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Discussions

Protection against lightning on the geomagnetic observatory

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Abstract

The Sinji Vrh Geomagnetic Observatory was built on the brow of the mountain Gora, above Ajdovščina, and all over Europe one may hardly find an area which is more often struck by lightning than this south-western part of Slovenia. When the humid air masses of a storm front hit the edge of Gora, they rise up more than 1000 m in a very short time, and this causes the additional electrical charge of stormy clouds.

The reliability of operations performed in the every building of observatory could be increased by understanding the formation of lightning in the thunderstorm cloud, the application of already proven methods of protection against a strike of lightning and against its secondary effects. To reach this goal the following groups of experts have to co-operate: the experts in the field of protection against lightening phenomenon, the constructors and manufacturers of equipment and the observatory managers.

1 Formation of lightning

The ionized air in the bottom layers of the atmosphere occurs because of the thermodynamic circulation of the air containing specific percentages of humidity, solid particles and ions (Handbook, 1985; Čop, 2013). Electrical charges inside a thunderhead start to separate as early as at the beginning of the thunderhead formation. There are different theories about the spatial distribution of charges inside a thunderhead.

The reason that the final explanation is not known with certainty yet is the lack of knowledge about conditions inside a thunderhead. Observations show that most of the positive charges are in the upper region of clouds, several kilometers from the negative charged region. For this reason the most likely is a theory which assumes that opposing charges within the cloud occur due to collisions between the solid particles within the thunderhead. The electric field inside a cloud, which rarely exceeds 100 $\mathrm{V\,cm^{-1}}$, is a result of opposing charges within the cloud (Ziegler, 1991). The point discharge streamers arise by an intensifying of the electric field and they occur if the strength of the electric field is greater than 4 kV cm^{-1}.

The critical value of the electric field strength in the air mixed with water drops is approximately 10 kV cm^{-1}. Above this critical value the air becomes conductive, or in other words the process of ionization starts. An intensifying electric field in the cloud forms the first stepped leader stroke which progresses through the channel of ionized air. Due to the excessive negative charge the leader is moving towards the opposing charge. It can move in steps of 5 to 50 m and is not the actual lightning strike. It can branch out and form more parallel channels with very high ohm resistance and consequently a small electric current of approximately 20 mA. Near the ground the positive streamers (point discharge currents) reach upward toward the negative leader. The positive streamers lengthen as the negative stepped leader moves toward the ground. The return stroke occurs when an ionized path between the cloud and the earth is completed – that is, when the leader stroke approaches one step or more above the ground a positive streamer shoots upward from a dominant object and meets the negative leader. Approximately 80 % of all lightning strokes have two or more return strokes. The lightning strike currents can increase quickly from 1000 amperes to 200 000 amperes and more. According to the place of occurrence the most common types of lightning are intracloud and only 10 % of all flashes are cloud-to-ground lightning.

The polarity of cloud-to-ground lightning is defined by a polarity of charge which will be neutralized after the electrical discharge. As the bottom region of a cloud is usually the centre of a negative charge, more than 90 % of all lightning flashes are negative. As a rule positive lightning flashes have high amplitudes and frequently occur before the decay of a cloud. During the summer most flashes are negative and during the winter half of all flashes are positive. However, the number of lightning flashes during the winter time is rather low, so the contribution of the positive lightning flashes to the results of overall statistical analysis may be deemed negligible.

According to their direction cloud-to-ground lightning flashes are divided into updraft and downdraft. The most common is downdraft lightning. Updraft lightning usually occurs where an electrical field is strengthened by the geometry of the objects located on the ground: TV towers, steeples, high and sharp spires, skyscrapers and trees.

Each thunderhead discharge causes a change in the electrical charge on the objects on the ground and on the ground surface under the thunderhead. The enormous surge of a current through the ground surrounding the object directly hit by a lightning strike is dangerous, causing damage to electric power devices and installations, and injuries to users and all other living beings standing on the ground in the vicinity of the strike, which can electrocute them. The electromagnetic waves which occur during the discharge cloud-to-air may induce high voltages in the electric power cables and signal cables.

Moving electrical charge, which occurs during a cloud discharge in the form of a lightning strike, causes an electromagnetic surge which propagates over the ground surface and may be recorded by appropriate sensors from relatively long distances.

The reason for the ionization of the bottom layers of the atmosphere are not only cosmic rays but also the thermodynamic phenomena in it. A thunderstorm cloud accumulates tiny ice-crystals that originate from water vapour and are mixed with a bigger, transparent and fragile formation called graupel-ice. Graupel-ice appears due to a sudden under cooling, in the same way as a white frost. The hard ice crystals are the positive charge carriers, while the graupel-ice formations are the negative charge carriers. The convective air currents in a thunderstorm cloud are carrying snow crystals upwards, onto the top of a cloud, while the graupel-ice formations stay on the bottom of a cloud. This process evolves at the temperature of $-10\,^{\circ}\mathrm{C}$ to $-20\,^{\circ}\mathrm{C}$ and stops at the temperature of $-40\,^{\circ}\mathrm{C}$. The difference between positive and negative charges in the thunderstorm cloud becomes enormous, reaching a value of 10^8 to 10^{10} V, and it is the voltage that can create a lightning stroke. The description of a charging mechanism presented in this article is rather simplified (Ziegler, 1991; Saunders, 2008).

A starting electrical discharge, or formation of a conductive channel of ionized air, is initiated in a thunderstorm cloud by a region of a negative charged mixture of water vapour and graupel-ice. This starting discharge is moving downwards from the cloud

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to ground approaching the ground in steps of 50 m (stepped leader), and it usually develops in several parallel channels. It lasts relatively long, up to several hundred milliseconds, and it is hardly visible. When the initial discharge strikes the ground it inducts an electric charge of opposite sign in exposed objects on ground, and this induced voltage will strongly intensify the original electrostatic field. When this field is strong enough, the new discharge is starting. When the conductive channel of ionized air is created between a thunderstorm cloud and ground, the strong electric current will flow through it. This return stroke is accompanied with a flash of a bright light (Staszewski, 2009). In addition to the described electrical discharge between the cloud and the ground (cloud-to-ground), there are also discharges inside a thunderstorm cloud (intra-cloud) and between two separate thunderstorm clouds (cloud-to-cloud).

The most common types of electrical discharges are respectively: within a cloud, from a cloud into the surrounding air, and between a cloud and the ground. Only a tenth of all electrical discharges happen between a cloud and the ground. After the first lightning flash from a thunderstorm cloud, the next lightning stroke usually appears with a delay of 8 to 20 min.

The lightning polarity is defined by a polarity of charge which will be neutralized after the electrical discharge. As the bottom region of a cloud is usually the centre of negative charge, more than the 90 % of all lightning flashes are negative. As a rule positive lightning flashes have high amplitudes and frequently occur before the decay of a cloud. In the summer more than the 90 % of all lightning flashes are negative, while in the winter the 50 % of all lightning flashes are positive. However, the number of lightning flashes during the winter time is rather low, so the contribution of the positive lightning flashes to the results of overall statistical analysis may be deemed negligible.

According to their direction lightning flashes are divided into updraft and downdraft. The most common is downdraft lightning. The updraft lightning usually occurs where an electrical field is strengthened by the geometry of the objects located on ground: TV towers, steeples, high and sharp spires, skyscrapers and trees.

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Approximately 80 % of all lightning strokes have two or more return strokes. The average initial negative lightning stroke has an electric current of 30 kA, while overall negative charge lighting has an electric current of 120 kA and positive charge lightning has a current of 300 kA. A lightning stroke has the electrical power of 10^{12} W and lasts an average 30 ms.

Each starting electrical discharge of a thunderstorm cloud also induces an electrical charge in objects and on the ground under this thunderstorm cloud. The induced electrical charge will remain as long as the cloud stays in vicinity and until the cloud charge releases in the form of a lightning stroke. At that moment the induced electrical charge is no longer tied to the cloud, and it starts to propagate through the ground radially outward from the lightning strike point in the form of a voltage surge and with a speed close to the speed of light: $e_{\mathrm{i}} = q/C$ [$\mathrm{A\,s\,F^{-1}}$]. This surge of voltage through the ground is called an indirect lightning stroke and it causes damage to living beings and objects near a point which is directly hit by a lightning strike. The voltage in the ground decreases as the distance from the point hit by a lightning strike increases (Punekar, 2011; West, 2011).

The enormous surge of a current through the ground surrounding the object directly hit by lightning strike is dangerous, causing damage to electric power devices and installations, and injuries to users and all other living beings standing on the ground in the vicinity of the strike, which can even electrocute them. A lightning stroke can also cause fire due to the high temperatures (25 000 K) in the lightning channel of ionized air. The electromagnetic waves which occur during the electrical discharge from a cloud into the surrounding air may induce high voltages in the electric power cables and signal cables.

2 Slovenian Centre for the Automatic Localization of Air Discharge

The Slovenian Centre for the Automatic Localization of Air Discharge, hereinafter referred to as the SCALAR, was established in 1998, with the task of locating lightning

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strike points between the cloud and the ground, and communicating the data to the final users.

SCALAR calculates the location of each lightning stroke on the basis of data recorded by sensors which monitor both components of the electromagnetic field or just its electrical component. Their sensors are shown in Fig. 1. which are part of the European network EUCLID (European Cooperation for Lightning Detection), transfer the detected data to Vienna which in the frame of the European network EUCLID calculates the location of each lightning stroke and all relevant data about it. More than 147 active sensors which cover the area from Sicily to Nordkapp are currently included in this European network as is shown in Fig. 2.

The following data are stored on the servers of SCALAR:

- Strike time
- The latitude and longitude of a lightning strike point
- Lightning current amplitude in kA and the number of return strokes
- The semi-axes and slope of an error ellipse
- The accuracy of the calculated parameters of the recorded lightning stroke

The statistical data on the lightning strokes in Slovenia, stored in SCALAR during the last fifteen years, are collected in Table 1 (SCALAR, 2012). The map of maximum density of lightning strokes in Slovenia is drafted on the bases of the SCALAR data (Map, 2007).

Mountain Gora above Ajdovščina is situated in a Slovenian region with a high density of lightning strokes with the maximum yearly density of 7.8 lightning strokes per km^2 is shown in Fig. 3. The density of lightning strokes in Slovenia is from 0.6–1.1 lightning strokes km^{-2} year^{-1} in Prekmurje region, through 2.5–3.7 lightning strokes km^{-2} year^{-1} in the depression of Ljubljana town, to as high as 6.3 lightning strokes km^{-2} year^{-1} and even more on Trnovo plateau. The western part of Slovenia is particularly exposed to

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lightning strokes and in accordance with the relevant recorded data their frequency is the highest in European continent.

3 Thunderstorm on Sinji Vrh Geomagnetic Observatory

The Report no. 30/1/8/2012 on lightning strokes for the period from 12 September 2012 at 00:00:00 UTC to 14 September 2012 at 23:59:59 was drafted on the basis of the measurements carried out by SCALAR. The Report describes 15 lightning strokes on the location 4.5 km around Sinji Vrh Geomagnetic Observatory; hereinafter refer to as the observatory. Table 2. with the data of lightning strokes was first supplemented with the results of calculations for distance L between the lightning strike point Y, X and the observatory.

The thunderstorm on 12 September 2012 damaged the electronics of 3-axis fluxgate magnetometer; hereinafter the variometer (Lanza, 2006). The magnetogram of variations of components of the geomagnetic field before the formation of the thunderstorm shows the typical double oscillation at 10:30 and at 12:00. Such oscillations were observed every time upon the arrival of thunderstorm fronts from south-west. In this case also the change in the geomagnetic field during a day and night is less distinctive than during a magnetically calm and sunny day. The magnetometer registered the first lightning stroke on 12 September 2012 at 12:47:25 and stopped registering at 12:55:02. At that time some electronic parts were burned out, including: the output parts of high frequency excitation and compensation with the DC current and operational amplifiers on all three input stages. The start of interruption of registration, shown in Fig. 4, was fitted with the SCALAR measurements presented in Table 2. However, during the thunderstorm the magnetometer also registered electrical discharges which were not from hitting the ground but from discharging intra-cloud or cloud-to-cloud.

The lightning stroke which, during the thunderstorm on 12 September 2012, destroyed the electronic parts of the variometer was the ninth in a row, and was 1 km from the observatory as can be seen in Table 2. The positive particles that carry an electric current of 106.264 kA reached 27.55 % of the strongest so far registered lightning stroke in the Primorska region presented in Table 1. The secondary influence of this lightning stroke exceeded the upper voltage limit for which the instrument was designed. This overvoltage occurred due to the electromagnetic influence of the lightning current pulses on the coils in the sensors of instruments. On the basis of this assumption the value of the induced voltage in each coil of the magnetometer sensor is given by the following Eq. (1).

$$\Phi u_i = -N \frac{\mathrm{d}}{\mathrm{d}t} = -N \frac{\mathrm{d}}{\mathrm{d}t} (S \mu_0 H) = -k \frac{1}{L} \frac{\mathrm{d}I}{\mathrm{d}t} \quad (1)$$

If the time-variation of the lightning currents is approximately equal, we can calculate the influence of each separate lightning stroke on a measuring instrument N_x/N_9 presented in Table 2. This assessment was given relating to the lighting stroke which destroyed the electronics of variomter. It can be used for the assessment of effectiveness of the built-in additional protection against lightning strike effects.

4 Protection against lightning strike effects

The first lightning strokes on the location where Sinji Vrh Geomagnetic Observatory is situated were recorded in the summer of 2009, during test measurements of changes in the geomagnetic field. These records were used for designing the appropriate electricity supply system of the observatory. For the final decision on the location of the measuring posts and temporary facilities of the observatory we had to comply with the regulatory provisions related to setting the posts in nature and to obey the conditions prescribed by environmental protection agency. In addition, we had to assure better reliability of the observatory operations and to reduce the effects of lightning strikes (Rupke, 2002; Protection, 2009). The first construction phase was carried out in three steps. For the reason of safety each step is equipped with its independent DC supply system 12 V. When the first phase was completed and after the connection of the

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measuring instruments, the comparison of the measurement results with those on the surrounding geomagnetic observatories was carried out (Čop, 2011).

Protection against overvoltage of atmospheric origin at the observatory was built up gradually, as there are no issued recommendations regarding the protection against lightning strike effects which would specifically address protection at geomagnetic observatories (Wienert, 1970; Jankowski, 1996). Classical system for overvoltage protection leans on the protection grounding. In the separate building standard elements for overvoltage protection are mounted in the main distributing box of electrical energy. They are connected to the protection ground with wires for protection which lead away the surplus electric charge. For more sensitive consumers the standard protection elements are mounted near to them. In these cases the protection connections are used for equilibration of potentials.

As early as during the planning process for the construction of the observatory, consideration was given to obtaining the complete protection of the observatory against overvoltage through the low voltage overhead lines in the public distribution network. Connection of the observatory to the public distribution network was carried out through two separation transformers connected in a series and via standard Surge Protection Devices (SPD) for the protection of consumers. These standard devices were integrated into the distribution units of electric power 220 V, 50 Hz, as shown in Fig. 5. The observatory is built on the brow of Gora, the highland Karst plateau on 867 m a.s.l. In distance of 2.8 km this plateau rises up from valley of around 100 m above sea level. In dry period same hundred meters thick limestone of Gora becomes excellent isolator and the ground wire becomes antenna for lightning strokes. For this reason the source of electrical energy for the variometers is totally isolated by cascade of two transformers.

We made efforts to reach the optimal solution for two opposing requirements relating the locations of the measuring instruments and other electronic devices: the first requirement regarding the accuracy of measurements tends to keep the distance between instruments/devices as long as possible to avoid the influence of one instrument/device on another; the second requirement regarding the decrease of lightning strike effects is the tendency to make electrical circuits as short as possible. Measuring data have therefore been transferred through optical fibers instead of long copper wires.

The protection of the observatory against lightning strike effects that may reach the observatory through the low voltage overhead lines in the distribution network with two transformers in cascade has proven to be very effective. The purchased communication converters were selected to comply with three requirements: (a) to be available for purchase, (b) to be industrially constructed and (c) to operate without malfunctions. The integrated parts of telemetry, analog-to-digital converters and battery chargers were selected in accordance with the same requirements as communication converters. The chargers are used for charging the stationary batteries which provide the observatory with electricity supply autonomy for at least a week.

Among all parts of the measuring systems at the observatory, the secondary effects of a strike of lightning in 2012 only destroyed the electronic parts of the variometers three times in a row. The analog parts were affected two times and the digital parts were affected once. Thereupon the distribution units of the electric power supply 12 V DC were additionally protected against overvoltage through the additionally installed TVS (Transient Voltage Suppresser) diodes (Protection, 2004) together with standard 1 A fuses. The DC supply of all magnetometers has additionally been galvanically separated from their electronic parts by DC-to-DC converters so that the lengths of incoming wires do not exceed 0.5 m. The length of a signal cables RS-232 were also shortened by optical interfaces.

For the protection of analogue electronics of the variometers against overvoltage of atmospheric origin we decided to install fast-acting diodes in all wirings between their sensors and analogue electronics (Transient, 2008). These diodes were envisaged being located between the wiring connections and supply cables. We were able to connect the fast-acting diodes in the measuring system of these variometers, which have virtual zero, only after we contacted the variometer's manufacturer for help. We installed diodes as a bridge between each input of operational amplifiers for each channel separately, outputs for HF excitation and outputs for compensation with direct currents as follows: TVS diodes to supply voltage + 15 V and Schottky diodes to supply voltage 0 V. This overvoltage protection of wiring was installed between the electronic parts and incoming sensor cables. As the non-linear elements of the protection were connected in parallel with the coils of the sensors, it was necessary to define ones again measuring coefficients between the analogue values of voltage of each component of the geomagnetic field in mV and the their values of the magnetic field density in nT. The first variometer with described overvoltage protection was put in function before 15 January 2013, when a huge snowstorm with lightning on observatory occurred (Čop, 2014).

In 2013 two of three battery chargers were destroyed because of an instance of atmospheric overvoltage but no one variometer. It will be necessary therefore to add a third protection against lightning strokes. The power supply cables 220 V, 50 Hz behind the separation transformer are envisaged to be additionally shortened, so that their length will not exceed 5.0 m. Our intention is to achieve this goal with additional fast-acting overvoltage protection MOV (Metal Oxide Varistor) which is usually used for the protection of small consumers 220 V, 50 Hz, such as: TV, computers and telephone sets. This overvoltage protection should be located as close to a consumer as possible. The consumer's metal housing determines the local grounding point, which is connected with a copper wire, no longer than 0.5 m, with the protection components. The important part is to provide the potential equalization through the common ground conductor (Transient, 2010).

5 Conclusions

The existing atmospheric overvoltage protection of the variometers at the observatory successfully endured all storm periods during the year 2013. So far in this period, in the vicinity of the observatory, none of the lightning strokes that have occurred were as strong as that with maximum amplitude registered in Slovenia as shown in Table 1. The reliable statistical data set is possible to take only through long-term research project paid by suitable source.

For safety's sake we still use the reserve electronics of a variometer during the absolute measurements with theodolite DI magnetometer. For the measurement of the components of the geomagnetic field we have lately used a basic electronic box of the variometer which is equipped with additional overvoltage protection.

The observatory operates without regular crew and it uses telemetry for transmission and reception of measuring data. Therefore it is not only at risk because of lightning strokes but also because of vandalism and forest fire. To solve these problems we spent a lot of time during 2013 searching for an appropriate reserve location for backup measurements. Should we install at least one variometer on the reserve location, we would significantly reduce the possibility of interruption of regular measurements carried out at the observatory. We can even avoid the difficulties should all equipment at the observatory be destroyed. The winter weather conditions on Gora above Ajdovščina temporarily prevent us from work on the preparation of the reserve location in the vicinity of the observatory. We will be able to continue this work in spring 2014.

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Table 1. Data on lightning strokes in Slovenia.

Region	Max Amplitude [kA]	Median Amplitude [kA]	$p = 98\,\%$ [kA]
Slovenia	416.28	10.82	58
Primorska	385.73	11.15	60
Central part	416.28	11.09	60

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Table 2. Data on lightning strokes during the thunderstorm on Gora above Ajdovščina.

No.	Date	Time	Y	X	Amplitude I [kA]	Distance L [km]	Ratio N_x/N_9
1	12 Sep 2012	12:47:25.4	5 414 100	5 083 344	−18.796	3.695	−0.05
2	12 Sep 2012	12:47:25.5	5 414 257	5 083 345	−19.203	4.043	−0.05
3	12 Sep 2012	12:47:25.5	5 413 911	5 083 661	−10.342	3.673	−0.03
4	12 Sep 2012	12:47:25.6	5 413 844	5 083 382	−98.975	3.837	−0.27
5	12 Sep 2012	12:47:25.9	5 414 250	5 083 286	−17.409	3.804	−0.05
6	12 Sep 2012	12:47:26.0	5 414 254	5 083 337	−18 371	3.634	−0.05
7	12 Sep 2012	12:47:26.9	5 414 192	5 083 464	−9.990	3.634	−0.03
8	12 Sep 2012	13:05:28.3	5 416 274	5 083 469	6.827	1.778	0.04
9	12 Sep 2012	13:55:07.4	5 417 713	5 083 341	106.264	1.111	1.00
10	12 Sep 2012	20:57:14.5	5 419 086	5 082 530	−4.052	2.319	−0.02
11	12 Sep 2012	21:18:11.7	5 417 455	5 081 774	9.102	2.753	0.03
12	12 Sep 2012	21:31:03.4	5 420 204	5 085 123	−10.619	2.341	−0.05
13	12 Sep 2012	21:31:03.5	5 419 871	5 085 407	−15.170	2.160	−0.07
14	12 Sep 2012	21:57:00.5	5 422 317	5 083 773	7.678	4.349	0.02
15	12 Sep 2012	21:57:00.6	5 420 535	5 081 331	178.081	3.915	0.48

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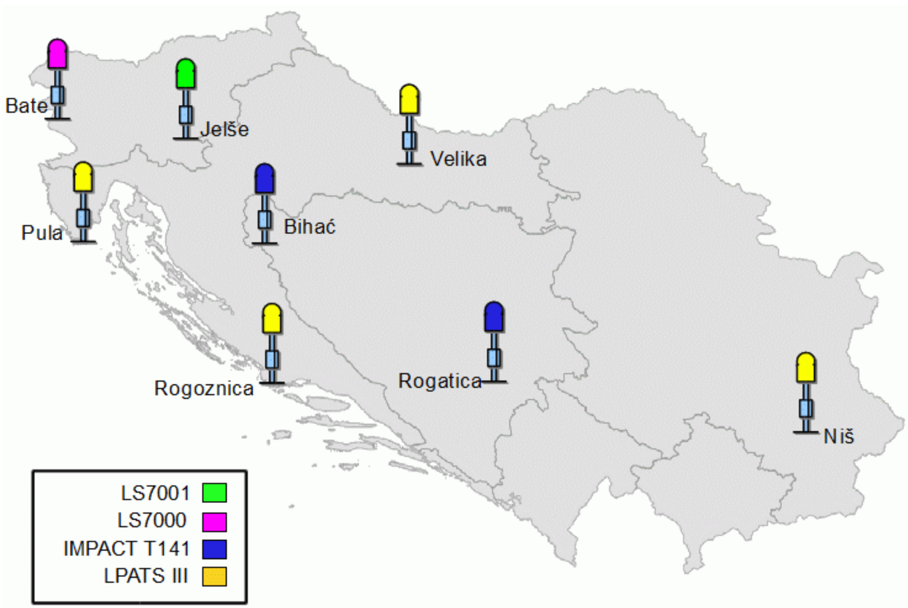

Fig. 1. Deployment of SCALAR sensors.

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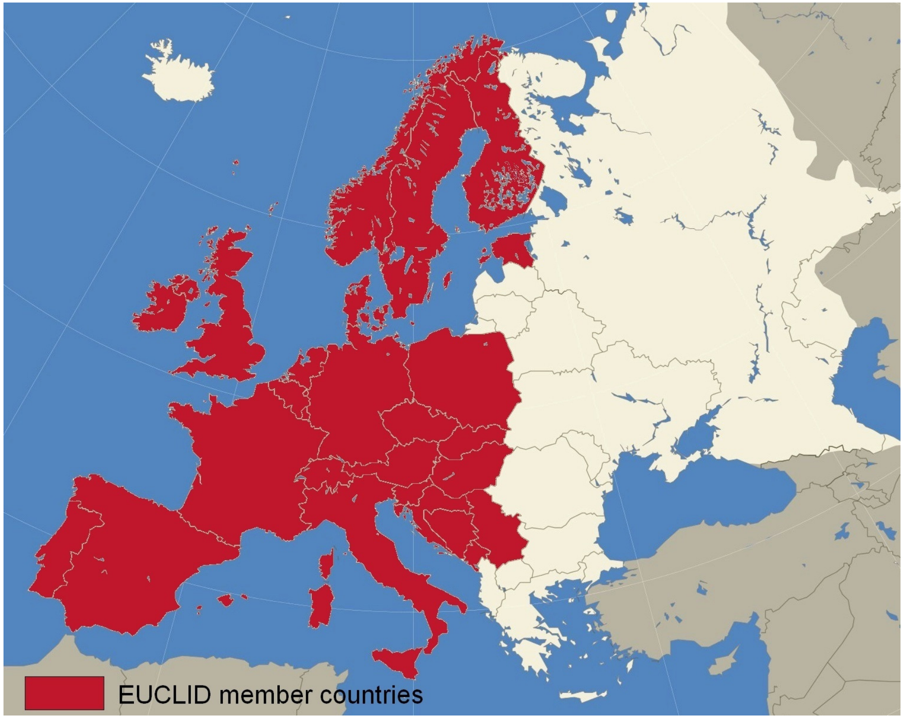

Fig. 2. EUCLID member countries in Europe.

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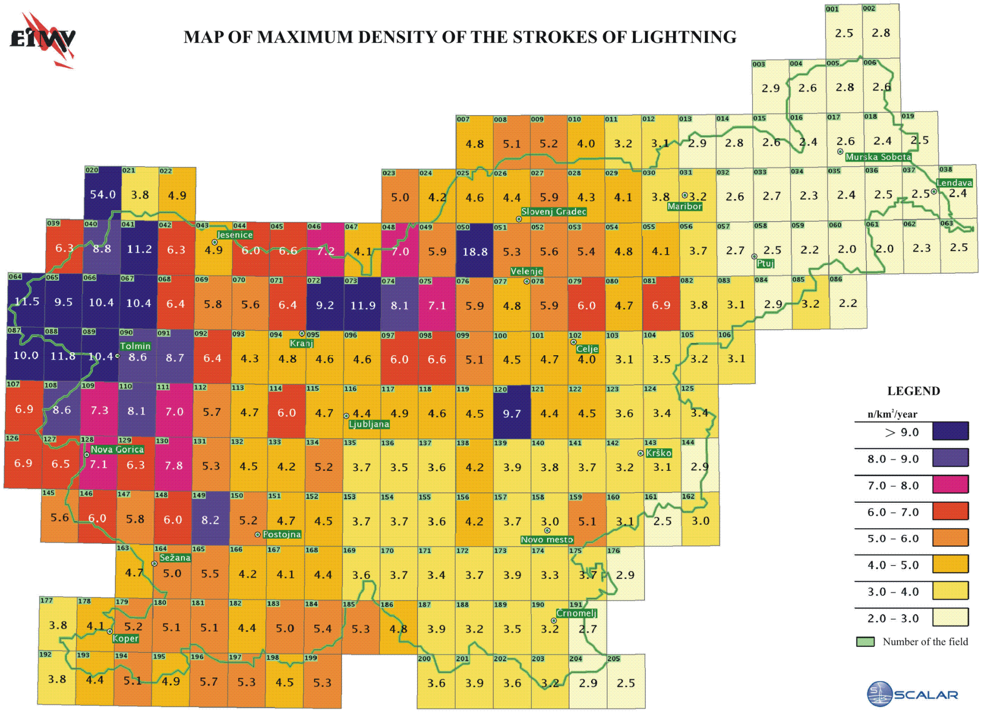

Fig. 3. Map of the maximum yearly number of lightning strokes per km^2 in the territory of the Republic of Slovenia.

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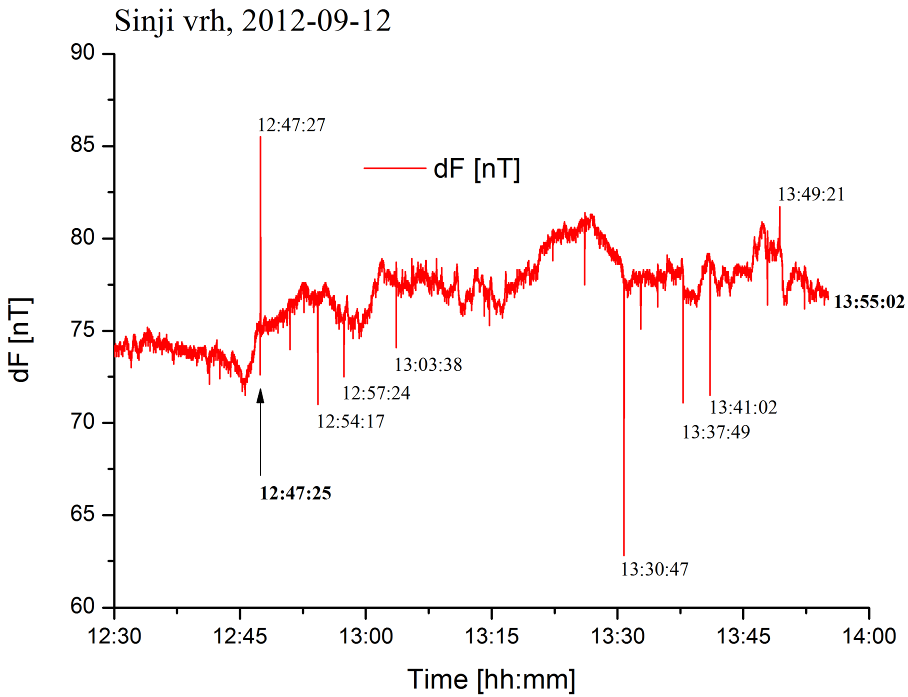

Fig. 4. Variations in the geomagnetic field's absolute values during the thunderstorm on Gora above Ajdovščina.

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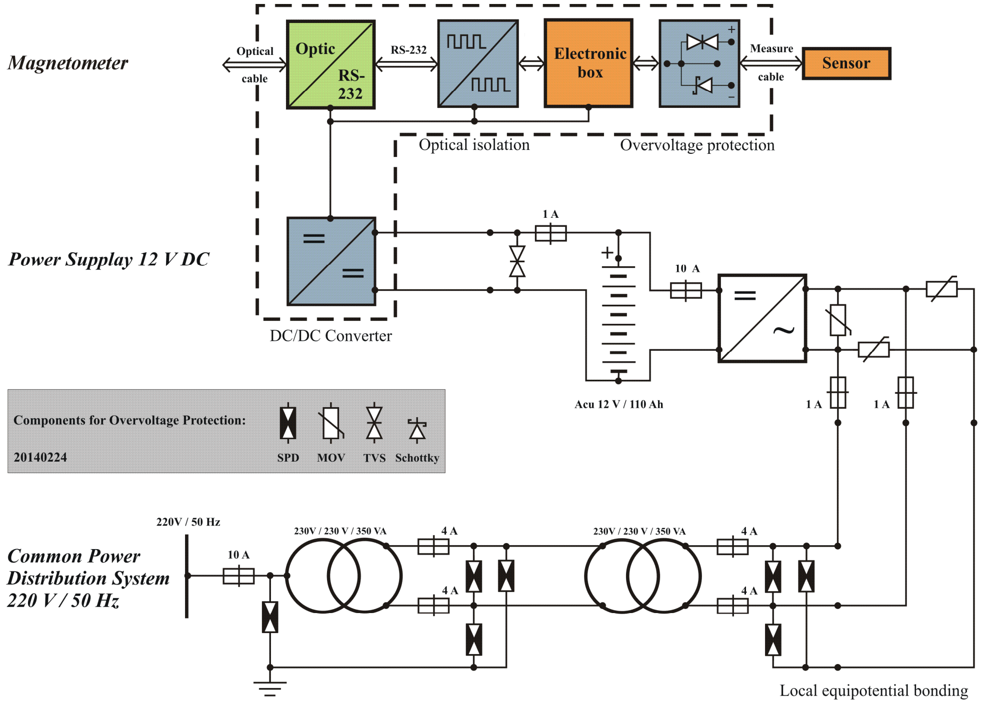

Fig. 5. Flow diagram of the connection of the magnetometer on the low voltage power supply network and its protection against overvoltage.

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