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2. APPLICATION OF OPTICAL SENSOR FOR MEASUREMENTS OF LIGHTNING STRIKE CURRENTS

2.1. Introduction

Optical sensors are usually equivalent to existing classical sensors, which are the result of many years of experience, research and improvement. Optical sensors are often characterized by high resolution, reliability and stability. The main reason for the introduction of optical waveguide sensors (optical sensors in general) lies in their insulating properties, which allow for safe operation in high current and voltage environment. Another advantage is their immunity to electromagnetic disturbances. This advantage is very important in measurements of electric current made (produced) by lightning strike in lightning protection systems (LPS) [6, 12]. Important advantages also include:

- large dynamic range;
- wide frequency response range;
- no magnetic saturation;
- no resonance phenomenon.

A large range of measured currents and work in the high voltage area do not significantly affect the size and weight of the sensor. It is not only light and small, but also relatively cheap.

Based on these features, the authors argue that it is possible to construct an optical current sensor that is simple and cheap enough to be used in monitoring lightning protection systems in buildings particularly exposed to lightning.

It is especially important to protect tall buildings such as office buildings, the so-called skyscraper. During storms, they are most vulnerable to direct discharges, it can be said that they take them over. This problem is also very important in the case of single-family housing estates, when there are no taller buildings over a large area.

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Modern lightning protection systems are very complex. Their purpose is to protect life, property (especially buildings) and electronic devices. Very often lightning protection systems (LPS - Lightning Protection System) are also equipped with discharge counters (LSC - Lightning Strike Counters), which record the date and time of discharge and the approximate value of the current. Additionally, the system can be equipped with a lightning detector that can record discharges from a distance of several or several dozen kilometres. In intelligent building systems, the data from these detectors can be used for early warning lightning systems, which can protect the building by switching off devices particularly sensitive to lightning. Such a detector registers with a special antenna the electromagnetic pulse generated during the discharge (LEMP - Lightning Electromagnetic Pulse). LEMP is one of the causes of electronic equipment interference.

During a direct discharge into a building occur the so-called overvoltages. These overvoltages are especially dangerous for electronic equipment and are often the direct cause of their damage. For this reason, modern LPSs are equipped with devices protecting electronic equipment against surges, known as: SPD - Surge Protective Devices.

The above-mentioned lightning detectors are used to build a network of EUCLID (EUropean Cooperation for LIghtning Detection) measuring stations, thanks to which a map of discharges in Europe is created on an ongoing basis (www.euclid.org/realtime.html). Based on the data on the occurrence of lightning at a specific location, the parameters and requirements of the building's LPS system are determined. In particular, the so-called LPL - Lightning Protection Level is calculated.

When considering the need to use lightning protection for buildings, the most important features of the objects themselves, which may have an impact on the effects of lightning, should be taken into account. Such features of building structures are:

- construction materials,
- functions (apartment building, office building, etc.),
- users and building content (people, animals, flammable materials, explosives, electrical and electronic devices),
- connected installations (power lines, telecommunications lines, pipelines),
- existing or envisaged protection measures (for example measures to reduce: physical damage, threats to life, equipment failure),
- the range of the spread of the threat (difficult evacuation, the possibility of panic, the object's materials or its contents are dangerous to the environment or the environment itself).

In order to assess whether the lightning protection of the structure is needed, the relevant risk associated with the potential types of losses should be determined in accordance with the guidelines of the standard [17]. The principles of LPS structure, including the LPS class, depending on the established LPL (Lightning Protection Level), are specified in detail in the standard [18]. This standard specifies the requirements for the protection of buildings against physical damage by lightning protection devices (LPS) and the requirements for the protection of living creatures against contact and step voltage shock in the vicinity of the LPS. Information on the design, installation, checking, maintenance and testing of protective devices used to protect electrical and electronic equipment in building structures against LEMP is provided in standard [19].

The classic LPS of the building consists of the following elements:

– air terminals;
– down conductors;
– ground terminal.

The LPS scheme for a single-family building is presented in Fig. 1. Air terminals can be horizontal or vertical. Both types of air terminals are most commonly used. These are elements of the LPS system that take over direct lightning discharges to the object, including discharges to the side of the object. Down conductors are used to discharge the lightning current from the point of impact to the ground, where the ground terminal is located. The ground terminal is used to safely dissipate this current in the ground.

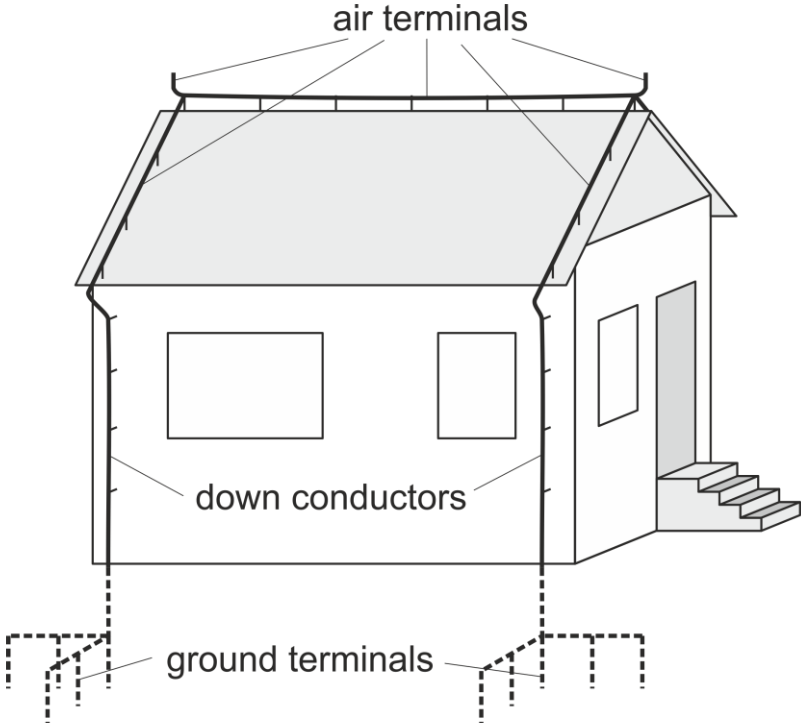

Fig. 1. Scheme of construction of the light protection system (LPS): example – single-family building [19]
Rys. 1. Schemat budowy light protection system (LPS) na przykładzie budynku jednorodzinnego [19]

The above-mentioned lightning strike counters (LSC) are installed on the down conductor at a height of approx. 1.5 to 2 m above the ground. An example of how the counter is mounted is shown in Fig. 2. In practice, the last section of down conductors is made of galvanized steel strip with a rectangular cross-section. According to the standard [18], the required cross-section for steel should be greater than 50 mm^2.

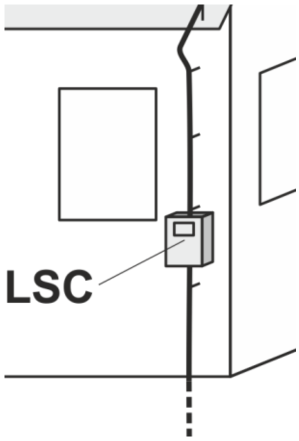

Fig. 2. An example of a lightning strike counter (LSC) mounting location
Rys. 2. Przykład lokalizacji licznika wyładowań (LSC)

2.2. Lightning current

Approximately 90% of ground discharges are downward negative lightning. In the first phase of this type of discharge, a leader is created, which moves towards the ground in a jump-like manner every few dozen meters. When the leader approaches the ground, the electric field intensity at the ground surface begins to increase up to 150 kV/m, which causes partial discharges that begin to move upwards. They are ion streams. At a distance of several dozen meters, these discharges merge with the leader. At this point, the discharge channel is closed. The next stage is the main discharge first return stroke, which is characterized by a high peak current value. If the first return stroke does not completely neutralize the charge in the cloud with the previously created channel, a dart leader develops from the cloud towards the ground and a subsequent stroke is created. Most of all lightning discharges are made up of several or even several dozen subsequent strokes, but there are also discharges with only one return stroke. The highest recorded value of the first return stroke current was 400 kA [1]. The main discharge is also responsible for the greatest damage and electromagnetic interference (LEMP). Table 1 shows the lightning current parameters for negative downward flashes. Example of negative lightning current waveform is shown in Fig. 3.

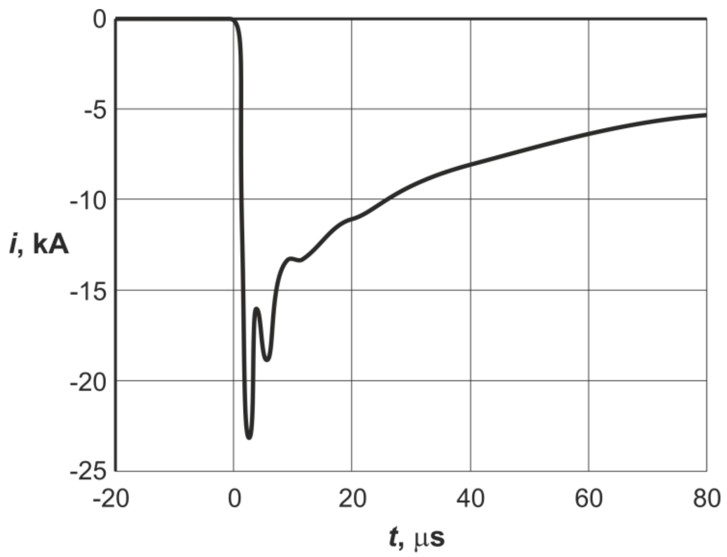

Fig. 3. Negative lightning current waveform recorded at the Gaisberg tower [13]
Rys. 3. Prąd ujemnego wyładowania piorunowego zarejestrowany na wieży Gaisberg [13]

In accordance with the European standard [14], the waveform of the short-term discharge current with a duration of less than 2 ms is described by a waveform with a sharply rising pulse edge – Fig. 4.

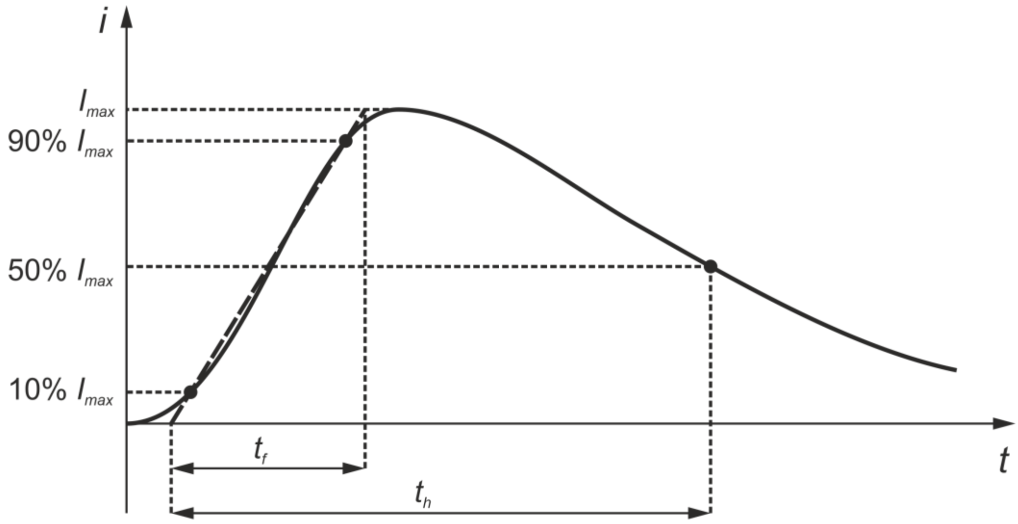

Fig. 4. Parameters of lightning current for short-term surge according to the standard [19]
Rys. 4. Parametry prądu piorunowego krótkotrwałego wyładowania wg normy [19]

The main parameters (according to [14]) of this impulse are:

- front time t_u;
- time to half t_h;
- the maximum value of the current I_{max}.

The electromagnetic pulse can reach very large values over long distances. It is assumed that modern electronic devices can be damaged even within a distance of 1.5 km from the main discharge channel.

Table 1

Lightning current parameters for negative downward flashes

Parameters	Return stroke	Percentage exceeding tabulated value		
		5%	50%	95%
Peak current (kA)	first	80	30	14
	subsequent	30	12	4.6
Maximum *di/dt* (*kA/μs*)	first	32	12	5,5
	subsequent	120	40	12
Front duration (2 kA to peak) (μs)	first	18	5.5	1.8
	subsequent	4.5	1.1	0.22
Stroke duration (2 kA to half peak value on the tail) (μs)	first	200	75	30
	subsequent	140	32	4.6
Impulse charge (C)	first	20	4.5	1.1
	subsequent	4	0.95	0.22

Source: [14]

2.3. Optical fiber current sensor with external conversion – current results of investigations

The optical fiber current sensor with external conversion (OFCS-EC) developed at the Department of Optoelectronics has been extensively tested [2-10]. This sensor is based on the magnetooptic Faraday effect. Its structure is based on a glass rod with high value of the Verdet constant. This rod is the head of the magnetic field sensor. In a current measurement application, the sensor head is positioned near the conductor along the force lines of the magnetic field originating from the flowing current. It is basically a magnetic field sensor used to indirectly measure the strength of an electric current. In classic measuring devices based on current transformers, the secondary current recorded at the output is also caused by the magnetic field of the core, the source of which is the measured current flowing in the primary winding (to be precise: alternating magnetic field).

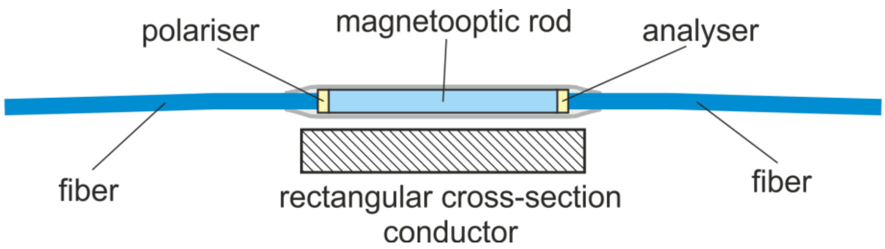

Fig. 5. Schematic view of the optical fiber current sensor with external conversion (OFCS-EC)
Rys. 5. Schemat budowy światłowodowego czujnika prądu z przetwarzaniem zewnętrznym (OFCS- EC)

The schematic drawing in Fig. 5 shows the structure of the fiber optic current sensor with external conversion and its positioning with respect to the current conductor. This diagram shows a conductor with a rectangular cross section. The value of the magnetic field at the point of measurement is depend on the current conductor place, among others on the its dimensions and shape of the conductor's cross-section. A simple analysis of the distribution of the magnetic field around the conductor (Fig. 6) shows that the rectangular shape of the cross-section is optimal for the proposed sensor. Thus, the sensitivity of the sensor depends on the cross-sectional shape of the specific conductor and the position of the head in relation to that conductor.

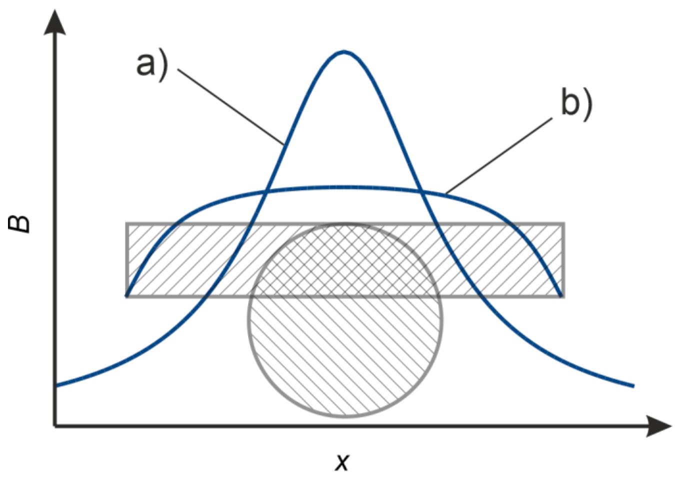

Fig. 6. Distribution of the magnetic field around a conductor with an electric current with a circular section (a) and a rectangular section (b)
Rys. 6. Rozkład pola magnetycznego wokół przewodnika z prądem o przekroju kołowym (a) oraz o przekroju prostokątnym (b)

It should be emphasized that this method of measuring the current is non-invasive and does not overload or modify the measured electric circuit. As mentioned above, additional sensors of this type are insensitive to electromagnetic interference and are fully insulated It is therefore possible to use such sensors for measuring currents at high voltage and in the presence of high electromagnetic disturbances, such as LEMP pulses created during a lightning discharge.

The above analysis in Fig. 6 shows the rectangular section as the most optimal. It is consistent with the practice of manufacturing the lower parts of LPS down conductors in the form of galvanized steel strips.

The authors investigated the insulation properties of the OFCS-EC sensor and tested the sensor's response under high voltage conditions [6-7]. As the insulation properties of the OFCS-EC sensor are determined by the insulation properties of optical fibers (and their shields) connecting the sensor head with the light source and detector, these elements were tested. The lengths of optical fibers used in the present version of the sensor have limited the possibilities of using this particular sensor design for networks with a maximum voltage of 30 kV (U_m = 36 kV). To confirm the possibility of working in networks with such rated voltage, it is required to carry out short-duration withstand voltage tests according to [15]. Required values of rated short-duration withstand voltages (power grid frequency and lightning impulse voltage) are shown in Table 2. The OFCS-EC sensor has already been tested with AC mains frequency. With a positive result (no discharge of any kind), a one-minute strength test was carried out at 70 kV alternating voltage. Additionally, tests were made to measure leakage currents at operating voltages up to 30 kV [6]. In order to fully check the insulation strength of the tested OFCS-EC, impulse voltage tests were required, the results are presented in the article [10].

Table 2

Values of rated insulation level for U_m = 36 kV

U_N/U_m	Phase-to-earth insulation	
	Rated short-duration withstand voltage U_w (kV)	
	Power grid voltage (rms value)	Lightning impulse voltage (1.2/50 μs, peak value)
30/36	70	145; **170**

To conduct the tests with the lightning impulse voltage, a test system was used, consisting of a surge voltage generator, a voltage divider and a system for measuring and recording impulse voltages. For the voltage U_m = 36 kV, the standard [15] gives two values of the required lightning impulse voltage, but for the voltage tests, a larger value of 170 kV was chosen for this voltage level. The operation of the optical fiber current sensor with external conversion was checked before performing the lightning impulse voltage test. The lightning impulse voltage test consisted in applying to the insulation system 3 surges 1.2/50 μs (with the tolerance of time parameters, respectively: ± 30% and ± 20%) with positive polarity and three pulses with negative polarity with a peak value of 170 kV (with tolerance ± 3%). The waveform of one negative polarity surge pulse is shown in Fig. 7. This figure also shows the recorded stroke parameters (peak value, front duration and time to half peak value on the tail). During the test, no discharges were found, especially on the surface of the optical fibers, nor any damage to the optical fibers, so its result should be considered positive. The recorded test voltage waveform does not show the surge cut-off, characteristic of a flashover in the insulation system - which proves a positive result. After performing the lightning impulse voltage test, the OFCS-EC operation was checked again, during which no changes in the metrological parameters of the sensor were found, which is also a confirmation of a positive result of voltage test.

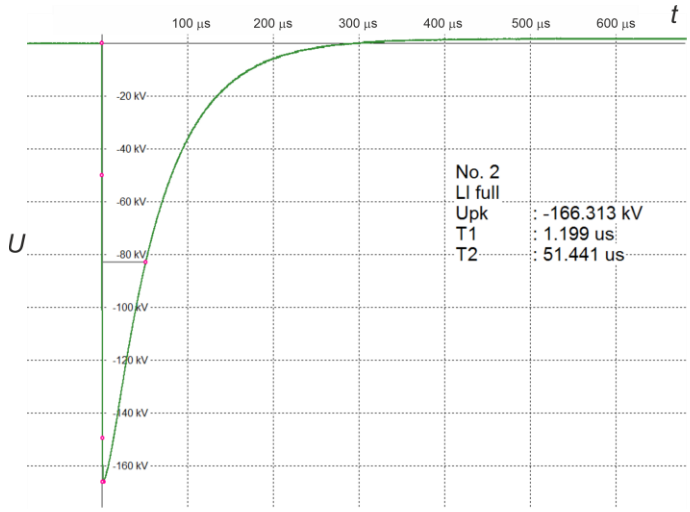

Fig. 7. Lightning voltage waveform recorded during the test of OFCS-EC
Rys. 7. Przebieg napięcia zarejestrowanego podczas testów światłowodowego czujnika prądu z przetwarzaniem zewnętrznym

The physical basis of the magnetooptic Faraday effect shows that this effect is very fast, with response times of 10^{-15} s. It enables measuring very high harmonics of the current waveform. It is especially important when recording unstable states and detecting short circuits in power systems, in particular in power system protections (PSP). At this point, it is worth emphasizing that this feature is also very important in lightning current measurements, the impulse with very short current rise times (Table 1). The sensor has been tested for use in PSP. The response to current waveforms corresponding to unstable states and the range of linearity were investigated. It was also proposed to operate the sensor at two wavelengths in order to increase its linearity range [8-9].

As a result of the tests, it was confirmed that the sensor in question is insensitive to exceeding the measuring range, except for damage to the sensor due to the thermal effects of the current flow. In the event of damage to the sensor, e.g. in a thermal manner, other systems of the measuring system and devices connected to it are not exposed to any danger. This aspect is also very important in the case of lightning current measurements because the values of this current may be of the order of several or tens of kiloamperes.

The analyses carried out so far show that the sensor can work in several ranges simultaneously by using several wavelengths of light. It is assumed that three ranges will be used at most, i.e. three wavelengths, including two in the visible range and one in the infrared range. This type of design will also allow the current impulse to be recorded in a wide range of values with the same accuracy (approximately).

It is worth mentioning that the discussed sensor was presented during the Entrepreneurship Fair in Katowice in 2017. The presented design was assessed at TRL = 7 (TRL - Technology Readiness Level).

2.4. Conception

The described properties of the sensor show its superior advantages in the measurement of high current values and at high frequencies. At the same time, the sensor head with fiber optic cables is not sensitive to electromagnetic interference and has very good insulating properties. These features, according to the authors, are ideal for applications in the measurement of lightning currents. For this purpose, the parameters of the sensor should be properly selected, in particular the measuring range and protection against thermal damage to the sensor. The influence of electromagnetic disturbances generated during the discharge, which may prevent the correct recording of the signal in the electronic part of the sensor, is not without significance. This aspect will be discussed in more detail in the next section.

The concept is based on the use of a sensor on an appropriately designed conductor with a rectangular cross-section adjusted to the expected maximum values of currents caused by lightning. It is assumed that the sensor will be installed on down conductors of lightning protection system in standard construction facilities, where it is also possible to install conventional LCs on down conductors. Adaptation of the sensor is facilitated as current research has focused on a conductor with a rectangular cross-section of 3 mm x 20 mm. In contemporary lightning protection installations in Poland, the last section of down conductors connecting to the ground terminal has similar cross-sectional dimensions. It was previously according to the standard [18], the area of the conductor cross-section shouldn't be less than 50 mm^2. For the typical commercially available tapes that meet this assumption are tapes with cross-sections and dimension similar to those assumed during the previous tests, i.e. 3 mm x 20 mm (Table 3).

Table 3

Typical dimensions of tapes used in LPS

No.	Dimensions, mm	Cross section area, mm^2	Min. cross section area, mm^2 according to [18]
1	25 x 2	50	50
2	**20 x 3**; 30 x 2	60	
3	25 x 3	75	
4	20 x 4; 40 x 2*	80	
5	30 x 3	90	
6	20 x 5*; 25 x 4; 50 x 2*	100	
7	30 x 4; 40 x 3	120	
8	25 x 5*	125*	
9	30 x 5*; 50 x 3*	150*	
10	40 x 4	160	
11	50 x 4; 40 x 5	200	
12	50 x 5*	250*	
* less common			

The occurrence of lightning discharges is an accidental phenomenon and depends on many conditions. In particular, the current weather conditions favouring the occurrence of lightning in a given area. The application of cheap and simple sensor facilitates increase in number of measurement points so that the probability of recording the discharge current is significantly improve. In another approach, the solution can be friendly enough to be installed in the facility and deliver its signal to standard facility operation monitoring systems. Data collected in this way can be used to modify and improve systems ensuring the safety of using the facility in the face of hazards related to lightning. The data collected by the sensors can be used by experts studying lightning phenomena and dealing with LPS protection systems. The authors also expect that more accurate characteristics of the discharge current will allow scientists to analyse the discharge problem more thoroughly.

Contemporary conventional direct discharge measurement systems (lightning counters) are mounted on down conductors close to the ground surface (usually approx. 1.5 m above ground level). As mentioned above, this part of these cables is most often in the form of a tape with a rectangular cross-section (Table 3). The lightning counters are designed to be mounted to the flat surface of the conductor. This is a very advantageous configuration also due to OFCS-EC. This is one of the most important arguments justifying the choice of this type of optical current sensor.

Mounting the OFCS-EC sensor close to the ground also has a safety aspect. When mounting close to the ground on down conductors, there is a voltage drop across the earthing impedance (voltage drop on down conductors is neglected). Despite this, the contact voltage can reach very high values, threatening the safety of both people in the vicinity of down conductors and the measuring instruments connected to them. Elements of the OFCS-EC sensor measuring system are in this case isolated from down conductors thanks to optical fibers connecting the sensor with the light source and detector. As demonstrated, the impact strength of such optical fibers is higher than 170 kV (this value does not damage them or cause a jump along their surface). This value is sufficient to ensure safety. One of the means of protection against contact shock voltage is use of casing pipes placed on a down conductor (walls have an electrical strength of 100 kV); this is defined in standard [18]. In the case of the OFCS-EC sensor in the current implementation there is a 70% safety margin.

The concept assumes that the detection system using the OFCS-EC sensor will be equipped with appropriate data acquisition and transmission systems. Operation of this system can be continuous, momentarily activated, or remotely activated. In the second and third cases, the system would remain in suspend mode during shutdown. The continuous operation of the system is considered first. The conventional system, which can be self-powered, has an advantage in this respect.

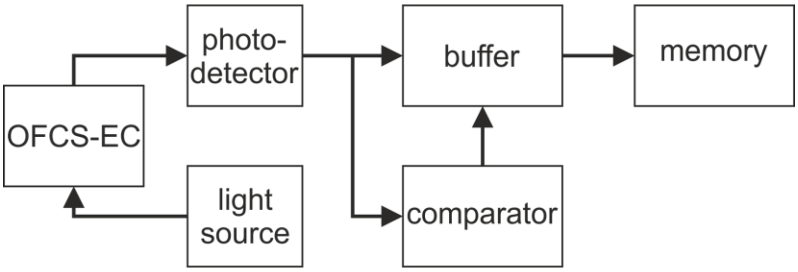

Fig. 8. Schematic structure of the lightning current detection system based on the OFCS-EC sensor
Rys. 8. Schemat blokowy systemu detekcji prądów piorunowych wykorzystującego światłowodowy czujnik prądu z przetwarzaniem zewnętrznym

In the continuous operation mode, the system should constantly record the signal and place it in the buffer. The buffered signal should be 1 second long. The comparator detecting the exceeding of the set signal threshold generates the rising edge signal, which triggers the recording of the signal from a specific (programmed) moment in the buffer for a specific programmed time (including the current date and time) – Fig. 8.

2.5. Preliminary tests

As part of the preliminary investigation, tests were performed using a surge generator connected to a spark gap. The sensor is mounted on the discharge path of the surge current from the spark gap to the ground potential (Fig. 10). It is a system that simulates a real lightning protection system. The grounded sphere of the spark gap, on which the sensor and the discharge cable are mounted, is a model of the lightning protection system, where the sphere acts as an air terminal. The second sphere connected to the surge generator is the source of the discharge that arises in the gap between the sphere (Fig. 9). The currents generated during this discharge are close to the values obtained in lightning protection systems [12].

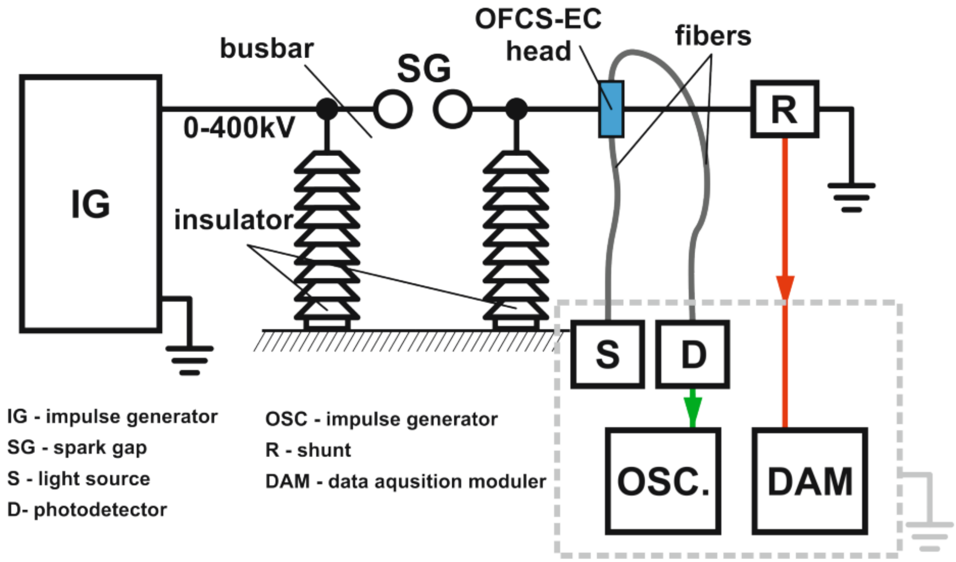

Fig. 9. Diagram of the experimental setup for testing current surges
Rys. 9. Schemat stanowiska do badania udarów prądowych

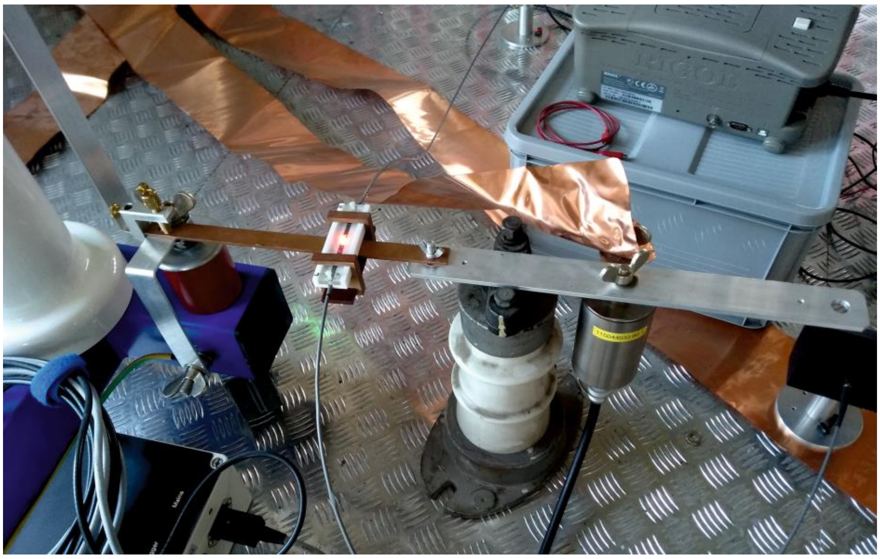

Fig. 10. Photo of the OFCS-EC sensor mounted on the ground down conductor
Rys. 10. Zdjęcie światłowodowego czujnika prądu z przetwarzaniem zewnętrznym zamontowanego na przewodzie uziemiającym

The first attempts showed very big problems with electromagnetic interference. The classic measurement is based on a shunt selected so that the voltage drop recorded on it is of the order of 1 kV. However, when using a current transformer or fiber optic sensor, signals are recorded at the level of single volts. It is very easy to disturb such a signal. Additionally, this type of electromagnetic disturbance has a wide frequency spectrum [11]. For this reason, measuring and recording devices should be very well shielded. Accordingly, a serious problem of electromagnetic compatibility has arisen. At the research stage, this problem is not easy to solve due to the extensive research infrastructure that requires shielding. According to the authors, this is a chance to simultaneously solve this problem in further research.

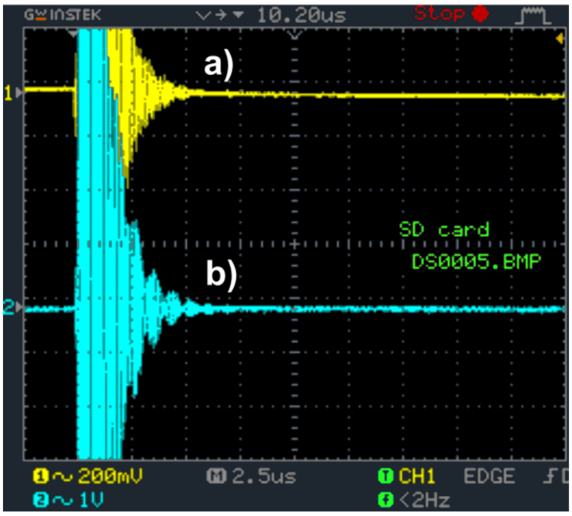

Fig. 11. Recorded signal on the OFCS-EC sensor (a) and on the current transformer (b)
Rys. 11. Sygnał zarejestrowany na światłowodowym czujniku prądu z przetwarzaniem zewnętrznym (a) oraz na przekładniku prądowym (b)

The recorded signal is an interference signal – see Fig.11. The signals come from completely different sources, and yet they have a very similar shape. These waveforms also have a component with a longer decay time, which is similar to the signals recorded during lightning strikes. Although the tests did not give the desired results, it was found that the conditions in the laboratory are very similar to the actual conditions prevailing during a lightning strike. Fig. 12 shows the spatial arrangement of the test apparatus. Particularly noteworthy is the distance between the photo detector, light source and oscilloscope and the spark gap. This distance can be increased by using longer optical fibers and placing the apparatus in conditions ensuring good shielding. The second solution is to build a dedicated transceiver system as well as data processing and acquisition system in one compact housing ensuring good shielding in the immediate vicinity of the spark gap. It is a complex problem that requires separate research. To summarise, this issue opens up a new scope of research focused on the problem of electromagnetic compatibility.

After several dozen tests, the sensor did not change its parameters, so its resistance to lightning strikes was once again confirmed.

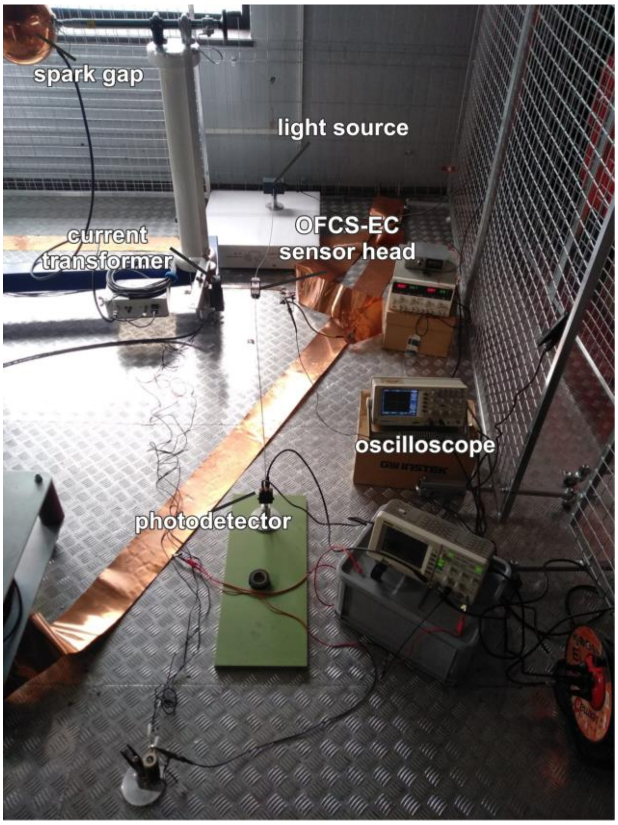

Fig. 12. Photo of the measurement stand showing the spatial distribution of its components
Rys. 12. Zdjęcie stanowiska pomiarowego przedstawiające przestrzenne rozmieszczenie jego części

During the research, flickering of monitors and a temporary loss of connectivity of wireless devices several meters away were observed. It is related to the electromagnetic pulse, which is large enough to disturb electronic devices. Such a pulse (LEMP) is also characteristic of lightning discharges.

2.6. Conclusions

Repeated tests with a surge of 170 kV (with positive result) showed that the sensor has high insulation strength. These experiences also show that the sensor could operate under continuous exposure to lightning strikes. The preliminary research presented in this article shows this.

The conducted analyses and tests allowed for the creation of the concept of using the OFCS-EC sensor in the lightning protection systems (LPS) measurements. The concept indicates the specific possibilities of placing the sensor in typical lightning protection installations and the functionality of electronic systems for detection and data acquisition. The need to construct an appropriate housing shielding from electromagnetic interference of the electronic part of the system was pointed out, but the sensor itself should not be sensitive to them.

Bibliography

1. Aniserowicz K.: Analysis of Electromagnetic Compatibility Problems in Extensive Objects under Lightning Threat. Wydawnictwo Politechniki Białostockiej, Rozprawy Naukowe No. 122, Białystok 2005.
2. Barczak K.: Optical fibre current sensor for electrical power engineering. Bulletin of The Polish Academy of Sciences-Technical Sciences, Vol. 59(4), pp. 409-414, 2011.
3. Barczak K.: Optical fiber current sensor with external conversion. 11th Conference On Integrated Optics: Sensors, Sensing Structures, and Methods, Proc. SPIE, Vol. 10034, 2016.
4. Barczak, K., Maźniewski K.: Investigation of optical fiber current sensor with external conversion in AC magnetic field. Optical Fibers and Their Applications, Proc. SPIE, Vol. 10325, 2017.
5. Barczak K., Maźniewski K.: Optical fiber current sensor with external conversion for measurements of low AC electric currents. 12TH Conference on Integrated Optics: Sensors, Sensing Structures, And Methods, Proc. SPIE, Vol. 10455, 2017.
6. Barczak K., Duda D., Maźniewski K.: Optical fiber current sensor with external conversion in high voltage environment. 13th Conference on Integrated Optics: Sensors, Sensing Structures, And Methods, Proc. SPIE, Vol. 10830, 2018.
7. Barczak K., Duda D., Maźniewski K.: Insulating properties of optical fiber current sensor with external conversion. Prz. Elektrot., Vol. 94(10), 53-56, 2018.
8. Barczak K., Szablicki M.: Investigation of optical fiber current sensor with external conversion in unstable stands. 13th Conference on Integrated Optics: Sensors, Sensing Structures, and Methods, Proc. SPIE, Vol. 10830, 2018.
9. Barczak K., Szablicki M.: Configurable optical fiber current transformer. 18th Conference on Optical Fibres and Their Applications, Proc. SPIE, Vol. 11045, 2019.
10. Barczak K., Duda D.: Lightning impulse withstand tests for optical fiber current sensor with external conversion. Conference on Optical Fibers and Their Applications, Proc. SPIE, Vol. 11456, 2020.
11. Díaz Cadavid L.F., Cano-Plata E.A., Younes-Velosa C.: A LEMP Generator-Simulator Circuit. Ing. Investig., Vol. 31 Suplemento No.2 (SICEL 2011), 27-35, octubre de 2011.
12. Qiu, Z., Gao, H., Yang, Y.: Lightning Parameters Measurement Systems and Instrumentation on Meteorological Gradient Observation Tower in Shenzhen China. 2015 International Symposium on Lightning Protection (XIII SIPDA), Balneario Camboriu, Brazil, 2015.
13. CIGRE Publ. No 376: Cloud-to-ground lightning parameters derived from lightning location systems. The Effects of System Performance, Working Group C4.404, April 2009.

14. CIGRE Publ. No 549: Lightning parameters for engineering applications, Working Group C4.407, 2013.
15. PN-EN IEC 60071-1:2020-04 Insulation coordination - Part 1: Definitions, principles and rules.
16. PN-EN 62305-1:2011 Protection against lightning - Part 1: General principles.
17. PN-EN 62305-2:2012 Protection against lightning - Part 2: Risk management.
18. PN-EN 62305-3:2011 Protection against lightning - Part 3: Physical damage to structures and life hazard.
19. PN-EN 62305-4:2011 Protection against lightning - Part 4: Electrical and electronic systems within structures.