The Principles of a New Line Surge Arrester's Transient Current Measurement System

Selma Grebović, Ivo Uglešić, Alain Xémard, Viktor Milardić, Silvia Sinčić, Luis Diaz

***Abstract*--Power systems are exposed to different types of electromagnetic transients, which involve a large spectrum of signals whose duration can range from several nanoseconds to several milliseconds, and whose peak values can also cover a wide range of values. Therefore, measuring electromagnetic transients in power systems is a challenging task. Fast front transients caused by lightning events are especially dangerous, and improved knowledge about them is essential for better protection design. The development of measuring systems for such phenomenon is important. This paper is dedicated to the development of a measuring system for lightning and line surge arrester currents. Modern electronic tools and equipment, as well as cutting-edge communication and information technologies, constitute the foundation of the proposed system. This includes the most recent models of acquisition units and GPS devices that are now available on the market, as well as communication networks including 4G, 5G, and WiFi. Software and hardware components of the system are described. The paper presents laboratory tests conceived to prove that the system operates correctly and provides accurate results. The measurements are compared to EMTP and MATLAB simulations. Both are in agreement.**

***Keywords*: high voltage, laboratory testing, lightning current, measurement, surge arrester, numerical simulations.**

I. Introduction

PERFORMANCE of the overhead transmission lines is largely influenced by lightning activity. Lightning current is often a source for line outages and system disturbances [1]. In order to protect the power system, it is advisable to know what to protect it from, i.e., how does the lightning current waveshape looks like. According to CIGRE Brochures 549 (2013) and 855 (2021) the lightning threat is associated with specific current parameters such as: lightning current peak, front duration, tail duration, maximum current steepness, charge transfer and specific energy [2], [3].

The lightning performance of overhead lines can be improved by: improvement of tower grounding system, increase of critical flashover voltage (CFO), installation of Line Surge Arresters' (LSA) and application of grounding wires [4], [5], [6].

The application of grounding wire, which intercepts lightning strokes so that they cannot directly strike the phase conductors in association with low tower grounding impedance, is the most common protection of overhead transmission lines.

Low tower grounding impedance decreases the risk of lightning back flashover occurrence to the overhead line. Nevertheless, in some specific environments, it is very hard to effectively reduce the value of the tower grounding impedance.

In addition, a significant increase of the length of the insulator strings to decrease effectively the lightning flashover rate is in most cases not possible.

The use of LSA is comparatively an efficient low-cost solution and is of simple installation. Consequently, their application on overhead lines (OHL) has increased [3].

The measurement of lightning current circulating in LSA and through the tower could be used to improve knowledge on:

- lightning parameters;
- methods used to calculate the flashover rate of OHL (as well as validation of EMTP-like software programs [7]);
- specification of the lightning impulse discharge capabilities of arresters [8].

Time and date of the lightning stroke, GPS coordinates (2D), lightning current amplitude, lightning type, height (for inter-cloud lightning), and 2D statistical error are all included in the formatted lightning data provided by lightning location systems (LLS). The front and tail times of the lightning current waveform are not recordable by lightning locating devices. It is generally known that these parameters are useful for insulation coordination studies and front time has a significant impact on insulation in power systems, but energy strains experienced by surge arresters, for example, are highly influenced by the overvoltage wave's tail time.

The variety of the lightning parameters used in practical engineering studies still deserves research [9],[10].

Around the world (Japan, Switzerland, Canada, Austria, etc.), there are many systems installed for measuring lightning current waveforms. Most of these systems are installed on high towers, like telecom towers [11] - [16].

Unfortunately, there are not that many such measurement systems installed on the OHL.

From all that has been mentioned above, it may be concluded that it is very important to measure lightning currents on overhead lines and that these results have practical application and value.

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In the past, a real time monitoring system for the lightning transient currents was developed and installed on two towers equipped with LSAs on a 110 kV overhead line in the Croatian transmission network [17]. During its operation, the measurement system provided data useful for performing correlations with lightning location system (LLS) data, as well as with data recorded by the overhead line's relay protection device. After several years in service, it was no longer possible to obtain measurement data from the system because of aging and obsolescence. Therefore, it was decided to develop a new measurement system, which would take advantage of the progress in electronics. The new system is based on state-of-the-art measuring sensors, communication, and information technologies, all of which are in detail described in Section II of this paper.

This paper describes the experimental real-time measurement system for monitoring the waveshape of the currents through surge arresters and the overhead line tower, including the results of its testing performed in high voltage laboratory.

The rest of the paper is organized as follows. Section II describes experimental system for measuring lightning currents. Section III depicts the laboratory tests, and the experimental results. The numerical simulations conducted with EMTP@ [18] and MATLAB@ as well as the comparison of both simulations and measurements are shown in section IV. Paper is concluded in section V.

II. Description of the Measurement System

The developed experimental measurement system consists of the following components (see Fig. 1):

- Sensor unit;
- Recording unit;
- Power supply unit;
- Communication and storage;
- Software;
- User interface.

This section describes the hardware and software details of the developed real – time system.

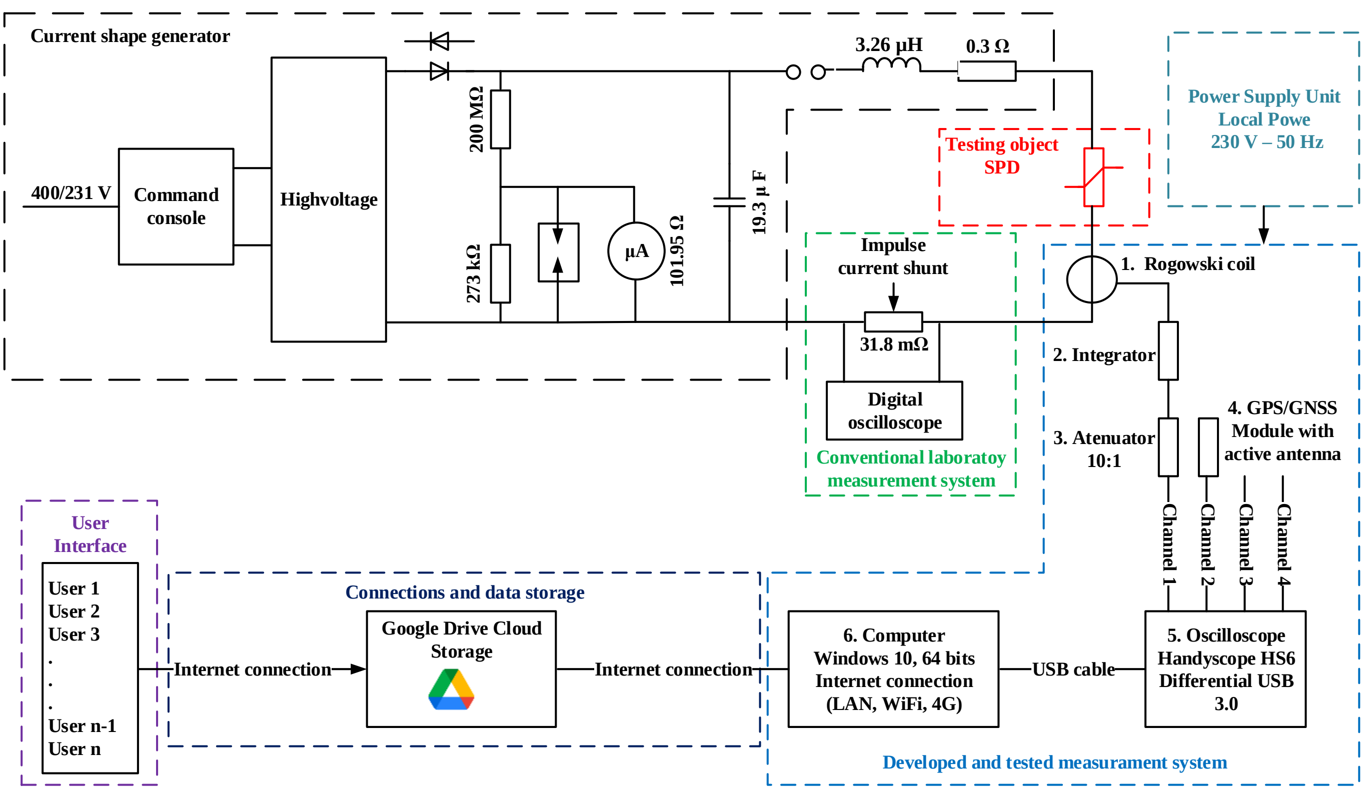

Fig. 1. Scheme of the test system in a high voltage laboratory

A. Hardware of the Proposed System

Rogowski coils or current transformers can be used as sensors to measure the lightning current. In this system a Rogowski coil is used to measure the current that passes through the distribution surge arrester (SPD). Rogowski coil integrator is wide bandwidth up to 8.3 GHz. For used Rogowski coil current is proportional to the output voltage with ratio: 10kA/1V. The Rogowski coil is labeled with number 1 in Fig. 1 and Fig. 2.

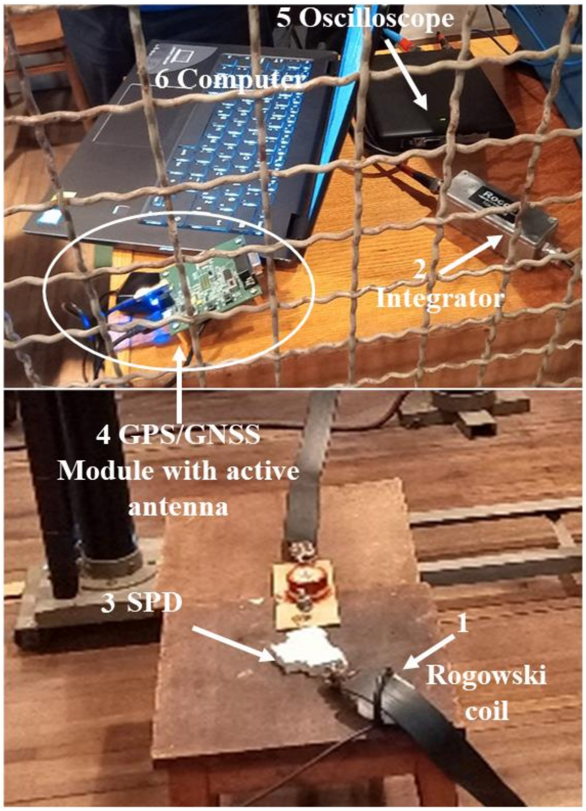

Fig. 2. Components of system in laboratory

Lightning is a fast phenomenon, to record it successfully, a card for downloading data must have a sufficiently high sampling rate (the duration of the wave front can be as short as 1 μs). The proper selection of an acquisition unit for satisfactorily recording the lightning current waveshape and preserving all the parameters is critical: current peak, front time, tail time, duration, polarity, and multiplicity.

An important parameter of lightning current is the peak value. It can be up to a few hundred kA, therefore the card must have an input range large enough to avoid saturation during measurements. Vertical resolution (in bits) also affects the accuracy of the measured lightning current peak.

Acquisition unit embedded in this system (marked with 5 in Fig.1 and Fig.2) is a differential oscilloscope that contains differential dividers and probes. The oscilloscope has a Safe Ground option that allows it to work either as differential or as a classic oscilloscope, the latter mode was used for the measurements. The oscilloscope has an adjustable measuring range (± 80V), and it is possible to use 14 bits of resolution for measuring on two channels simultaneously.

A voltage divider is necessary to protect the oscilloscope from damage during the tests. A 10:1 voltage divider is placed between the integrator (marked with 2 in Fig.1 and Fig. 2) of the Rogowski coil and one of the inputs of the data download card (e.g., as in Fig.1 Channel 1).

The selected acquisition unit has 4 channels and maximum possible sampling 1 GSa/s with high resolutions of 12, 14 and 16 bit. With the eXtended Memory option, up to 256 MSamples of memory is available per channel. Developed system uses two channels and it is set to 64 Mpts (mega points) per channel to be used, and this mean recording frame of maximum 1.28 (s).

The lightning discharge data retrieval system must also be equipped with a precise GPS receiver that sends a PPS (Pulse Per Second) signal at an output, where the PPS signal is an electrical signal that repeats once per second. In addition to the acquisition card measuring the discharge current, it should be possible to record the PPS signal. Therefore, the acquisition card must have at least two input channels (one for measuring the discharge current and the other for measuring the PPS signal), at the same acquisition rate. The PPS signal is connected directly via a cable to the acquisition card. In addition to the PPS output, the GPS receiver must have satisfactory self-accuracy, which is the result of direct processing of the received GPS signals and transformation of this data into GPS precise time. Used GPS/GNSS module with active antenna is marked with number 4 in Fig. 1 and Fig. 2.

Due to the synchronization of measurements on two channels (channel for measuring discharge current and channel for PPS signal) it is very important that the data acquisition card has a very precise internal timer, which is measured in PPM (Part-Per-Million). For this special application, a precision of up to 5 PPM is considered satisfactory (1 PPM time base accuracy is for selected acquisition unit).

A computer (number 6 in Fig. 1 and Fig. 2) is used for storage and transfer measured data from acquisition unit to the cloud. Data from acquisition unit to computer are transferred via Super Speed USB 3.0 (up to maximum 5 Gbit/s). The used computer is equipped with Windows 10, 64 bits and an internet connection (LAN, WiFi and 4G). It is common use a PC with an Intel processor i5-8250U, 8GB of RAM and SSD disc of 256GB.

During the test, a 4G connection was used for data transfer to the cloud storage. When data are stored in the cloud, they are available to all authorized users.

In the laboratory, local power was used as a power supply unit for the developed system, but if this system should be installed on site, then it is necessary to consider alternatives for power supply either from solar or wind energy.

B. Software and Data Storage in the Cloud

The lightning current measuring system is equipped with a custom developed software in order to perform the following operations:

- Downloading of data by the measuring card, i.e. from the measuring device (in this case Rogowski coil), all the way to the computer, via USB 3.0 interface;
- Processing of this data, i.e. recording on the controller disk;

- Sending the processed data to the cloud, via a network communication (LAN, WiFi, 4G).

All events are recorded in .csv format and the maximum duration of the recorded events according to the card characteristics is 1.28 (s). It is also necessary to record some time before the trigger to ensure correct recording the entire curve. It is common to take this time as 20% of the total time in which an event is recorded.

In the case of multiple lightning flashes all components in the flash (all strokes) will be recorded.

Due to card limitations, the system will not be ready for a new recording until the recording sends the data to the computer. The time required (minimum) to send one recorded event (one .csv file) is less than 0.5 (s). It is a challenge to achieve the maximum sending speed, so the exact sending time can be determined by testing with an oscilloscope and optimizing the software. This problem cannot be solved by software, while sending data from a computer to the cloud is possible continuously via thread functions.

For the purpose of testing the system and because of possible interruptions of the automatic operation of the system, it is necessary that the software has the ability to manually execute commands such as:

- Trigger,
- PPS signal,
- GPS and
- Recording and sending data.

The system must be conceived so that data may be automatically sent from the computer to the cloud, for instance, once per day (or as required by the user). The sent data must then be automatically removed by the program to free up space in the computer's memory, which may be in a remote location. The program should be made to launch automatically as soon as the computer is powered on because of the potential distant location of the system. In laboratory, these options have also been checked.

III. EXPERIMENTAL MEASUREMENT SYSTEM TESTING

The major objective of this task is to develop a system that can be installed in remote locations. Fig. 3 illustrates the installation of the Rogowski coils for monitoring the currents through the tower and surge arresters. Transient current flowing through the each of the surge arresters is measured by the Rogowski coil installed around the ground lead conductor of the surge arrester. A specifically developed Rogowski coil is installed around the tower in order to measure the total lightning current flowing through it. Before installation on site, it is very important to test all functionalities of the system in a laboratory. Therefore, an experimental system for measuring lightning currents was developed in the high-voltage laboratory of the University of Zagreb.

The aim was to perform the tests with a large number of pulse currents of various waveforms. Due to generator characteristics, it was possible to generate standard lightning current waveshape 8/20 µs [8] with amplitudes up to 10 kA. The optimal performance of the individual system's components was identified. The scheme of the test setup for the experimental measurement system testing in the high voltage laboratory is shown in Fig. 1.

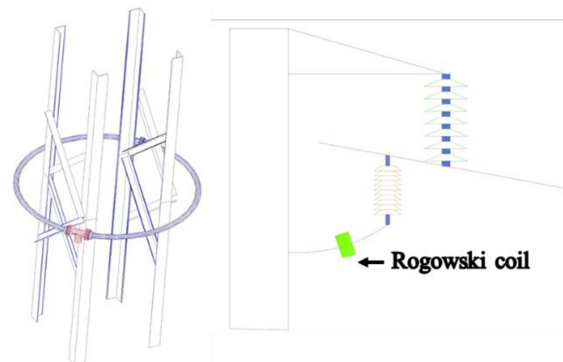

Fig. 3. Principle of the installation of the measuring system on the transmission line tower

The experimental laboratory measurement system was developed based on the previous experience with the custom designed real time measurement system for lightning transient currents monitoring [19], [20], [21].

To perform tests in the laboratory it was necessary to make use of the following equipment (as it is shown in Fig.1):

- Impulse current generator;
- Testing object;
- Conventional laboratory measurement system;
- Developed system (the system that was tested);
- Power supply for developed system;
- Internet connection.

The impulse generator can generate surge currents up to 10 kA peak values of both polarities of standard waveform 8/20 µs (or some other wave-shape). As it can be seen from the Fig. 1 the condenser with the capacitance C=19.3 µF is charging and the spark gap reacts after the voltage has reached a critical value.

The currents measured with the experimental system were simultaneously compared with the ones observed with a conventional laboratory measurement system. This system consisted of an oscilloscope with sampling rate of 50 MSa/s. Voltage was measured at low inductive resistance R = 31.8 mΩ (see Fig. 1.). The current was obtained via this voltage drop.

A distribution surge arrester (SPD) was used as test object. Characteristics of tested SPD are given in table I.

TABLE I
CHARACTERISTICS OF DISTRIBUTION SURGE ARRESTER (SPD)

Maximum discharge current	40 kA
Nominal discharge current	15 kA
Voltage protection level	1.2 kV
Maximum continuous voltage	275 V
U – I Characteristic	
Voltage [V]	Current [A]
344	0.001
402	0.01
459	0.1
517	1
575	10
632	100
690	1000
1100	10000

The experiments performed for the lightning-first stroke test and for communication and data storage tests are described in this section. Acquisition unit was set to record events with sampling rate of 50 MSa/s with resolution of 14 bits and duration of events to be recorded was set to 200 µs, with a pretriggering time of 20 µs.

A. Lightning First Stroke Test

The first experiment consisted of the generation of a single 8/20 µs impulse, with a low peak current. This preliminary test was important to check that the laboratory set-up was operational, and the equipment responded to desired requirements. The low amplitude of the first impulse was used to check the accuracy of the thresholds that have been selected. If this generated impulse is acquired correctly by the monitoring system and sent to the server, all the other ones with higher peaks should be recorded as well. Once this first test was successfully performed, a more complicated exercise was done.

The second experiment consisted of the generation of current shapes with different peaks. Several impulses with different current peaks were generated. The aim was to make sure that the monitoring system acquire all of the impulses and send them to the server over the mobile network. If all the acquired shapes and received in the server were identical to the generated ones the experiment was considered successful.

B. Communication Test

The purpose of this test is to see if the monitoring system can communicate over the different networks (software and hardware test). It is particularly important to check if the monitoring system can communicate over the mobile network with a telecom base station with the default internal antenna. Since the communication card is installed inside the EMC enclosure (on the site – tower etc.), it is uncertain if the radio waves will pass through it. Keeping this internal antenna would be interesting because it would avoid the installation of an external one mounted on the tower, with additional cabling and transient protection. Communication between acquisition unit and computer should also be monitored and time of sending data should be determined.

C. Testing results

Fig. 4 shows current shapes recorded during the laboratory testing. Results of tests performed with the generated current shapes with different peaks are shown on the Fig. 5. – Fig. 7.

It can be observed that there is some noise in the recorded signal. This noise is due to the spark gap reaction. Later in the data analyses stage this noise can be removed using appropriate filtering techniques such as: the Fourier transformation, the short Fourier transformation (STFT), the wavelet transformation (WT), etc. Also, this noise was observed to be significantly reduced once the measuring system was encapsulated in a metal box.

The laboratory tests have shown excellent matching in amplitude and shape of impulse current through the SPD, i.e. matching of current shape recorded by tested system and recorded on impulse current shunt and conventional laboratory oscilloscope. Also, communication tests and tests for data transfer to cloud were successful.

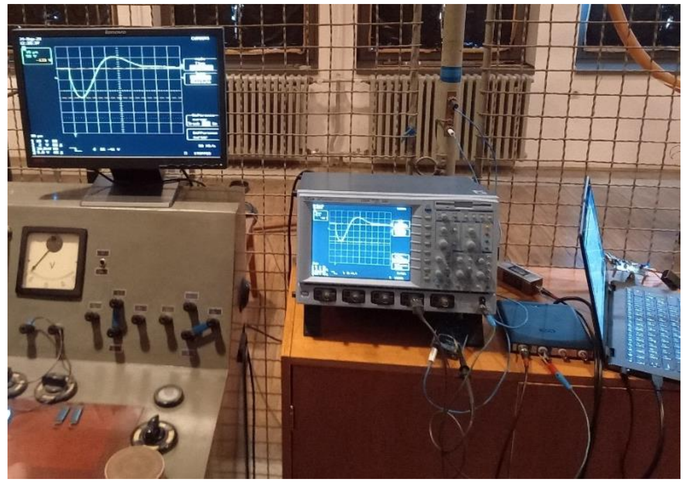

Fig. 4. Current shapes recorded on impulse current shunt

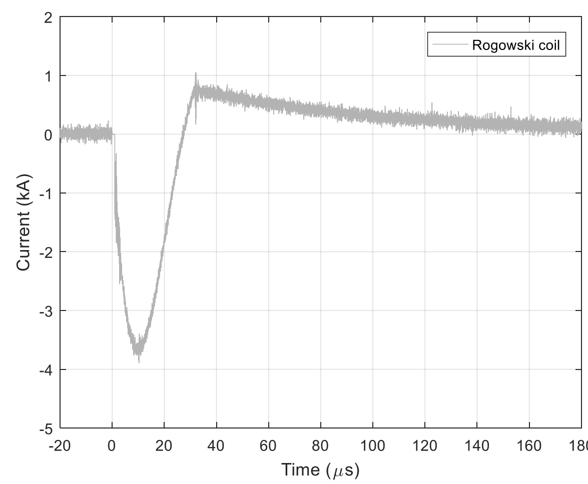

Fig. 5. Measured current with the peak value I ≈ 4 kA

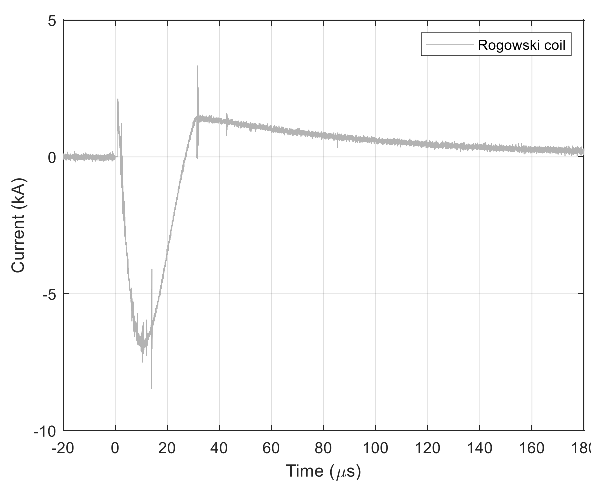

Fig. 6. Measured current with the peak value I ≈ 6,3 kA

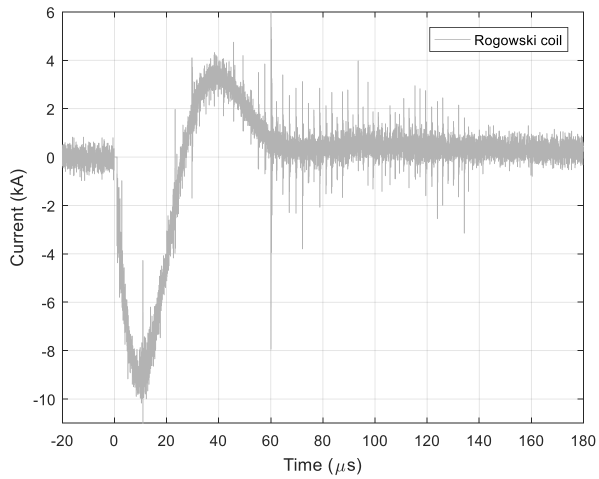

Fig. 7. Measured current with the peak value I ≈ 8,3 kA

The directly measured surge currents are shown in Fig.8. and Fig. 9. and it can be observed that there is no noise in recorded signal due to existing of enclosure on the laboratory oscilloscope.

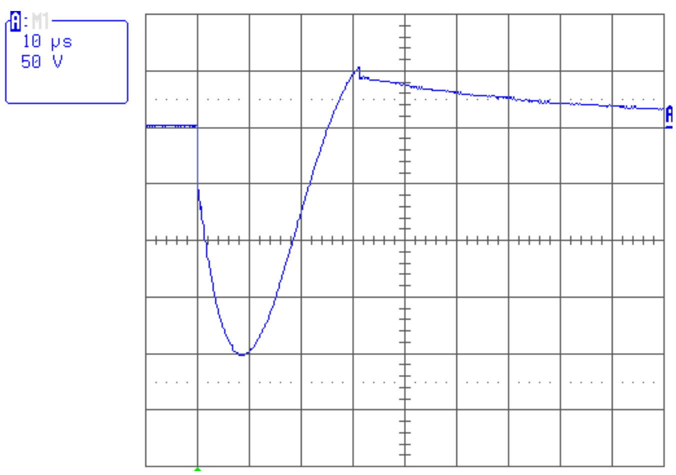

Fig. 8. Directly measured surge currents with the peak value I ≈ 6,3 kA.

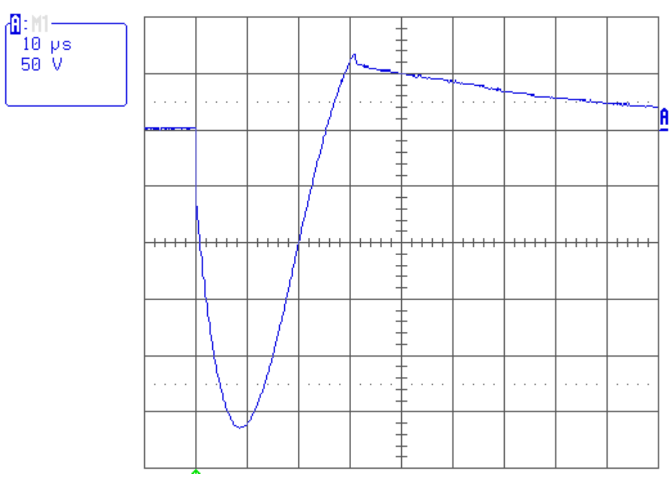

Fig. 9. Directly measured surge currents with the peak value I ≈ 8,3 kA

IV. Numerical Simulations and Comparison with Measured Data

Numerical simulations were conducted in EMTP and MATLAB in order to compare the simulated results with the results of the measurement system.

An impulse current generator (for generating 8/20 μs standard current waveform) with the same characteristics and model as the generator used in laboratory at University of Zagreb was used in simulations (see Fig. 10). Parameters of generator are given in section III of this paper, as well as in Fig.1. The SPD is also modelled with U-I characteristic and basic data that are given in section III.

The EMTP model for generating impulse current with testing object (SPD) is presented in Fig. 10. The same model is developed in MATLAB. Comparison between data recorded by the developed system and simulation results from models developed in MATLAB and EMTP are shown in Fig. 11. – Fig. 13. The difference between the simulated results and the recorded data is due to the modelling of spark gap and SPD. The spark gap has a non-linear characteristic and, together with the SPD, stops conducting current when the voltage drops below a certain value. This behaviour has not been taken into account in the model and it is not included in the simulations performed in MATLAB and EMTP.

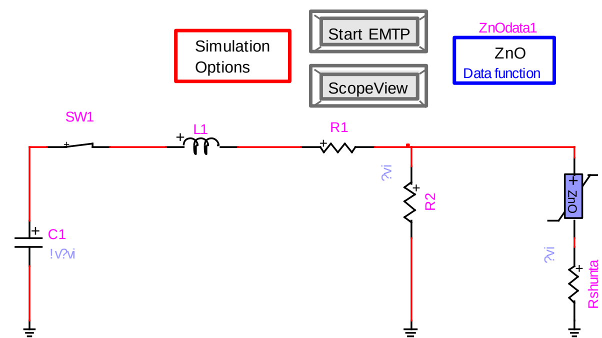

Fig.10. Model for generating impulse currents in EMTP

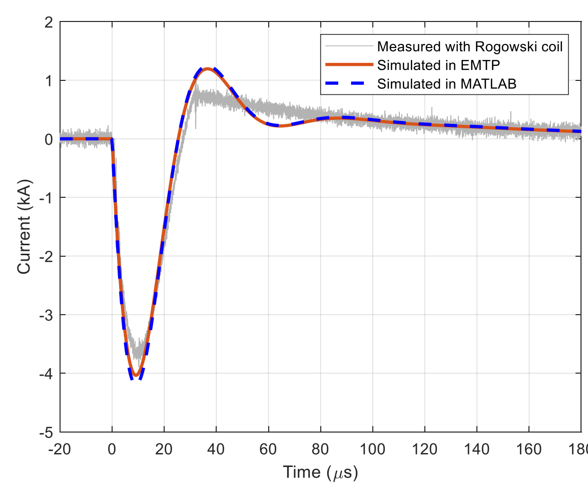

Fig.11. Comparison of measured surge current (using proposed system) with current simulated in EMTP and MATLAB - with the peak value I ≈ 4 kA

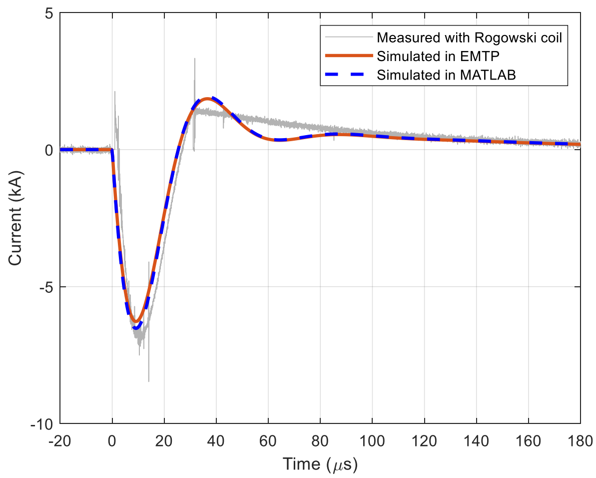

Fig. 12. Comparison of the measured surge current (using proposed system) with the current simulated in EMTP and MATLAB - with the peak value I ≈ 6.3 kA

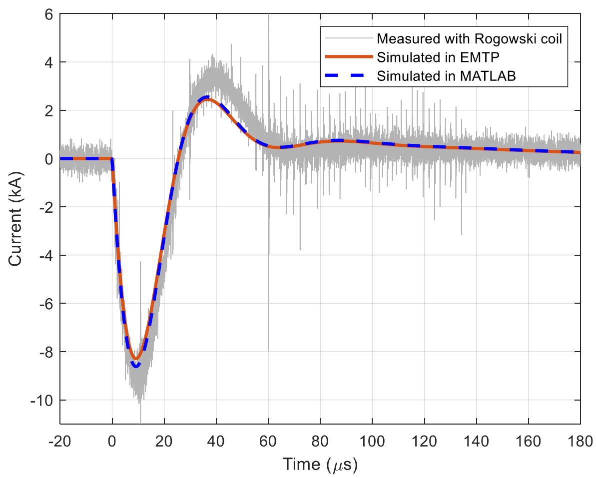

Fig. 13. Comparison of the measured surge current (using proposed system) with the current simulated in EMTP and MATLAB - with the peak value I ≈ 8,3 kA

V. Conclusions

A measurement system for monitoring in situ transient currents through line surge arresters was conceived. It is a solution for monitoring the effects of the lightning activities to the transmission network and power system.

The laboratory tests have shown excellent matching in amplitude and shape of impulse current and, also, communication tests and tests for data transfer to cloud were successful. They suggest that the real time measurement system can also operate properly on the site installed on transmission line tower.

The development and the testing of the new experimental system for monitoring the amplitude and shape of currents through surge arresters can be installed at the tower of the overhead line equipped with the line surge arresters to measure lightning currents circulating in line surge arresters and through the transmission line tower.

Connecting real time measurement system with other systems like weather monitoring system, lightning location system and SCADA could enable the transmission system operator to detect faults' locations faster and to minimize the outage time of the overhead lines due to lightning. Data recorded by the real time monitoring system could also give the opportunity to calibrate lightning location sensors.

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VII. References

[1] A. Atputharajah., T. K. Saha, Power system blackouts-literature review. In 2009 International Conference on Industrial and Information Systems (ICIIS) (pp. 460-465). IEEE, December 2009.

[2] Lightning parameters for engineering applications, CIGRE Brochure 549, August 2013.

[3] Effectiveness of line surge arresters for lightning protection of overhead transmission lines, CIGRE Brochure 855, December 2021.

[4] IEC 62305-1: (2010), Protection against lightning –Part 1: General principles.

[5] M. Mesić, J. Radovanović, D. Škarica, and S. Sadović, "Improving of Reliability Overhead Line 110 kV Ston–Komolac by Line Surge Arrester Installation", Colloquium on Lightning and Power Systems, Kuala Lumpur, 2010., (pp. 16-19).

[6] A. R. Hileman, *Insulation coordination for power systems*, CRC Press, 2018.

[7] B. Badrzadeh, Z. Emin, E. Hillberg, D. Jacobson, L. Kocewiak, G. Lietz, F.F. Da Silva, and M. Val Escudero, "The need for enhanced power system modelling techniques and simulation tools", CIGRE Science & Engineering, Vol N°17, February 2020.

[8] IEC 60099.4: 2014, Surge arresters – Part 4: Metal-oxide surge arresters without gaps for a.c. systems.

[9] Procedures for lightning performance of transmission lines, CIGRE brochure 63.

[10] Procedures for estimating the lightning performance of transmission lines – New aspects, CIGRE brochure 839, 2021.

[11] N. Watanabe, A. Nag, G. Diendorfer, H. Pichler, W. Schulz, V. A. Rakov, and H. K. Rassoul, "Characteristics of Currents in Upward Lightning Flashes Initiated From the Gaisberg Tower," IEEE Transactions on Electromagnetic Compatibility, vol. 61, no. 3, pp. 705-718, Jun. 2019.

[12] F. H. Heidler, and C. Paul, "High-Speed Video Observation, Currents, and EM-Fields From Four Negative Upward Lightning to the Peissenberg Tower, Germany," IEEE Transactions on Electromagnetic Compatibility, vol. 63, no. 3, pp. 803-810, Jun. 2021.

[13] M. Azadifar, M. Rubinstein, F. Rachidi, V. A. Rakov, G. Diendorfer, W. Schulz, and D. Pavanell, "A Study of a Large Bipolar Lightning Event Observed at the Säntis Tower," IEEE Transactions on Electromagnetic Compatibility, vol. 61, no. 3, pp. 796-806, Jun. 2019.

[14] S. Kazazi, A. M. Hussein, and P. Liatos, "Evaluation of the performance characteristics of the North American Lightning Detection Network based on recent CN Tower lightning data," 2015 International Symposium on Lightning Protection (XIII SIPDA), pp. 327-333, Sept. 2015.

[15] https://www.aldis.at/en/lightning-research/lightning-research-at-gaisberg/general/?ADMCMD_view=542

[16] C. Romero, A. Rubinstein, M. Paolone, F. Rachidi, M. Rubinstein, P. Zweiacker and B. Daout, "Instrumentation of the Säntis Tower in Switzerland for Lightning Current Measurements", International Journal of Plasma Environmental Science & Technology, Vol.4, No.1, 2010.

[17] G. Levačić, L. Ćurin, S. Piliškić, D. Škarica, I. Ivanković and M. Mesić, "Overview of the Line Surge Arresters Application in Croatian Transmission Network", CIGRE SEERC Colloquium, Vienna, 2022.

[18] www.emtp.com

[19] T. Sadović, "Real-time remote monitoring of high voltage surge arresters", Graz University of Technology: Graz, Austria. 2010.

[20] M. Muhr and T. Sadovic, "Real-Time Remote Monitoring of Line Surge Arresters", CIGRE Colloquium, Cavtat, Croatia, 2008.

[21] A. Balota, S. Grebović and T. Sadović, "Lightning Activity Monitoring System in Real Time", MECO 2016 - 5th Mediterranean Conference on Embedded Computing, Bar, Montenegro, 2016.