer. Data is transmitted in real-time over the internet to a central server, where it is stored in a dedicated information system. A block diagram of the system, detailing all components, is provided in Figure 2 [9].

Figure 1: Broadcasting tower on Mount Lovćen

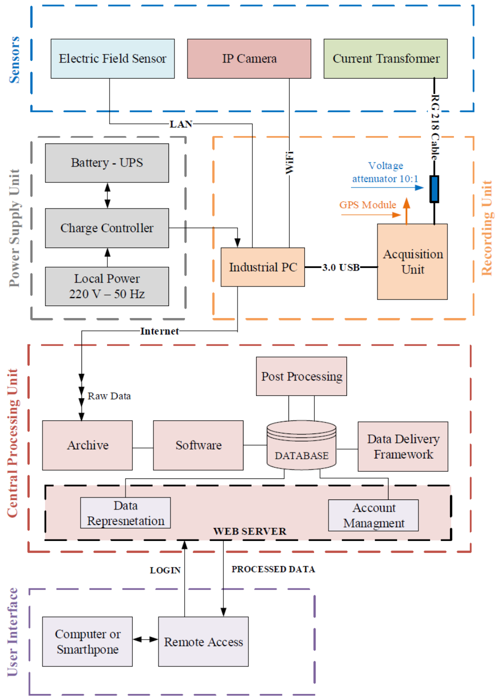

Figure 2: Lightning current monitoring system diagram [9]

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Example of the lightning event, recorded on Lovćen on the 2016-09-01 at 16:10:26,364915480, is shown on Figure 3, whit original measured and enhanced signal. It is negative multicomponent lighting flash consisting of four strokes, which illustrates the system's capability to capture complex discharge processes. The recorded oscillography reveals high-frequency oscillations, which are attributed to interference within the measuring system.

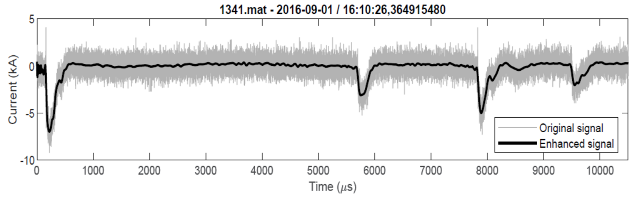

Figure 3: Negative multicomponent lighting flash [9]

1.2. Lightning current measurement system for wind turbines

The lightning current measurement system for wind turbines consists of two current sensors and a real-time controller. Both sensors are Rogowski coils connected to an integrator via a coaxial cable, and they were custom-made based on specified requirements by an experienced manufacturer. They are different in terms of current and frequency ranges for which they are optimized. The first sensor is a high-frequency and high-current sensor, while the second sensor is optimized for lower current amplitudes and frequencies. Real-time controller cRIO is used for digitizing, timestamping and storing the information obtained by the sensors. It utilizes three modules to accomplish previously listed tasks: two digitizers, one for each sensor, and a GPS synchronization module. The controller's exact modules are a high-speed digitizer, a low-speed digitizer and a GPS synchronization module. Figure 4. shows a schematic illustration of the prototype measurement system intended for installation on wind turbines.

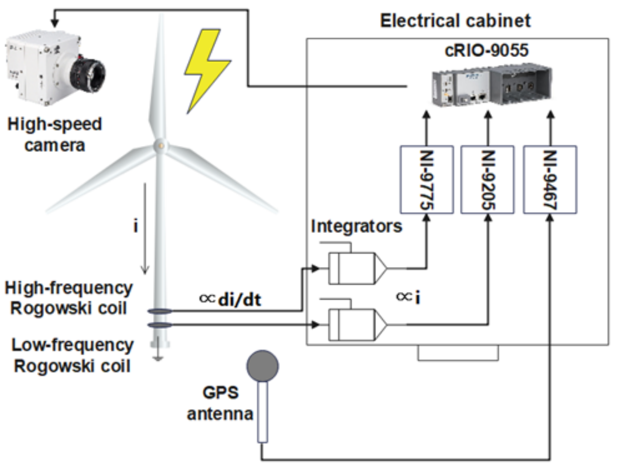

Figure 4: Lightning current measurement system for wind turbines [10]

Rogowski coils encircle the base of a wind turbine to detect the lightning current flowing through the tower. Their output voltage is proportional to the time derivative of the lightning current. The coils are connected to the integrators to reconstruct the lightning current signal. The voltage signals on the integrators' outputs are proportional to the lightning current and are directly connected to the real-time controller. The integrators and the real-time controller are mounted together in an electrical cabinet. The high-speed digitizer acquires data from the high-frequency sensor and, as such, has a sampling rate of up to 20 MHz. On the other hand, a low-speed digitizer acquires data from the low-frequency sensor, and its sampling rate can only go up to 250 kHz. The GPS synchronization module is connected to the GPS antenna to synchronize the real-time controller to GPS time in order to provide precise timestamps for the acquired lightning current measurement. Figure 5. shows an example of recorded lightning current through a wind turbine tower on April 25, 2023, at 18:00:05.865077022.

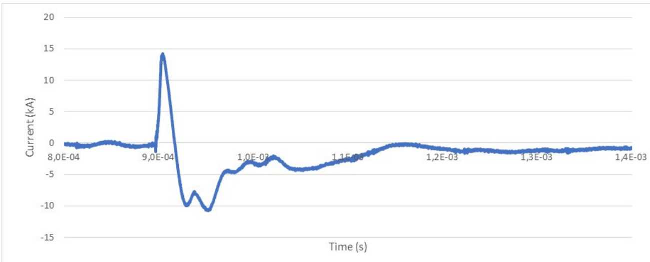

Figure 5: Example of recorded lightning current through a wind turbine tower

2. IMPLEMENTATION OF A LIGHTNING CURRENT MONITORING SYSTEM ON THE OVERHEAD LINE'S TOWER

Due to their locations the 110 kV overhead lines on the island of Brač were significantly exposed to the influence of the lightning activities. A keraunic level of 40 lightning days per year is commonly used when performing computations of lightning performance in this. There were significant numbers of the operational events of the lines caused by the atmospheric discharges.

The overhead lines were equipped by the LSAs in order to improve the line's operational reliability and protection against lightning. The observed overhead line is approximately 14,200 meters long. There are 22 towers along an overhead route of 5,900 meters on the island and an undersea cable section of 8,300 meters. The line was equipped with the 20 LSAs in total as follows: 15 towers with the one LSA in bottom phase, 1 tower (close to the undersea cable section) with two LSAs in bottom and middle phases and 1 tower (closest to the substation) with three LSAs in all of the phases [11]. The correlation of the line's relay protection tripping data and lightning location system data was performed for the period before and after LSAs were installed to the overhead line. The analyses showed the decreased impact of lightning on the operation reliability of the overhead lines i.e. decreased number of outages in correlation to the total lightning activity detected by the LLS in the observed area [12]. Nevertheless, according to the faults' analyses some improvements of the LSAs configuration are still possible [12, 13].

Further research focusing on the lightning phenomena influence on the overhead lines' operation by measuring the lightning current flowing through the LSA and through the tower could contribute to a deeper understanding of lightning parameters, methods for calculating the flashover rate of OHL, and the specification of the lightning impulse discharge capabilities of arresters [14].

The literature does not provide a clear methodology for measuring the lightning current waveform using existing methods nor the commercial equipment is available for recording lightning current through line surge arresters. The proposed transient current measurement system was developed based on the previous experience with the custom designed real time measurement system for lightning transient currents monitoring [15].

Initially experimental measurement system was designed, developed and tested in high voltage laboratory of University of Zagreb Faculty of Electrical Engineering and Computing as described in [16] and [17].

The laboratory tests have shown matching in amplitude and shape of impulse current through the tested object, i.e. matching of current shape recorded by experimental system and recorded on impulse current shunt and conventional laboratory oscilloscope.

Communication tests and tests for data transfer to cloud were successful, without any fail. During testing, there was no evidence of system component overheating or any malfunction. An automated power-on option was tested and after the each of numerous simulated power outage, the measuring system automatically restarted and was ready for the measurement with all previously chosen measurement parameters preserved.

The laboratory testing results have affirmed the proper functionality of the developed system in recording transient events and examining surge arrester performance also in the remote location.

The monitoring system aimed to analyse the distribution of lightning transient currents through the tower and LSAs on all three phases of the 110 kV overhead line. This required equipping the overhead line tower with LSAs in all phases.

The connection scheme of the measurement system installed to the overhead line tower is represented in Figure 6. Figure 7 shows the tower with installed measurement system.

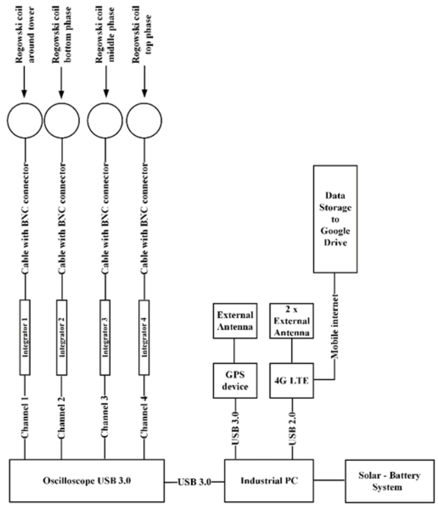

Figure 6: The transient current measurement system connection scheme

Figure 7: Lightning current monitoring system on the overhead line tower

The installation process for the measurement system on transmission line towers posed a complex challenge as described in [18].

The lightning current monitoring system which has been installed on the site consists of:

1. Four Rogowski coils with integrators and cables for connection with acquisition unit,
2. Acquisition Unit with appropriate cables: USB cable for connection with industrial computer and cables for power supply,

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3. GPS/GNSS device with external antenna and cables for connection with industrial computer and acquisition unit,
4. Industrial Computer with 4G LTE module with sim card slot and antennas and custom designed software installed,
5. Outdoor housing,
6. Solar kit (panels, battery, inverter, cables for connection and electric outlet).

There are four Rogowski coils, three of which serve as sensors for measuring currents through the line surge arresters and the one is used as sensor to measure currents through the transmission line tower. The placement of the Rogowski coil for measuring currents through the tower is shown on Figure 8, while the placement of the Rogowski coils for surge arrester currents measurements is on Figure 9.

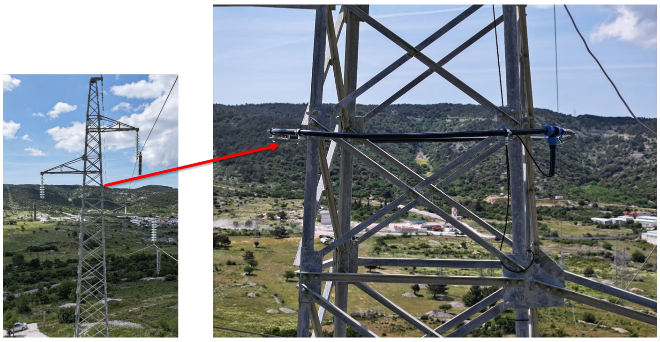

Figure 8: Placement of the Rogowski coil around tower

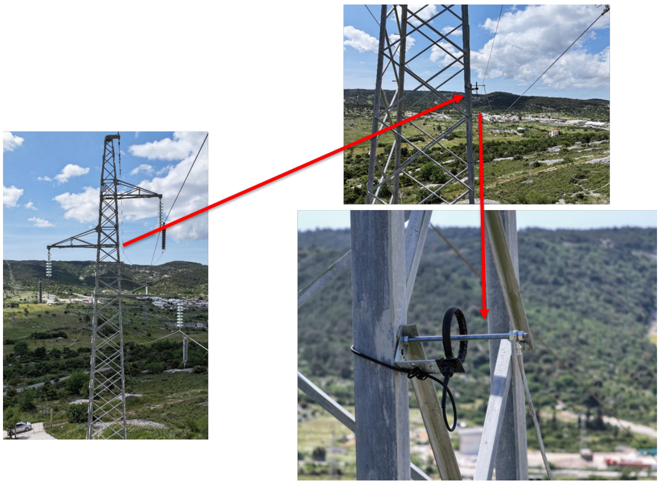

Figure 9: Placement of the Rogowski coils for surge arrester currents measurements

In order to ensure seamless data acquisition and transmission to a central computer for analysis the following system components were housed in an outdoor cabinet mounted on the tower (Fig. 7):

1. Fuses for solar power supply,
2. A charging controller, inverter, and batteries for energy management,
3. Coil integrators connected to an acquisition device,
4. Communication devices, including a GPS receiver and a USB dongle for mobile internet, equipped with corresponding antennas for reliable operation.

The system has been operating continuously since it was installed in May 2024, with no reported disruptions or operational issues.

The solar-battery power supply enabled uninterrupted functionality throughout the monitoring period. The mobile internet connection was continuous and reliable and remote access to the system has operated without any failures, enabling regular access to the measurement system and the database.

The measured data has been downloaded and compared with data from the lightning location system. Two significant events were recorded and are described in [19].

A current measurement was recorded by the system on July 20, 2024, at 11:27:08.918147. The current was measured through the tower using a Rogowski coil placed around it. Simultaneously current was measured with three Rogowski coils through the LSAs installed on the bottom, middle, and top phases of the tower. The current measured through the tower is shown in the diagram in Figure 10. In the graph shown in Figure 11 the currents measured through the LSAs installed on the bottom, middle, and top phases are presented.

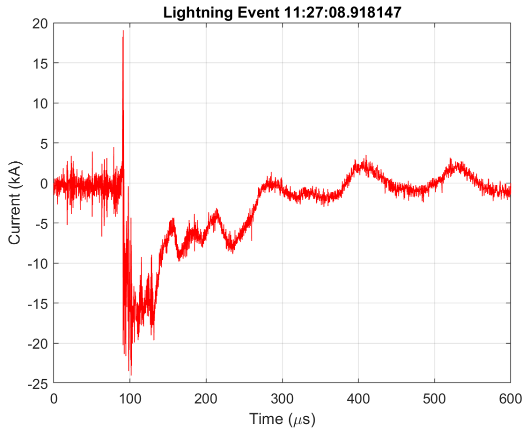

Figure 10: The current measured through the tower [19]

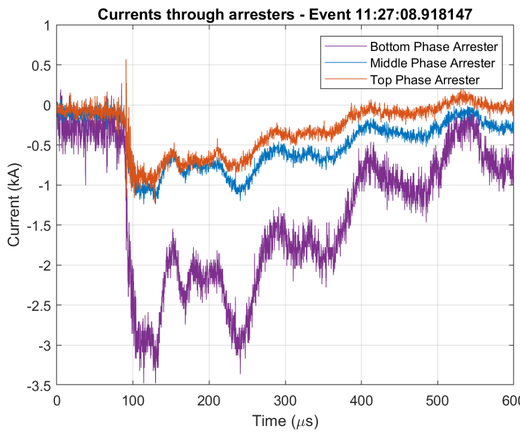

Figure 11: Currents measured through the surge arresters tower [19]

The amplitude of the current measured through the tower was -17.8 kA (Fig. 10). The distribution of the currents amplitudes measured through the LSAs (Fig. 11) reflects the effect of the coupling between the phases and the sky wire in the case of the lightning stroke: 3 kA through the arrester on the bottom phase, 1 kA through the arrester on the middle phase, and 0.9 kA through the arrester on the upper phase.

The LLS registered a negative lightning stroke within the alarm zone of the observed 110 kV overhead line with a current amplitude of -18.2 kA, occurring on July 20, 2024, at 11:27:08.860. According to the time and spatial correlation i.e. as the time of the events and current amplitudes match it can be concluded that both systems recorded the same lightning stroke.

Since the event did not influence the operation of the overhead line and was not registered by the relay protection system, it could be concluded that the LSAs performed their function correctly.

Another event, the activation of the surge arrester installed on the top phase of the tower, was recorded by the system on June 21, 2024, at 14:53:40. This event shows the excellent time correlation with the reactivation of the transmission line where the developed measurement system is installed, at 14:53:41 on June 21, 2024 as registered by the SCADA system during the grid restoration process after a major power outage in Bosnia and Herzegovina, Montenegro, Croatia, and Albania [19].

3. CONCLUSION

The reliability of the operation of overhead lines and the power system as a whole can be influenced by the lightning, especially due to the extreme weather conditions which occur more frequent recently as the consequence of climate change.

Worldwide lightning transient voltage and current measurement systems are increasingly being used. The results of such measurements can contribute to the better understanding of the lightning phenomena and its impact on the operation of the power system, but also to the reduction of number of operational failures, to the faster detection of the causes of failures and their elimination and to the faster clearing of the failures.

This article describes regional experiences with the real-time lightning activity monitoring system on a broadcasting tower and on wind turbines. The emphasis is on the implementation of a lightning current monitoring system on the overhead line's tower which measures the distribution of the lightning currents through the overhead line tower and through the line surge arresters installed to the overhead line.

The implementation of the lightning current monitoring system not only addressed the challenges of frequent lightning-related outages but also established a robust framework for analyzing lightning transient behaviour in high-risk areas. The strategic design and meticulous installation of the system components ensure accurate and reliable data collection, contributing to improved overhead line performance and protection strategies.

The development of an Electromagnetic Transient (EMT) model of the lightning protection system will be in the focus of the next phase of the research in ordered to simulate the lightning currents' impact on surge arresters and the operation of the overhead lines.

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BIOGRAPHY

Selma Grebović, holding a Ph.D. in electrical power engineering from Graz University of Technology, Austria, is an Associate Professor at the University of Sarajevo. With a background in electrical power engineering, she specializes in high voltage engineering and system performance. Selma's expertise spans various domains, including IIoT solutions, embedded systems design, insulation coordination studies, and advanced measurement systems development for high-voltage applications. Selma possesses expertise in analyzing transient phenomena in electrical power systems. Engaged in numerous industrial projects, she actively contributes to advancements in her field. She is a member of IEEE and CIGRE.

Ivo Uglešić is the author of numerous scientific and professional papers as well as many studies and technical solutions that have been implemented in the practice. Prof. Uglešić was granted by the International Council on Large Electric Systems – CIGRE in 2018 for his remarkable work in the study committee „System Technical Performance" with the title of Fellow. His scientific and professional work includes areas of high voltage engineering, overvoltage protection, electric power transmission and electric traction.

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.

Silvia Sinčić, received M.Sc. and Ph.D. from the Faculty of Electrical Engineering and Computing in Zagreb (Croatia) in 2011 and 2020, respectively. Currently she is advisor in executive office in Croatian Transmission System Operator where she is also responsible for the projects related to the overhead lines lightning protection. As a member of the Study Committees C1 and C1 she actively contributes to the work of the Croatian National Committee CIGRE. She is author of expert and scientific papers with topics covering overhead lines lightning protection.

Alan Županr, Ph.D., was born in 1985 in Zagreb. He is the Executive Office Director at the Croatian Transmission System Operator (HOPS). He completed his graduate studies in 2011 and his doctoral studies in 2016 at the Faculty of Electrical Engineering and Computing, University of Zagreb. Over his professional career, he has actively contributed to ten-year development plans; performed power-flow studies, security analyses, and short-circuit calculations in the transmission network; managed assets; conducted investment analyses; planned investment implementation; and assessed asset condition. In addition, he is an expert in transient calculations and in selecting parameters for variable shunt reactors in high-voltage networks. Besides being a member of CIGRE internationally and of the Croatian National Committee (NC) of CIGRE for a number of years, he is also a member of the Croatian NC CIGRE Study Committee C5 and a member of the Executive Board of the CIRED Croatian National Committee (HO CIRED).

Luka Ćurin was born in Split, Croatia. He graduated Science and Mathematics High School, Split in 2009. He received the B.Eng. and the M.Sc. degree in electrical power engineering from University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture in 2014. and 2016., respectively. He is currently working as Engineer at Croatian Transmission System Operator Plc. at the Department of overhead lines and cables. He is a member of CIGRE. He has many years of practical experience in maintenance of overhead lines and cables and was author and coauthor of multiple papers for CIGRE regarding lightning protection on overhead lines.